Using Conceptual Graphs to build failure knowledge model for forensic in civil engineering

Quynh Anh Hoang

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POUR OBTENIR LE GRADE DE

DOCTEUR DE

L'UNIVERSITÉ DE BORDEAUX

ÉCOLE DOCTORALE DES SCIENCES PHYSIQUES ET DE L'INGENIEUR

SPÉCIALITÉ: Mécanique

Par Quynh Anh HOANG

USING CONCEPTUAL GRAPHS TO BUILD FAILURE KNOWLEDGE MODEL FOR FORENSIC IN CIVIL ENGINEERING

Sous la direction de Denys BREYSSE et Mehdi SBARTAÏ
(Co-encadrants: Cédric BAUDRIT et Franck TAILLANDIER)

Soutenue le 15 mars 2021

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Titre: Utilisation des graphes conceptuels pour construire un modèle de connaissances des défaillances pour l'Ingénierie Forensique en Génie Givil

Résumé:

L'industrie de la construction est très complexe et implique de nombreux risques. Bien qu'elles procurent des bénéfices importants, les infrastructures telles que les barrages, les ponts, etc. peuvent en cas de défaillance entraîner de lourdes conséquences tant en pertes de vies humaines que matérielles. De nombreux travaux se sont penchés sur les défaillances des barrages permettant de faire évoluer la réglementation pour accroître la sécurité de ces ouvrages. Cependant, malgré ces progrès, des défaillances, parfois majeures, de barrages continuent à se produire, et cela dans le monde entier.

Les approches de gestion des risques permettent de fournir des outils pour minimiser les probabilités et ou les conséquences des défaillances. L'approche traditionnelle de la gestion des risques repose sur l'identification des événements risqués, puis sur l'évaluation de leur probabilité et de leur impact potentiel avant de décider des mesures d'atténuation des risques. Cependant, ces approches ne prennent que pauvrement en compte les retours d'expériences, et les leçons tirées des défaillances passées alors qu'elles pourraient riche d'enseignement pour faire progresser les pratiques.

L'ingénierie forensique est une discipline qui vise à investiguer les défaillances afin de tirer des leçons et d'améliorer les pratiques quant à la conception, la gestion et l'exploitation des ouvrages. L'investigation forensique consiste à étudier les structures, les matériaux, les composants ou les infrastructures ayant fait l'objet d'une ou de défaillances afin de déterminer les causes de ces défaillances. L'analyse croisée de différentes défaillances permet d'identifier les dénominateurs communs à l'origine des défaillances. Les résultats de ces analyses peuvent être utilisés pour améliorer la prise en compte des risques, induire de meilleures pratiques dans la conception et la construction de structures similaires. Cela peut permettre d'éviter la répétition de ces défaillances et de contribuer à l'amélioration de la sécurité de ces structures.

Afin de tirer parti des informations sur les défaillances obtenues à partir des investigations forensiques, de nombreuses bases de données sur les défaillances ont été créées au cours de la dernière décennie. Toutefois, la principale faiblesse de ces bases de données est la difficulté de leur exploitation directe et la cohérence intrinsèque de leurs données. En effet, si elles sont utiles pour référencer des cas et parfois offrir des données statistiques, elles ne permettent pas d'analyse croisée, ou d'inférer automatiquement de la connaissance à partir des cas passés, faute d'un vocabulaire unifié et de moteur d'inférence. Une base de données pour cela, devrait être organisée de manière à ce qu'il soit non seulement facile de trouver les informations, mais aussi de les utiliser pour des études et des analyses ultérieures.

Pour répondre à ces enjeux, nous avons proposé d'avoir recours aux graphes conceptuels (GC) pour construire un modèle de connaissances des défaillances. La structure du modèle que nous avons construit le rend applicable à tout type de défaillance et de structure, mais nous avons plus particulièrement développé le modèle pour les défaillances de barrage. Les graphes conceptuels sont un formalisme de représentation de la connaissance et du raisonnement sous forme de graphe. Ils fournissent un vocabulaire unifié qui forme un support de vocabulaire permettant ainsi de partager et de réutiliser une représentation d'un phénomène ou d'une situation dans le domaine étudié. Les GC fournissent des mécanismes de raisonnement visuel qui peuvent permettre de décrire les processus de défaillance en simulant des interactions entre les composants du système, mais aussi la recherche d'informations et la création de nouvelles connaissances à partir des connaissances déjà présentes.

Afin d'illustrer le fonctionnement du modèle et sa capacité à traiter des défaillances variées, nous l'avons appliqué à cinq cas d'études (deux défaillances de barrages en béton et trois défaillances de systèmes de barrages en remblai). Ces exemples sont utilisés pour démontrer l'intérêt du modèle pour trouver des cas de défaillance similaires, pour proposer des causes possibles de défaillance dans le cadre d'une investigation foresique, ainsi que comme support à l'analyse de risque.

Mots clés: *Ingénierie Forensique, Gestion des risques, Graphes conceptuels, Défaillance structurelle, Connaissance des défaillances*

Titre : Using Conceptual Graphs to build failure knowledge model for forensic in civil engineering

Abstract

The construction industry is very complex and involves many risks. Although they provide essential benefits, infrastructures such as dams, bridges, etc., may, in case of failure, lead to severe consequences in terms of loss of human life and material damage. Numerous studies have looked at dam failures, which have led to changes in regulations to increase the safety of these structures. However, despite this progress, dam failures, sometimes significant, continue to occur throughout the world.

Risk management approaches provide tools to minimize the probability and/or consequences of failures. The traditional approach to risk management is based on identifying risk events, then assessing their probability and potential impact before deciding on risk mitigation measures. However, these approaches take little account of feedback and lessons learned from past failures when they could provide valuable lessons for advancing practice.

Forensic engineering is a discipline that aims at investigating failures in order to learn lessons and improve practices in the design, management, and operation of structures. Forensic investigation is the study of structures, materials, components, or infrastructure that have failed in order to determine the causes of those failures. Cross-analysis of different failures enables the identification of common factors at the origin of the failures. The results of these analyses can be used to improve risk awareness and induce better practices in the design and construction of similar structures. This can help avoid the repetition of these failures and contribute to the improvement of the safety of these structures.

In order to take advantage of failure information obtained from forensic investigations, numerous failure databases have been created over the past decade. However, the main weakness of these databases is the difficulty of their direct exploitation and the lack of intrinsic consistency of their data. Indeed, while they are useful for referencing cases and sometimes offering statistical data, they do not allow cross-analysis or automatically infer knowledge from past cases due to the lack of a unified vocabulary and inference engine. A database for this purpose should be organized in such a way that it is not only easy to find the information but also to use it for further study and analysis.

To address these issues, we have proposed to use Conceptual Graphs (CGs) to build a knowledge model of failures. The structure of the model we built makes it applicable to any type of failure and structure, but we have more specifically developed the model for dam failures. CGs are a formalism of representation of knowledge and reasoning in the form of a graph. They provide a unified vocabulary that forms vocabulary support allowing to share and reuse a representation of a phenomenon or a situation in the studied domain. CGs

provide visual reasoning mechanisms that can be used to describe failure processes by simulating interactions between system components, but also to search for information and create new knowledge from existing knowledge.

In order to illustrate how the model works and its ability to deal with a variety of failures, we applied it to five case studies (two concrete dam failures and three embankment dam system failures). These examples are used to demonstrate the interest of the model to find similar failure cases, to propose possible causes of failure in the context of forensic engineering, and as a support to risk analysis.

Keywords: *Forensic Engineering, Risk Management, Conceptual Graphs, Structural Failure, Failure Knowledge*

Résumé substantiel

Contexte de l'étude

La construction est l'une des principales industries dans tous les pays du monde. Ces produits vont du bâtiment aux infrastructures (routes, voies ferrées, etc.) et aux ouvrages de génie civil (barrage, pont, etc.). Les systèmes de barrages jouent un rôle essentiel dans le système d'infrastructures de nombreux pays. Ils répondent à la demande en eau pour la production alimentaire, la production d'énergie, la lutte contre les inondations et l'utilisation domestique. Si les barrages apportent des avantages en matière de développement, ils peuvent également constituer une menace pour la vie humaine et les biens. Les ruptures de barrage déchargent généralement les flux d'eau en aval, provoquant des inondations qui peuvent balayer des villages, détruire des bâtiments et faire des victimes. Plusieurs ruptures de barrages sont devenues des désastres pour la vie humaine. En 1975, la catastrophe du barrage de Banqiao en Chine a tué environ 171 000 personnes (Mattox et Higman, 2016), (Xu, Zhang et Jinsheng, 2008). Le 11 août 1979, le barrage de Machhu II s'est rompu, provoquant une inondation massive qui a fait entre 5 000 et 10 000 morts (Dhar et al., 1981). Le 31 mai 1889, le barrage de South Fork s'est rompu aux États-Unis, causant plus de 2 200 morts. En France, le 2 décembre 1959, lors du premier remplissage du réservoir, le barrage de Malpasset s'est soudainement rompu et a libéré environ 50 millions de m^3 d'eau, entraînant la mort de 433 personnes.

Après une défaillance, il est essentiel d'identifier l'origine et la séquence des facteurs qui y ont conduit. L'ingénierie forensique est une discipline qui vise à enquêter sur les défaillances afin d'identifier les causes pour en en tirer des leçons et améliorer les pratiques en matière de conception, de gestion et d'exploitation des structures. Les résultats des enquêtes sur les défaillances peuvent être utilisés pour améliorer la sensibilisation aux risques et induire de meilleures pratiques dans la conception et la construction de structures similaires. Ils peuvent aider à éviter la répétition de ces défaillances et contribuer à améliorer la sécurité de ces structures.

Afin de tirer profit des informations sur les défaillances obtenues lors des enquêtes forensiques, de nombreuses bases de données sur les défaillances ont été créées au cours de la dernière décennie. Cependant, la principale faiblesse de ces bases de données est la difficulté de leur exploitation directe et le manque de cohérence intrinsèque de leurs données. Cela est dû au fait qu'elles n'ont pas été organisée de manière à faciliter la recherche des informations et leur utilisation pour des études et analyses ultérieures. Différentes approches et outils ont été proposés pour modéliser et simuler les défaillances, comme les méthodes de gestion des risques, qui sont l'analyse d'arbre des défaillances (FTA), l'analyse des modes de défaillance et de leurs effets (FMEA), le diagramme en arête de poisson, le diagramme d'influence, et d'autres outils comme le modèle Mandalas, le modèle de Risque et le modèle des modes de Défaillance. Néanmoins, ces outils et méthodes présentent des inconvénients pour l'ingénierie forensique. Ils ne décrivent pas la structure entière d'un système de barrage. Par conséquent, il sera difficile de suivre le processus d'une défaillance complexe. Ils

manquent également de généricité, ce qui signifie qu'ils n'ont pas de vocabulaire commun ni d'approche formelle pour décrire la défaillance. Ils ne permettent pas non plus de stocker et de partager les connaissances. En outre, pour un système vaste et complexe, ces méthodes peuvent être compliquées.

Des graphes conceptuels (CGs) (Sowa, 2009) sont proposés pour surmonter ces inconvénients. Un graphe conceptuel (CG) est un formalisme basé sur les graphes pour la représentation des connaissances. Un modèle de connaissance peut instancier des faits (par exemple, un cas d'échec) composant une base de données de connaissances. Les graphes conceptuels offrent l'avantage de fournir la possibilité de partager et de réutiliser une représentation dans le domaine donné. Ils offrent de bonnes capacités de visualisation qui favorisent une compréhension intuitive pour les utilisateurs humains.

Dans ce contexte, nous avons proposé un modèle de connaissance sur la défaillance des barrages basé sur le formalisme des GCs. L'objectif est que le modèle puisse formaliser une défaillance, et que les connaissances issues d'une défaillance puissent être partagées et réutilisées pour tirer les leçons des expériences précédentes.

Démarche méthodologique

Afin de construire un modèle formel de connaissance des défaillances, l'étude a été divisée en trois parties principales : (1) exposer les connaissances relatives au système de barrage pour faciliter l'analyse fonctionnelle et l'analyse des défaillances, (2) analyser les défaillances du barrage pour extraire les facteurs liés à la défaillance, (3) Analyse fonctionnelle du système pour comprendre comment les composants d'un système sont liés entre eux et comment ils interagissent pour atteindre l'objectif du système.

1. Exposer les connaissances relatives au système de barrage

L'objectif principal de cette partie est de fournir des connaissances sur les systèmes de barrages et leurs composants. Elle présente les éléments du système : composants et sous-composants et leurs rôles dans le système. Cette étude se concentre sur les trois principaux types de systèmes de barrages, notamment le barrage en béton, le barrage en remblai et le système de barrage de résidus. Ces trois systèmes de barrages sont différents dans leur conception structurelle et leurs matériaux. Leurs natures et leurs fonctions peuvent varier en fonction de l'objectif du système de barrage.

2. Examen théorique de l'analyse des défaillances des barrages

Afin d'identifier les éléments et d'organiser la structure du modèle de défaillance, il est nécessaire de comprendre les caractéristiques des défaillances des barrages. Cette étude identifie les caractéristiques des ruptures de barrages en se basant sur l'examen de la littérature et l'analyse statistique d'une base de données de vingt ruptures de barrages historiques. À partir de ces analyses, les principaux concepts et relations du modèle de connaissance des défaillances seront définis.

Les caractéristiques d'une défaillance peuvent être :

- La défaillance est généralement le résultat d'une combinaison de facteurs. Les facteurs peuvent être des facteurs environnementaux tels que les tremblements de terre, les inondations, la neige; des activités humaines telles que la construction, l'exploitation, la maintenance qui provoquent des impacts négatifs ; des caractéristiques du système de barrage telles que le type de structure, le matériau et la durée des événements qui peuvent avoir un effet significatif d'une défaillance.

- La défaillance est le résultat d'un processus causé par les interactions entre ces facteurs, qui conduit à modifier l'état du système, et qui aboutit finalement à une défaillance. Ce processus peut être considéré comme une chaîne de cause-conséquences liée à la fonction des composants, déclenché par un ensemble d'événements initiaux.

3. Analyse fonctionnelle

L'analyse fonctionnelle est menée pour étudier un système ou ses parties, pour comprendre la structure du système et son fonctionnement par la formalisation de ses fonctions (modèle fonctionnel). Sur la base de ce modèle fonctionnel, une description de la défaillance ou du processus de défaillance peut être effectuée. L'analyse fonctionnelle est réalisée par la méthode APTE (APplication aux Techniques d'Entreprise), dérivée de l'analyse de la valeur, a été utilisée avec succès et appliquée aux systèmes du domaine du génie civil.

L'analyse fonctionnelle se compose de deux phases, consacrées à deux types de fonctions: l'analyse fonctionnelle externe et l'analyse fonctionnelle interne. Parallèlement, dans l'analyse fonctionnelle, deux catégories de fonctions sont considérées comme reflétant les actions d'un système : les fonctions principales et les fonctions techniques. L'analyse fonctionnelle externe identifie les interactions du système avec des facteurs de l'environnement externe. Elle analyse les fonctions exécutées par le système dans son ensemble. Après avoir terminé l'analyse externe du système, l'analyse fonctionnelle interne peut être utilisée pour formaliser les fonctions de chacun des composants et sous-composants. Les informations obtenues par l'analyse fonctionnelle ont servi de base pour développer le modèle de connaissance des défaillances et évaluer l'état du système.

Résultat de l'étude

Graphe générique

Sur la base des étapes de recherche effectuées ci-dessus, une liste des concepts et des relations est proposée pour développer un modèle de connaissance générique. La figure 00.1 montre le modèle générique du système de barrage au niveau des composants.

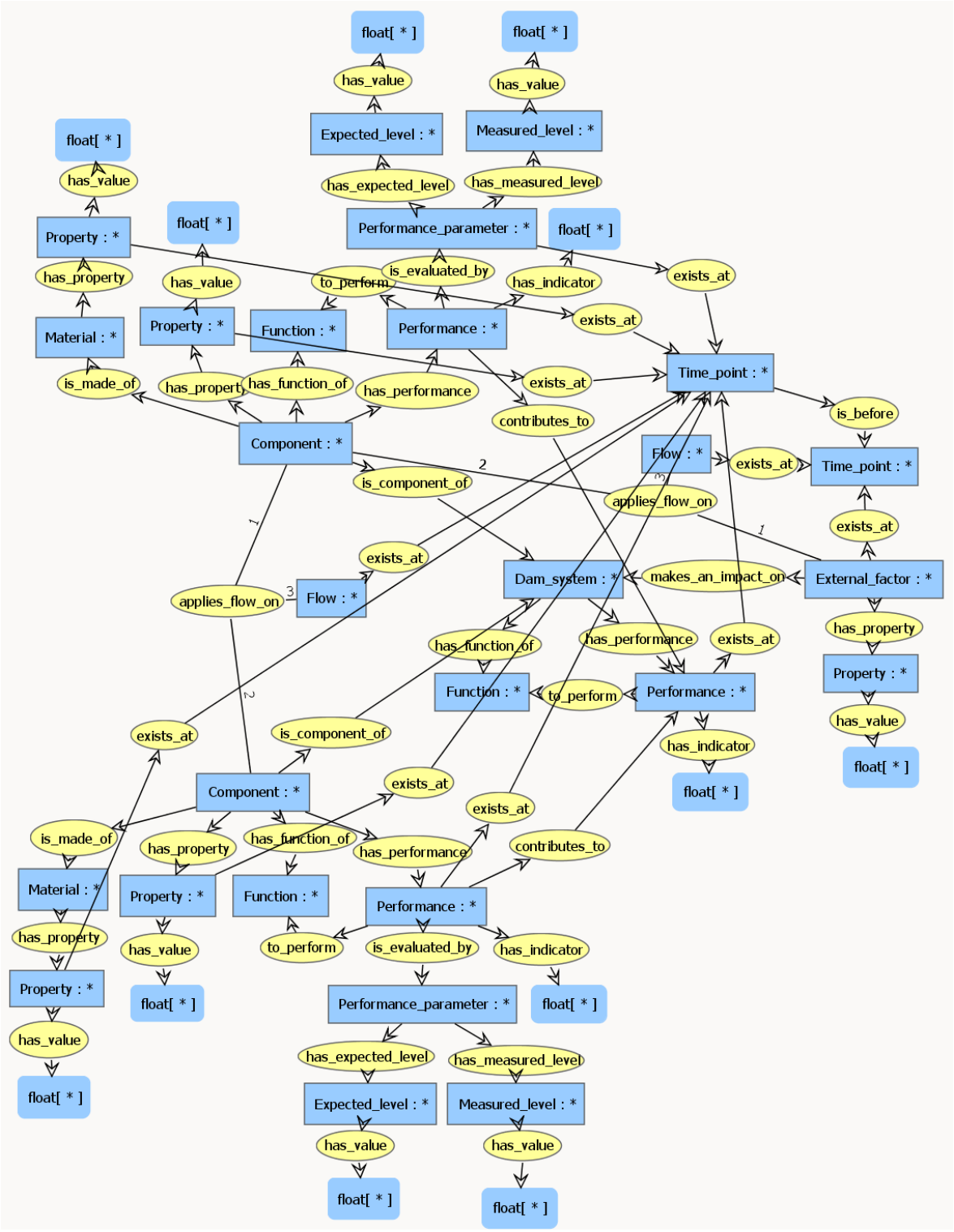

Figure 00.1. Modèle générique au niveau des composants

Le modèle générique intègre :

(1) Une modélisation de la structure du système :

- La structure du système de barrage est présentée avec une hiérarchie de partonomie.

- Le système de barrage est décrit par sa fonction et sa performance ;

- Chaque composant est décrit par sa propriété, son matériau, sa fonction et sa performance;

- L'interaction entre les composants est modélisée par la relation ternaire *applies_flow_on*;

(2) Facteur externe :

- Les facteurs externes sont liés à leurs propriétés;

- Les interactions entre les facteurs externes et le système sont modélisées par la relation binaire *makes_an_impact_on;*

- Les interactions entre les facteurs externes et les composants sont présentées par la relation ternaire : *applies_flow_on* (Flux);

(3) Le temps:

- L'état du système à un moment donné est défini par la relation binaire *exist_at*;

- L'apparition du facteur externe et son impact sur le système à un moment donné est déterminé par la relation binaire *exists_at*;

- L'ordre chronologique entre les deux points temporels est décrit par la relation binaire *is_before*.

Création d'une base de données

Le modèle a été instancié avec cinq études de cas. Les résultats archivés démontrent la capacité du modèle à formaliser différents mécanismes de défaillance pour différents types de barrage.

Utilisation de la base de connaissances

Des graphes requêtes et des graphes règles ont été utilisés pour interroger la base de données afin de (1) diagnostiquer l'état du système, (2) prédire les risques et (3) identifier les causes liées aux défaillances pour en tirer des leçons afin d'éviter que les défaillances ne se reproduisent à l'avenir

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Introduction

1. Context

Construction industry is one of the major industries in all countries in the world. Its products extend from building to infrastructure (roads, railways tracks, etc.) and civil engineering structures (dam, bridge, etc.). In addition to its contribution to the social economy, this industry always has high risks. Although building techniques have been improved year by year, structural failures are still widespread and can cause huge losses regarding people, property, and environment. For example, according to the statistic of the National Crime Records Bureau (NCRB) in India, from 2001 to 2015, the number of fatalities due to the collapse of various structures in India was 38,363 (Dubbudu, 2017). A study of building failures in the United States also showed that between 1989 and 2000, 225 building failures were recorded, increasing year by year (Wardhana and Hadipriono, 2003). In 2011, the disaster of Fukushima Daiichi Power Plant (Japan), due to the combination of a magnitude 9.0 earthquake and a tsunami caused by the earthquake, took over 20,000 lives with long-term health consequences and psychological, social, and economic consequences (Samet and Chanson, 2015). Recently, on August 14th, 2018, the collapse of the Morandi bridge in Genoa has shocked the world. The bridge, built in the 1960s, which connects the Italian Riviera and southern coast of France, collapsed during a sudden, violent storm. Thirty-eight people were killed when a 250m long deck section of the 1.1 km long viaduct, including one of three 90m high bridge towers, crashed to the ground (Wynne, 2018).

Dam system is an essential part of the infrastructure system of many countries. Dams meet demands for water for food production, energy generation, flood control, and domestic use. It is estimated that, currently, dams irrigate about 30 percent of the 271 million hectares worldwide and provide 19% percent electricity supply of the world (Duflo and Pande, 2007). Dams also contribute to 12 - 16% of world food production, and about 12% of large dams are designated as domestic water supply dams (Altinbilek, 2002).

The Report of the World Commission on Dams (WCD) showed a rapid increase in the building of large dams in the 20th century. Specifically, from 1949 to 2000, the number of large dams rose dramatically from 5,000 to over 45,000 large dams throughout the world (Figure 0.1) (World Comission on Dams, 2000)

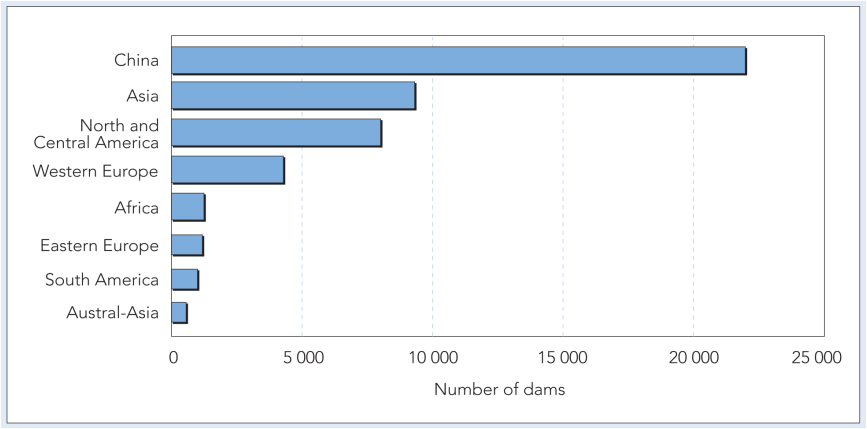

Figure 0.1. Number of large dams distributed by region at the end of the 20th century (World Comission on Dams, 2000)

While dams provide benefits concerning development, they can also be a threat to human life and property. Dam failures usually discharge water flows downstream, causing floods that can sweep away villages, destroy buildings, and take away lives. Several dam failures became disasters to human life; for instance:

- Banqiao dam disaster, China: In 1975, an extremely severe typhoon with rainfall exceeded six times the yearly average toppled Banqiao dam in Henan province, China. The collapse sent water rushing through dozens of dams downstream, killed an estimated 171,000 people, and made 11 million people homeless (Mattox and Higman, 2016), (Xu, Zhang and Jinsheng, 2008). It was one of the worst structural failures in history in the world.

- Machhu II dam, India: on August 11th, 1979, the Machhu II dam broke during exceptionally heavy rains causing massive flooding, resulting in deaths ranging from 5,000 to 10,000 people (Dhar *et al.*, 1981). This disaster was listed as the worst dam burst in the Guinness Book of World Records 1997 (McWhirter, 1997)

In the United States

- South Fork dam: On May 31st, 1889, the South Fork dam breached when it was overtopped during a large storm, releasing the Johnstown flood, which caused over 2,200 fatalities - one of the highest civilian death tolls in the U.S. until today - and damaged the city of Johnstown (Spragens, 2014), (Coleman, Kaktins and Wojno, 2016).

- Teton dam: On June 5th, 1976, the over 93-m-high dam failed during the first filling of the reservoir, releasing a wall of water described as 22.9 m high (Compelo Ltd, 2002). It caused the deaths of 11 people and an unprecedented amount of property losses totaling more than $1 billion (Compelo Ltd, 2002), (White House Records Office, 1976).

In Europe

- Vajont dam, Italy: On October 9th, 1963, approximately 270 million m^3 of a landslide from the southern slope of Vajont dam reservoir suddenly slid into the reservoir, creating a gigantic wave that overtopped the dam and destroyed several villages downstream, causing more than 2,000 casualties in seven minutes (Ward and Day, 2011).

- Malpasset dam, France: On the December 2nd, 1959, during the first filling of the reservoir, the Malpasset dam breached suddenly and released about 50 million m^3 of water, resulted in the death of 433 people and property loss of nearly $70 million (Erpicum *et al.*, 2004).

Every year, the average number of dam failures worldwide is from 1 to 2 (Talon and Curt, 2017). There have been about 200 notable dam failures globally in the 20th century, and more than 8,000 people died in these disasters (excluding fatalities in the Banqiao disaster)

(Jansen, 1983). Many studies investigate dam failures, and regulation has evolved to increase dam security. However, dam failures continue to occur repeatedly throughout the world:

- Oroville Dam, U.S: In February 2017, Oroville Dam gained worldwide attention when its main spillway suddenly failed, resulting in the largest evacuation in California history and nearly resulted in the complete failure of the tallest dam in the United States (Hollins, Eisenberg and Seager, 2018)

- Lao's hydroelectric dam: Recently, on July 23rd, 2018, the collapse of Lao's hydroelectric dam triggered massive flooding and devastation; hundreds of people have been missing, and twenty-six people have been confirmed dead (IFRC, 2018)

Unlike conventional water storage dams, which often store water for electricity production, irrigation, water supply, flood control, tailings dams often contain mill process tailings (or tailing). In the last century, due to the increased number of mining operations and the development of new mining technologies, a lot more waste was generated. According to The Worldwatch Institute (2003), the amount of waste produced by mines is staggering every year. In 2000, mines worldwide extracted more than 900 million tons of metal and generated some 6 billion tons of waste ore. It is currently estimated that there are somewhat more than 3500 tailings dams worldwide (Davies, Martin and Lighthall, 2000). However, it is evaluated that many tailings dams are not being designed, constructed, and/or operated with adequate standards (Davies, Martin and Lighthall, 2000). At least, there was one significant tailings dam failure each year over the past 30 years of the mining industry (Davies, Martin and Lighthall, 2000) (Figure 0.2).

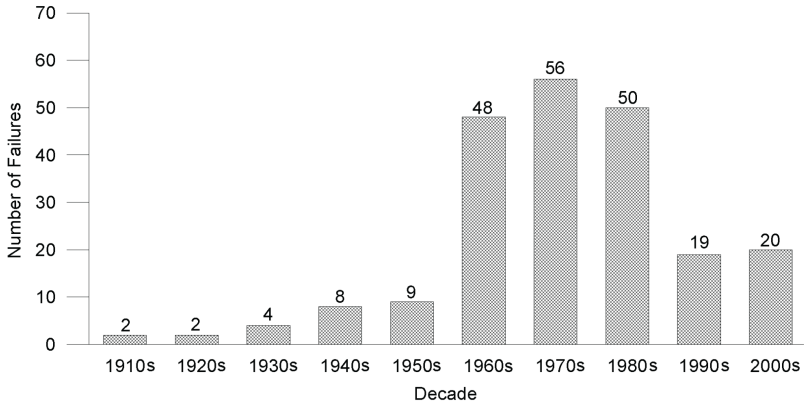

Figure 0.2. Tailings Dam Failures over time (Azam and Li, 2010)

Tailings dam failure and uncontrolled release of the impounded waste have caused casualties and long term environmental damage. Tailings often contain hazardous contaminants such as heavy metals and other pollutants. Heavy metals can lead to long-term consequences to flora and fauna, and cause adverse effects regarding human health.

There were several significant tailings dam failures in recent history:

- **Buffalo Creek (USA)**: On February 26th, 1972, the Buffalo Creek dam collapsed, flowing millions of gallons of water and sludge into the valley below, causing the deaths of 125 persons and the loss of over 500 houses (Green, Lindy and Leonard,

1990)

- **The Church Rock uranium mill tailings spill, USA**: In July 1979, the failure of the retention dam released the most extensive single of liquid radioactive waste in the history of the U.S., causing radiation levels in the Puerco river at 7,000 times the safe drinking water level (Millard *et al.*, 1983), (Morris, 2017).
- **Ajka Alumina Refinery, (Hungary):** On October 4th, 2010, the partial collapse of the dam of vast toxic red mud reservoir No. 10 collapsed. It was followed by a flood of near one million m^3 of alkaline red mud mixed with water plunged into the valley. It resulted in 10 dead people, 123 injured, and significant ecological disasters (Mecsi, 2013).
- **Mount Polley tailings dam (Canada)**: On August 4th, 2014, a partial collapse of the Mount Polley tailings dam released a flow of 25 Mm^3 of mine tailings and water into the Quesnel River basin. The failure was the largest oil spill ever in an accident environment at the time of the accident (Petticrew *et al.*, 2015).
- **Brumadinho dam disaster (Brazil):** On January 25th, 2019, the collapse of a dam storing mining waste in southeast Brazil releases a wave of iron ore waste, which caused 110 killed and 238 missing people. This disaster is now considered Brazil's Worst industrial disaster in Brazil (Burlleigh, 2019)**.**

It should be noted that the Brumadinho dam disaster was the second dam disaster in the state of Minas Gerais in just 4 years. In 2015, another dam, Samarco dam, broke in a different part of the same state of Minas Gerais, causing 19 dead people and hundreds of kilometers of river polluted. That disaster was considered the country's worst environmental disaster (Salinas, 2016)**.**

After a failure, it is essential to be able to identify the origin and the sequence of factors that led to it. This investigation can have several purposes: (1) to define the responsibilities (legal issues) and (2) to draw lessons enabling designers and builders or managers to develop safer alternatives and to improve their practices. This thesis focuses on this second objective, called forensic engineering. Forensic engineering aims to understand the mechanisms that were responsible for the failure (Breysse, Taillandier and Baudrit, 2018). It is based on a thorough analysis of the failure requiring in-depth knowledge of the structure and related risks.

Nevertheless, that is not an easy task because of the broad range of considerations and the number of disciplines involved, and notably regarding dams. The dam is a complex structure. It is composed of many components that have many different properties. A large number of heterogeneous factors such as natural hazards, stakeholder behaviors, construction activities, etc., may impact component properties, which can create a process of chained influences that may lead to failure. To address several fundamental issues from this complexity, it is necessary to establish, organize a model able to formalize the knowledge related to the structure of the dam system, the flows that may impact it, and the

interaction between components. From this knowledge, it would be possible to model how a failure occurred.

In particular, a suitable model should integrate:

- vocabulary that provides background knowledge on a specific application domain; this vocabulary must be consistent with the domain practices and able to support the dam failure model,
- a generic structure based on the vocabulary that allows us to represent failure enabling us to understand how it occurred or may occur,
- modeling of relationships between external factors and the dam structure, and between the components of the dam,
- modeling of the failure process that describes events, influences, characteristic mechanisms in a chronological sequence.

In addition, we want the model will be:

- flexible in use; it must be easy to update and improve,
- understandable and accessible to non-computer scientists (ergonomics),
- allow an easy instantiation: One can quickly enter a new failure case,
- allow anyone to perform requests on the database in order to be able to infer new knowledge; it requires an adapted inference engine.

2. Problematic

We highlighted the importance of forensic engineering and of having a dedicated model and method. However, the scientific literature has not yet shown much interest in this field. On the contrary, the technical and scientific literature is rich in terms of risk analysis methods. They are generally performed before a failure in order to identify potential problems in a structure. But some of these analysis techniques and tools allow to simulate and/or formalize failures that could happen, their consequences, or how a failure occurred; regarding this last issue, they could be relevant in a forensic engineering use. Chapter 1, dedicated to state of the art related to risk analysis, will expose in more detail these methods and tools that can be really useful in a forensic engineering investigation. Nevertheless, these tools and methods present some limitations:

- Few of these methods allow identifying or formalizing chained failures (multi-risk perspective) (D. N. D. Hartford and Baecher, 2004), (Larrucea *et al.*, 2011), (Schiller, Miller-Kovach and Miller, 1994), (Doggett, 2005).
- Most of these methods consider only a part of the system (e.g., one component) and not the whole system with different components in relation (T Aven, 2008), (Larrucea *et al.*, 2011).

- They may overlook causes but focus on consequences (Rausand and Hoyland, 2004), (Harrington and Voehl, 2016), (Aven, 2008);
- They do not consider (or in a straightforward way) the time dimension, which is essential to understand a failure process.
- For analyzing a large and complex system, they tend to become heavy and tedious works. They may require a great deal of time and a significant resource in the application (Larrucea *et al.*, 2011), (Baig, Ruzli and Buang, 2013), (D. N. D. Hartford and Baecher, 2004), (Ericson, 2005), (Stamatis, 1997).
- The result of these methods (e.g., failure diagram) can be challenging to understand by a non-expert, specifically when the analyzed system is complex (D. N. D. Hartford and Baecher, 2004), (Ericson, 2005).
- They lack genericity; they can be performed in different ways, and therefore, produce non-consistent results (Baig, Ruzli and Buang, 2013), (D. N. D. Hartford and Baecher, 2004), (Rausand and Hoyland, 2004), it means that they lack common vocabulary and a formal approach to describe failure. They do not compare different diagrams built with these approaches quickly and draw knowledge from their comparison.

Conceptual Graphs (CGs) (Sowa, 2009) are proposed to overcome these drawbacks. A conceptual graph (CG) is a graph-based formalism for knowledge representation. They depict significant structures and facts about the world (Mineau, Stumme and Wille, 1999). Conceptual graphs offer many benefits. The first one is to provide a common vocabulary on which a knowledge model can be based. This benefit supply the capability to share and reuse a representation in the given domain. The knowledge model can instantiate facts (e.g., failure case) composing a knowledge database.

Furthermore, it offers different inferences on the knowledge base, allowing the user to perform requests in the new knowledge (e.g., “find the case similar to mine in the knowledge base”) and to infer knowledge based on a rule system (Croitoru, 2006). The second benefit is they offer good visualization capabilities that support an intuitive understanding for human users. Conceptual graphs formalism can allow users to have a maximal understanding of failure, failure process, and its causal interactions.

Building the knowledge model via the CG involves several challenges. The first challenge is to account for the suitability of common vocabulary for any type of structure system, considering the heterogeneity of the components of the system. The second challenge concerns the formalization of the structure of the model, which should be able to support reasoning about failure fact. The third challenge is to be able to model the relationships between the external factors and the system and causal interactions between components of the system.

3. Objectives of the thesis

This research aims at developing a knowledge model about the failure of dams based on CGs formalism. It results in a graph-based approach, which has the advantage of providing visual reasoning that facilitates an intuitive understanding of the failure. The objective is that a failure can be formalized by the model, and so knowledge from failure can be shared and reused to make lessons from previous experiences. Thus, specific objectives of our research are as follow:

1) Development of a common vocabulary (concepts – relations)
2) From the established vocabulary, the development of the graphs-based model by using the GCs formalism. The model will have to capable of (1) representing all type of Dam systems and (2) describing failure modes over the times
3) From the established model,
    a. the building of a graph database on which to rely to find similar cases faced with a new failure
    b. the simulation and forecasting of failures (forward)
    c. give the most likely explanations that led to a failure (backward-forensic)

4. Thesis outline

This thesis is organized as follows:

Chapter 1 provides a general introduction to risk management in civil engineering. In this part, the main concepts of risk, risk management steps, and their tools and techniques are discussed. Specific tools and techniques to manage risk for the dam system are introduced. This chapter provides an overview of risk management, which is the background to develop the next chapters.

Chapter 2 deals with two topics: forensic engineering and conceptual graphs formalism. The first one introduces forensic engineering investigation, where the goal of learning from failure is emphasized. As an answer, the second topic consists of presenting conceptual graphs formalism to build a failure knowledge modeling. The main elements and properties of the conceptual graphs are introduced. A brief introduction of the CoGui software, which is used in this work, is proposed.

Chapter 3 exposes knowledge related to the dam system and dam failure to understand the structure of the dam system to facilitate functional analysis and failure analysis. It begins with a description of the dam system with its components, the functions of the dams and other components. An analysis of dam failures is then conducted by analyses of their historical failures to define the factors related to the failure process, i.e., factors that can trigger a failure to occur, participate in the failure process, exacerbate, or minimize it. The

next part is a functional analysis of the system to understand how the elements are interrelated and how they interact to achieve the system's purpose.

Chapter 4 is dedicated to build a formal failure knowledge model. The model allows describing failure for all dam and other structures based on a unified understanding of the structural components. It integrates the relationships between the components, interactive flows between the system and external factors, and the system itself. Besides, it considers effects, changes in the system according to chronological order and describes a system's state at a point in time. It also explores failure at a different systemic level to logically and systematically describe it. The next part presents the method to initiate the knowledge model and how to use it.

Chapter 5 provides an application of the failure knowledge model to instantiate the proposed model based on a real failure case. A fact graph of failure, formalizing the failure process of historic dam failure, will be created based on the vocabulary and the set of rules in the knowledge base. Then, the fact base is used to infer new knowledge. The set of failure instances can be used to identify similar past failure cases. It also enables creating a set of rules allowing to identify risks related to a dam.

Appendix 1 presents a set of definitions of terms used to develop fact graphs of dam system failure. Appendix 2 exposes components and their functions of the dam system. Appendix 3 provides a database of twenty failure cases of dam systems. Appendix 4 deals with the functional block diagrams for the concrete dam, embankment dam, and tailings dam system. Appendix 5 gives a table of functions of sub-components of the dam system. Appendix 6 shows the hierarchies of concepts and relations of the model developed in CoGui. Appendix 7 deals with the instantiation of four failure knowledge model of Pilarcitos dam, Sella Zerbino Secondary dam, Tous dam system, and Sparmos dam system failure. Appendix 8 present a set of rules for the instantiation of the failure model.

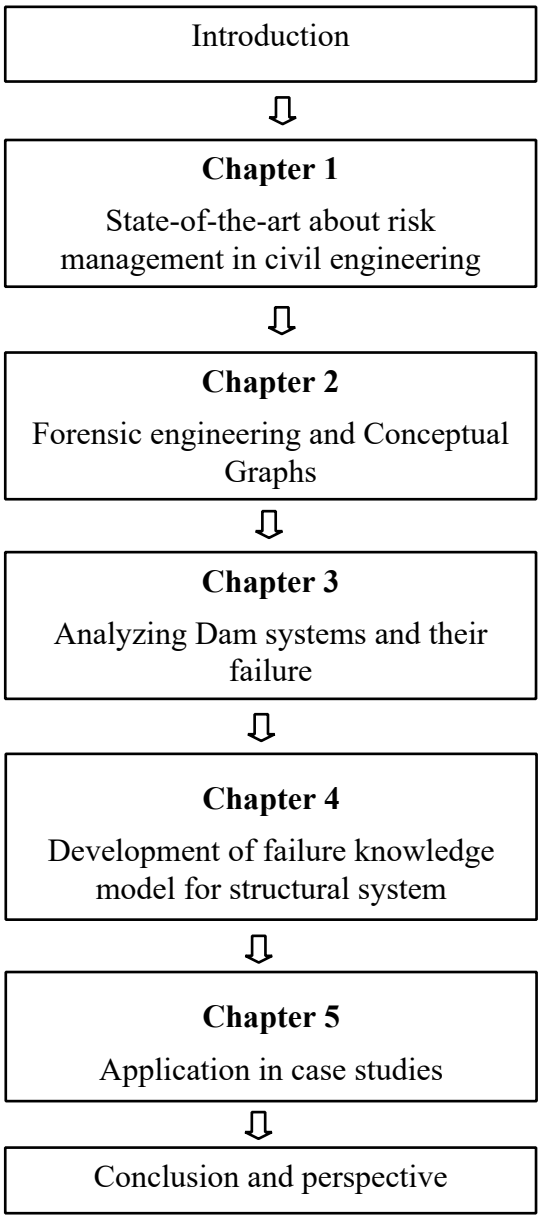

Figure 0.3. Outline of the thesis

DEFINITIONS

1. System

The term *system* is derived from the Greek word *systema*, describing an entity consisting of several parts or elements (Fleming, Kokkos and Finnegan, 2019). The concept system exists in many fields. There are several definitions of the word *system*:

- *Definition 1*: Merriam-Webster's Collegiate Dictionary defines a system as "a regularly interacting or interdependent group of items forming a unified whole".
- *Definition 2*: A system is an assemblage formed to satisfy specific objectives and consisting of two or more components that are interrelated and compatible, each component being essential to the required performance of the system. (Merritt and Ricketts, 2001)
- *Definition 3*: A system is "a set of elements or parts that is coherently organized and interconnected in a pattern or structure that produces a characteristic set of behaviors, often classified as its "function" or "purpose." (Meadows, 2008)
- *Definition 4*: "A system is a set of interrelated components working together toward some common objective" (Kossiakoff *et al.*, 2011)
- *Definition 5:* The International Council on Systems Engineering (INCOSE) defines a system as " a purposeful whole that consists of interacting parts." (INCOSE, 2015) .
- *Definition 6:* A system is "a group of elements, that is organized and arranged in such a way that the elements can act as a whole toward achieving some common goal or objective" (Kerzner, 2017)
- *Definition 7:* "A system consists of a set of elements (e.g., components) that work together to perform one or more functions" (Bhise, 2014).

These definitions concern with system that is a whole (i.e., *definition 1, 5, 6*) consisting of elements or parts interacting (*i.e., definition 1, 2, 3, 4, 5, 6, 7*) to perform system function (*i.e., definition 3, 4, 5, 6, 7*). So, we can define a system as:

A system is a whole composed of components organized in such a way that the components interact with each other to perform designated functions of the system.

For example, a bridge is considered as a system consisting of integrated components such as piers, abutments, wing walls and returns, parapets and handrails, and foundation. Similarly, the dam system is organized as a system consisting of interacted components such as a reservoir, dam, abutments, and foundation. None of these components is used as a single, independent unit. When they function and integrate with each other, the system can work effectively and efficiently. Each component is part of the total system and has to perform to achieve the intended function.

2. Component of the system

According to the Cambridge dictionary, the term ***component*** is defined as "a part which combines with other parts to form something bigger". In combination with the definition of a system, the word ***component*** is defined as follow:

Component is a part that, in interaction with other parts, form a system

A system can be decomposed into components, which can be decomposed into a further level of subcomponents or elements. Thus, a system consists of a hierarchy of components. For example, a system such as a building will have a number of components such as roof, foundation, columns, beams, staircase, etc.,. Each of the components can be further divided into subcomponents. For example, the stairs will have tread, riser, nosing, skirting, handrail, … so on.

3. Interaction

A system comprises two or more components. In general, a function performed by a component requires other functions performed by other components. It means that each component performs its function by interacting with each other. There are many definitions of the term ***interaction***:

- *Definition 1*: According to the Merriam-Webster dictionary:

  Interaction (n): mutual or reciprocal action or influence;

  Interact (v): to act one upon another;

- *Definition 2:* IEEE Standard for Modeling and Simulation (M&S) High-Level Architecture (HLA) provides a definition of interaction as follow:

"An interaction is any action taken by an object that may have some effect or impact on another object" (Birta *et al.*, 2015).

- *Definition 3:* Regarding Model-oriented Systems Engineering Science, (Hybertson, 2016) defines interaction:

  Interaction: action among two or more parties.

  With a note that the number of parties involved in any interaction is two or more one or more connector parties, and zero or more intermediary parties.

  Action: Act; the smallest unit of an activity or process.

- *Definition 4:* Many authors provide the concept of interaction:

  "An interaction is a kind of action which occurs as two or more objects affect one another" (Khosrowpour, 2012), (Irfan, 2018), (Becnel, 2019).

  In which, (Khosrowpour, 2012) emphasis that the idea of a two-way effect is essential in the concept of interaction, as opposed to a one-way causal effect.

- *Definition 5*: (Gupta, 2011) defines interaction in a system concerned with the functions of components:

  Interaction refers to the manner in which each component functions with other components of the system.

- *Definition 6:* In an alternative definition of interaction (Schindel, 2013) defines interaction in terms of exchange:

  Interaction: an exchange of energy, force, mass by two entities, in which one changes the state of the other.

- *Definition 7:* (Jos P. Leeuwen and Timmermans, 2006) in the context of a design optimization system, introduces the concept of interaction as the key element of the system because it establishes the relationships between components of the system, and it provides the opportunity for change. The author said that ***interaction*** refers to a situation in which every component has the potential to induce changes in other components.

- *Definition 8:* (Antonelli, 2011), regarding the functional representation of a system, stresses the idea of changing. The term ***interaction*** means changing the state (some of their parameters/ characteristics) of the system. This is explained by the mutual interaction between the system and flow in the system, which modifies their statuses. In other words, interaction determines the changing of the system's states.

- *Definition 9:* (Tutorials Point, 2018) in system analysis and design suggests that

Interaction is defined by the manner in which the components operate with each other.

From the above definitions, there are some characteristics of interactions:

- Action among two or more parties (*i.e., definition 1, 2, 3, 4*);

- Mutual or reciprocal action or influence (*i.e., definition 1, 2, 3, 4*) means that two-way effect upon one another (i.e., definition 4);

- An exchange of energy, force, mass by two entities (*i.e., definition 6*);

- The manner in which each component functions with other components (*i.e., definition 5, 9)*;

- A situation in which each component has the potential to induce changes in other components (*i.e., definition 7, 8);*

We can see that action of an element in system can be considered as its function; the exchange of energy, force, mass by two entities is a type of action of the component; the changes due to other component is the result of an action. So, the characteristics of interaction are: action among two or more parties and have reciprocal mutual influence.

Definition of ***interaction***:

An interaction is a kind of action that occurs as two or more objects affect one another.

For example, a building can be treated as a system. It is composed of building components such as walls, floors, foundation, beams, columns. The components are interacted with each other to provide their functions:

1. Walls can support the load from the roof, floors, and divide the spaces in the building.

2. Floors provide surfaces to support loads placed on it, including the weight of the walls

3. Foundation transmits loads of the superstructure to the ground

4. Beams connect columns and support floors.

5. Columns support beam and transmit the weight of the structure above to other structural elements below

Interaction means acting reciprocally, acting upon each other. Nevertheless, interaction is more than action followed by a reaction. It means that one object acts on another, and the response will subsequentially change its next action, and so on.

When any system component is changed or eliminated, the rest of the system's components are also significantly affected. For example, in a dam system, the dam component interacts with the foundation and abutments. If the foundation slips or deforms, the dam will have significant potential to collapse.

In interaction, each component performs its function and contributes to the function of the system. The performance of the system in serving its specific function is contributed by the performance of each component in meeting its function. For example, the combination of walls, floors, foundation, beam, columns in the building system contributes to the function of providing shelter for the building. The required performance of the building to perform this function is provided by the performance of each component.

4. Structural system

Based on the EN 1990 Eurocode (CEN, 2005), the term *structural system* is defined:

A structural system is an assemblage of load-bearing components that interact with each other to perform a designated function of the system.

For example, building system, bridge system, dam system.

The basic function of a structural system is to resist all applied loads without failure during its intended life (Mrema *et al.*, 2011). For example, bridge structure systems support a deck that allows the passage of pedestrians and vehicles; dam systems retain large volumes of water. The function of a system is provided by the function of structural components, such as a function of dam system is provided by functions of the dam, e.g., to resist earthquake, to resist hydraulic load; functions of foundation, e.g., to resist weight load of the dam, to

resist shear load; functions of the spillway, e.g., to resist discharge flow. The performance of the system will be unacceptable if the performance of each component that makes up it is not satisfied.

The dam system is a hydraulic structure, which is a subtype of a structural system. Its functions are related to the flow and transport of fluids, mainly water. Hydraulic structures must withstand the mechanical impacts of environmental conditions, flow conditions, and loads caused by static and flowing water.

5. Function

Any civil engineering structure is intended to fulfill one or many functions. For example, dam systems are built for water supply or irrigation. They also can be used for flood control or electrical generation. For a bridge, the primary function is to span a physical obstacle, such as a body of water, valley, or road, without closing the way underneath. There are many definitions of function:

- *Definition 1:* The European Norm EN NF 50-151 gives the following definition of a function: "Action of a product (system) or from one of its components express exclusively in terms of finality". (ZIV, 2018)
- *Definition 2:* (Ayyub, 2014) discussed function in the context of risk analysis in engineering and economics. A function is defined:

  Functions are what a system should do.
- *Definition 3:* According to (Wasson, 2006), in the Wiley series in system engineering and management, a function is defined as "an operation, activity, process, or action performed by a system element to achieve a specific objective within a prescribed set of performance limits."
- *Definition 4:* (Wilde, 2018) talk about function in the building performance analysis. Here the function is defined as "what a system or object is expected to do".
- *Definition 5:* (Cremona, 2011) defines the function of a structure

  "The functions of a structure generally describe the requirements to be fulfilled".
- *Definition 6:* (Carlson, 2012) defined:

  "A function is what the item or process is intended to do, usually to a given standard of performance or requirement."
- *Definition 7:* (Stone and Wood, 2000) defines function in the development of a functional basis for design:

  "Function is a description of an operation to be performed by a device or artifact"
- *Definition 8:* (Terje Aven, 2008) defines function in risk analysis:

  "The function of the component, i.e., its working tasks in the system."

These above definitions refer to the term function, which is the intended purpose, an operation, or action, requirement, working task, performed by an object such as a system, component, structure, or a device, usually to a given standard of performance (i.e., *definition 2, 5*). So, we can define a function as:

Function is what the system or component is intended to do, usually to a given standard of performance.

6. Performance

When studying a system, we are concerned with how well a structure performs its functions. There are many definitions of the term *performance* as follow:

- *Definition 1:* The Cambridge dictionary (Cambridge University, 2020) defines performance as:

  "Performance refers to how well an activity is done."

- *Definition 2:* (Cremona, 2011) defines structural performance as:

  *"*The structure's ability to fill its function is known as performance."

- *Definition 3:* In decision making in systems engineering, (Parnell, Driscoll and Henderson, 2011) defines:

  Performance of a structure let us know how well a structure perform its mission

- *Definition 4:*

  In the context of systems engineering, performance is defined as a quantitative measure characterizing a physical or functional attribute relating to the execution of a process, function, activity, or task. (INCOSE, 2015) p264

- *Definition 5:*

  Performance is an attribute of a system that describes 'how good' a system is at performing its functional requirements in a way that can be measured (Wilde, 2018)p10.

- *Definition 6:* (Leonardo da Vinci Pilot Project CZ/02/B/F/PP-134007, 2004), in providing a manual for the development of skills facilitating the implementation of Eurocodes, discusses performance as a quantitative expression (value, grade, class, and level) of the behavior of a structure for an action to which it is subject.

- *Definition 7:* (Curt, Peyras and Boissier, 2010), in the assessment of dam performance, suggests that

  "Performance is defined as the capability of an infrastructure to perform the functions for which it was designed."

- *Definition 8*: (Ayyub, 2014) in risk analysis in engineering and economics defines that "Performance of a system or component is its ability to meet functional requirements."
- *Definition 9*: (Serre *et al.*, 2008) in performance assessment of levee suggests that performance is the aptitude of the structure to render the service for which it was designed.
- *Definition 10*: (Peyras, Royet and Boissier, 2006) in dam aging diagnosis and risk analysis defines:

  Performance is defined as the ability of the dam or one of its components to perform the functions for which it was designed.

From the above definitions, it is clear that the performance of a system or component relates to how well it's function is performed (i.e., *definition 1, 3, 5*), which is similar to the description as a quantitative expression of the execution of a function (i.e., *definition 4, 6*), or in general performance is capacity to perform a function (i.e., *definition 2, 7, 8, 9, 10*). So, we have the definition of performance as follow:

Performance is the capacity of a system or component to fulfill its function.

For example, a reservoir of a dam system performs its function that is retaining water. The corresponding performance for this function is the capacity to retain water, which can be expressed through performance parameters such as the volume of the reservoir or the height of water. Another example is about dam component. This component has to meet the function of resisting sliding. Its respective performance is the capacity to resist sliding, which can be measured by the factor of safety against sliding.

Performance is an attribute of structure. It can change over time due to the effects of external loads or degradation processes. Comparison between designed performance with measured performance helps assess the progress of a function. If the measured performance exceeds a predetermined reference threshold, the structure can be failed.

7. Failure

To describe failures, defining the term ''failure'' is essential. To some, the word "failure" implies real physical failure, such as a fracture or collapse. There are definitions as follow:

- *Definition 1:* According to the International Commission on Large Dams (ICOLD, 2017), the term failure of the dam is defined as a "collapse or movement of part of a dam or its foundation, so that the dam cannot retain water".
- *Definition 2:* The Federal Emergency Management Agency (FEMA, 2013) defines failure as " Catastrophic full or partial collapse of a dam structure characterized by the sudden, rapid, and uncontrolled release of impounded water."
- *Definition 3:* A definition of a dam failure states failure "in terms of a complete dam

breach followed by a significant release of water from the reservoir" (E. Slunga, 2001).

- *Definition 4*: The Guidelines Management Committee of the Canadian Dam Association (CDA) (Taiao, 2017) approve the following definition of dam failure:

  "Failure was defined as damage sufficient to lead to breaching of the reservoir, or its abandonment or temporary removal from an operation."

Nevertheless, failure in civil engineering not only limited to catastrophic structural collapse or rupture but also encompasses structural issues during construction or throughout the design life of structures; examples include unacceptable cracking, differential settlement, excessive seepage, poor quality material, erosion, which can lead to dysfunction of the structure. Further definitions of failure are given below:

- *Definition 5:* The Committee on Forensic Investigation of the Forensic Engineering Division of the American Society of Civil Engineers ASCE considers failure in civil engineering as:

  "Failure may be considered as an unacceptable difference between expected and observed performance" (Barrow *et al.*, 2018).

- *Definition 6*: (Johnson *et al.*, 2011) gives the following definition: "A failure is defined as the unacceptable performance of intended function".

- *Definition 7*: (Rao and Babu, 2016) has introduced the definition of failure:

  "Failure is generally defined as the inability of a component, structure, or facility to perform its intended function".

- *Definition 8:* According to (Tinga, 2013), failure of structures or (parts of) systems is "considered as reaching such a state that the intended function of the part or system can no longer be fulfilled".

- *Definition 9*: (Vincoli, 2014) sees failure as "the inability of a component or system to perform its designed function within specified limits".

These definitions concern with failure that is an unacceptable performance (*i.e., definition 5, 6*) or the inability of a structure (*i.e., definition 7, 9*) to perform its designed function (*i.e., definition 6, 7, 8, 9*). This also corresponds to the intended function of a structure that cannot be implemented longer (*i.e., definition 8*).

So we choose a definition of *failure* as follow:

Failure is defined as an unacceptable performance of a structure to perform its designed function.

There is a relation between failure, function, and performance. Failure is identified through the evaluation of performance. Performance, in turn, relates to the function of the structure. For example, the function of a conduit in a dam system is to control the level of the reservoir. If the capacity of the conduit to discharge water is unacceptable, then the conduit cannot fulfill longer. This means that failure is generally related to the performance

requirements of the structure.

It is evident that failure related to the performance of a structure provides a concept of failure that is much larger. It is a broad range from a spectacular dam collapse to relatively simple deficient structural, material problem, such as concrete crack, excessive movement of the structure, causing a complete shutdown of a component or system. This definition, along with the complexity of structure, may present a large number of failures. It should be noted that minor failures are not an immediate threat to the overall stability or integrity of the dam. However, minor failures are progressive and often lead to failure if untreated. Therefore, for the discussion of failures to be most helpful, performance problems that are less than catastrophic or life-threatening must be included

Failure can be defined on several levels or parts of the system or the system as a whole. For example, one failure of an embankment dam is the dam breach. The dam also has several failures of its components, like inadequate drainage of horizontal drainage blanket, cracks of the core wall, or sliding of the downstream face.

8. Knowledge model

The term *knowledge model* deals with the understanding of what constitutes "knowledge". Knowledge relates to data and information, yet knowledge is neither data nor information. There exists a hierarchical order between data, information, and knowledge. Information is derived from data, and knowledge is derived from information (Zins, 2007).

- Data are sets of raw facts, observations, and figures without context (Karagözoğlu, 2017), (Henry 1974; Rowley and Hartley 2006), (Belinger et al. 2004), (Elearn, 2007). For example, data of dam failures over the world during the 1980's and 1990's.
- Information is data that has been organized, processed, and interpreted in a given context, and thus gives meaning to the recipient (Davis (Jamie Brown Kruse, Crompvoets and Pearlman, 2018), (Karagözoğlu, 2017). For example, data of earth dam failures are analyzed and show that over 80% of all failures of earth dams are caused by overtopping and seepage. It is information that has meaning for civil engineers.
- Knowledge is a general understanding, and awareness garnered from accumulated information, tempered by experience, enabling new contexts to be envisaged (Zins, 2007), (Sage and Rouse, 2009). Take an example such as information about the failure of the earth dam, which can be used to investigate and diagnose causes of dam failure, and it becomes knowledge.

Knowledge assets can be explicit or tacit. Explicit knowledge is easily captured, codified, and transferred (Wu, Zhao and Pan, 2016), (Kivrak *et al.*, 2008). It consists of the facts and figures, things that can be written down or found in a database. It can be stored for later use as written documents or procedures and made available to others. Specifications, textbooks, and design codes are some examples of explicit knowledge (Kivrak *et al.*, 2008). Unlike

explicit knowledge, tacit knowledge is that knowledge gained from experience, actions and usually depends on the context of its application (Johnson *et al.*, 2011). Therefore, it is hard to formalize and communicate. It is stored in humans' minds and is difficult to see, share, copy, and manage. Tacit knowledge is accessible if converted to the explicit one (Wu, Zhao and Pan, 2016). The tacit knowledge is optimized in that many techniques will be skipped because of prior experience.

Knowledge is developed over time through experience that includes what we absorb from courses, books, and mentors, as well as informal learning. Experience refers to what we have done and what has happened to us in the past (Davenport, Prusak and Webber, 2003).

Modeling techniques allow the physical system or process to be visualized. A model is defined as a simplified and abstract representation of something (content, meaning), for some purposes (usage context) (Muller *et al.*, 2012), (Sage and Rouse, 2009), (Birta *et al.*, 2015). For a system or process is complex, models are used to illustrate relationships and interactions among system component (Bartolomei, 2007). They are tools for description, analysis, prediction, and communication (Sage and Rouse, 2009).

So **a knowledge model is a simplified representation of knowledge of a given domain, for some purposes**.

For example, a failure knowledge model in civil engineering shows us understanding about the failure process, behaviors of a system under impacts of external factors, and interactions of components of the system. The model can provide failure knowledge, building a failure database, sharing knowledge or knowledge management. Another example is a project knowledge model, which describes processes, procedures, requirements when implementing a project. It will be helpful for project management.

A knowledge model can provide an effective means for capturing and retaining knowledge in an organization, especially tacit knowledge (Bessick and Naicker, 2013). This knowledge, which can be reused and evolved, provides a basis for supporting the evolution of the knowledge, such as updating knowledge.

Chapter 1
State-of-the-art about risk management in civil engineering

Contents

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1.1 Introduction

As exposed in the introduction, this work is positioned in the forensic engineering domain. It aims at providing a model and an approach to better learn from past failures. We introduced that this domain is heavily related to risk management. Risks have been the subject of numerous works, whether in the scientific or technical fields. Indeed, the construction industry is more risky and uncertain than many other sectors (Flanagan and Norman, 1993), (Best and de Valence, 1999), (Akintoye and MacLeod, 1997), (Dey and Ogunlana, 2004). The process of building and civil engineering work must face many uncontrollable factors. They are diverse and include the occurrence of unforeseen events, inadequacies in the design and implementation, and deterioration with time, etc. A variety of unexpected events may occur in that process and may harm people and damage property.

Such events are commonly called risk. Risks related to civil engineering often refer to a potential situation in which the structure fails to perform its functions (Flint, 1981). In the most severe case, this loss of function is global, leading to the structure collapse (or partial collapse), which can occur during the service life of the structure or take place during the construction stage (Hadipriono, 1985). Risks of civil engineering structures may involve significantly high numbers of victims (as mentioned in section Problematic). In France, the engineer André Coyne, a pioneer in arch concrete dams, stated in a course named "Leçons sur les Grands Barrages" that "*In dams engineering, the security is of utmost importance. Among all structures built by Man, they indeed are the most murderous, when they turn back against him.*" (Delage, 2003). It is thus essential to manage risk in civil engineering and notably in dam management. The overall goal of risk management is to minimize threats and maximize opportunities (Hillson, 2005). Classical risk management methods are based on identifying possible risk events and then assessing their likelihood and potential impact before deciding mitigation action. However, structural systems may face reoccurring or repetitive risks, which may be easily mitigated through practice and experience.

This chapter provides a study of risk and risk management in order to determine whether risk analysis methods could be used in forensic engineering, or at least what elements of these approaches could be of interest to build a model dedicated to forensic engineering. In the first section, we will expose the definition of risk in civil engineering. Then, we will present the risk management process, and after, in several sections, we will show different risk management methods that can be used for dams.

1.2. Risk definition in civil engineering

Risk is considered to be a significant factor that influences construction activities' success. The term risk closely refers to other terms such as uncertainty, hazard, and vulnerability in literature. Many authors discussed these terms, which can have different meanings (James, 2006), (T Aven, 2008), (Andersen, Garvey and Roggi, 2014), (Pritchard, 2015). Therefore, the concept of risk should be considered according to viewpoint, attitudes, and experiences to avoid misunderstand (Baloi and Price, 2003).

There are many definitions of risk in literature. Most of them express risk as a source, consequence, or probability of occurrence of an adverse event (Dikmen, Birgonul and Arikan, 2004), (PMI, 2013), (Garrido *et al.*, 2011), (Modarres, Kaminskiy and Krivstov, 2017). According to PMI (2013), risk "is an uncertain event or condition that, if it occurs, has a positive or negative effect on one or more project objectives such as scope, schedule, cost, and quality". Modarres, Kaminskiy and Krivstov (2017) define risk "as the potential of loss (e.g., material, human, or environmental losses) resulting from exposure to a hazard". ISO 31000:2018 defines risk as the effect of uncertainties on objectives (ISO 31000, 2018), in which an effect is a deviation from the expected situation. Risk always implies uncertainty regarding how likely the risk event occurs or what will be its consequences (Aven, 2008). Although the risk may have positive or negative effects, it is often perceived as something negative to be minimized or avoided (Andersen, Garvey and Roggi, 2014). From many above definitions and characteristics of risk, we can draw that **risk** is associated with **uncertain events** that have an **effect on objectives**.

Civil engineering facilities such as bridges, buildings, power plants, dams, and offshore platforms, etc., are designed and constructed to provide benefits for people. The structural safety is important to the functionality of the structure (Terwel, Mud and Frijters, 2014), (Delage, 2003). Classically, structural safety is measured by the reliability of the structure, which is assessed by a safety factor (Sørensen, 2004). This factor is a ratio between the strength and the load. If the load does not exceed the strength of the material, structural security is theoretically ensured (Ullman, 1986). However, the safety factor does not prevent significant errors in the design or implementation (Flint, 1981). It led to the development of the concept of structural safety based on risk analysis. (Terwel, 2014) defined structural safety "as the absence of risk associated with a structure's failure". In this chapter, we will then study risk analysis methods that can be applied to **civil engineering structures concerning structural safety**.

For this study, the concepts of risk and structural safety defined above are combined, resulting in a definition of structural risk in civil engineering:

Risk in civil engineering is the effect of an uncertain event on structural safety

The primary aim of this study will be to establish a failure knowledge model to formalize a risk event of civil engineering, which could lead to a structural failure.

1.3. Risk management process in civil engineering

Risk management is a systematic process of identifying, assessing, and responding to risks throughout the life-cycle of a structural system in order to mitigate them. The risk management process can be applied at many levels in a system. It can be applied at the system level as well as at the component level or sub-component level to provide a comprehensive understanding of risk. In this work, we consider the risk management process as a coordinated set of activities to mitigate risks that can have a negative impact on

structural safety. There are a variety of risk management methods and models with different numbers of stages that can be found in the literature.

The Australia/ New Zealand code on Risk management proposed a process of risk management (AS/NZS Standards, 2004), which includes five principal elements: establish the context, risk assessment, treat risks, communicate and consult, and monitor and review. In this process, risk assessment is divided into three actions: identify risks, analyze risks, and evaluate risks. “Monitor and review” and “Communicate and consult” are transversal activities concerning all other activities. (US Department of Defense, 2014) applied a four-step process that includes risk identification, risk analysis, risk mitigation, and risk monitoring. According to Practice Standard for Project Risk Management (PMI, 2013), the risk management process comprises six steps, including risk management planning, identification, analysis (quantitative, qualitative), response planning, and controlling risk on a project. (Flanagan and Norman, 1993) developed the risk management process into five steps: risk identification, risk classification, risk analysis, risk response, and risk attitude. WSDOT’s Project Management Online Guide (PMOG) (Strategic Analysis and Estimating Office (SAEO), 2014) described the process into six steps: risk management planning, identify risk events, qualitative risk analysis, quantitative risk analysis, risk response, and risk monitoring & control. Finally, (ISO/IEC, 2014) suggested in ISO/IEC Guide 51 a risk management process, which is an iterative process of risk assessment and risk reduction for each hazard in order to achieve tolerable risk (see Figure 1.2).

Regarding dam and flood risk, the risk management process follows globally the same structure. (Zhang *et al.*, 2016b) proposed a description of risk management for dam safety in three steps: risk analysis, risk assessment, and risk management, as shown in Figure 1.1. (Schanze, Zeman and Marsalek, 2006) suggested a process that includes three tasks: risk analysis, risk assessment, and risk reduction. (D. Hartford and Baecher, 2004) exposed a dam risk management process, which is an enhancement of the traditional dam safety management process, including five activities: risk analysis, risk evaluation, risk communication, risk assessment, and risk control.

Although there are many descriptions of the risk management process and differences in using terminology, they all follow a similar basic approach of risk identification, risk assessment, and risk reduction. In the following parts of this chapter, these main steps will be further explained.

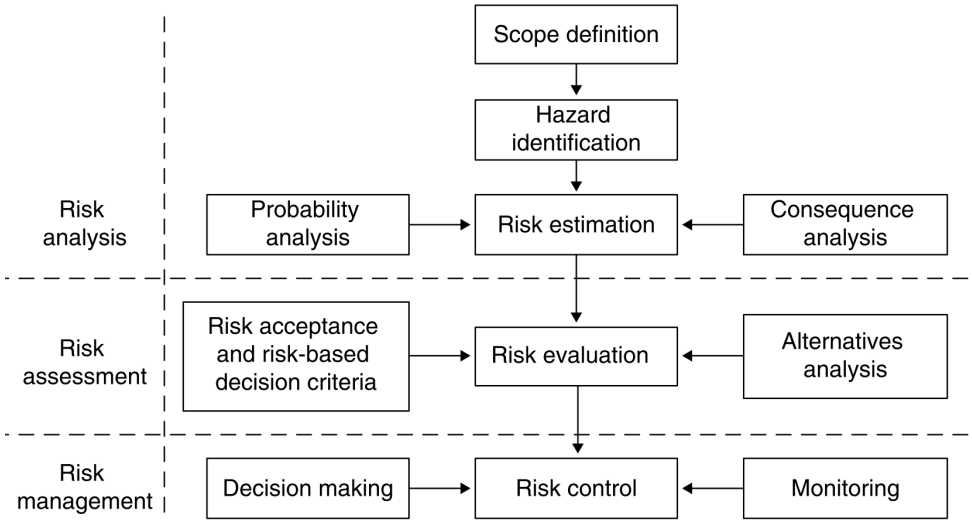

Figure 1.1. The process of risk management *(Zhang et al., 2016)*

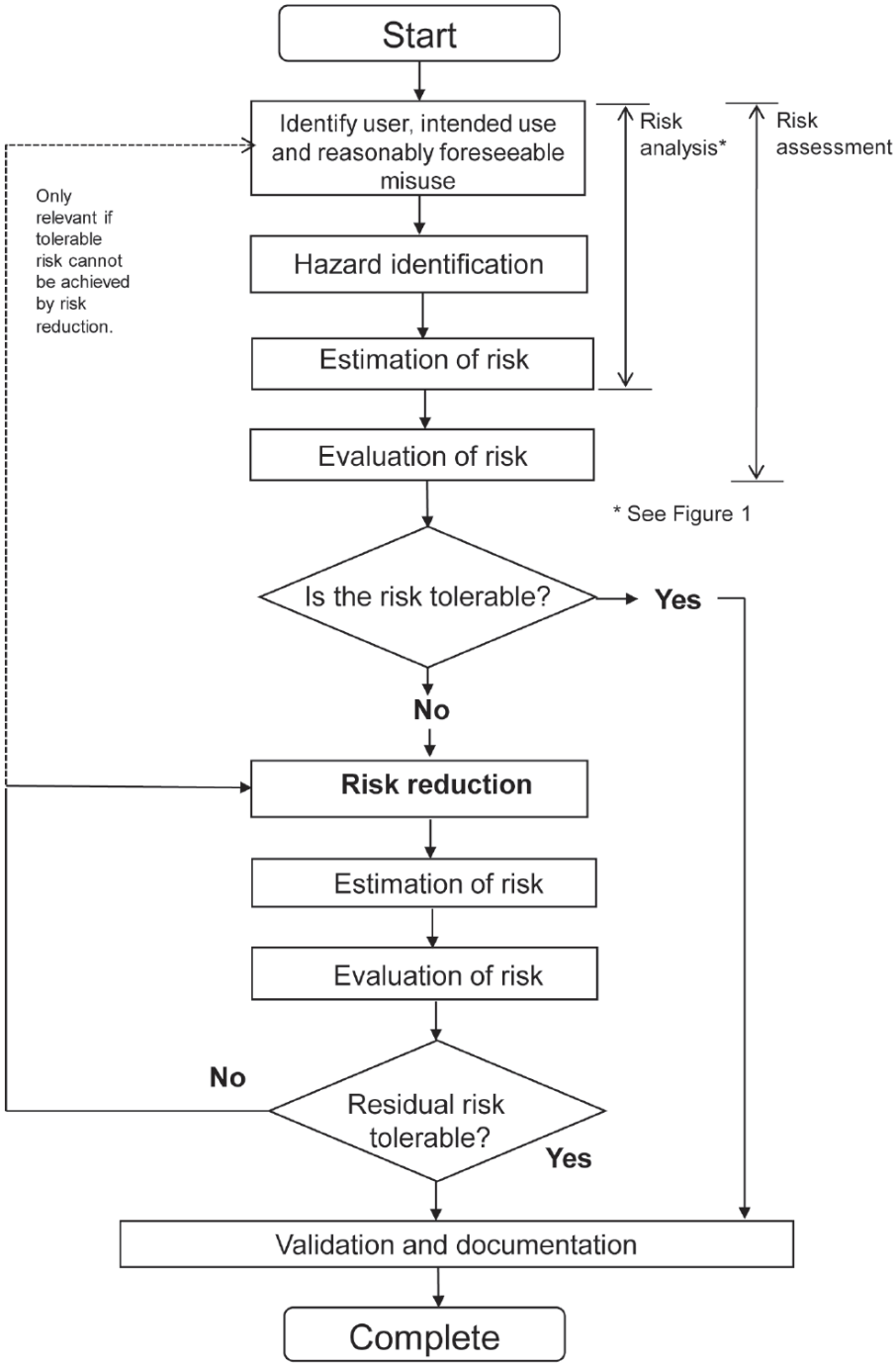

Figure 1.2. Risk Management overview (ISO/IEC, 2014)

1.3.1. Risk identification

The risk management process begins with the first task, identifying the relevant and potential risks associated with the civil engineering structure. It may be considered the most essential stage within the risk management process since further actions, i.e., risk assessment, risk reduction, and risk control may only be performed on identified risks (Molenaar, 2010).

Some authors define the risk identification phase as the moment in which we determine the risks that might affect the structural safety, as well as identifying their characteristics (PMI, 2013). It can also be characterized as "the process of determining what will happen, and how it will occur" (AS/NZS Standards, 2004).

The objectives of risk identification are 1) to identify and categorize risks that could affect structural safety; and 2) to document these risks (Molenaar, 2010). This task needs to expose and capture details of as many risks as possible. However, it is never possible to identify all risks that a structural system might face since some risks are inherently unknowable and cannot be identified, i.e., uncertain events or combinations of conditions that have not yet occurred and that cannot be predicted before they occur (Hillson, 2005). In some cases, historical data about events or similar failures can be used to determine the likelihood and probable impact of risk events. The risk identification task should be repeated regularly throughout the project and structure life to find new risks that have become knowable since the previous iteration of the process.

The outcome of the risk identification phase is a document that integrates a comprehensive list of risks and events that may impact structural safety called risk register. It contains all identified risks and detailed information on them as causes, source, risk owner, a timeframe of the risk, proposed mitigation strategies, magnitude, and impact of any risk event (Obicci, 2017). The description of the risk should also include the main assumptions and mechanisms leading to the risk arising (Cooper *et al.*, 2005). It can help parties review risks regularly so that appropriate control measures can be taken (Hopkin, 2010). The risk register should be comprehensive because missing risk could lead to adverse consequences on structural safety.

Participants in risk identification activities can be the following: project manager, end-user, local people around the construction site, stakeholders, experts in engineering disciplines, and risk management experts (Mojtahedi, Mousavi and Makui, 2010). This phase usually involves simultaneous or sequential applications of several engineering disciplines.

A large number of techniques are available for risk identification: brainstorming, checklist, interviewing, documentation review, or diagramming techniques: event tree analysis, fault tree analysis, cause and effect diagram. Table 1.1 shows a list of tools and techniques for risk identification that could be used for the dam system, highlighting their strengths and weaknesses.

Table 1.1. Risk identification tools and techniques available for dam structure system

(Burtonshaw-Gunn, 2009), (PMI, 2013), (AS/NZS Standards, 2004), (Rausand, 2011), (D. Hartford and Baecher, 2004)

Technique	Strengths	Weaknesses
Assumption analysis	- Allows identifying risks specific to a structure	- strong subjectiveness - Produces an unstructured list of risks
Documentation review	- Provides access to a comprehensive review of historical information that exists as a basis for failure analysis	- limited to risks contained in project documentation - Risk is not described in a structured manner
Brainstorming	- Takes advantage of group thinking by gathering stakeholders together to identify risk - It can produce a much large quantity of useful information in less time	- Many of the ideas may not be quality - Can be affected by social issues such as status differences, shyness, informal relationships, ego, and cultural factors - Does not provide a structured approach to describe risk
Delphi technique	- Reduces bias in the data - Offers the broad experience of experts	- Does not offer a structured approach to describe risk
Interviewing	- Addresses risks in detail - Flexible - Easily adaptable to different types of the dam system	- Depends on the ability of the interviewer in determining the collected and on the knowledge of the interviewed - Does not provide a structured approach to describe risk
Risk breakdown structure	- Provides a structured description of dam system risk - Identifies risk at different levels - Quick and economical	- Does not link risk to the structure - Interaction between risks are not well considered
Causes and Effect diagram	- Provides a structured approach - The main causes are grouped according to categories for each effect	- Interactions between potential causes are not be considered adequately - Does not consider multi-effects - Can become complex for a structural system
Fault tree analysis	- Offers a logic model of a system that is visual and easy to view	- A large fault tree can be challenging to understand

	- Permits the identification of combinations or interactions of events that cause failure events	- Its complexity increases rapidly with the number of levels. - Requires many resources
FMEA	- Allows structuring the cause/consequence chain efficiently at a component level - Easy to apply	- Requires many data - Requires a lot of resources and knowledge - Does not allow to consider the interaction between failure of different components
Event tree Analysis	- Provides a visual model - is widely used and well accepted - It is simple to use;	- Considers one initiating event at a time, and not the combination of events - becomes large for a complex system and hence inefficient - is difficult to identify multiple initiating events
Influence diagram	- Exposes key risk drivers - Can generate counterintuitive insights not available through other techniques	- Not always easy to determine the appropriate structure
Five ways	- Is a simple technique - Provides a systematic questionnaire technique	- May overlook causes - May not suitable for a complex system
What-if	- Is a simple method and can be accomplished with a relatively low skill level	- Does not provide a structured approach
Lesson learned/ historical information	- Allows gaining knowledge from past case - Is efficient to prevent a similar failure	- Limited to those risks that have occurred previously - Does not provide a structured approach

1.3.2. Risk assessment

Risk assessment is a part of the risk management process (Flanagan and Norman, 1993). It is the overall process of risk analysis and risk evaluation.

Risk assessment has several objectives (Cooper *et al.*, 2005):

- to give an overview of the level of risk impacting the structure,
- to focus attention on the high-risk items in the list,
- to help to decide where the action is needed immediately and where action plans should be developed for future activities,
- to facilitate the allocation of resources to support management's action decisions.

Analyzing each identified risk brings a better understanding of the cause, effects, and priorities in order to manage the risks more effectively. This process is considered in combination with the analysis of related social, environmental, temporal factors. It must necessarily be carried out by experts in various fields, such as geologists, geotechnical engineers, hydrologists, hydraulic and structural engineers, and mechanical and electrical engineers (Nasrat Adamo *et al.*, 2017). The risk analysis process begins with a documented description of the risks generated from the risk identification process.

It is an iterative process to examine each identified risk in order to evaluate its consequences and the likelihood of these consequences. Consequences and likelihood are combined to produce a risk level. The magnitude of the risk is often considered as the product of the consequences by the probability of occurrence (expected value). Qualitative analysis is first carried out in order to prioritize risks. This is followed by a semi-quantitative analysis and quantitative analysis of the high priority risks.

- **Qualitative analysis** is based on a descriptive or nominal scale to describe risk events and their consequences. This analysis is mainly used in an initial evaluation of risks or for a rapid assessment. The risk events assessed as a high priority may be further analyzed using quantitative risk analysis methods.
- **Semi-quantitative analysis** extends the qualitative analysis process by assigning numerical values to a descriptive scale.
- **Quantitative analysis** uses numerical ratio scales for likelihoods and consequences rather than descriptive scales.

1.3.2.1. Qualitative risk analysis

Qualitative risk analysis is the process of prioritizing identified individual risks based on agreed-upon characteristics for further study or action by assessing and combining their likelihood of occurrence and impact. The key benefit of this process is that it may be used as an initial screening activity to identify risks that require more detailed analysis. Thus, it enables reducing the level of uncertainty and focusing on high-priority risks.

Qualitative analysis can be accomplished with qualitative scales for consequences and likelihood and a matrix defining the significance of various combinations (Figure 1.3). This matrix allows rating risks to be of "major," "moderate," or "minor" importance according to their impact and probability of occurrence.

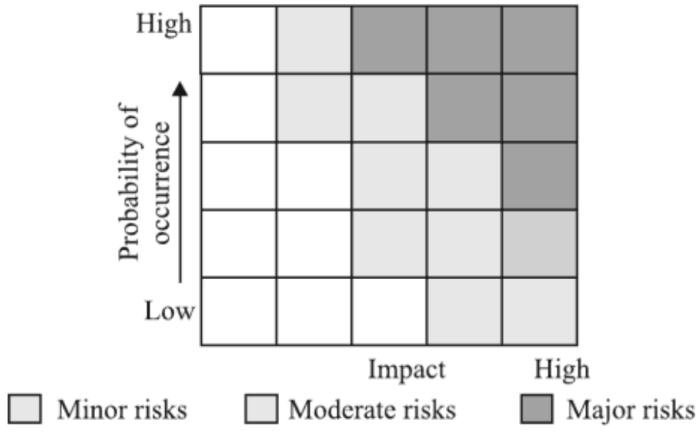

Figure 1.3. Likelihood and impact matrix (Khanna, 2011)

The qualitative risk analysis techniques are Checklist, Preliminary Hazard Analysis (PHA), Safety Flowchart, What-If Analysis (WIA), Bow-Tie Analysis, HAZOP, Layers of Protection Analysis (LOPA), Security Vulnerability Analysis (SVA), FMEA, Fault tree analysis (FTA), Delphi method and Influence diagrams (Ostrom and Wilhelmsen, 2012), (Flanagan and Norman, 1993), (Bartlett, 2004), (Pamukcu, 2015).

The qualitative risk analysis is often not sufficient in itself and must be completed by a semi-quantitative or quantitative analysis (Peltier, 2005), (Loosemore, Raftery and Reilly, 2006).

1.3.2.2. Semi-quantitative risk analysis

To complete the qualitative analysis, it is possible to use a semi-quantitative analysis. A semi-quantitative analysis is based on the qualitative analysis results. It provides an intermediary level between the qualitative evaluation of qualitative risk assessment and the numerical evaluation of quantitative risk assessment (WHO/FAO, 2009), (Loosemore, Raftery and Reilly, 2006). It is often based on a scoring system: a score is given to each risk regarding its probability of occurring and its impact

The advantage of semi-quantitative risk assessment is that it is very convenient in rapid or comparative assessments. It also can be applied to risks and strategies where precise data are missing. Nevertheless, obviously, it is less accurate than quantitative analysis.

1.3.2.3. Quantitative risk analysis

A quantitative risk analysis is a further analysis of the high priority risks. It consists of a quantitative rating of both consequences and likelihood, using data from various sources (Loosemore, Raftery and Reilly, 2006). Quantitative Risk Assessment should be made by a

working team with experience in elaborating risk models and estimating risk model input data.

Many techniques can be used for quantitative risk analysis for dam safety: historical performance methods, event tree analysis (ETA), fault tree analysis (FTA), deterministic analyses, stochastic analyses, judgment, failure mode and effects analysis (FMEA) (Pamukcu, 2015), (Fell *et al.*, 2000), (Hill *et al.*, 2003), (Hartford and Baecher, 2004).

1.3.3. Risk reduction

Risk reduction (or risk mitigation) are techniques and management principles to reduce either likelihood of an occurrence or its consequences, or both. It may be either proactive or reactive. A response that minimizes the probability of a failure's occurrence is usually proactive in order to prevent rather than palliative. However, it may take resources or time, and this should be considered in such a way the cost of implementing the action should be less than the reduction in the risk's expected value (Bartlett, 2004), (E Slunga, 2001).

Proactive risk mitigation that reduces the impact of failures is carried out before the failure occurs. It usually aims at making the structure more robust in its ability to absorb adverse events. Reactive responses are implemented to limit the consequences when a failure occurs. In such cases, the response time is the key to the effectiveness of risk impact reduction. Therefore, it is essential to define a trigger upon which these reactive responses will be used (Bartlett, 2004).

1.4. Techniques and tools for risk management for dam system

In the previous part, we expose the general process of risk management. In this part, we will more precisely focus on risk management methods that are dedicated or can be used for dam risk management.

Each dam is unique in terms of purpose, geologic and demographic setting, design, structure, operations, and consequences (FMEA, 2015). Risk analysis involves evaluating the design, construction, analysis, and performance of a dam and identifying the specific potential failure modes that apply to it. If critical potential failure modes are overlooked, the risk analysis results will be incomplete and misleading (FMEA, 2015). Various methods will generally be used to analyze potential failures. The four main methods which have been used for risk assessment for dam system are failure modes and effect analysis (FMEA), event tree analysis (ETA), fault tree analysis (FTA), and influence diagrams (IDs) (Hartford and Baecher, 2004), (Campbell, 2001), (Zhang *et al.*, 2016b).

1.4.1. Failure modes and effect analysis (FMEA)

Failure modes and effects analysis (FMEA) was introduced in the late 1904s by the US military and is now used extensively in various of industries (Zhang *et al.*, 2016). FMEA can be applied for different purposes. A straightforward application is to give a structured description of the failure modes applicable to the components of an engineered system. It

allows us to take into account each component of the system and describes its failure modes, causes, and effects. The results of an FMEA analysis are usually presented in tabular and/or spreadsheet form adapted to the analyzed system.

The process includes:

- Functional analysis of the system,
- Identification of the potential failure modes,
- Identification of failure modes effects on the components or the global system

FMEA can be carried out at different scales (from the component to the whole system). It is essential to define the level at which the analysis will be conducted. The system can be broken down into components, sub-components, etc., until an elemental level. In general, the system is broken down to a level where there is an adequate understanding of the failure modes of the elements and the system.

The disadvantages of this method are:

- FMEA requires large amounts of data (Stamatis, 2014).
- FMEA may require time and a very significant resource commitment when used in dam safety applications because the dam system is constituted by many components, each involving examining a complex series of failure modes.
- FMEA is insufficient to represent interactions between various components to identify combined failures; the analysis is generally performed component by component.

FMEA was applied to the dam system (Peyras, Royet and Boissier, 2006), (Serre, 2005), (Zhang *et al.*, 2016b), (Santos, Caldeira and Serra, 2011). Table 1.2 shows an example of FMEA describing failure modes of an embankment dam with a concrete core (MEDDE/DGPR, 2015). The concrete core component is described with its failure modes, its causes, and effects. For example, the concrete core component has the function "limit the water ingress from upstream embankment"; this function can suffer the failure mode "failing" because of cracking or scouring (causes), and lead to "ingress of water in the waterproof core" (effect).

Table 1.2. Failure mode and effect analysis for the concrete core of embankment dam

COMPONENT	FUNCTION	FAILURE MODE	POSSIBLE CAUSE OF FAILURE	POSSIBLE EFFECT OF FAILURE	SYMPTOMS OF FAILURE
Concrete core	Limiting hydraulic flows 1. Limit the water ingress from upstream embankment 2. Limit the water ingress from upstream foundation 3. Limit the water ingress from downstream foundation	The function "limit the hydraulic flows" is damaged or failing	- Component intrinsic state: ● Cracking ● Scouring ● Dissolving ● Drying - Hydraulic flows ● Ingress water from downstream foundation	- Hydraulic flows ● Ingress of water in the waterproof core ● Ingress of water in the vertical drain - Water pressure ● Interstitial pressure in the waterproof core	

	4. Limit the water ingress from the crest		● Ingress water from upstream foundation - Design achievement process		piezometry
	Resist to hydro mechanic stress 1. Resist to internal erosion due to water ingress from upstream embankment 2. Resist to internal erosion due to water ingress from upstream foundation 3. Resist to internal erosion due to water ingress from downstream foundation 4. Resist to desiccation phenomenon	The function "resist to hydro mechanic stress" is damaged or failing	- Conception achievement process: ● Composition - Hydraulic flows ● Ingress in the waterproof core - Intrinsic component state ● Dissolution ● Cracking	- Intrinsic component state ● Erosion	● Observation of the particles flow ● Measurements of the drain flow

1.4.2. Event tree analysis (ETA)

An event tree analysis is a representation of all the possible chains of events resulting from an initiating event. ETA formalizes the sequence of failure events, and how and why a disaster may occur, and identify its consequences (Srivastava and Bowles, 2008). A typical use of ETA for dam safety is a post-failure analysis to determine the sequence of events that follow the initiating event and produce specified consequences (Zhang *et al.*, 2016), (Hartford and Baecher, 2004). The initiating event may be external to the dam system, such as heavy rain or earthquake, or internal to the dam system, such as the deterioration of material over time. The series of subsequent events following an initiating event describes the various responses of the dam system to the initiating event. The event tree shows us a path of failure events that may occur for a given consequence.

One advantage of ETA is to provide a graphical display of the sequence of failure events that lead to a particular consequence. Besides, it also provides a straightforward and logical matter to construct a chain of cause/consequence. It is excellent support for probabilistic assessment.

However, ETA has its disadvantages when it is applied for the dam system:

- It considers one initiating event at a time and not the combination of events.
- It becomes large for a complex system and hence inefficient.
- It is challenging to use ETA to identify multiple initiating events, which is a common situation in dam safety applications.

Figure 1.4 shows a simple event tree with an initiating event, "Earthquake," and several possible chained consequences "Gates closed and inoperable → Loss of reservoir control → Dam fails by overtopping".

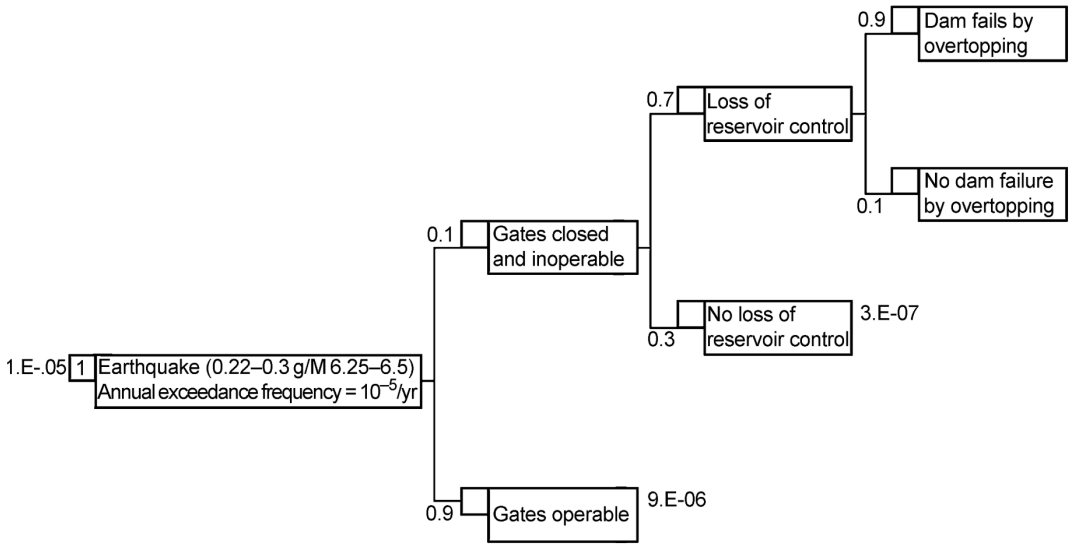

Figure 1.4. Example of event tree from earthquake to overtopping (Hartford and Baecher, 2004)

1.4.3. Fault tree analysis (FTA)

The Fault Tree Analysis is a deductive analysis method that is used to obtain information about a failure in the system. The FTA provides a concise and orderly description of the various combinations of possible events that can result in a predetermined critical output event. The first step in FTA is to choose an undesired event to analyze, called "top event". Then a tree is developed by successively developing the lower levels of the tree using logic connector "AND" and "OR". It allows modeling the various risk events or failure conditions, or combinations of these, leading to the top event. This process is continued to a level that is considered as relevant regarding the available. The events at this level are called the basic events. FTA allows us to identify failure paths and critical components of a system. FTA provides a graphical formalization of a failure, which is easy to follow and adapted to probabilistic assessment. However, FTA also has different disadvantages:

- A large fault tree can be difficult to understand since it can be difficult to "see" the system failure modes and the main events causing the failure.
- A fault tree does not represent a physical system, but the way failure can happen (SPANCOLD, 2013). Therefore, it is difficult to image the entire structural system and interactions of risk within the system.
- The complexity of the FTA increases rapidly with the number of levels.
- Build a complete FTA can be long and complicated, requiring many resources.

Figure 1.5 is an example of an FTA applied to the failure of an emergency spillway generator. The top event is the failure of the emergency generator. This failure can be explained by two sub-failures, which can also be explained by other sub-events. From this graph, we can identify specific causes and how the top event may occur.

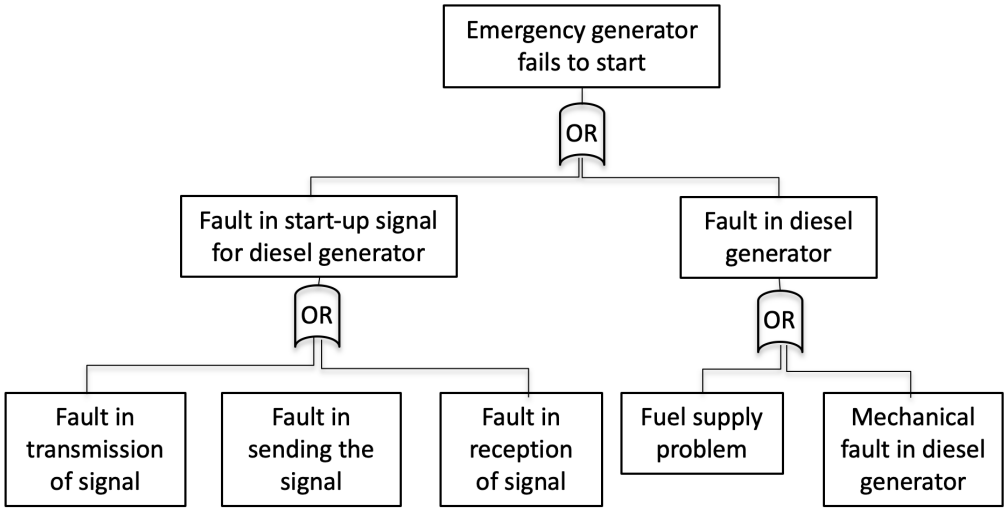

Figure 1.5. Fault tree for the failure of an emergency spillway generator (Hartford and Baecher, 2004)

1.4.4. Influence diagrams (IDs)

Influence diagrams (IDs) are graphical representations that can be used for representing and solving complex decision-making problems based on uncertain information (Bielza, Gómez and Shenoy, 2011), (Ayyub, 2014), probabilistic and causal models (Dawid, 2002), and risk analasys (D. Hartford and Baecher, 2004), (SPANCOLD, 2013). An influence diagram includes a set of nodes and a set of arcs. The nodes correspond to the variables of states or conditions, and the arcs represent influence among variables. For risk analysis, an influence diagram graphs relationships among initiating events, conditions of the system, and consequences in order to visualize how system components, uncertainties, and outcomes are interrelated.

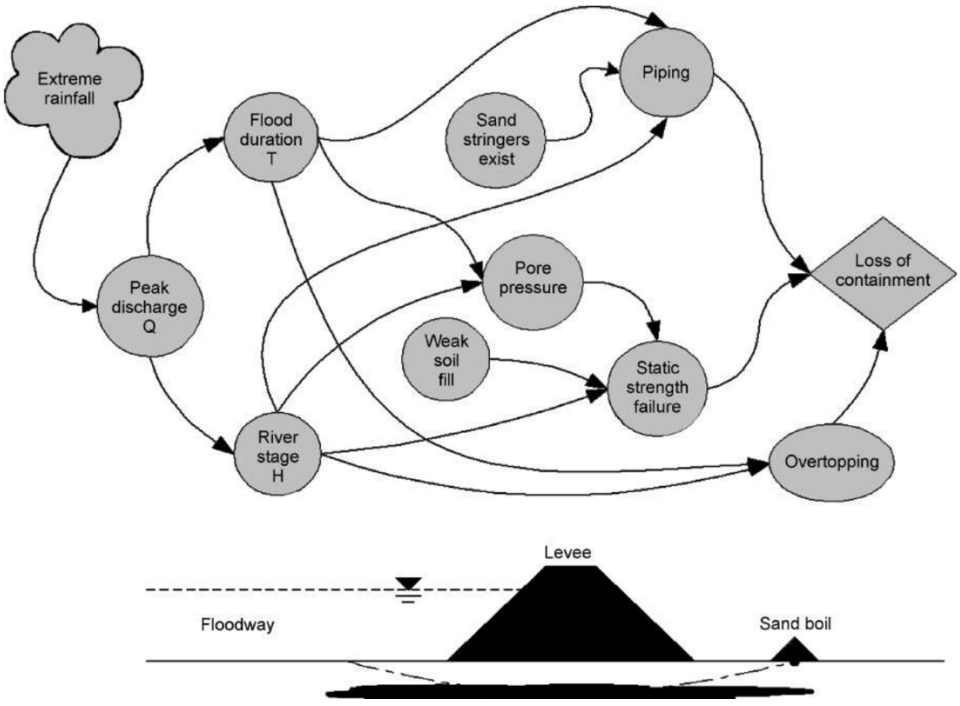

Figure 1.6. An influence diagram for levee failure (D. Hartford and Baecher, 2004)

Figure 1.6 shows an example of an influence diagram for levee failure. The initial event is extreme rainfall. The round nodes and the oval node represent properties of rainfall and system states. The diamond-shaped node represents the consequence that is the loss of containment. The direction of the connectors indicates that the loss of containment depends on piping, static strength failure, and overtopping. Following this, these variables depend on other variables. For example, overtopping depends on flood duration and river stage.

An influence diagram has the advantage of offering a visual representation of a risk model. It provides a straightforward means of graphically representing events and the influences between them. However, the influence diagram can quickly become overwhelming and confusing when tracking a failure path because it doesn't have a specific structure. Besides, it does not provide an overall structure of the system, so the influence between a complex system's components is not clear.

1.4.5. Lessons learned from existing methods

In this section, we described four methods to analyze risks: FMEA, ETA, FTA, and IDs. These methods have been applied to dams and could be useful to analyze failure and not only risk. Indeed, using them, it is possible to investigate specific consequences corresponding to what happened to a structure. Unfortunately, these methods also present some drawbacks that prevent to use them directly in forensic engineering. Firstly in civil engineering, at the beginning of the investigation, we do not know the failure mechanisms nor the implied components, knowing that it is often a combination of causes that lead to the failure. We have to consider the whole system to examine all hypotheses. These four methods are not adapted to this kind of analysis and are, above all, relevant for analyzing a specific element (event and/or component). Secondly, they require an in-depth analysis of the system, which requires many resources and time and available data and knowledge. One can argue that it is obvious the case of any in-depth analysis, which is also required in forensic engineering. It is true, but with these methods, each case corresponds to a specific analysis; they do not allow to hoard knowledge. However, it would be very interesting to capitalize on the knowledge in order to be able to build new analyses using those already done previously. Finally, FTA, ETA, and IDs have the advantage of proposing a graphical representation easy to follow, but only when the number of elements is not too high. The complexity of the graph increases rapidly with the number of elements.

If these methods do not completely answer our needs, they are still impressive. They allow to give some orientations for building a failure knowledge mode for the dam system:

- The model must be structured in order to formalize the failure process (cause/consequences chain)
- The model must be intuitive, easy to read to provide understanding to users; for this, a graph structure is beneficial.

- The model must be generic to be adapted to any dam, but must also lay on a structure allowing capitalizing the knowledge to build a knowledge base. It requires a common structure to describe failures and a common vocabulary to ensure the consistency of the knowledge base.

In addition to the four main methods used to describe dam failure, other models also describe failure for other objects. These approaches will be analyzed in the next section.

1.5. Summary and conclusion

In this chapter, the concept of risk related to structural safety in civil engineering has been discussed; the relation between risk and failure was also exposed. Furthermore, the literature about risk management and structural safety was introduced and, notably, the main steps of the risk management process. Then, we focused on available tools and methods for risk identification for dam systems, which were analyzed. Three methods dedicated to risk management used for dams and which appeared as particularly relevant are discussed in detail; the aim was to expose the useful points when describing risks and what needs to be improved to develop an efficient failure knowledge model. This results in some essential features that our model must have: a graph structure, the capacity to formalize a chain of cause/consequences, and a knowledge-base to capitalize knowledge from each investigated case and analyze new cases.

In the next chapter, we will introduce forensic engineering and conceptual graphs in order to expand the study of failure and provide a means to develop the failure knowledge model.

Chapter 2
Forensic engineering and Conceptual Graphs

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2.1 Forensic engineering

2.1.1 Introducing forensic engineering

To understand what is forensic engineering, we need to look at the meaning of the two terms. The term "forensic" comes from the Latin *forensic,* means 'Public' and refers to the law, courts, public debate, or arbitration proceedings, usually related to accidents, crimes, etc. In modern practices, it is used as a form of legal evidence and a category of public presentation (Rao and Babu, 2016). "Engineering" can be seen as a branch of science and technology concerned with putting scientific knowledge to practical uses (Min and Christian, 2017). So, forensic engineering implies applying engineering precepts and methodologies for litigation support, i.e., if there were injury or property damages resulting from a failure, forensic engineering results can be used as evidence in a potential court. However, it is now widely accepted that a forensic investigation is no longer restricted to legal purposes nor result in litigation. It can be conducted for various purposes: researching purposes, improving the performance of a structure or exploring deterioration of materials. Forensic investigations aim to identify and understand the causes of failure (Heywood, 2010), (Carper, 2001).

A formal definition of forensic engineering is given by the American Society of Civil Engineering (ASCE, 2019):

Forensic engineering is broadly defined as applying engineering principles to the investigation of failures or other performance problems.

Failure is not limited to catastrophic failure or collapse, such as the Malpasset dam collapse, but also includes any situation in which there is an unacceptable difference between expected and designed structural performance or worrying symptoms such as cracking, corrosion, and excessive vibration. Forensic engineering is obviously not limited to civil engineering, and such investigation can be made, for instance, in aeronautic or computer science.

Forensic engineering has grown dramatically over the past four decades, especially in the United States (Carper, 2001). One of the reasons is the significant influence of a series of catastrophic structural failures of the 1970s and early 1980s. In response to them, ASCE established the Technical Council on Forensic Engineering (TCFE) in 1985, with the mission "to develop practices and procedures to reduce failures, to disseminate information on failures and their causes, providing guidelines for conducting failure investigations, to encourage research and education in forensic engineering" (Heywood, 2010), (Carper, 2003). Besides that, in 1982, the Architecture and Engineering Performance Information Center (AEPIC) and the National Academy of Forensic Engineers (NAFE) were also established. Since 1984, the ASCE has sponsored nationwide short courses on forensic engineering. ASCE encouraged universities to include forensic engineering and failure case studies in civil engineering education (Delatte and Rens, 2003). TCEF has organized numerous forensic engineering conferences and has published the Guidelines for Forensic Engineering Practice (Lewis and Reynolds, 2002) and Journal of Performance of

Constructed Facilities. These efforts play a primary role in developing forensic structural engineering as a distinct specialty within structural engineering.

2.1.2. The forensic process

After a failure, the forensic engineer will try to find why and how this failure happens. Performing a failure investigation is applying the forensic process characterized by evidence collection, developing a wide range of failure hypotheses, and testing these hypotheses to reconstruct the real sequence of events (Fiorentini and Marmo, 2019) (Figure 2.1). Initially, only the failure is known; this may be a bridge collapse, dam breach, or damage to a tunnel. From this starting point, the forensic engineer searches for evidence then build failure hypotheses based on found evidence. This evidence might either deny or support hypotheses. Forensic engineers apply engineering expertise and skills to relate evidence and facts into a cohesive scenario of how the failure occurred.

The fundamental basis for the forensic process is essentially the implementation of the scientific method (Noon, 2009). It means that the investigative analysis is based on actual physical evidence and verifiable facts. A hypothesis is derived from investigating analysis and measurements, verifiable facts, and observations.

The application of the scientific method for the reconstruction of the failure consists in:

- proposing a first hypothesis about the cause of a failure, based on first verified information;
- modifying the original hypothesis as more information is collected to fit the observations progressively gathered;
- after a specific time, testing the hypothesis to predict the presence of unobvious or overlooked evidence during the initial information gathering effort. (Noon, 2001)

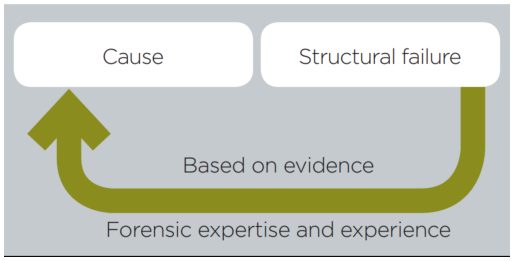


Figure 2.1. Forensic process (Brady, 2019)

The scientific investigation and analysis of a failure are based on facts found at the site of failure. If only a few data are available, it could not deduce a unique, logical conclusion. Therefore, there should be a large foundation of verifiable facts and evidence. It is a reason why the scientific investigation and analysis of a failure are structured like a pyramid (Figure 2.2). The large foundation of facts forms the basis for analysis according to proven scientific principles and methods. Finally, the analysis is the base to support a small number of conclusions (the apex of the pyramid) (Fiorentini and Marmo, 2019). When a large base of facts are logically arranged in chronological order and with clear cause-effect relations, conclusions should be almost self-evident. Conclusions should be directly based on the facts

and analysis and must not be based on other conclusions or hypotheses; otherwise, the investigation pyramid collapses.

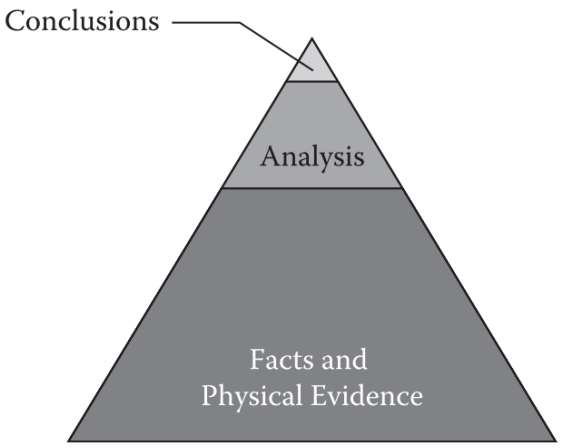


Figure 2.2. Investigation pyramid (Noon, 2009)

A hypothesis is considered as strong enough if:

- it encompasses all the verified observations
- it predicts (when possible) the existence of additional unknown evidence; and
- it is consistent with the scientific method (principles, knowledge, and methodology).

According to (Campbell, 2001), the first hypothesis could be formulated from various sources:

- Accounts of the failure by the owners, in which evidence is usually filtered, and the critical features are emphasized.
- An examination of the failure evidence. The examination needs to be undertaken in the most thorough way possible to prevent the loss of significant evidence.
- A consideration of the context, engineering, and environmental principles likely to be applicable to the problem to have a global understanding of the engineering interactions before considering the detail.
- The records, documents that could indicate a problem leading up to the failure or a previous history of similar components or systems.
- Additional measurements made by the investigators in order to confirm or infirm a theory.
- The investigator's experience regarding previous cases

As a general rule, a failure is not the result of a single cause or event but rather a combination of several causes or events that occur in a scenario. This combination could occur simultaneously or sequentially in which related events, causes follow each other. An example of events acting in sequence might be a dam overtopping during an extreme storm:

- The dam was overtopped because of the combination of low capacity of the spillway and the rainfall that exceeds the peak design flood of the spillway

- The maintenance staff could not control the valve gates of the spillway because the way to the monitor house was flooded.

- Inflows reached maximum quantity because extreme storm and watershed retained very little flow

- Watershed retained tiny flows because foothills area were already saturated

2.1.3. Implementation of Forensic process

Forensic investigation is a process for gathering, reporting, tracking, and investigating failures. It includes a process for investigating them to reconstruct the sequence of the failure event, finding all the causes and their interconnections, and identifying more general issues that can be addressed (e.g., need for regulation evolution). Forensic investigations differ from conventional engineering investigations in that they are retrospective. They seek to explain what has happened rather than predict future performance (Rao and Babu, 2016).

As the forensic analysis is basically a back analysis based on actual failure observations, standard procedures of testing, analysis, design, and construction are not adequate in the majority of cases. The forensic process does not follow standard procedures: each failure investigation is unique and different and depends on a particular failure. Therefore it requires a tailored approach. Nevertheless, there are some guidelines which can outline some common fundamental steps in the failure investigation such as *Guidelines for Failure Investigation* (Barrow *et al.*, 2018), *Guidelines for Forensic Engineering Practice* (Kardon, 2012), and *Beyond Failure - Forensic Case Studies for Civil Engineers* (Delatte, 2009). They support the forensic engineer in the planning and implementation of a particular investigation. The five common fundamental steps for a failure investigation process are (Barrow *et al.*, 2018):

1. Investigation planning and coordination,

2. Data collection,

3. Development of testing protocol,

4. Data analysis and hypotheses development,

5. Presentation of opinions and conclusions.

Although the forensic process varies widely in scope, objective, and complexity, most of the time, it follows the fundamental steps above. The order of these activities is not intended to imply any sequence in time. Indeed, many activities are undertaken simultaneously. The investigative plan is continuously revised and refined to account for new information and evolving theories (Ratay, 2010). Failure hypotheses are analyzed, eliminated, added, and revised. Depending on the nature and magnitude of the failure, some of these steps may be altered, expanded, or occasionally omitted without compromising the findings of the investigation. A complicated investigation will typically consist of multiple steps or phases,

while a simpler investigation may require only a brief site visit and a summary of observations and findings.

2.1.3.1. Investigation planning and coordination

This phase describes the typical steps to start a forensic investigation. In particular, forensic engineers need to determine their available time, personnel, and expertise to accept the assignment or not. The forensic investigator must also check for any conflict of interest that could hinder giving an unbiased opinion or that the opinion may be perceived to be biased by others. This phase requires an understanding of the investigation's scope and requirements regarding expertise, time, budget, and staffing (Barrow *et al.*, 2018), (Day, 2011).

2.1.3.2. Data collection

Data is the raw material collected, organized, reviewed, and analyzed to acquire meaningful information. That information can represent physical properties, data on environment, material, events, etc. It usually includes factual information analyzed to understand what happened, the conditions and circumstances leading to the failure, and environmental factors that influenced the structure's behavior.

Data sources may include the historical documents from the original design, construction, maintenance, repair of the facility, data collected on-site regarding the actual physical conditions before and after the failure, and the observed deterioration or damage of the component, structure, or facility being investigated (Kjell, 2002).

Data can be acquired through measurements, observations, testing, analysis, documents, research, or interviews (Kardon, 2012). Sometimes, means of rapid data collection, such as laser scanning, pictures, and video recordings, are used to prevent the rapid changing of conditions due to rescue efforts, shoring, or demolition at the failure site. Distant measurements, such as optical surveying, laser distance measurement, or visual scale, can be used if there are observational gaps at the failure site.

Data can be in different formats: oral communication, text (word and/or numbers), electronic signals, graphs, charts, drawings, physical or digital models, pictures, video, etc (Kardon, 2012). It is essential to ensure the quality and the validity of the collected data, and that only useful and relevant information is extracted from them (Barrow *et al.*, 2018).

2.1.3.3. Development of Testing Protocol

This phase aims at identifying the need for testing and addressing considerations for performing tests. The purpose of testing is to gather specific quantitative information that can be used as a solid foundation for building hypotheses and drawing conclusions. Testing must be based upon appropriate testing standards and should be performed by certified personnel. The test method selected should be appropriate for the question to be answered.

Results should be presented in an unbiased and realistic manner. Information related to testing, such as the testing method, sampling protocol, collection methods, reference

standards used, and sampling and testing dates and conditions, should be identified in the report along with the results. Uncertainties on testing results must be clearly formalized and presented (Barrow *et al.*, 2018).

2.1.3.4. Data analysis and hypotheses development

After data has been collected from the site, the document reviewed, and testing performed, the data needs to be analyzed, and the hypotheses must be developed using inductive reasoning, i.e., based upon the factual facts and verifiable evidence. The investigator may use their experience and knowledge in combination with specific observations to develop general hypotheses.

The development of hypotheses must use the scientific method and the forensic investigation process. Often, there is an initial site investigation, and failure hypotheses are set forth, data are collected, and analyzed, which allows revising failure hypotheses when new information is obtained. As the investigation proceeds, some failure hypotheses may be eliminated; new hypotheses may be developed. Each alternative hypothesis should be fully verified by evaluating the collected data, testing materials or components, and/or using computational modeling and analysis. This process of developing and verifying hypotheses allows the investigator to develop a list of hypotheses that can be subjected to additional testing and detailed analysis (Kardon, 2012). The forensic analysis is an iterative and incremental approach.

In developing and refining hypotheses, the investigators should not limit the investigation to likely or apparently obvious causes of failure; they should have a broad-mind approach in order to avoid cognitive bias of confirmation (i.e., take into account only evidence that is consistent with their a priori ideas) (Barrow *et al.*, 2018). The preliminary analysis may be helpful or even necessary to evaluate the validity of the hypotheses. Occasionally, due to lack of information or other causes, it may not be possible to pinpoint a single mode and cause of failure. In such cases, it is entirely legitimate, and indeed it is incumbent on the ethical investigator to present opinions in terms of several most likely modes and causes of failures, along with an opinion of their relative likelihoods.

Once alternative hypotheses have been eliminated through the evaluation of the collected data, computational analysis, physical testing, or cognitive reasoning, conclusions can be developed. When a hypothesis is confirmed to be at an acceptable level of confidence, it may be presented as a conclusion (Barrow *et al.*, 2018). In some cases, it is possible to not be able to give priority to one conclusion over the others. In this situation, all the likely conclusions have to be kept, with the associated confidence in them.

2.1.3.5. Forensic Engineering Reports

This step consists of presenting the investigation findings, opinions, and conclusions at the end of the investigation process (Kjell, 2002). The report may be a comprehensive report or an oral report depending upon the intended audience and the client agreement, as stated in the scope of the investigation (Noon, 2001).

The reports often include the structure history, the description of the failure, a design review, the analysis of the mode and cause of failure, the hypothesis or/and conclusions about the cause of the failure, and, in some cases, several recommendations. They should be carefully prepared and ensure accuracy, reliability, and clarity. They should provide a narrative and graphical overview of the investigation and discovery process, including comments (Kjell, 2002).

2.1.4. Capitalize knowledge and lesson learned

Each structure is unique, and forensic investigation can be specific to each study case. However, the modes of failure regarding a type of structure are not so diversified. The same failure mechanism can be responsible for many structure failures. Similar failures can occur again and again if its cause hadn't been analyzed and effective countermeasures hadn't been provided. (Sibly and Walker, 1977) observed that the same failures had occurred in bridge design every thirty years or the ICE virtual library showed the recurrence of 30 to 40 years cycle of similar types of failures (Wood, 2015).

From this perspective, the information resulting from the forensic investigation can be really interesting to facilitate new investigations and to prevent new similar failures. The information resulting from such investigation can be classified, evaluated, and interpreted, leading to the identification of the common conclusions which can be applied to different failures. This process forms failure knowledge constituting lessons for engineering practice.

There are several definitions of the term "lesson learned". Guide to the Project Management Body of Knowledge (PMI, 2013) defines lessons learned as the knowledge gained from the process of performing the project. NASA suggests that lessons learned are the significant knowledge or understanding gained through the past that is documented and collected to benefit current and future projects (Touhara, 2007). American, European, and Japanese Space Agencies suggested a lesson learned is knowledge or understanding gained by experience having a real impact on operations, reduces or eliminates the potential for failures and risks (Weber, Aha and Becerra-Fernandez, 2001). We can conclude from these definitions for a dam system that lessons learned are knowledge or understanding that come from failure information, which can be applied to reduce or eliminate the potential for failures and to prevent the recurrence of similar kinds of failures in the future.

Some notable historic dam failures which have influences in dam engineering as follow:

+ The failure of the Teton Dam in Idaho, USA, during initial filling of the reservoir on June 5, 1976 killed fourteen people and caused approximately $400 million in damages. This failure provided lessons learned to safety improvements for the design and construction of earthen dams (Solava and Delatte, 2003).

+ Two case failures in France: the first one of the Malplasset concrete arch dam on 2 December 1959, a prominent industrial catastrophe in France within the 20th century, caused 423 casualties (Duffaut, 2013). The second one is the Bouzey small gravity dam (eastern

France) (Smith, 1994) that failed on 27 April 1895, drowned 85 people and extensively damaged. These failures brought attention to the role of uplift force, which was neglected before, in the design of the arch dam and gravity dam (Bretas, Lemos and Loureno, 2012), (Duffaut, 2013). This led to studies and the recognization of drainage as essential for the safety of concrete dams and was contemplated in new dam designs.

+ Three case important failures in Pennsylvania, the USA relating to the origin and evolution of Pennsylvania's dam safety laws (Rose, 2013). The first failure, the 1889 failure of the earth embankment of the South Fork dam, resulted in 2209 deaths and is still the worst U.S. dam disaster in terms of loss of life. This failure promoted engineering publications called for the need for governmental oversight of dams. The next failure, the 1911 catastrophic failure 1911 of the Austin dam, caused 78 deaths when the concrete gravity dam slid on its foundation and broke apart into massive pieces, leading to the passing of the nation's first dam safety law 1913 to provide state oversight for dams. The third failure, the catastrophic failure of the Laurel Run dam, overtopping due to the extreme rainfall event of July 19-20, 1977, combined with the inadequate capacity of its spillway, claiming 40 lives, brought to the need for proper inspection and enforcement of dam safety laws. These failures' investigations show flaws in the design, construction, and maintenance of dams and provide technical lessons for the dam engineering profession, which are the base to develop and evolve Pennsylvania's dam safety laws.

Also, there have been a lot of lessons learned from some dam failures recently:

The Banqiao dam, China, failed in August 1975 when typhoon Nina collided with a cold front, which caused heavy rain in 24 hours, causing about 171,000 fatalities and destroying the homes of 11 million people. Different lessons were learned from this failure:

- International standards have not been used for design, and/or climatological records were inadequate to determine adequate dam storage and spillway capacity
- Improper modification of a dam increased the risk once overtopping occurred
- Reactive responses to failure were slow
- Embankment dams constructed of clay are resistant to erosion but are still at risk of failure (Toledo, Morán and Oñate, 2015).

Another example of dam failure is those of Oroville Dam in February 2017. The catastrophic failure of the main spillway of Oroville Dam, which is the largest dam in the United States, required the evacuation of 188,000 people living in downstream communities. (Stork *et al.*, 2017) proposed the main lessons, which are:

- California's dam infrastructure is aging and needs to meet modern standards
- Dam operations need periodic reviews
- Floodplain capacity is limiting flood protection, environmental quality, and local economies
- People and communities matter

Analyzing past failures brings many lessons learned that could provide valuable insights into associated technical, ethical, and professional issues. Application of lessons learned can prevent the recurrence of similar kinds of failures. Also, it will instruct how to improve engineering practices. Liu et al. (2008) pointed out that through lessons learned, risks can be reduced by professionals who can use previous experiences, avoid pitfalls and come out with the right decision in the first chance itself.

2.2 Model and tools for Forensic engineering

2.2.1. Failure database

(Breysse and Ndiaye, 2014) have synthesized in a state of the art paper how failure databases can be used in the civil engineering domain. Many engineers and researchers observed the interest of building a failure database in order to enable the identification of trends and quantification of probability occurrence of adverse events or inform on failure mechanisms (e.g., deterioration of material). It led to the development of several failure databases (Breysse and Ndiaye, 2014). Some of them aim at providing easy access to rough data, and others provide an analysis of these data. The most complete of the database is those of the CROSS-SCOSS report system. It aims at identifying repeated weaknesses that require a specific action in the construction industry. In a close perspective, (Terwel, Boot and Nelisse, 2014) proposed a database for netherland structure failure aiming at increasing the safety and quality of construction. (L. Zhang, Xu and Jia, 2009) proposed a data-base dedicated to earth dam failures. It has been used to quantify the probability of occurrence of several failure modes and their relation to the construction methodology. In a close perspective, (Hood *et al.*, 2018) proposed a database dedicated to earthen embankment dams. The Association of State Dam Safety Officials (ASDSO) hosted the website https://damfailures.org/about/ which proposes links to dam failure case analysis and lessons learned pages that summarize historical dam incidents and failures and the valuable information obtained from their analysis.

All these databases constitute a valuable source of information. But, they also have some limitations regarding the objectives of this thesis. Most of these databases are, above all, a set of data, which are not analyzed, compared, put in relation. It poses the question of drawing knowledge from a set of independent case studies. This is all the more difficult because the data is not always in comparable formats, the vocabulary is not unified. Building knowledge from data is a challenging issue. It requires to be able to formalize in a consistent format these data and to be able to perform requests on this database. In conclusion, this analysis demonstrates the need to provide a model able to formalize generically and holistically structure failure. In the next section, we will analyze the failure model from the scientific literature.

2.2.2 Modeling failures of structure

2.2.2.1. Model of Mandalas failure

(Hatamura, 2005) proposed a model called “the failure Mandalas model” to formalize the structure of failure. This model is the basis of the Failure Knowledge Database, which was created by the Japan Science and Technology Agency. Its purpose is to provide knowledge on failure to people who encounter failure and help them to prevent the repetition of the failure. The model is based on the structuring of failure knowledge by breaking the failure down into its parts with a specific focus on human factors. Indeed, Hatamura said that all failure is the result, more or less directly, of human error. The occurrence of failure consists of a human cause, followed by human action, leading to a result (see Figure 2.3). Human action can be regarded as the human intervention that links the cause and result of the failure, and failure can only result when both cause and action exist.

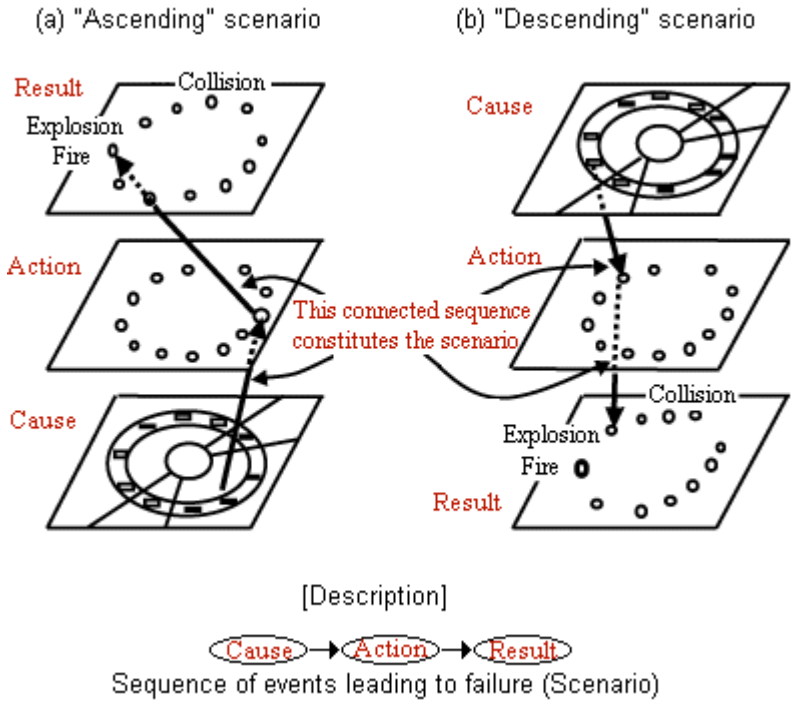


Figure 2.3. Three-dimensional expression leading to failure (Scenario) (Hatamura, 2005)

All the elements of each component of failure are categorized and put in their hierarchical relationship and expressed through the form of Mandalas, which are Buddhist representations of the universe. Three mandalas were defined: Cause, Action, and Result. Figure 2.4 is, for instance, the Mandala of Cause.

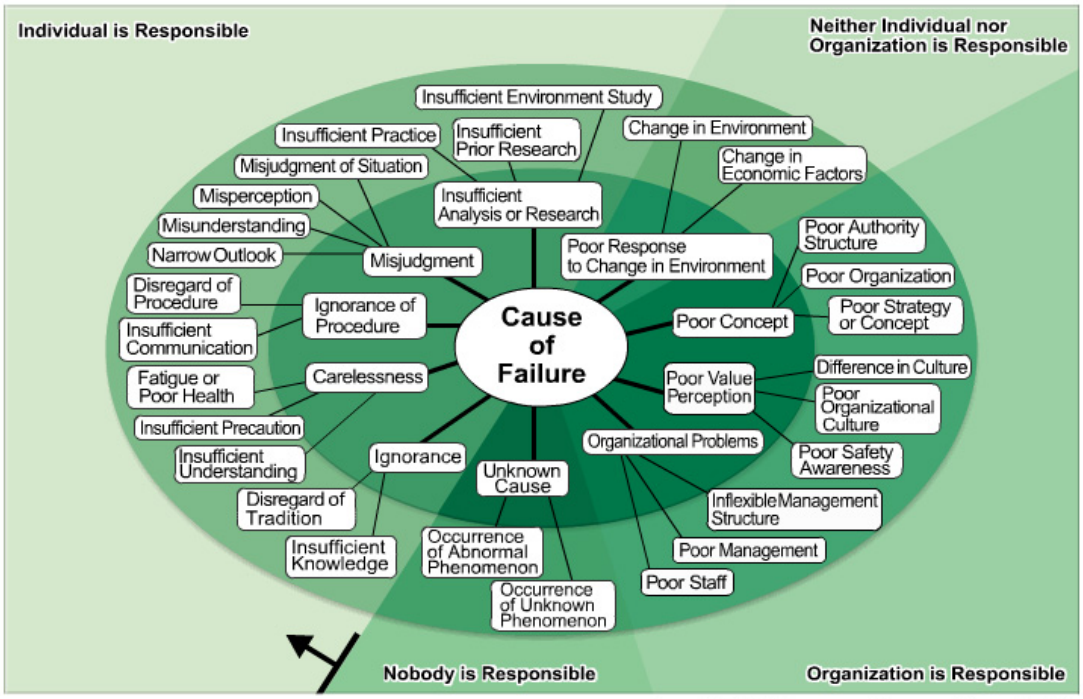


Figure 2.4. Cause Mandala (Hatamura, 2005)

The three Mandalas are put in a three-dimensional expression of the occurrence of failure (see Figure 2.4): Cause is represented as the bottom layer, Action as the middle layer, and Result as the top layer. By using solid lines to represent the connections between these components, we can produce a three-dimensional expression of the scenario of a failure.

This approach is very interesting from a theoretical perspective. It allows enriching the reflection on the failure by proposing to replace humans at the center. But it can also be considered as a limitation, because it does not allow to consider other failure cause as natural factors, force majeure such as earthquake, flood, etc. Furthermore, the modeled scenario of failure considers only the relationship between the three components: Cause, Action, and Result, without considering the interactions between failures. In addition, each scenario only describes one result effect. Finally, this model is difficult to instantiate to each structure failure; it remains at a theoretical level, far from the classical way a forensic engineer analyzes a failure. Indeed forensic investigation is based primarily on facts, physical laws, tests, which are not made explicit in this model.

2.2.2.2. Risk model

(SPANCOLD, 2013)**,** a dam safety technical guide edited by the Spanish National Committee (SPANCOLD), proposed a risk model to analyze, assess, and manage dam safety. The model is based on a definition of risk that is a combination of three questions: *What can happen*?, *How likely is it to happen*?, and *What are its consequences*? (Kaplan, 1997). According to this definition, the risk model architecture includes three nodes: Loads, System response, and Consequences (Figure 2.5). Each node refers to one question as follows:

+ The first node (in white color) of the diagram refers to the loads that originate failure. It is the answer to the first question of *what can happen*. It defines a situation or an event that creates the loads, being called load scenarios. For instance, a dam can fail when subjected to a flood or an earthquake, and then the corresponded load scenario is the hydrologic scenario or seismic scenario.

+ The following node (in light gray), system response (also known as failure probabilities of the system), contains information on the failure modes. A failure mode is defined as a particular sequence of events that can cause a dam failure. The concept of failure is not limited exclusively to the catastrophic breakage of the dam but includes any event that might produce adverse consequences (SPANCOLD, 2013).

+ Finally, the node of consequences (in dark color) refers to those resulting from the dam's failure, including economic consequences and loss of life.

These nodes are defined by variables, including probabilities. As such, risks can be calculated.

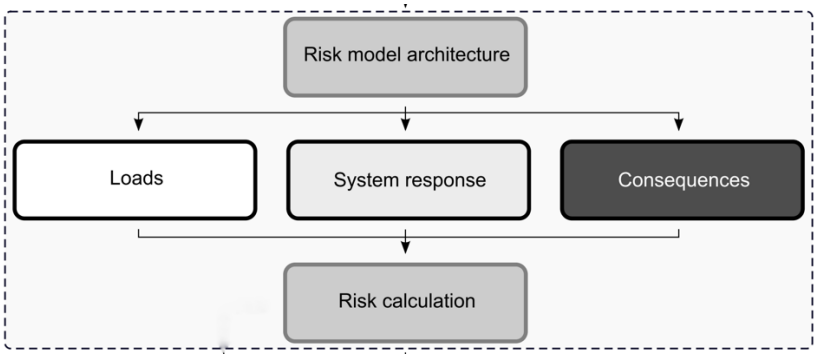


Figure 2.5. The architecture of the risk model (SPANCOLD, 2013)

Figure 2.6 shows an example of a risk model for a hydrologic scenario of a concrete gravity dam equipped with a spillway controlled by two gates. The same color code (white, light gray, and dark gray) is used, likes the generic risk model. The first node introduces the flood entering the reservoir. The next node (previous pool levels) represents the pool level in the reservoir at the instant preceding the arrival of the largest flood of the year. The spillway availability is the probability of this device functioning properly (or not) when a flood arrives. The following node, flood rooting, results from each possible combination of the three variables (i.e., previous pool level, entering flood, and spillway availability).

Based on the combination of the probability of occurrence of the loads and the conditional failure probability of the dam given those loads, the probability of each failure mode is quantified. The total failure probability is the sum of the probabilities of each failure mode. The following two failure modes are identified and described as two branches in the diagram:

+ Break discharge of the dam due to sliding of block produced by high uplift pressures and water level.

+ Erosion of the foot of the dam produced by overtopping

The consequences will be analyzed twice: on the hypothesis of failure of the dam and the hypothesis of non-failure to obtain the incremental risks.

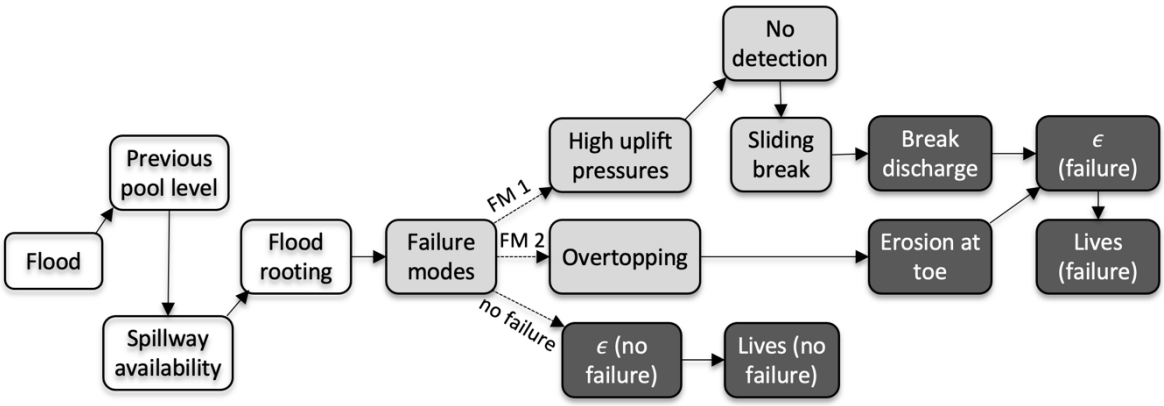


Figure 2.6. Architecture of the risk model of the example (SPANCOLD, 2013)

The risk model provides a visual architecture of risk, where failure is described based on a load scenario. Like the event tree method, it provides a failure path derived from a start event, then a series of events developed, propagated, and culminated in dam failure. It also shows a combination of factors such as impact load, water level, spillway reliability to induce a failure mode. However, it also has disadvantages to applying in forensic engineering. It does not describe the entire structure of a dam system. Therefore, it will be difficult to track the process of a complicated failure. Also, failures are described based on failure modes and probability calculation and lack information about the structure's materials and properties to provide for a forensic investigation. Besides, each model studies only one initiating event.

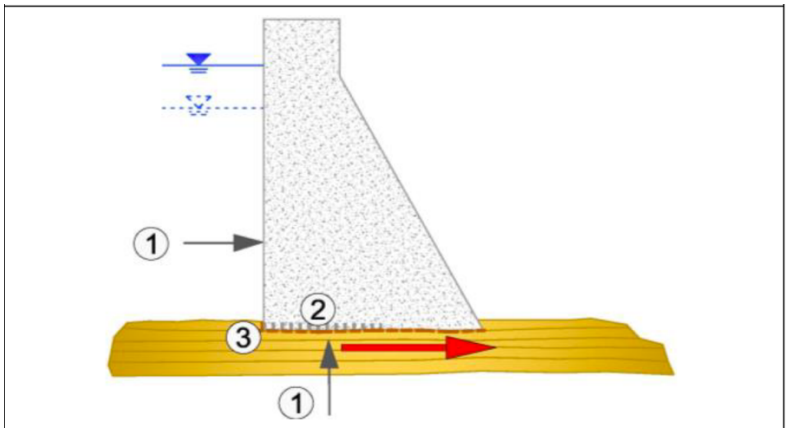
2.2.2.3. Failure modes

The Polytechnic University of Valencia proposed an approach to detail the failure modes of a dam system (Polytechnic University of Valencia, 2019). A failure mode is defined as a specific sequence of events that can lead to dam failure. This sequence has a logic that a failure mode is started with an initiating event, continued with one or more events, and ended with a dam failure. Therefore, a failure mode is structured by three stages: Beginning, Development, and Failure.

The detailed description of the failure modes begins with identifying load scenarios and identifying the component or sub-component where the initial or development process occurred. Each event is associated with the most influential monitoring variables such as stress or uplift pressure, and the instruments to measure it, such as the piezometer.

Figure 2.7 shows a failure mode of a gravity dam illustrated with a graphical scheme and a codification. The graphical scheme illustrates a typical gravity dam section subjected to hydrology scenarios (coded 1), which are water pressures and uplift pressures increment. The location of the failure mode is the foundation component (coded 2). The event occurring in the failure progress is tensile cracks (coded 3).

The failure mode code table describes a process with elements coded. The first event is tensile cracks (coded 3-2), which is triggered by the hydrology loads (coded 1-H) at the foundation subcomponent (coded 2a-Ci). This event is associated with a variable that is tensile stress (coded 3a), measured by electrical extensometers, pressure cells, rigid inclusions, and visual inspection (coded 3b). The next event in the development process is the same as the initial event, but associated variables are leakage, uplift pressure, and turbidity (coded 3a). The measuring instruments are piezometer, gauging elements, turbidimeter, and visual inspection (coded 3b). This event leads to the sliding failure of the foundation (coded 4-I).



FAILURE MODE CODE

SCENARIO	BEGINNING	DEVELOPMENT	FAILURE
1 H	2 2a 3 C - Ci (2)	2 2a 3 C - Ci (2)	4 I
3a VARIABLES	Stress	Leakeage, uplift pressure, turbidity	-
3b INSTRUMENTS	Electrical extensometers, pressure cells, rigid inclusions, visual inspection	Piezometer, gauging elements, turbidimeter, visual inspection	-

Figure 2.7. Failure mode of gravity dam (Polytechnic University of Valencia, 2019)

Like the risk model in the previous section, this approach provides a practical view of the failure description of the dam system: it considers the essence of the impact, that is, load. Propagation of the load flow in the system leads to the propagation of the failure mode. It gives an understanding of how the failure events began or how they are propagated until the ultimate failure. Besides, tools for structuring failure modes provide a common vocabulary and definitions about dam failure and dam system.

This model is interesting, but it also has some drawbacks:

- Each failure mode is only described with one load scenario, while a dam system can be suffered from some simultaneous load scenarios such as filling activity and ground water.
- The failure mode does not describe the interactions between different events.

- The failure mode does not describe the interactions between components of the system, just consider the component or subcomponent where the failure occurred.
- The coding of the scenarios and events can make it difficult to track failure modes, especially as the number of events in failure mode increases.

2.2.2.4. Conclusions on the failure models

We analyzed in this section three models. We exposed for each of them several drawbacks which prevent us from using them in this work. However, some features of these models which appear as particularly interesting, can give us some research orientations:

- We will develop a semantic knowledge base (structured vocabulary) including concept and relation, specifically dedicated to the failure of the dam system. This vocabulary will be organized by a hierarchical model to facilitate its reuse and sharing to formalize a dam failure.
- The failure knowledge model needs to be structured, based on a simple, clear, and generic structure, to fully represent the necessary information related to failure in order to create a full understanding of the failure of the dam system.
- It is necessary to consider all factors affecting the dam system, not only human factors but also other factors such as environmental factors, material deterioration, etc.
- The failure knowledge model needs to be able to formalize interactions between failures, between components, and between the different levels of the system.
- Modeling the propagation of interactions of failure within the system by the propagation of impact flows.

Based on these considerations and those previously exposed, we propose using Conceptual graphs as the main framework of our failure model. The next section is dedicated to the presentation of the Conceptual graphs.

2.3. Conceptual graphs formalism

2.3.1. Introducing Conceptual Graphs

In the 1970s, researchers developed the first knowledge representations based on the use of graphical interfaces developed in the 1970s; it used semantic networks and frames (Baader *et al.*, 2010). Most of the early knowledge models focus on the fields of linguistic knowledge (Schank and Rieger, 1974) or logical semantics. A basic principle of knowledge representation, as a medium of human expression, is that it is “a language in which we say things about the world” (Sowa, 2000).

Conceptual graphs (CGs), which can be viewed as descendants of the semantic network, are a knowledge representation language developed by John F. Sowa (Sowa, 1984). The CGs were developed as “a graph representation for logic based on the semantic network of

artificial intelligence and Pierce existential graphs" (Harmelen *et al.*, 2008). Sowa developed CGs as an intermediate language for mapping natural language assertions to a relational database. CGs can be viewed as a diagrammatic system of logic to express meaning in a precise form, humanly readable, and computationally tractable (Harmelen *et al.*, 2008). They allow filling the gap between the natural language used by human and computer logic.

CGs have been applied in a wide range of fields with applications from data representation to database interfaces, text retrieval, and natural language processing. Here are some examples of their use: (a) maintain knowledge on text equipment descriptions in Non-destructive testing for health monitoring of aircraft structures (Kamsu-Foguem, 2012), (b) represent knowledge and data in the domain of biomedical information (Volot, Joubert and Fieschi, 1998), (c) support reasoning in African traditional medicine (Kamsu-Foguem, Diallo and Foguem, 2013), (d) formalize the information derived from the risk assessment in production logistics (Kamsu-Foguem and Tiako, 2017), (e) the construction and validation of domain expertise (Thomopoulos, 2007), etc.

2.3.2. Conceptual graphs representation

Conceptual graphs provide a formalism to structure and represent different knowledge components: concepts and their relation, assertions, facts, rules, and queries. A fact is composed of actual entities related to each other by different relationships (Chein and Mugnier, 2008). Each entity corresponds to a concept. A concept represents a set of terms that have a common meaning for the domain. These concepts are linked by relations defined by an arity; the arity is the number of arguments (i.e., concepts) of the relation. CGs include a set of concepts and a set of relations that compose a vocabulary, which is an elementary component of conceptual graphs.

A vocabulary can be seen as an ontology that defines the basic concepts and relations in a given domain. Formalizing this vocabulary provides several benefits, including reuse, sharing knowledge (Goos, Hartmanis and Leeuwen, 2009). In the CGs, the vocabulary consists of two distinct hierarchies:

1. a hierarchy of concepts, noted (C)
2. a hierarchy of relations, noted (R)

These two hierarchies are organized in partially ordered sets, i.e., in a taxonomic relation, also called *a-kind-of* relation (e.g., *Concrete* concept *is a kind of* the *Material* concept), or specialization relation. It used the same logic as Object-oriented programming (OOP), where the OOP class is equivalent to Concept/Relation in CGs.

The partial order represents an *a-kind-of* relation as follows: If *t* and *t'* are concepts, *t* is a sub-concept of *t',* or t is a specialization of t', which means that every instance of the concept *t* is also an instance of the concept *t'.* This relation also supports inheritance: all properties of *t'* are inherited by *t*. On the other hand, *t* can acquire new properties that *t'* does not have. There is a most general concept, called the *universal* concept, noted *Top*.

Relations are also organized as a hierarchy. If *t* and *t'* are relations with *t* is a sub-relation

of *t'*, these relations have the same arity *k*, and *t* and *t'* make the link between the same concepts.

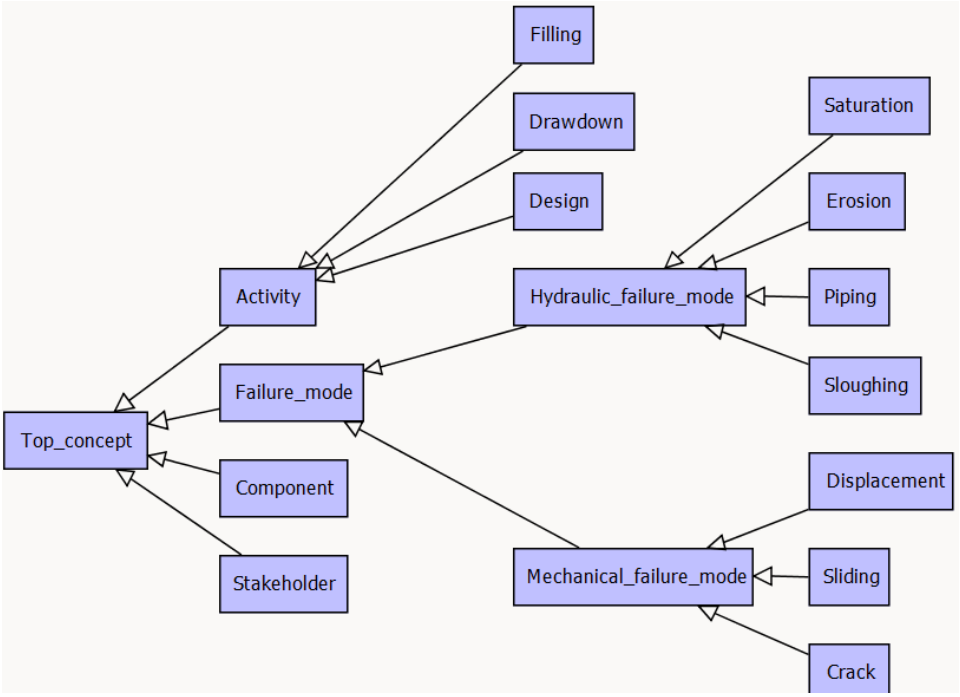


Figure 2..8. Concept hierarchy in a graph view

Figure 2.8 shows a hierarchy of concepts. C = {*Top_concept, Activity, Failure_mode, Component, Stakeholder, Filling, Drawdown, Design, Hydraulic_failure_mode, Mechanical_failure_mode, Saturation, Erosion, Piping, Sloughing, Displacement, Sliding, Crack*}. Concepts are displayed as nodes (boxes on the figure). An arrow connecting concept *t* to concept *t'* means that *t* is *a-kind-of t'* (sub-concept); e.g., *Filling*, *Drawdown*, *Design* are sub-concepts of *Activity* concept. *Hydraulic_failure_mode* is a sub-concept of *Failure_mode* concept, which means all sub-concepts of *Hydraulic_failure_mode,* which are *Saturation, Erosion, Piping,* and *Sloughing* are also sub-concepts of *Failure_mode* concept, Properties of concepts are also inherited by the *a-kind-of* relation, such as *Saturation* inherits properties of *Hydraulic_falure_mode* concept.

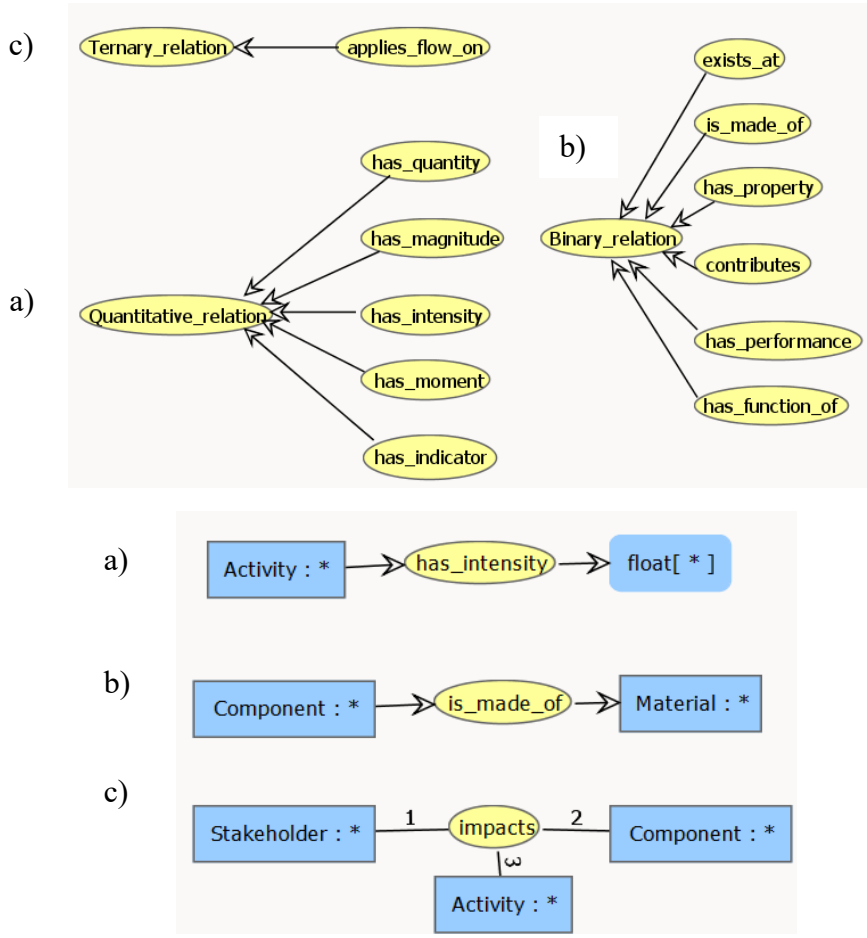


Figure 2.9. Relation hierarchy in a graph view with a) quantitative relation, b) binary relation, and c) ternary relation

Figure 2.9 illustrates three sets of relations. The difference with concept hierarchy is that relations are grouped by arity, i.e., its number of arguments. The quantitative relation shows a relation with only one argument, allowing concepts to be quantified and characterized. For instance, *has_intensity* relation corresponds to an attribute of the *Activity* concept (Figure 2.9 a). The binary relations (i.e., relation with two arguments) describe a relationship between two concepts. For example, *is_made_of* relation determines a link between two concepts: *Component* and *Material*. It can be formalized as a graph or expressed in a textual way: *Component is made of Material* (Fig 2.9 b). Similarly, the relation with three arguments, which is named ternary relation, considers the participation of three concepts in a relationship (Figure 2.9 c). Generically, the number of arity relations corresponds to n-ary. By heritage, a sub-relation inherits its arity from its parent.

Based on this vocabulary (i.e., Concepts and Relations), it is possible to formalize a system using conceptual graphs. CGs use two kinds of nodes corresponding to concepts and relations, whereas edges link a concept node to a relation node. Concept nodes are entities, properties, states, and events, used to represent concrete concepts (the system, the component, …) or abstract concepts (load, strength, ...). Relation nodes indicate the relationship between concepts connected to them. A concept node is connected to another related concept by a conceptual relation node. Each relation must be linked at least to one

concept or more (depending on their n-ary). Relation nodes are connected to concept nodes through directed arrows. The direction of the arrows formally defines the order of the arguments in the relation and helps produce an interpretation (usually in natural language) for the relation. For instance, the relation [has an impact on(Concept1, Concept2)] means that Concept1 has an impact on Concept2. In the graphical representation, they are an arrow from Concept1 to [has an impact] and a second arrow from [has an impact] to Concept2. If a relation has more than two arguments, the arrowheads are replaced by integers 1,…,n defining the position of the argument. Conceptual graphs are bipartite connected graphs involving both concept nodes and relation nodes. "Bipartite" means that a conceptual graph has two disjoint sets of nodes (set of concept nodes and set of relation nodes) and that two nodes from different sets are joined by an edge, i.e., every edge of the conceptual graph links one concept node and one relation node. There are no arrows that link concepts to concepts or relations to relations (Chein and Mugnier, 2008). It makes the representation of conceptual graphs accurate and highly structured.

Each concept can be instantiated, i.e., to define an individual of a specific concept; e.g., "Malpasset dam" is an instance of the concept "*Dam*". Instance inherits all its properties from the concept it belongs, e.g., if the concept *Dam* has properties such as height and date of construction, so is the Malpasset dam. Describing a fact such as a case of dam failure consists of instantiating the model.

For instance, Figure 2.10 illustrates a conceptual graph that corresponds to the statement: *Koyna dam is made of concrete*. In this graph, the rectangles are concept nodes, and the ovals are conceptual relation nodes. The arrows make the link between concept and relation, considering the order of argument. For example, [Gravity_dam: Koyna_gravity_dam] is the first argument and [Concrete:*] is the second of the relation *is_made_of*. In the concept boxes, the first element (e.g., Gravity_dam) is the concept, and the second one (e.g., Koyna_gravity_dam) is an instance of this concept. So, [Gravity_dam: Koyna_gravity_dam] means that Koyna_gravity_dam is an instance (i.e. a concrete element) of the concept type Gravity_dam. The symbol * for the instance indicates that the concept is not instantiated, i.e., it is the concept that is directly used. [Gravity_dam: Koyna_gravity_dam] à (is_made_of) à [Concrete:*] means that the Koyna_gravity_dam (which is a Gravity_dam) is made of concrete (the concrete here is not specified).

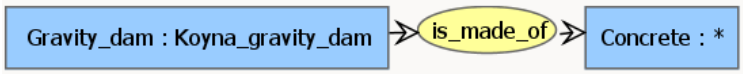


Figure 2.10. Conceptual Graph

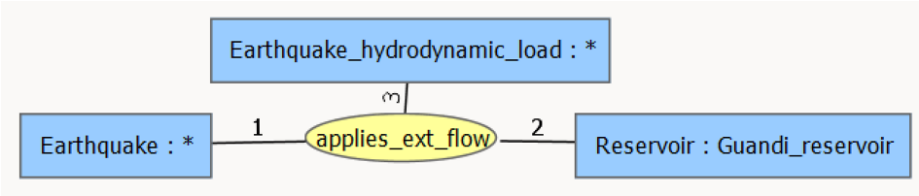


Figure 2.11. Relation with three arguments

Figure 2.11 illustrates a relation node having three edges numbered consecutively. The numbers indicate the order of arguments. The interpretation of the graph in natural language is: *earthquake applies an earthquake hydrodynamic load to the Guandi reservoir.*

2.3.3 Generic graph and Fact graph

The vocabulary makes it possible to build a model representing the system/process to study. We called the generic model, the not instantiated structure of the model; it used the previously defined Relations and Concepts. Pragmatically, in our approach, the generic model will consist of a representation of a failure at a generic level: the Concept will be used at the most high level as possible to be relevant to most of the cases. However, it must be not too generic to be meaningful; for instance, working only with the top Concept and Top relation brings no knowledge on a failure process. The building of the generic model consists of a trade-off between meaning and genericity. Its graphical representation is called a generic graph.

This generic graph will serve as a framework to instantiate the facts. Fact is an assertion regarding the system; it could be an example, a situation, … Regarding our problem, a fact will be a defined failure of a structure. It corresponds to the instantiation of the generic graph to a specific failure (e.g., The Malpasset dam failure). The fact graph is then the graphical representation, using our model, of a fact. The fact graphs will be compiled into the fact base.

2.3.4. Homomorphism (“Projection”) and Subsumption

The CGs propose a graphical representation of the studied system, but they also provide different reasoning mechanisms. The main reasoning mechanism, directly inherited from the graph structure, is the homomorphism (traditionally called projection). A homomorphism from a graph G to a graph H is a mapping from the nodes of G to the nodes of H (pictured in dotted lines on Figure 2.12), which preserves the relationships between the entities of G and may specialize the labels of concepts and relations.

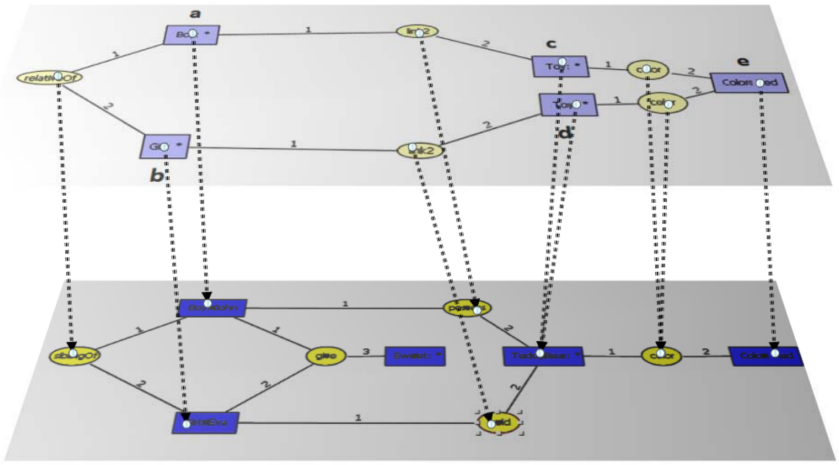


Figure 2.12. Illustration of homomorphism (Chein, Mugnier and Croitoru, 2013)

The existence of a homomorphism from G to H means that the knowledge represented by G is contained in (or implied by) the knowledge represented by H. The reasoning processes are logically founded because the homomorphism is sound and complete concerning logical deduction in first-order logic (Chein and Mugnier, 2008).

If there is a homomorphism from G to H, it exists a subsumption relation (i.e., generalization/specialization) over these graphs, which is defined by G is more general than H (or G subsumes H, or H is more specific than G) (Chein and Mugnier, 2008), or the two following propositions are equivalent:

1. G is a generalization of H
2. H is a specialization of G

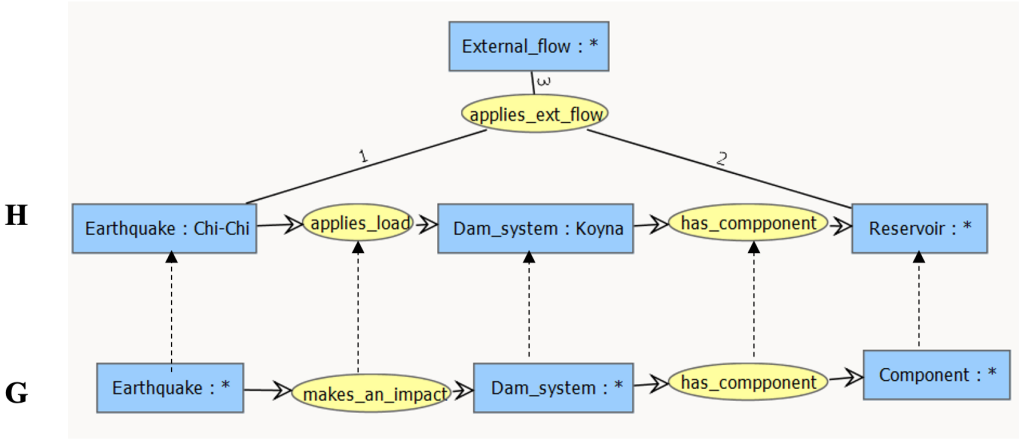


Figure 2.13. Subsumption relation: G is a generalization of H

Considering the graphs G and H in Figure 2.13, the following mapping from the nodes of G to the nodes of H (pictured in dashed lines) defines a homomorphism from G to H:

- the concept node [Earthquake:*] is mapped to the instantiated concept node [Earthquake: Chi-Chi] (then unspecified earthquake is specialized into the Chi-Chi earthquake),

- the concept node [Dam_system:*] is mapped to the instantiated concept node [Dam_system: Koyna] (then unspecified dam system is specialized into the Koyna dam system),

- the concept node [Component:*] is mapped to the concept node [Reservoir:*], with *Reservoir* being a sub-concept of *Component*,

- the relation node labeled (*make_an_impact*) is mapped to the relation node (*applies_load*) (the relation *applies_load* is a sub-relation of the *make_an_impact* relation),

- the relation node labeled (*has_component*) is mapped to the same relation node.

This homomorphism is feasible because each concept node or relation node of G is mapped to a specialized node (or identical node) respectively of H. The subsumption relation over these graphs is defined as G is the generalization of H.

The homomorphism allows inferring knowledge based on graph similarities. For instance, it makes it possible to find in the fact base all the past cases that share the same components (e.g., an earthfill dam in a tropical country), and project on the current graph the explanations of the failure from the past case graphs. This use of the tool is similar to a documentary search, in which the tool automates the search. This allows the user to benefit from previous concrete examples, allowing her/him to enrich her/his analysis and find potential explanations. It is a precious feature for forensic engineering.

2.3.5. Rule graph

In addition to homomorphism, CGs also provide an inference engine based on rules. A rule represents an implicit or general knowledge in the form:

If ***Hypothesis*** *then* ***Conclusion***

The rule graph is composed of a hypothesis and a conclusion, with a correspondence between some of their concept nodes. These correspondences denote that two concepts refer to the same unspecified entities. Figure 7 shows two correspondences drawn as two dotted line segments connecting two concepts *First_filling*, and two concepts *Reservoir*. These concept nodes are said to be connection nodes.

Within the rule graph, a homomorphism is used to make a mapping between the hypothesis of the rule graph to a fact graph. Indeed, the rules can be projected on a fact graph in order to infer knowledge: the conclusion is projected if the hypothesis is present in the fact graph.

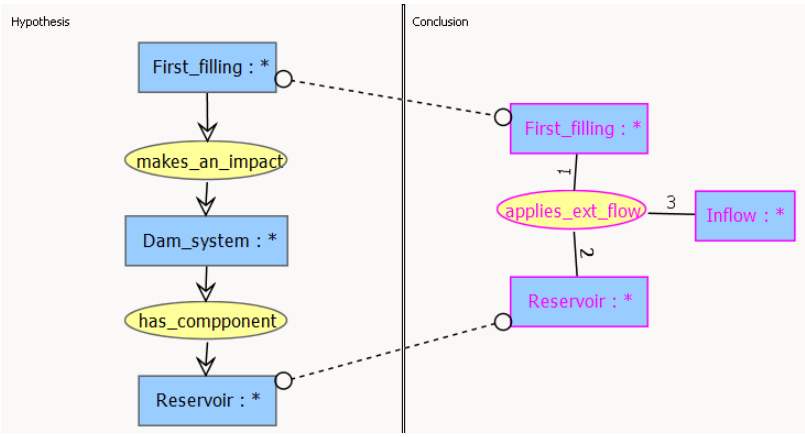
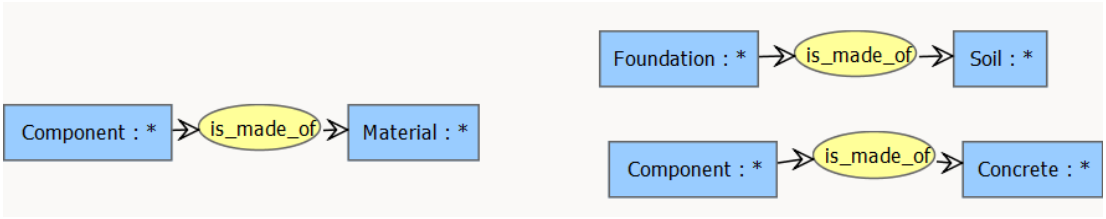


Figure 2.14. The rule graph of inflow

For instance, Figure 2.14 shows a rule graph with the hypothesis on the left side and the conclusion on the right, separated by a vertical line. The rule graph says that **if** *First_filling* activity *makes an impact* on *Dam_system*, and *Dam_system* has *Reservoir* component, **then** *First_filling* applies *Inflow* on *Reservoir*. In this rule, the *Inflow* is created. This rule can be applied to any fact graph containing *First_filling*, *Dam_system*, and *Reservoir* concepts.

2.3.6. Query-Answering mechanism

The homomorphism and rule graphs allow building a query-answering mechanism. Given a query graph G (in a CG format) and a knowledge base composed of a set of fact graphs, defined over the same vocabulary, there is a homomorphism from G to a fact graph if the information represented by G can be deduced from it. A query graph can be seen as a "pattern" allowing the inference engine to extract knowledge from the fact graphs.



A query graph Answers

Figure 2.15. A query and possible answers

Figure 2.15 shows an example of the query-answering mechanism. The query graph can be interpreted as "find all patterns in which a component is made of material". With this interpretation, each homomorphism from G to knowledge base identifies an answer to the query. An answer is defined as the elements in fact graph that entails G, or equivalent elements that are specializations of G, or also, elements that are subsumed by G. In figure 8, two answers were provided: *Component* is made of *Concrete* (which is a type of material), and *Foundation* (which is a component) is made of *Soil* (which is a type of material). The interest is to be able to interrogate the fact base, for example, to find all the failures that share a common point (e.g., all failures by overflow).

2.3.7. CoGui editor

CoGui (COnceptual Graphs User Interface) is a visual, graph-based knowledge representation editor developed by the GraphiK team at LIRMM, Montpellier, France. CoGui is dedicated to implementing CGs, allowing to encode knowledge as graphs and to perform graph inferences. The CoGui editor is compatible and can import and export all major Semantic Web main languages (RDF/S, OWL, Datalog, CGIF, CogXML) (Sowa, 1984). It integers a semantic in first-order logic (FOL), and reasoning tasks operate directly on the knowledge defined by the user (the graphs) and not on their translation into logical formulas (Chein, Mugnier and Croitoru, 2013). All the vocabulary, facts, rules, queries are expressed in a graphical format using a user-friendly interface, and the results of inferences are also given in a graphical format. This is done by the COGITANT library, which is a set of C++ classes enabling easy to build applications based on the Conceptual Graph model.

CoGui provides a Java graphical interface for editing vocabulary, CGs, rules, and constraints. According to (Baget *et al.*, 2010), to represent knowledge visually, the CoGui editor syntactically and semantically overcomes drawbacks of other ontology editors (e.g., Protégé), such as difficulty to visualize/explore concept/relation hierarchies. It also allows the presentation of relevant knowledge about instances by displaying vocabulary along with fact graphs, and each fact graph is visualized in the editor graphically.

In this work, we used CoGui to implement our CGs model of dam failure.

2.4. Conclusion

In this chapter, we analyze the literature foundation about the forensic investigation in civil engineering. It allows us to highlight the lack of scientific literature regarding models for forensic engineering. Nevertheless, it also allows us to provide several orientations that a forensic model must have to fulfill our needs. These needs can find a solution by the use of the conceptual graph. So, we propose to use conceptual graphs in order to formalize knowledge regarding civil engineering failure. It is the first attempt to use such a framework in forensic engineering. In the next chapter, we will develop a generic failure model for a structural system based on CGs. It requires defining, in a first step, the required vocabulary (concepts and relations). In addition to vocabulary and generic model, we will present rules we implemented to support forensic engineering. Finally, we will expose how the inference mechanism provided by the CGs can be useful for forensic engineering and how an investigator can use it in a forensic process.

Chapter 3
Analyzing Dam systems and their failures

Content

3.1 Introduction

3.2 Dam system - general

3.3. Theory review of dam failure analysis

3.3.1 Theory review of failure analysis of dam system

3.3.2 Analyzing a set of past dam failures

3.4. Functional analysis

3.4.1 Functional analysis of system

3.4.2. Application of functional analysis to dam system

3.5. Conclusion

3.1 Introduction

This chapter exposes knowledge related to the dam system and dam failure. The purpose is to understand the structure of the dam system, to facilitate functional analysis and failure analysis.

In the first part, we provide a description of the dam system. The dam system is considered according to the three main dam types: embankment dam, concrete dam, and tailings dam.

In the second part, we analyze dam failures through analyses of their historical failures. The objective is to define the factors related to the failure process, i.e., factors that can trigger a failure to occur, participate in the failure process, exacerbate, or minimize it. This is further reinforced by a review of twenty actual dam failures. Each failure case is described in detail regarding the structure, the factors that affect components of the system, the changes made to the system due to these effects, and the failure process.

The next part is a functional analysis of the system. Functional analysis is an essential step because it allows us to identify the functions of each element constituting a system. It is the basis for evaluating the state of the system based on its performance. It provides an understanding of how the elements are interrelated and how they interact to achieve the system's purpose. The function analysis includes two phases: external functional analysis and internal functional analysis. It is performed at two levels: the whole system, component. The functions at subcomponent level is developed in Appendix 5.

Figure 3.1 shows the plan of this chapter.

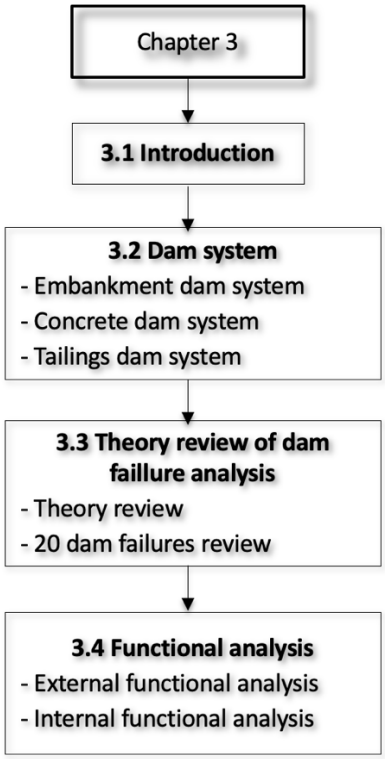


Figure 3.1. Plan of chapter 3

3.2 Dam system - general

The main goal of this section is to provide knowledge about dam systems and their components. It presents the elements of the system: components and subcomponents, as well as their roles in the system. Figure 3.2 illustrates a typical dam system.

A dam system is a hydraulic structure system. It has to control flows and propagation of the flows for human purposes. The three major categories of dam system types upon which this study will focus on include the concrete dam, embankment dam, and tailings dam system. These three dam systems are different in their structural design and material. Their natures and functions can vary depending on the dam system's purpose. However, each dam system usually consists of the following key components:

1. Dam: an obstruction or a barrier across a watercourse to impound water, tailings, or any liquid-borne material.

2. Reservoir: the body of water or tailings impounded by a dam.

3. Foundation: it includes the excavated surface or layer of undisturbed material upon which a dam is placed and the structures to control under seepage.

4. Appurtenant structures (Spillway, Bottom outlet): ancillary features that contribute to the operation of the dam and reservoir for its intended purposes.

5. Abutments: the parts of the valley, to the right and to the left of the river bed, upon which a dam is supported.

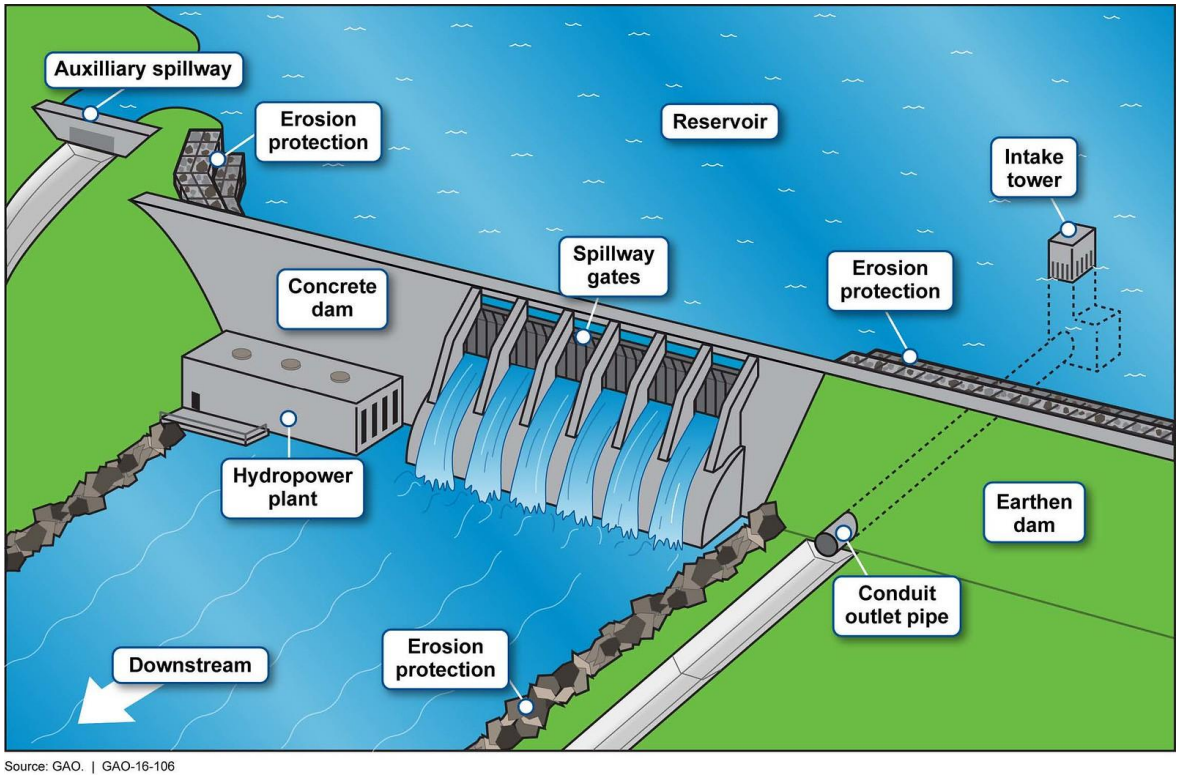


Figure 3.2. Illustration of a dam system (US.GAO, 2020)

In this section, we will first expose some generalities on dams and the different dam types. Other components of a dam system, including reservoir, foundation, abutment, appurtenant structures, and drainage, will be described in appendix 2.

3.2.1. Dam

3.2.1.1. Terminology

The following are basic terms and their definitions that are frequently used when discussing dams' characteristics, illustrated in figure 3.3.

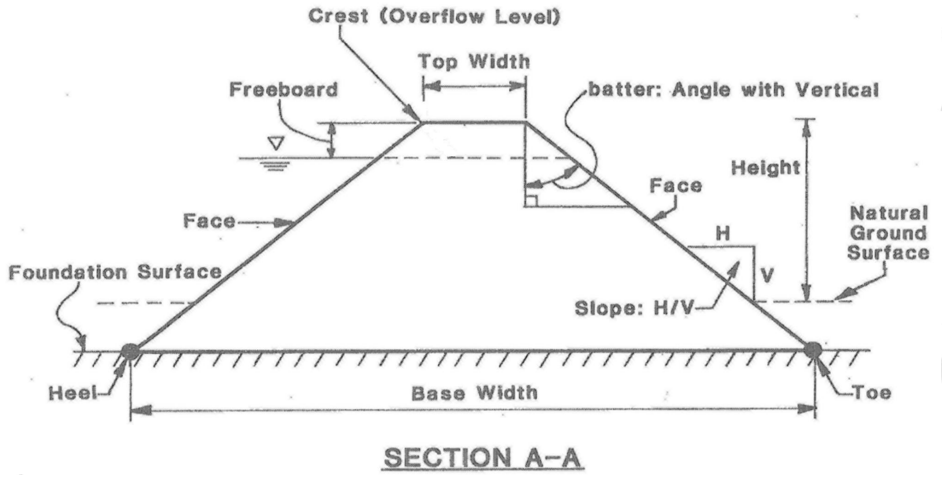


Figure 3.3. Cross-section of a dam component (NH-DES, 2011)

Crest of dam: the elevation of the uppermost surface of a dam, usually a road or walkway, excluding any parapet wall, railings, etc.

Freeboard: the vertical distance from the water surface to the lowest elevation at which water would flow over the dam at a section not designed to be overflowed.

Upstream face: the inclined surface of the dam that is in contact with the reservoir.

Downstream face: the side of the dam that is not in contact with the water.

Toe: the junction of the downstream face of a dam with the natural ground surface. It is also referred to as the downstream toe. For an embankment dam, the junction of the upstream face with the ground surface is called the upstream toe.

Heel: the junction of the upstream face of a gravity or arch dam with the ground surface. In the case of an embankment dam, the junction is referred to as the upstream toe of the dam.

3.2.1.2 Embankment dam

Embankment dams have been built since the early days of civilization. They are very common: more than 70 percent of the world dams are embankment dams. Embankment dams can be defined as dams that are constructed mainly with soils and rock.

Embankment dams have advantages over concrete dams with regard to site topography and cost. They can be built on either rock or soil foundations, making them suitable for many sites. Materials of this dam are excavated at, or near, the dam site, minimizing the

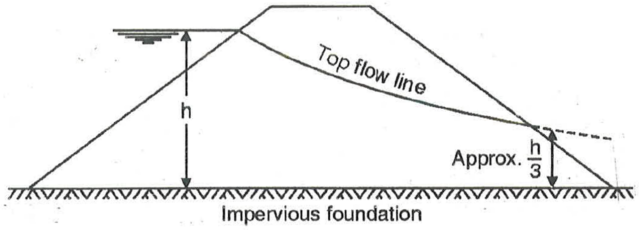
construction process and representing an economic advantage. However, the nature of earth and rockfill materials can create specific issues with seepage, erosion, etc.

Depending upon the primary material used to build the dam, embankment dams can be divided into three main categories: homogeneous embankment, diaphragm embankment, and zoned embankment type.

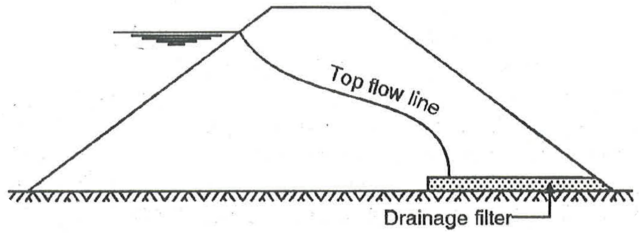
3.2.1.2.1 Homogeneous embankment dam

This type of dam is made of a single kind of material. Homogeneous dams have been built since the earliest times and are used today whenever only one type of material is economically available. However, they are used only for low to moderate heights. Homogeneous dams are usually composed of impervious or semi-impervious soils to provide an adequate water barrier. Many successful embankments have been built to relatively pervious sands and sand-gravel mixtures.

A purely homogeneous section can be replaced by a modified homogeneous section in which an internal drainage system in the form of horizontal blanket drainage or rock toe is provided. This change allows to control the action of seepage and to permit much steeper slopes. The drainage system also keeps the phreatic line within the body of the dam (Figure 3.4).



(a) Homogeneous dam



(b) Modified homogeneous dam with horizontal blanket drainage

Figure 3.4. Homogeneous dam (Punima *et al.*, 2009)

The homogeneous embankment dam can be composed of:

(1) Dam body: the portion of material that fill up the volume of dam. It is available to contain internal structures within the dam body.

(2) Drainage system: horizontal blanket drainage, rock toe;

(3) Slope protections: layers of material that protect the slopes against wave action or erosion.

3.2.1.2.2 Diaphragm embankment dam

Diaphragm embankment dam is a modification of the homogeneous embankment type, in which the dam body of the embankment is constructed of pervious material, and a thin diaphragm of impermeable material is provided to control the seepage. The diaphragm may be of impervious soil, cement concrete, bituminous concrete, or any other material, and may be placed either at the center of the section as a central vertical core or at the upstream face as a blanket (Figure 3.5).

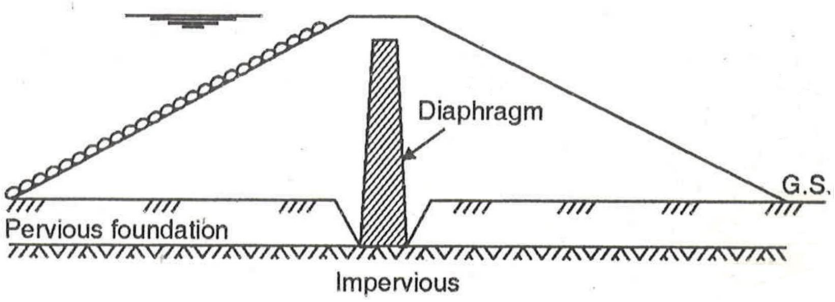


Figure 3.5. Diaphragm type embankment (Punima *et al.*, 2009)

A diaphragm dam is composed of:

(1) Dam body: the portion of material that fill up the volume of dam. It is available to contain internal structures within the dam body.

(2) Diaphragm: a water retention element that is thin compared to the surrounding embankment to prevent seepage;

(3) Slope protections: layers of material that protect slopes against water action (flow and waves) or erosion;

(4) Drainage system: it includes horizontal blanket drainage and upstream impervious blanket. The upstream blanket is a layer of impervious material (usually is clay) laid out at the natural ground level on the upstream side. It increases the path of percolation to reduce seepage pressure (Duggal and Soni, 1996).

3.2.1.2.3 Zoned embankment dam

The zoned dam is a dam is made of more than one material. It consists of an impervious central core flanked by zones of the material considerably more pervious called fills. A suitable drainage system, in the form of a horizontal drain or a rock toe, is also provided at the downstream side. These dams are usually constructed in areas where several material types are available, such as clays, silts, sands, gravels, and rock.

It consists of (Figure 3.6):

(1) Central impervious core: the central portion or zone consisting of impervious material;

(2) Upstream shell: soil embankment located on the reservoir side; its mass provides stability to the dam.

(3) Downstream shell: soil embankment that, together with the upstream shell, provides stability to the structure.

(4) Drainage system which is composed of:

+ Horizontal blanket drainage for drainage seepage

+ Upstream impervious blanket for reducing seepage

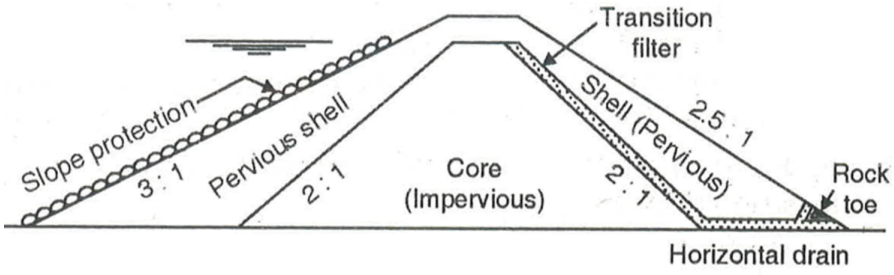


Figure 3.6. Zoned dam (Punima *et al.*, 2009)

3.2.1.3 Concrete dams

There are three main types of concrete dams: gravity dams, arch dams, and buttress dams. They are more expensive to build than embankment dams but are generally stronger and more durable. The design of these dams requires specific consideration of the geological material of the abutments and the rock on which the foundation sits to ensure adequate strength and stability.

3.2.1.3.1 Gravity dam

A gravity dam is a concrete structure designed so that its own weight resists external forces to maintain its stability. They are constructed on a straight axis but may be slightly curved or angled to accommodate the specific site conditions.

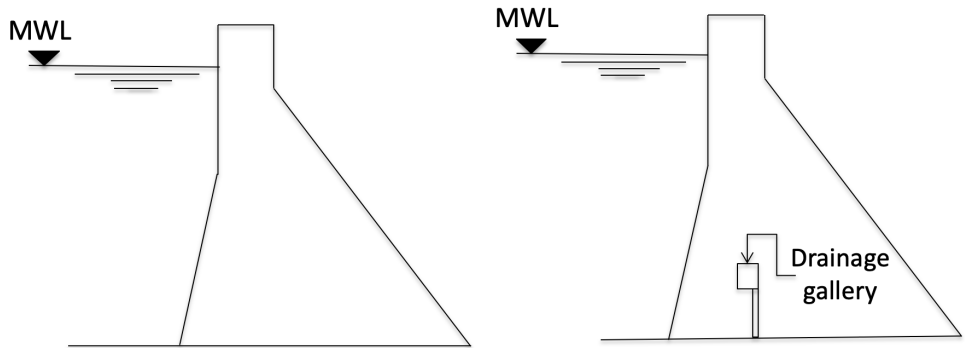
The advantages of a concrete gravity dam are their relatively simple design. They are durable and require very little maintenance. Among concrete dams, gravity dams are mostly constructed. They can be constructed on any dam site, where the natural foundation soil is strong enough to bear the weight of the dam.

A drainage gallery may be used in order to relieve the uplift pressure exerted by the seeping water.

A gravity dam can be composed of:

(1) Gallery drainage: is the horizontal or sloping openings or passages left in the body of the dam to drain off the water which percolates through the foundation and serve inspection purpose;

(2) Dam body: is the portion of material that fill up the volume of a dam;



(a) Gravity dam without drainage gallery *(b) Gravity dam with drainage gallery*

Figure 3.7. Cross-sections of gravity dam

3.2.1.3.2 Arch dams

An arch dam can be defined as a shell structure curved both longitudinally and transversely, carrying a significant part of its water load horizontally to the abutments by arch action. The abutment, thus, must be robust, stable, and rocky. The balance of the water load is transferred to the foundation by cantilever action. An arch dam is usually made of cement concrete.

Since concrete has high compressive strength, the cross-section of an arch dam can be significantly smaller than a concrete gravity dam. Concrete arch dams are common for narrow gorges or canyons where the abutment walls would be stable and steep for support.

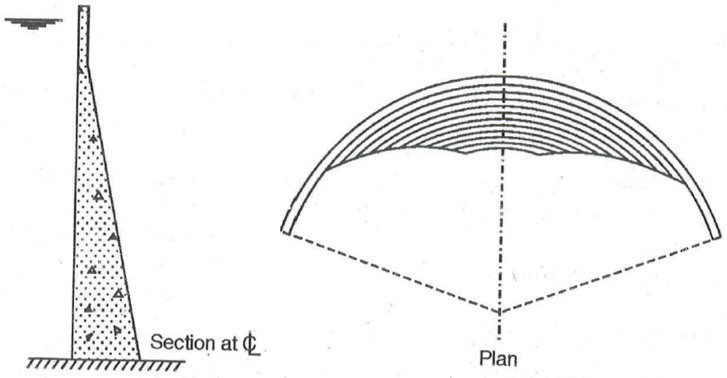


Figure 3.8. Arch dam (Punima *et al.*, 2009)

Likes gravity dam, an arch dam can be composed of:

(1) Gallery drainage;

(2) Dam body.

3.2.1.3.3 Buttress dams

A buttress dam, also called a hollow dam, is an improvement of the gravity dam to minimize the cost for concrete quantity by removing the concrete in the unstressed area of the dam. Buttress dams became popular during the early 1900s and are a common choice for wide valleys where solid rock is rare.

A buttress dam is a gravity structure that, in addition to its weight, uses the weight of water over the upstream face to provide stability (Jansen, 1988). A buttress dam consists of constructed walls parallel to the water flow with some specified thickness at regular intervals. On these buttresses, an arch slab or inclined deck slab is provided to support upstream water.

A buttress dam has the following components (Figure 3.9)`:

(1) Deck: the upstream slope membrane or deck supports the water load and transmits it to buttresses.

(2) Buttresses: the buttresses are located at certain intervals at right angles to the axis of the dam to support the deck to transfer the load to the foundation.

(3) Concrete cutoffs: the cutoff walls are constructed to reduce or prevent seepage.

(4) Lateral braces: a cross-bracing system between buttresses is provided to effect lateral stiffness and resistance to buckling of counter forts.

(5) Mat foundation: foundation provides the distribution of the pressure to the soil.

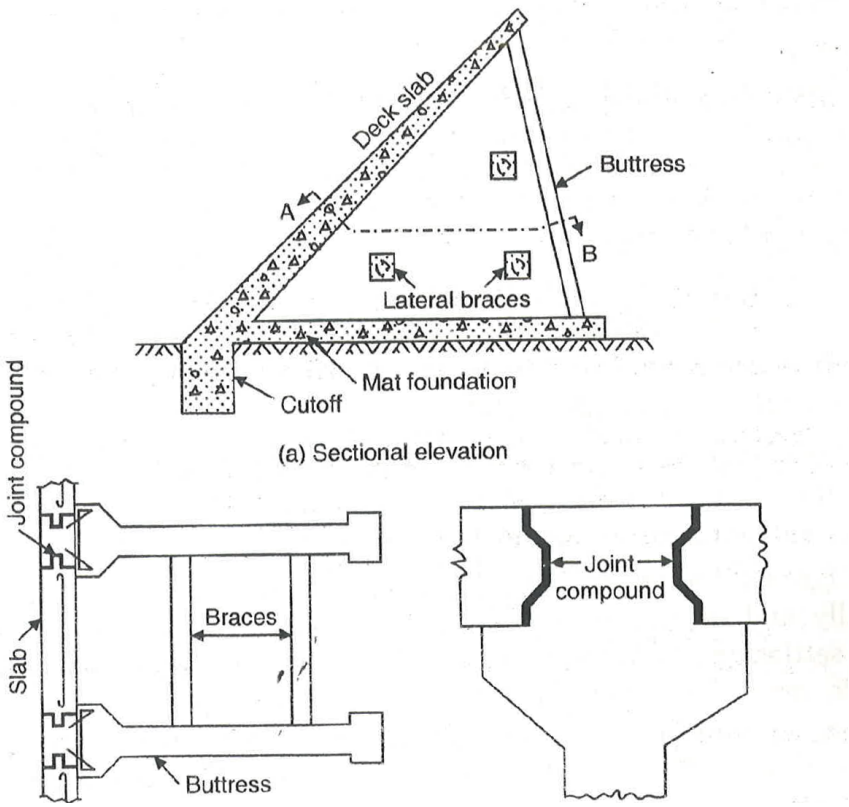


Figure 3.9. Buttress dam (Punima *et al.*, 2009)

3.2.1.4 Tailings dams

Tailings dams are built to retain impoundments of tailings, and when possible, materials extracted from the tailings themselves are used in their construction. Tailings are defined as a waste product from mining activities (Benckert and Eurenius, 2001), such as heavy metal, mixtures of waste rock, and processing fluids from mills or concentrators that remain after

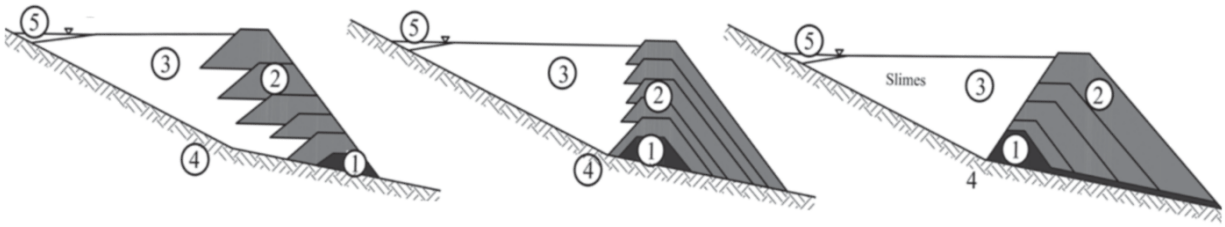
the extraction of economic metals, minerals, mineral fuels, or coal from the mine resource (Hudson-Edwards *et al.*, 2001), (Lottermoser, 2007), (Kossoff *et al.*, 2014).

Even though there are several similarities between embankment dams and tailings dams, some significant differences exist. Embankment dams are used mainly to store water, whereas tailings dams must store unwanted waste at minimum cost. Embankment dams are usually built at one time, while tailings dams are often built slowly in stages over many years.

The classification of tailings dams is based on the methods of construction. There are two basic types, namely raised tailings dam and water-retention type for tailings storage (US-EPA, 1994). Retention dams are constructed at a full height from the beginning, whereas raised embankments are constructed in several stages the need for additional disposal capacity arises. Raised embankments begin with a starter dike, and more height is added to the embankment as the volume of tailings increases in the impoundment.

3.2.1.4.1 Raised tailings dam

Raised tailings dam design (Figure 3.10) is the most common construction technique used in tailings storage facilities. Construction begins with a starter dam, which is similar to conventional dams. The starter dam should be able to pass seepage water, and the downstream portion should be resistant to piping. A centrifugal mechanical device called a cyclone separates the tailings into a coarse portion, generically referred to sand and fine portion. The tailings are discharged peripherally from the crest of the starter dam using spigots or cyclones. Sand can be deposited hydraulically on the growing dam slope. As the impoundment is raised, the crest of the dam moves progressively upstream, or downstream, or in a constant position in plan corresponding to upstream, downstream, and centerline structures, see Figure 3.11.



Upstream method *Centerline method* *Downstream method*

Figure 3.10. Typical cross-sections of tailings dams (Valenzuela, 2016)

(1) Starter dam; (2) Sand dam; (3) Slimes; (4) Foundation soil; (5) Reservoir

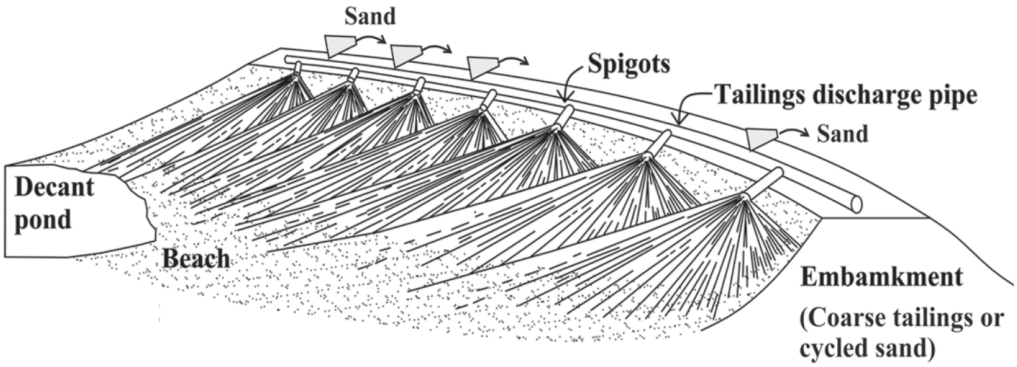


Figure 3.11. Sand deposited on the slope from the dam crest (Valenzuela, 2016)

A raised tailings dam is composed of:

(1) Dam body: is constructed by natural soil, tailings, and waste rock in any combination

(2) Drainage: it dissipates pore pressure across the embankment. It is composed of:

- Chimney drains: vertical curtains of high permeability material,
- Blanket drain: horizontal layers of high permeability material.

(3) Liners: in some cases, liners are required to maintain embankment stability and control releases to the environment. Liners can be composed of compacted native soils, compacted tailings slimes, imported or local clays, synthetic materials, gunite, etc.

3.1.1.4.2 Water-retention type for tailings storage

Water-retention dam for tailings storage (Figure 3.12) is similar to the zoned embankment type dam regarding material, design, and construction method. They are suitable for any type of tailings and deposition method (US-EPA, 1994).

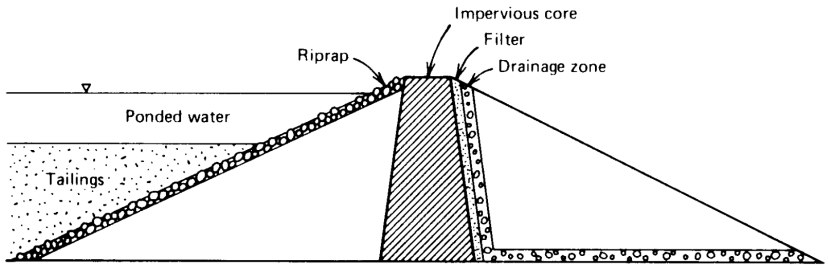


Figure 3.12. Water-Retention Type Dam for Tailings Disposal (US-EPA, 1994)

Conclusion

In this part, we presented general knowledge about the dam system and dam component. Along with the content in appendix 2, we exposed the other components, their functions, and materials. This knowledge is required to perform failure analysis and functional analysis.

In the next part, we will review failure analysis dedicated to dam systems to identify factors contributing to the failure processes. Then, these factors will be analyzed in regards to 20 actual dam failure cases. The results will be used to model concepts and relations of the failure knowledge model.

3.3. Theory review of dam failure analysis

A comprehensive understanding of the characteristics of dam failures is required to identify elements and organize the structure of the failure model. To investigate the characteristics of dam failure, an effective way consists of analyzing past failure cases. Based on a statistical analysis of the dam failure database and literature review, this section will examine the characteristics of dam failures to identify factors involved in the failure processes. From this analysis, we will define the main concepts and relations which will be at the center of the failure knowledge model.

3.3.1 Theory review of failure analysis of dam system

Many works have been made to compile and analyze dam failures. From 2012 to 2014, a working group on forensic structural engineering (WG8) of the International Association for Bridge and Structural Engineering (IABSE), formed in 2011, conducted an international survey of forensic practices and failure statistics in 48 member countries of IABSE (Terwel *et al.*, 2013), (Terwel *et al.*, 2013), (Robert T. Ratay, 2014). The survey consisted of a questionnaire composed of eight groups of questions related to forensic engineering practices. The answers to the question groups “Causes of Failures” and “Failure Statistics” show a variety of factors that contribute or cause a failure (Godart, 2016). They can be environmental factors such as earthquake, flood, strong wind, snow; activities in periods of design, construction, operation, maintenance which cause adverse impacts such as design deficiencies, construction defects, poor maintenance; intrinsic vulnerabilities of structure such as deterioration of materials. The survey also shows that failures are usually the consequences of the interaction of multiple causes (Terwel *et al.*, 2013).

(Bonelli *et al.*, 2012) present a database developed as part of a national research project in France called ERINOH (2006-2012). The ERINOH project examines the mechanisms of erosion in dams and their foundations. The database lists the 41 cases of incidents, accidents, and failures caused by internal erosion and external erosion of embankment dams, most of which are in France. It demonstrates that failure comes from the combination of the dam type and design deficiency, e.g., internal erosion occurred in an embankment dam of homogeneous type without filter and poorly designed; the failures also relate to the characteristics of the dam components, e.g., a breach due to an inadequate reservoir volume. It also shows that failure can come from lack of performance of a or several components, e.g., the clogging of the drain led to a lack of drainage.

(E Slunga, 2001) describes a sub-project of the RESCDAM project (1999-2001) (Maijala, 2001), dealing with a risk assessment for dams. It analyzes the causes of dam failure related

to the different types of dams. The study was based on data from 17.200 dams of more than 15 m high, and contains 204 failures related to these dams. It revealed that 80% of masonry and concrete dam failures are due to excessive stresses in the dam or foundation, while more than 80% of embankment dam failures come from internal erosion or external erosion by overtopping. The results confirmed that the concrete gravity dams have a lower probability of failure, and the dams with the higher failure occurrence were old masonry dams, buttress, and multiple-arch dams. The results also expose that the factors that are likely to cause dam failure are floods, upstream dam-break wave, earthquakes, and the first filling. Furthermore, failure is most likely to occur if there is a combination of these factors.

(L. Zhang, Xu and Jia, 2009) conducted a statistical analysis of failure characteristics based on a database of 1065 earth dam failure cases. In 2016, this study was updated by the statistics on failures of embankment dams regarding 1443 cases (Zhang *et al.*, 2016a). It should be noted that in these studies, the failure of a dam is identified as the complete collapse of the dam or a failure that, at the time, may have been severe but has since been successfully repaired. The failure cases were collected from the literature (e.g., (Vogel, 1980), (USCOLD, 1988), (USCOLD, 1976), (Singh, 1996), (Stanford University, 1994). Based on the database, the failure modes and causes of earth dams were analyzed according to the dam type, material, and failure process. Several conclusions can be drawn:

- The disasters such as earthquakes, reservoir landslides, and extreme floods exceeding design criteria are considered the most frequent cause of failure.
- The failure modes and causes of a dam system can be better characterized by dividing the dam system into several parts; each part of the system can be a potential source of risk. For example, the foundation can be a potential risk source because a weak foundation can cause the settlement of the dam.
- The modes and causes of failures are different regarding the type of dam. For example, the failures are mostly attributed to overtopping for the diaphragm dam, whereas piping appears to become less likely because the core wall plays a crucial role in preventing piping in this type of dam (L. M. Zhang, Xu and Jia, 2009).
- The causes are interrelated. For example, the insufficiency of a spillway capacity may cause an overtopping; or differential settlement of a dam may cause a crack of the core walls, which may cause piping in the dam.

Several investigations of failure reveal some characteristics of dam failure. For concrete dams, (Zhang et al., 2016), (Broberg and Thorwid, 2015), and (Imbrogno, 2014) identified the failure factors and sources. It can be a component, such as a foundation. Indeed, the foundation has a crucial part in a concrete dam system because the main cause of concrete dam failure is internal erosion in the foundation and structural instability. The time dimension has also to be considered because, over time, seepage passing through the foundation material underneath the dam can create damaging uplift forces, and these forces are large enough to create sliding. The concrete material itself has been identified as having an essential role in the safety of concrete dams. This inadequate or degraded concrete can

lead to the inability of the dam to sustain large loads and results in a failure (Imbrogno, 2014). Usually, dam failures are a result of a combination of one or more factors.

To sum up, we can note that:

- Failure usually is the result of a combination of factors. The factors can be:
    + Environmental factors such as earthquake, flood, strong wind, snow;
    + Activities in periods of design, construction, operation, maintenance that cause adverse impacts such as design deficiencies, construction defects, poor maintenance;
    + Characteristics of dam system such as type of dam, materials of the dam components, the structure of the dam and its components, properties of component such as reservoir level, the height of the dam, performance of a component; a default in a component performance can be a source of failure.
    + The chronology, the duration, and the time of the events can have a significant impact on a failure. For instance, a long rainfall duration can lead to a high reservoir level, which increases pressure on the upstream dam.

- Failure is the result of a process. It is created by a series of changes in chronological order. It is often triggered by an external factor such as an earthquake or heavy rainfall, or a combination of factors, introducing changes in the dam components (e.g., decreasing their performance). These, in turn, can lead to effects on other components due to interactions between components. The process will proceed until the performance of the dam is not satisfied, i.e., the dam fails.

- The dam system is composed of components. The performance of a system to fulfill its functions depends on the performance of its components. Therefore, the failure of a system can be induced by the failure of its components.

3.3.2 Analyzing a set of past dam failures

This section provides an analysis of historical dams in order to validate failure characteristics identified from the previous analysis. Twenty historic dam failures have been compiled in Tables 3.1 and Table 3.2. Table 3.1 lists the general dam parameters (e.g., dam name, location, dam height, year of completion/year of failure) with sources used to compile the data. Table 3.2 lists the factors related to the failure and describes the failure process briefly. For a full compilation of these data, see appendix 3. In some cases, information is missing, and this is denoted with the symbol "-". Note that these historic dam failures all concern a failure as defined previously, i.e., an unacceptable performance of a structure to perform its designed function.

Table 3.1. Database of dam failures

Nº	Dam system name	Country	Dam type	Dam height (m)	Year of completion / Year of failure	Information Source
1	Pilarcitos	USA	Homogeneous earthfill	23.8	1874/ 1969	(VandenBerge, Duncan and Brandon, 2013), (Vandenberge, 2014), (Fredlund, Lu and Feng, 2011)
2	Nishinotani-Ike	Japan	Homogeneous earthfill	4.0	- /2011	(Cheng, Draper and An, 2014)
3	Takayama-ike	Japan	Homogeneous earthfill	10.4	- /2011	(Cheng, Draper and An, 2014)
4	Sparmos	Greece	Homogeneous earthfill	Appr. 15.8	1990 / 2016	(Dounias and Bardanis, 2019), (Zekkos *et al.*, 2016)
5	Gibson	USA	Concrete arch dam	60.6	1929 / 1964	(FEMA, 2014), (Annadale, 2006), (Anderson *et al.*, 1998)
6	Koyna	India	Concrete gravity dam	103	1963 / 1967	(Anderson *et al.*, 1998), (Mansouri, Neshaei and Aghajany, 2011), (Pekau and Cui, 2004)
7	Buffalo Creek	USA	Tailings dam	13	1970 / 1972	(Jansen, 1983), (Davies, Bailey and Kelly, 1972), (NOAA, 1972b), (USBR, 2015)
8	Canyon Lake	USA	Earth dam	6	1938 / 1972	(USBR, 2015), (NOAA, 1972a), (National Weather Service, 2015), (USGS, 2002)
9	Upper Stillwater	USA	Gravity dam	88.4	1987 / 1987	(Anderson *et al.*, 1998)
10	Acude da Nacao	Brazil	Earth dam	12	1980 / 2010	(Borela and Melo, 2017), (Moura *et al.*, 2017a), (Moura *et al.*, 2017b)
11	Morvi	India	Zoned dam	25	1972 / 1979	(Dhar *et al.*, 1981), (Gujarat State Centre, 2019), (Gee, 2020), (Toledo, Morán and Oñate, 2015), (Jansen, 1983)
12	Ulley	UK	Diaphgram dam	16	1873 / 2007	(Charles, Tedd and Warren, 2011), (Hinks, Mason and Claydon, 2008), (Smith, Goff and Panzeri, 2014)
13	Maich	UK	Diaphgram dam	9	1850/ 2008	(Charles, Tedd and Warren, 2011), (Mann and Mackay, 2009)

14	Moihne	Germany	Gravity dam	40.3	1913 / 1943	(Jansen, 1983), (Mason, 2018)
15	Sgorigrad	Bulgaria	Tailings dam	12	- / 1966	(Jansen, 1983), (Stava1985, 2020)
16	Kasho	Japan	Gravity dam	46.4	1989 / 2000	(Ohmachi *et al.*, 2003), (USSD, 2014), (NS Energy, 2011)
17	Oroville	US	Zoned embankment dam	235	1968/ 2017	(Koskinas *et al.*, 2019), (Stork *et al.*, 2017), (France *et al.*, 2018)
18	Sella Zerbino Secondary	Italy	Gravity dam	14	1925/ 1935	(Alvi, Engineer and Associates, 2015), (Bonaria and Tosatti, 2013), (Petaccia *et al.*, 2016)
19	Stava	Italy	Tailings dam	28	1969 / 1985	(Chandler and Tosatti, 1995), (Luino and De Graff, 2012), (Luino and De Graff, 2012), (Luino, Tosatti and Bonaria, 2014)
20	Tous	Spain	Zoned embankment dam	98.5	1978/ 1982	(Alcrudo and Mulet, 2007), (Alcrudo and Mulet, 2006), (Serra-Llobet, Tàbara and Sauri, 2013), (Dragados, 2015)

Table 3.2. Factors related to failure and failure description

Nº	Dam system name	External factors	External factor properties	Components at risk	Material	Influences/ Changes	Failure description
1	Pilarcitos	Rapid drawdown activity	Duration: 43 days	Reservoir	Water	Reservoir level lower 10.7 m	Upstream slope slides because a rapid drawdown occurred
				Dam	Sandy clay	Sliding of upstream slope	
2	Nishinotani-Ike	Typhoon No. 12	Duration: 1 day	Reservoir	Water	Full	The dam collapsed was caused by piping due to heavy rains and an increase in storage water level caused by Typhoon No. 12 piping
				Dam	Diluvial sandy silt	Saturation	
3	Takayama-ike	Typhoon No. 12	Duration: 1 day	Reservoir	Water	Full	Sloughing occurred until the reservoir broke.
				Dam	Granite soil	Saturation	
4	Sparmos	First filling	-	Reservoir	Water	Full	After the first filling activity, seepage developed in the embankment and internal erosion was initiated. The process of erosion took 27 years and eventually led to the breach of the dam.
				Dam	Weathered gneiss	Seepage	
5	Gibson	Rainstorm	Duration: 30 hours	Reservoir	Water	Overtopping	During a rainstorm, the dam was overtopped and some erosional damage occurred on the abutment.
				Spillway		Poor performance	
				Abutment	Dolomite rock	External erosion	
6	Koyna	Earthquake	Magnitude: 6.5 M	Reservoir	Water		The dam was subjected to a large magnitude earthquake. It survived the earthquake without any loss of water. However, it was significantly damaged
				Dam	Rubbe concrete	Earthquake load	
				Foundation	Massive basalts rock	Earthquake load	
7	Buffalo Creek	Storm	Duration: 3 days	Reservoir	Tailings	Overtopping	The collapse of the dam resulted in an overtopping of the reservoir, which washed dumped waste, in combination with slumping of the downstream face, which is triggered by erosion in the foundation.
				Dam	Porous mine waste	Slumping of the downstream face	
				Foundation	Soft sediment	Erosion	
8	Canyon Lake	Heavy rain	Duration: 6 hours	Reservoir	Water	Overtopping	The dam washed out after 6 hours of heavy rain. The failure was contributed to the relatively small volume
				Dam	Soil	Scour	

				Spillway		Obstructed by debris	of the reservoir and the poor performance of the spillway.
9	Upper Stillwater	First filling	-	Reservoir	Water	Increased to the maximum elevation	Under the effect of hydrostatic force due to the first filling of the reservoir, the foundation was displaced far exceeded the expected values.
				Dam	Concrete	Reservoir load, uplift load	
				Foundation	Interbedded sandstone and argillite	Seepage flow	
10	Acude da Nacao	Rainstorm	-	Reservoir	Water	Increased reservoir level	The reservoir was quickly filled due to heavy rain and the poor performance of the spillway. Internal erosion started with the excessive hydraulic flow at the open ace and proceeded to breach the dam.
				Dam	Soil	Internal erosion	
				Spillway	Concrete	Poor performance	
11	Morvi	Rainstorm	Duration: 10 days	Reservoir	Water	Overtopping	The dam failed because of the combination of excessive flood, inadequate capacity of the spillway, and overtopping of water over the embankment dam.
				Dam	Soil	Erosion	
				Spillway	Mansory	Poor performance	
12	Ulley	Heavy rain	Duration: 1 day	Reservoir	Water	Overtopping	Following a day of heavy rain, the downstream shell of the dam was eroded by the high turbulence flows, which were initiated by the collapse of the retaining wall of the chute spillway.
				Dam	Soil	External erosion	
				Spillway	Masonry	Collapse	
13	Maich	Heavy rain	Duration: 18 hours	Reservoir	Water	Overtopping	Heavy rain caused local flooding and severe damage to the Maich dam by overtopping. The overtopping had eroded a large part of the downstream fill.
				Dam	Soil	External erosion	
14	Moihne	Bombing	-	Reservoir	Water	Released in 12 hours	As a result of an attack on the dams when the reservoir was filled to its capacity, water was released through a large breach.
				Dam	Concrete	Broken	
15	Sgorigrad	Heavy rains	Duration: 3 days	Reservoir	Waste muds	Reservoir level increased	The dam's collapse was probably due to overflow after heavy rains, resulting in dam instability and sudden collapse.
				Dam	Sand and mud waste	Instability	
16	Kasho	Earthquake		Reservoir	Water	Earthquake load	

			Magnitude: 7.3	Dam	Concrete	Earthquake load	The dam was shaken by a major earthquake, which led to a permanent displacement of the dam and concrete cracking.
				Foundation	Rock	Earthquake load	
17	Oroville	Heavy rainfall	Duration: 5 days	Reservoir	Water	Increasing level	The failure process began with heavy rains, which caused the water to discharge into the main spillway, resulting in erosion of a large area of the concrete surface. Subsequently, the inflow increased the reservoir level continuously to pass the top of the emergency spillway, causing downstream erosion.
				Main spillway	Concrete	Overflow, erosion	
				Emergency spillway	Soil	Overflow, erosion	
18	Sella Zerbino Secondary	Storm	Duration: 9 hours Intensity: 40.7 mm/h	Reservoir	Water	Overtopping	Failure of the Shella Zerbino dam results from a combination of the heavy rain with the absence of spillway, which causes overtopping of the reservoir. The overflow from the reservoir removed the soil on the foundation, leading to the sliding of the dam.
				Dam	Concrete	Sliding	
				Foundation	Rock	Erosion	
19	Stava	Ground water		Reservoir	Tailings		The Stava tailings dams consist of two separate tailings dams, one up-slope of the other. The failure occurred due to the collapse of the upper dam, which released the stored tailings, which, in turn, over-whelmed the lower dam, causing it, too, to collapse. Failure of the upper dam was due to instability caused by the combination of several concurrency factors: construction method, inhomogeneous material, geometric characteristics of the dam, and hydrogeologic of the area chosen for the Stava tailings dams.
			-	Upper dam	Sand and silt	Hindered silt consolidation	
		Construction activity: silt deposit	Increasing weight	Drainage		Sagged, significant leaks	
				Lower dam	Unconsolidated silt	Collapse	
20	Tous	Extreme storm	Duration: 24 days	Dam	Rock	External erosion	On 19 - 20 October 1982, an extreme storm fell over the catchment of the Tous dam system. Due to the weather conditions, electrical power supply was out of order, making the opening of Tous dam spillway gates and bottom outlet gate impossible. The reservoir was quickly filled up and surpassed the dam crest, causing erosion of the dam's downstream slope.
				Reservoir	Water	Overtopping	
				Spillway	-	Impossible opening of gates	
				Bottom outlet	-	Impossible opening of gates	

The failure cases were chosen with various types of dam systems such as homogeneous earthfill dam, concrete gravity dam, arch dam, tailings dam system. The heights of dams range from small dams (i.e., < 15 m high) to large dams (i.e., ≥ 15m high, according to ICOLD). The failure cases are from 11 countries, including the USA, India, the UK, and China, over a period of nearly 100 years. The set of dam failures is representative of previous studies which have covered a much larger number of cases (at least a thousand dams).

Table 3.2. exposed different elements involved in the failure process:

- External factors: they are factors outside the system that interact with it. Interactions can be hydraulic flow or load - for example, heavy rain, earthquake.

- Properties of external factors: they are properties that quantify the influences of the external factors, such as the duration of heavy rain, the magnitude of an earthquake.

- Component: they are a components of the system, impacted by external factors.

- Material: it is material constituting the component

- Impacts/Changes: Impacts refer to the interactions of the components with other components and external factors. There are two main types of impacts: hydraulic flow and load, such as seepage flow, uplift load, and reservoir load. Changes refer to the changes in the system under impacts regarding the state, properties, performance of the system such as reservoir level, saturation, insufficiency of capacity.

The analysis of the failure cases shows that:

- For the analyzed case (Table 3.2), external factors such as earthquake, storm, filling, drawdown are often implied in the failure. They are classified into two main categories: environmental and human activity factors. Specifically, among the 20 failure cases, 16 cases (i.e., 80%) implied environmental factors and 5 cases (i.e., 25%) human activity factors. Furthermore, 1 cases (i.e., 5%) were due to both environmental and human activity factors.

- As shown in table 3.2, no failure comes from a single factor. All the failures are the result of a combination of factors.

- The data also shows that the failure of a component contributes to the failure of the whole system. In the studied cases, 95% of the dam failure is related to the failure of the reservoir, 90% to the dam, 30% to the spillway, 10% to the abutment, 25% to the foundation, 5% to the bottom outlet. It means that the failures of a dam system are concerning the failure of its components.

- The interactions between external factors and components and between components can trigger or transmit a failure process. For instance, for the Sparmos dam failure, the first filling activity led to the increase of the water level in the reservoir, resulting in seepage through the dam and internal erosion, which caused the dam to piping and subsequent breaching.

To sum up, the characteristics of failure obtained from this analysis are in accordance with those from the literature. As a conclusion, we can state that dam failure is impacted by

different internal and external factors. Failure is the result of a process caused by the interactions between those factors, leading to modifying the system's state, ultimately leading to a failure. This process can be seen as a chain of cause-consequences related to component function, triggered by a set of initial events.

3.4. Functional analysis

3.4.1 Functional analysis of system

To understand how a system can fail, it is necessary to understand how the system operates. Functional analysis is conducted to study a system or its parts, to understand the structure of the system and how the system works by the formalization of its functions (functional model). Based on this functional model, a description of the failure or failure process can be conducted. In order to meet the aim of this study, functional analysis is made for the dam system. A function is what the system or component is intended to do, usually to a given standard of performance. The functional analysis is the fundamental preliminary step before evaluating the performance and giving a conclusion about the state of the system. The purpose of functional analysis is to identify the system's functions while breaking down the system into components, which functions have also to be identified. According to (Beullac, Meriaux and Peyras, 2010), functional analysis "allows an understanding and a synthetic description of the functioning of the system studied, and it establishes in a formal and exhaustive way the functional relations inside and outside the system". The functional analysis results in a list of the functions of the system and its components.

3.4.1.1 Method and tools associated

There are many functional analysis methods suitable for industry, services, or organizations: Reliasep, FAST, DEN, SADT ... One of them, the APTE (APplication aux Techiques d'Entreprise), deriving from value analysis, was successfully used and applied to civil engineering systems (Serre *et al.*, 2005). The APTE was created by Gilbert Barbey in 1964 and focused on functional analysis at the early stages of the design phase. It has the advantage of carrying out a structural analysis before doing the functional analysis, i.e., making a description of the system (components and relationships between them). Literature provides different applications of the APTE method:

- Diagnosis and analysis of risks linked to the aging of dams (Peyras, Royet and Boissier, 2006), (Peyras, 2003);
- Performance assessment of dikes (Serre *et al.*, 2005), (Serre *et al.*, 2008);
- Identify the failure modes for a civil engineering system (Baroth, Schoefs and Breysse, 2013);
- Waste management system (Beraud, Barroca and Hubert, 2012);
- Functional analysis of long-linear hydraulic structures (Beullac, Meriaux and Peyras, 2010);

- Functional analysis for cities impacted by flooding (Bambara *et al.*, 2015);

- Study of the operating safety of a hydraulic engineering structure (Peyras *et al.*, 2006).

In this study, we will use a functional analysis based on the APTE method, which already demonstrated its relevance in the civil engineering domain, for analyzing dam failure.

The Tools

The APTE method uses two functional analysis tools: the functional block diagram (FBD) and the functional analysis table (FAT).

The functional block diagram is the primary tool in functional analysis. It represents the system, the system's outside environments, and the interactions between components and the environment. It enables functions to be identified by examining the flows that put the different components in relation to each other and the environment (Peyras, 2003). It is based on a structural analysis that enables a detailed understanding of the system's general framework (Figure 3.13).

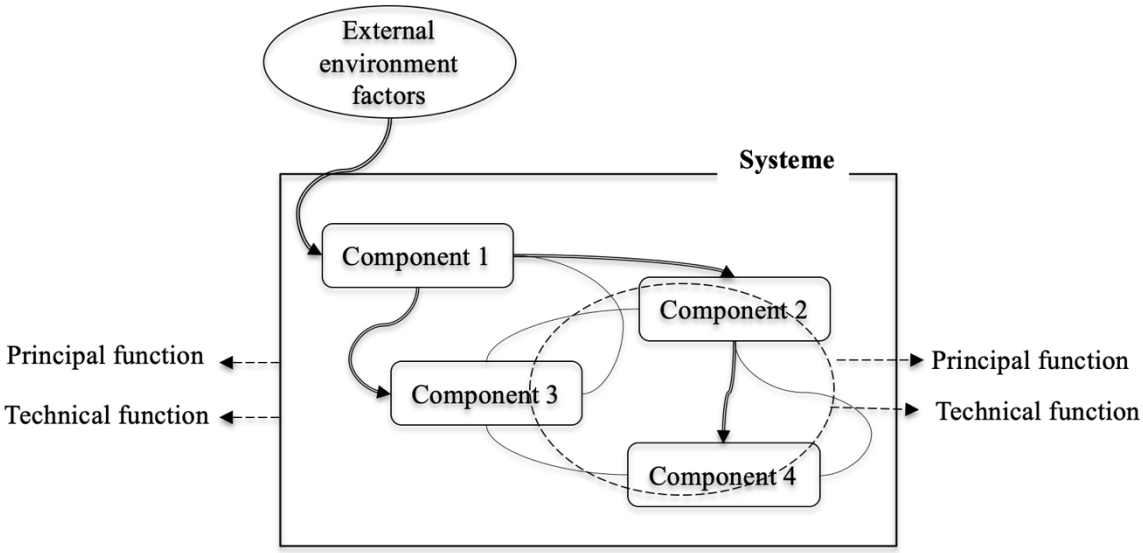


Figure 3.13. FBD applied to four components (Serre *et al.*, 2005)

The Functional Analysis Table (FAT) derives from the FBD analysis. It presents the functions carried out by the system, depending on the considered component (Peyras, 2003). It identifies and allocates functions to the system and to the different components, i.e., to map functions to physical elements. It enables the "who does what" to be defined (Beraud, Barroca and Hubert, 2012), thereby supporting the failure identification at different levels. (Table 3.3)

		Main function	Technical function
N°	System		
	Component		
	Sub-component		

Table 3.3. Structure of a Functional analysis table

3.4.1.2 Two levels of analysis

The functional analysis consists of two phases, dedicated to two types of function: external functional analysis and internal functional analysis. In parallel, in functional analysis, two categories of functions are considered to reflect the actions of a system: main and technical functions (Bambara *et al.*, 2015). Figure 3.14 exposes the process of functional analysis.

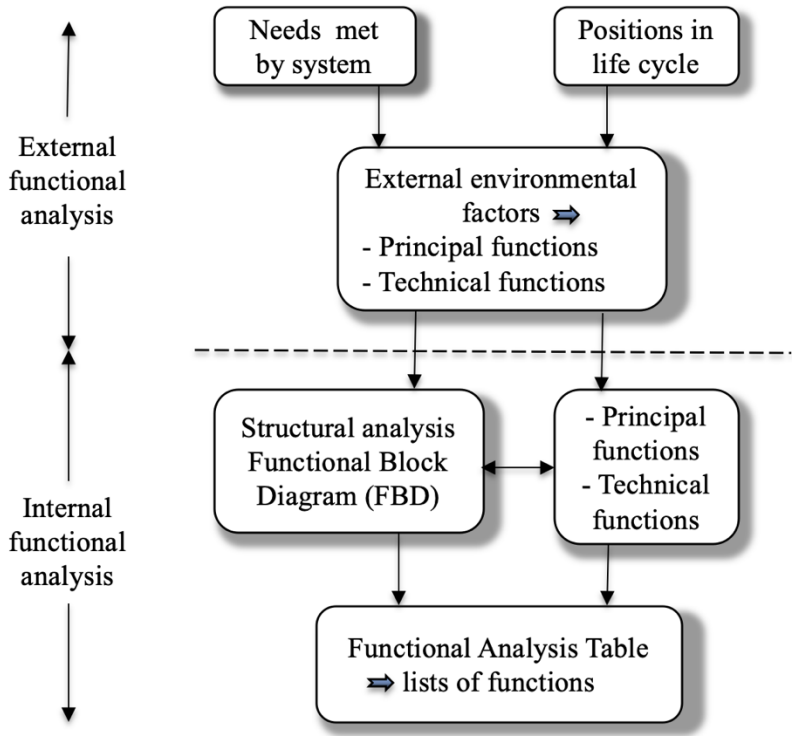


Figure 3.14. Functional analysis process (Peyras, 2003)

3.4.1.2.1 External functional analysis

External functional analysis is an approach in which the system's interactions with factors of the external environment are studied. The interactions between the system and external factors are modeled in a functional block diagram (FBD), showing mechanical relations and transfer flows. The external functional analysis formalizes the functions performed by the system as a whole. It includes defining precisely the system which will be examined, its limits, and the external environments in interaction. It is composed of 4 steps: determination of the system, determination of the external environmental factors, determination of the primary functions of the system, and determination of the technical functions of the system.

- Determination of the system

A system is defined according to its structural components and its functions. At each level of decomposition of the system, structural components perform functions that contribute to the global functions of the system (Cremona, 2011). Thus, a civil engineering system can be

defined either from the structural elements (or components) that make it up or from the functions it performs (Beullac, Meriaux and Peyras, 2010).

- Determination of external environmental factors

In the external functional analysis, the system is considered a black box whose interactions with the environment are studied. In this step, the external environmental factors are identified by the interactions of the external environment with the system.

- Determination of the primary functions of the system:

The primary functions of a system are the essential functions that the system was designed to perform. They highlight the need satisfied by the system (Serre *et al.*, 2005); they are obtained from the FBD. For example, the primary function of a dam system could be to control floods, to provide water for irrigation, to produce energy...

- Determination of technical functions:

The technical functions are the reactions of the system to the constraints imposed by the external environmental factors in order to achieve the primary functions (Peyras, Royet and Boissier, 2006). They support the primary functions and result from the specific design approach. They can be identified from the FBD. For example, the technical function of a dam system could be to resist water load.

3.4.1.2.2 Internal functional analysis

After the external analysis of the system, the internal functional analysis can be used to study to formalize the functions of each of the components and subcomponents. The environment of a component is constituted by the other components and by the external factors (Beullac, Meriaux and Peyras, 2010). The internal functional analysis includes a structural analysis that aims to define all the system components and determine the interactions between them and external factors. It is based on a top-down analysis, in which the system is broken down into several components, which are composed of subordinate levels called subcomponents. The flows through or inside the system and components formalize the interactions between constituent elements or the outside environment.

- Determination of the primary functions of the component:

The primary function of a component reflects the essential functions that the component was designed to perform to contribute to the system's function. It is identified by examining the interactions between the considered component with the external factors and the other components. For example, the primary function of a dam is to retain water in the reservoir. This function contributes to the primary function of the dam system (e.g., provide water for irrigation).

- Determination of the technical functions of the component:

The technical functions of the components are the reactions of the components to the constraints imposed by the external factors and by the other components; they are required to achieve its principal functions. For example, the technical function of a gravity dam is to

resist sliding. It is a reaction of the dam to constraints imposed by external factors such as earthquakes and other components such as the hydrostatic load of the reservoir. The technical functions of the components are determined by examining the interactions of the components to the external factors and the other components.

- Internal functional analysis at different levels of the system:

The functional analysis is a repeatable process at different systemic levels (ZIV, 2018). For instance, it can be applied for a dam system at the system level for the whole dam system and at the component scale or subcomponent scale. Therefore, at the subcomponent level, we can perform the same analysis steps for the component level.

3.4.1.2.3 Relations between functions

- Relation between primary function and technical function

The primary functions of the system and the components are the essential functions that the system was designed to perform. The technical functions are the reactions of the system to constraints imposed by external factors and other components in order to achieve the primary function. The technical functions are then the guarantee for the execution of the primary function. Therefore, the satisfaction of the technical functions is a condition for the satisfaction of the primary functions. In other words, the primary functions are fulfilled only when the associated technical functions are satisfied.

- Relation between functions at different systemic levels

As for a system that is breakdown into its parts, functions are also analyzed by decomposing higher-level functions into lower-levels. The sub-functions provide a more detailed description of the function. They express how a higher-level function is performed. The performance requirements associated with the higher-level function are allocated to the lower level. It formalizes the dependence of the performance requirement of the system to sub-level. It means that the low performance of a sub-component can lead to low performance of the component and potentially to the whole system.

3.4.2. Application of functional analysis to dam system

3.4.2.1. Position in the life cycle

The system goes through different chronological phases during its life cycle. It is necessary to define those of interest for our analysis. If all the phases of the life cycle of a dam can be impacted by a failure, depending on the type of the dam, certain phases are particularly critical. For the embankment dams, the concrete dams, and the water-retention tailings dams, the operation phase is particularly interesting, as the design and construction process impact this phase. For the tailings dams, the process of design and construction is a dynamic process, i.e., the embankment is growing during operation to accommodate the increased tailings over its life. Therefore, the operation phase is exciting, and we must also consider design and construction activities.

3.4.2.2. External functional analysis

External functional analysis is performed through 4 steps: determination of the system, determination of the external environmental factors, determination of the primary functions of the system, and determination of the technical functions of the system.

- Definition of the system

The dam system is constructed for different purposes related to hydraulic flow, such as storing water or controlling the flood. As we exposed before in this chapter, depending on the type of dam, it could have different purposes and components. Nevertheless, all the dams have the following main components: reservoir, dam, foundation, abutments, spillway, and bottom outlet (Figure 3.15).

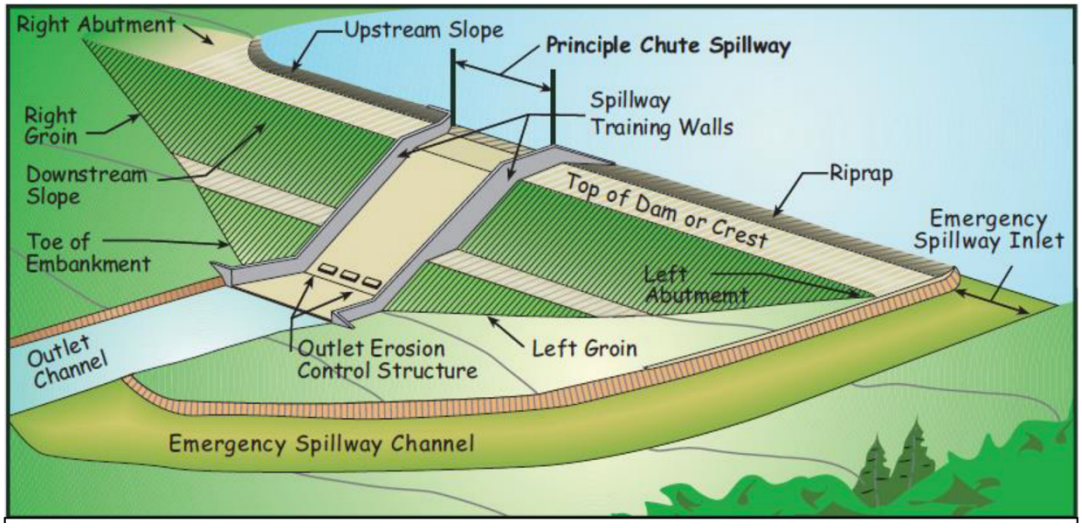


Figure 3.15. Typical dam system configuration (Association of State Dam Safety Officials, 2018)

- Determination of external environmental factors

The external factors impacting the system are made up of material elements, natural or forming part of other systems, which can act on the structure or undergo its actions (Peyras, 2003) (Figure 3.16).

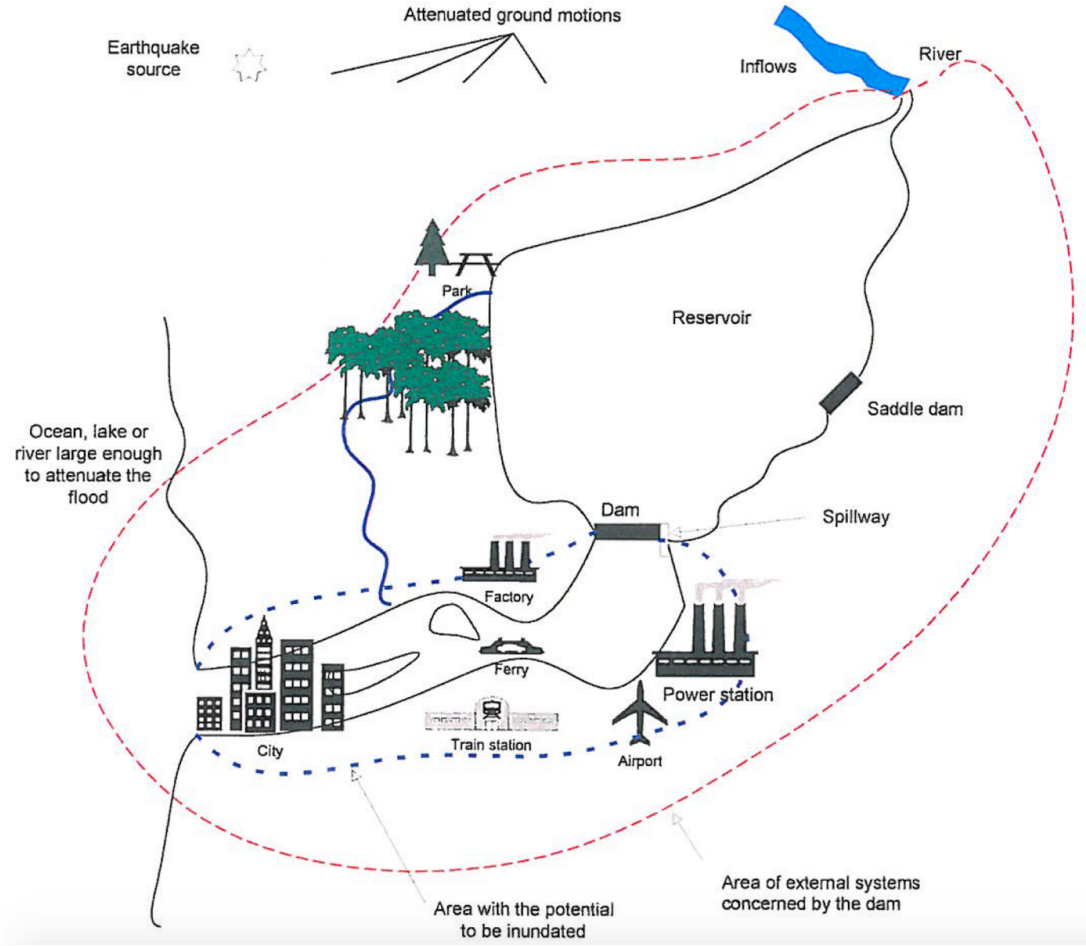


Figure 3.16. External environment of dam system (Peyras, 2003)

We identified the external factors by combining a literature review and an analysis of past dam failures. The external factors we identified are listed in Table 3.4, according to two categories: human activity and the natural environment.

Type	External factors
Human activity	First filling, Filling, Drawdown, Tailings deposition, Soil placing, Bombing, Gate opening, etc.
Natural environment	Gravity, Rain, Earthquake, Groundwater, Tailwater, Flood, Temperature, Landslide, etc.

Table 3.4. External factors impacting the dam system

- Determination of the primary functions of the system:

The external functional analysis is an approach in which the system is considered a black box, and in which we analyzed the interactions between the external environment with the system. These interactions are characterized by two types of flow: load flow (earthquake load, tailwater load, gravitational load, …) and material flow (water flow, tailings flow, …).

Figure 3.17 exposes the functional block diagram of the dam system, which shows interactions between the dam system and the external environmental factors.

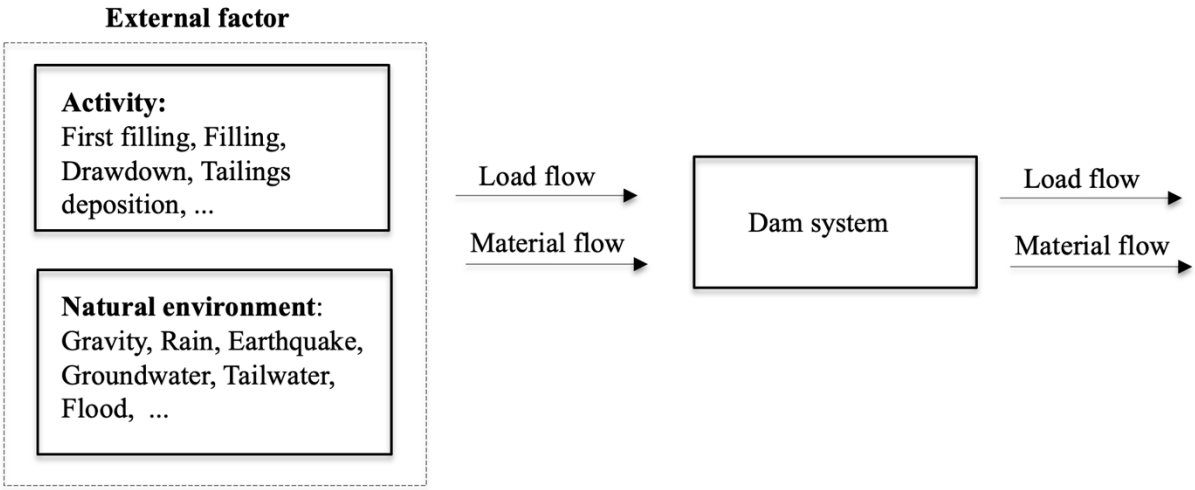


Figure 3.17. Functional block diagram of the dam system

The primary functions of the dam system highlight the needs that must be satisfied by the system. The needs can be formalized by three questions (Peyras, 2003) (Figure 3.18):

(1) Whom does the system serve?

⇨ Different stakeholders (human purpose) depending on the activity: infrastructure manager, agricultors, downstream residents, energy suppliers...

(2) What is it effective on?

⇨ It has an impact on upstream (water basin) and downstream.

(3) Why this action? (for what purpose does the system exist?)

⇨ Retaining water to support different possible activities: irrigation, hydroelectric, supplying water for domestic and industrial use, …

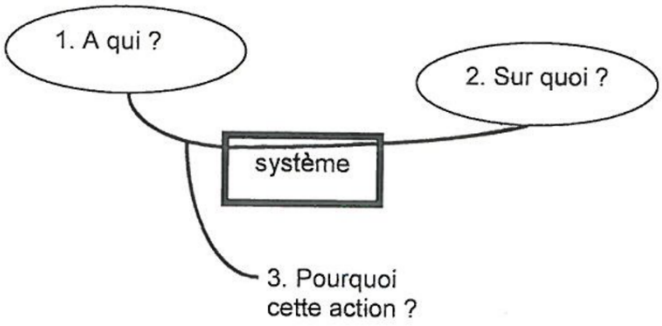


Figure 3.18. The expression of the need by the system (Peyras, 2003)

From the interactions of the dam system with external factors described in the Functional block diagram and the expression of the need, the primary functions of the dam system were identified and are presented in Table 3.5.

- Determination of the technical functions of the system:

To achieve its primary functions, the dam system must be able to react to constraints imposed by factors of the external environment, i.e., must ensure its technical functions. The technical functions are obtained by examining the interactions of the system with the external factors, which are expressed through two types of flows: load flow and material flow. Thereby, there are two main types of technical functions:

- Mechanical functions are functions to resist mechanical loads;
- Hydraulic functions are functions related to the transfer of hydraulic flow.

Technical functions at the system level were identified and are presented in Table 3.5.

Table 3.5. Functional analysis table for dam system

	Principal functions		Technical functions	
	Hydraulic function	Mechanical function	Hydraulic function	Mechanical function
Dam system	- Retaining water - Enabling irrigation - Controlling flood - Supplying water for domestic and industrial use - Producing hydroelectricity - Allowing recreation activities - Retaining tailings		- Controlling flows through the system	- Resisting instability - Resisting deformation - Remaining durability

3.4.2.2 Internal functional analysis

3.4.2.2.1 Structural analysis

In order to describe in details the structure of the dam system and its failure, three levels of granularity are considered:

- Level 1: the system as a whole, i.e., the dam system.
- Level 2: the main components within the system which their functions contribute to the overall system functions, such as a reservoir, dam, foundation, abutments, spillway. The components can be atomic (i.e., not further decomposed), or they can be decomposed into further subordinate levels (subcomponents).
- Level 3: the subcomponents of each principal component, such as drainage, slope, core, cut-off wall, etc.

We then proceed with the structural analysis of the different dam system types (concrete, embankment, tailings) and examine the typical designs with the maximum number of supplementary features so that the structural breakdown can apply to any existing dam system. In this way, we can list all the components in a dam system and determine their interactions.

In the following tables, we list the structural components corresponding to each type of dam system and the corresponding subcomponents. Regarding the spillway component, due to the diverse combination of each spillway type with the different dam types, it is established in a separate table (*Table 3.14*).

Table 3.6. Structural components of the homogeneous embankment dam system

System	Component	Subcomponent
Homogeneous embankment dam system	Homogeneous dam	Upstream slope protection
		Downstream slope protection
		Homogeneous dam body
		Horizontal blanket drainage
		Toe drain
	Reservoir	
	Foundation	Bed foundation, Cut-off wall, Grouting
	Abutment	Drainage, Abutment
	Spillway	
	Bottom outlet	Intake structure, Conduit, Gate, Valve, Trash rack, Terminal part

Table 3.7. Structural components of the diaphragm embankment dam system

System	Component	Subcomponent
Diaphragm embankment dam system	Diaphragm dam	Upstream slope protection
		Downstream slope protection
		Diaphragm dam body
		Impervious core
		Horizontal blanket drainage
		Upstream blanket
		Toe drain
		Filter
	Reservoir	
	Foundation	Bed foundation, Cut-off wall, Grouting
	Abutment	Drainage, Abutment

	Spillway	
	Bottom outlet	Intake structure, Conduit, Gate, Valve, Trash rack, Terminal part

Table 3.8. Structural components of the zoned embankment dam system

System	Component	Subcomponent
Zoned embankment dam system	Zoned dam	Upstream slope protection
		Downstream slope protection
		Upstream shell
		Downstream shell
		Impervious core
		Horizontal blanket drainage
		Upstream blanket
		Filter
		Toe drain
		Chimney drain
	Reservoir	
	Foundation	Bed foundation, Cut-off wall, Grouting
	Abutment	Drainage, Abutment
	Spillway	
	Bottom outlet	Intake structure, Conduit, Gate, Valve, Trash rack, Terminal part

Table 3.9. Structural components of the gravity dam system

System	Component	Subcomponent
Gravity dam system	Gravity dam	Gravity dam body, Gallery drainage
	Reservoir	
	Foundation	Bed foundation, Cut-off wall, Grouting
	Abutment	Drainage, Abutment
	Spillway	
	Bottom outlet	Intake structure, Conduit, Gate, Valve, Trash rack, Terminal part

Table 3.10. Structural components of the arch dam system

System	Component	Subcomponent
Arch dam system	Arch dam	Arch dam body, Gallery drainage
	Reservoir	

	Foundation	Bed foundation, Cut-off wall, Grouting
	Abutment	Drainage, Abutment, Thurst block
	Spillway	
	Bottom outlet	Intake structure, Conduit, Gate, Valve, Trash rack, Terminal part

Table 3.11. Structural components of the buttresses dam system

System	Component	Subcomponent
Buttresses dam system	Buttress dam	Deck, Buttresses, Concrete cutoff, Mat foundation
	Reservoir	
	Foundation	Bed foundation, Drainage, Grouting
	Abutment	Drainage, Abutment
	Spillway	
	Bottom outlet	Intake structure, Conduit, Gate, Valve, Trash rack, Terminal part

Table 3.12. Structural components of the raised tailings dam system

System	Component	Subcomponent
Raised tailings dam system	Raised tailings dam	Dam body, Outlet pipe, Liner,
	Reservoir	
	Foundation	Bed foundation, Drainage

Table 3.13. Structural components of the water-retention tailings dam system

System	Component	Subcomponent
Water-retention tailings dam system	Water-retention tailings dam	Upstream slope protection
		Downstream slope protection
		Upstream shell
		Downstream shell
		Impervious core
		Horizontal blanket drainage
		Upstream blanket
		Filter
		Chimney drain
	Reservoir	
	Foundation	Bed foundation, Cut-off wall, Grouting

Table 3.14. Structural components of the spillways

N°	Type of spillway	Subcomponent	Type of dam
1	Free over-fall (Straight drop) spillway	Weir, Gates, Terminal part	Arch dam
2	Ogee (Overflow) spillway	Weir, Gates, Terminal part	Gravity dam, Buttress dam, Embankment dam
3	Chute (trough) spillway	Approach channel, Weir, Gates, Chute (trough), Terminal part	Embankment dam
4	Side-channel spillway	Side channel, Weir, Gates, Chute (or tunnel), Terminal part	Embankment dam
5	Shaft spillway	Weir, Gates, Shaft, Conduit (Tunnel), Terminal part	Embankment dam and Concrete dam
6	Siphon spillway	Closed conduit, Terminal part	Embankment dam and Concrete dam

3.4.2.2.2 Determination of the environment of a component

The environment of a component is constituted by other components and external factors. For example, the environment of a gravity dam is constituted by the external factors and the other components: reservoir, foundation, abutment, spillway, and conduit. Therefore, to identify its functions, it is necessary to consider the interactions between the external factors and the dam and between the dam and the other components.

3.4.2.2.3 Determination of the primary function of the component

Figure 3.31 exposes a functional block diagram (FBD) established at the component level, showing the interactions between the external factors and the components and their interactions.

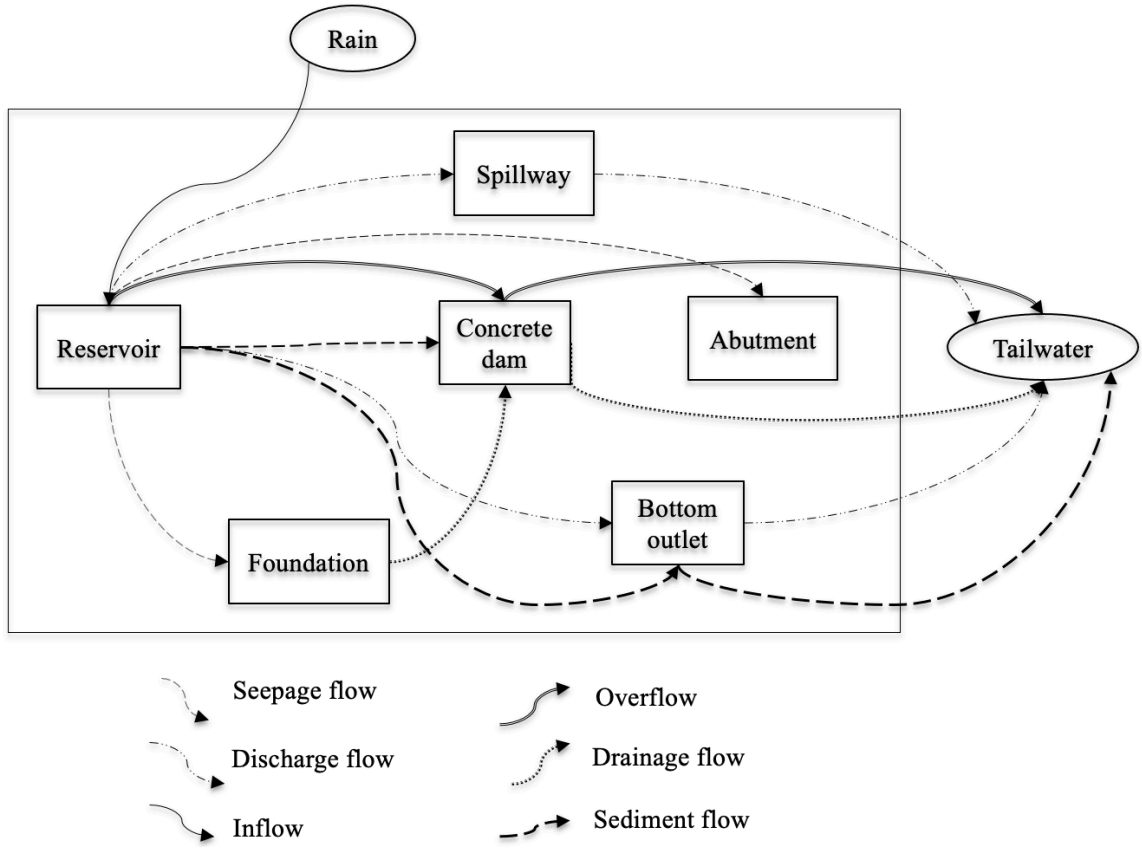


Figure 3.19. Functional block diagram relating to hydraulic flows (Concrete dam system)

The FBDs for different types of dam systems are presented in Appendix 4.

From the FBD, two types of flows can be identified:

- Load flow, which can be used to identify mechanical functions

- Hydraulic flow, which can be used to identify the functions that involve the propagation of hydraulic flows from external factors to components, or between components.

Respectively, there are two main types of functions: mechanical functions and hydraulic functions.

The functions of components of dam systems are presented in Table 3.15. Functional analysis at the component level. The functions of sub-components of dam systems are presented in Appendix 5.

Table 3.15. Primary functions and technical functions at the component level

Component	**Primary functions**		**Technical function**	
	Hydraulic function	Mechanical functions	Hydraulic function	Mechanical functions
Reservoir	Retaining water Retaining tailings			
Gravity dam	Retaining water in the reservoir		- Draining seepage - Limiting flow from the reservoir	- Resisting sliding - Resisting crushing - Resisting overturning
Arch dam	Retaining water in the reservoir		- Draining seepage - Limiting flow from the reservoir	- Resisting sliding - Resisting crushing - Resisting overturning
Buttress dam	Retaining water in the reservoir		- Draining seepage - Limiting flow from the reservoir	- Resisting sliding - Resisting crushing - Resisting overturning
Homogeneous embankment dam	Retaining water in the reservoir		- Preventing seepage -Draining seepage	- Resisting sliding of US shell - Resisting sliding of DS shell - Resisting external erosion - Resisting internal erosion - Resisting piping - Resisting sloughing - Resisting breach - Resisting settlement

				- Resisting erosion along the conduit - Resisting erosion of the downstream toe - Resisting cracking
Zoned embankment dam	Retaining water in the reservoir		- Draining seepage - Preventing seepage	- Resisting sliding of US shell - Resisting sliding of DS shell - Resisting internal erosion - Resisting external erosion - Resisting piping - Resisting sloughing - Resisting breach - Resisting settlement - Resisting erosion along the conduit - Resisting erosion of the downstream toe - Resisting cracking
Diaphragm embankment dam	Retaining water in the reservoir		- Draining seepage - Preventing seepage	- Resisting sliding of US shell - Resisting sliding of DS shell - Resisting external erosion - Resisting internal erosion - Resisting piping - Resisting sloughing - Resisting breach - Resisting settlement - Resisting erosion along the conduit - Resisting erosion of the downstream toe - Resisting cracking

Water-retention tailings dam	Retaining tailings		- Draining seepage - Preventing seepage	- Resisting external erosion - Resisting internal erosion - Resisting piping - Resisting breach - Resisting settlement - Resisting erosion the onononduit - Resisting cracking
Raised tailings dam	Retaining tailings		- Draining seepage	- Resisting external erosion - Resisting internal erosion - Resisting liquefaction - Resisting piping - Resisting settlement - Resisting breach - Resisting erosion along cotheuit
Foundation		- Supporting weight load of the dam - Supporting the reservoir load exerted on the US side of dam	- Preventing seepage	- Resisting sliding - Resisting piping - Resisting liquefaction - Resisting settlement
Spillway	Controlling flood water from the reservoir		- Discharging surplus flows from the reservoir - Resisting insufficient capacity	- Resisting cavitation - Resisting head-cutting - Resisting spillway foundation erosion - Resisting hydraulic jacking - Resisting improper gate operation - Resisiting ball milling

				- Resisting abrasion of stilling basin - Resisting erosion of stilling basin
Bottom outlet	Regulating reservoir level		Discharging water from the reservoir	- Resisting piping along the outside of conduit - Resisting piping by flow from a conduit - Resisting piping of soils into a conduit - Resisting deterioration - Resisting abrasion of conduit - Resisting cavitation of conduit - Resisting clogging of trash rack
Abutment		Providing stability for the dam	Draining seepage	- Resisting piping - Resisting sliding - Resisting external erosion

Conclusion of functional analysis

At the end of the functional analysis, we have:

- A hierarchical description of the structure of the system and a formalization of the interactions between the system and the factors of the external environment.

- A list of functions for the system and its components, considering two types of functions: primary function and technical function.

The information obtained by the functional analysis served as a basis for developing the failure knowledge model and the evaluation of the system state.

3.5. Conclusion

In this chapter, we provide an analysis of the dam. In the first step, we present the main types of dams. Then, we expose the failures related to dams through a literature review and an analysis of historic dam failures. We state the interest of the functional analysis to make the connection between the component and the failure via the notion of function. All these elements composed a corpus of knowledge, which will be used to build our knowledge model of dam failure.

In the next chapter, we will develop a generic failure knowledge model for dams. However, this model can be extended to any civil engineering structure. The model will use the Conceptual graphs framework, formalizing the concepts and relations which can describe a dam failure.

Chapter 4

Development of failure knowledge model for structural system

Content

4.1. Introduction

4.2. Concepts

4.3. Relations between concepts

4.4. The knowledge model of dam system failure

4.5. Method to instantiate a failure knowledge model

4.6. Using the failure knowledge model

4.7. Conclusion

4.1. Introduction

In the previous chapter, we presented knowledge regarding the dam systems: the different types of the dam system and their components, the functions of the dams and other components. All these elements will enable, in this chapter, to build a knowledge model of failure. This model uses the Conceptual Graphs (CGs) framework with the concepts and relations formalized. In a first step, we will expose the concepts (part 4.2) and relations (part 4.3) of the model we designed to describe and analyze the dam failure. It will allow us to build, in a second step, the generic graph (part 4.4), which will support the failure analysis.

The model we developed has to meet different requirements:

- It has to propose a formal failure knowledge for the dams. It means that the model must allow describing failure for all types of the dam, based on a unified understanding of the structural components of the dam. It has to integrate the relationships between the components, interactive flows between the system and external factors, and within the system itself.

- It must be able to consider effects, changes in the system according to chronological order, as well as to describe the state of a system at a point in time;

- It has to make it possible to explore failure at a different systemic level in order to logically and systematically describe the failure.

The third step provides a method to instantiate the failure knowledge model. The method includes steps to identify the system, external factors, and interactions between the system with the external factors and within the system. Failure process will be created by connecting the snapshots describing the states of the system.

The final step introduces how to use the knowledge model to acquire failure knowledge. It includes similarity requests identifying failure conditions from the previous failure cases and the inferring rules from the database of facts, which shows the process of failure.

Figure 4.1 shows the plan of this chapter.

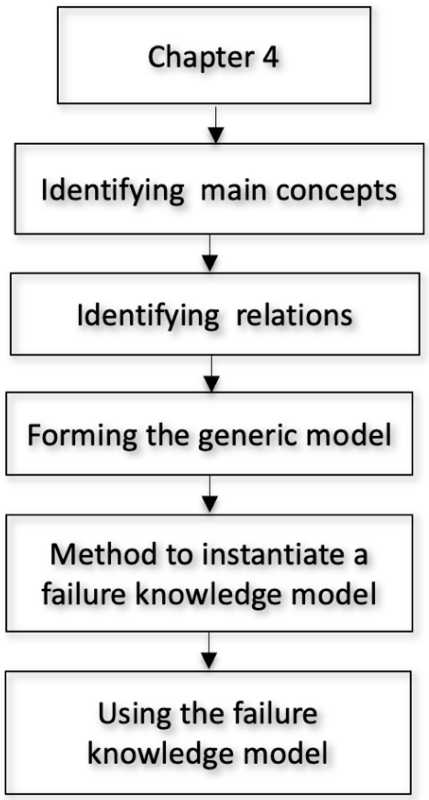


Figure 4.1. Steps to develop the failure knowledge model

4.2. Concepts

Based on the literature review exposed in the previous chapter, we identified the main concepts to describe failures of structural systems, in accordance with the conceptual graphs formalism. They are grouped into six categories, as exposed in Table 4.1.

Table 4.1. Main concepts

Nº	**Concept category**	**Main concept**
1	Concept to identify the external factor	External factor
2	Concepts to identify structural system	Structural system
		Component
		Material
3	Concept to describe	Property
4	Concepts relating to function and performance	Function
		Performance
		Performance parameters
		Expected level
		Measured level
5	Concepts to identify flow	Flow
6	Concepts to identify time	Time

These main concepts will be decomposed according to a taxonomy hierarchy. Indeed, the set of concepts is ordered by a partially ordered relation, also called a specialization relation or a-kind-of relation (e.g., the concept *Dam system* is a kind of the concept *Structural system*) (Chein and Mugnier, 2008). Depending on their nature and purpose, each principal concept can be decomposed into different levels of granularity. For example, the concept *External factor* is decomposed in two levels, while the concept *Structural structure* is decomposed in only one level.

4.2.1. Concept to identify the external factor: External factor

It is all factors outside of the system that interacts with the system through a flow such as energy or physical (e.g., heavy rain created water flows which flow into the reservoir, earthquake impacts, via earthquake loads, impact on components of the dam system) (Kossiakoff *et al.*, 2011).

The concept *External factor* is decomposed into two sub-concepts: *Human activity* and *Natural environment*. The sub-concepts of the concepts *Human activity* and *Natural environment* are collected from real failure cases. For example, regarding the Sparmos dam (Dounias and Bardanis, 2019), (Zekkos *et al.*, 2016), and the Upper Stillwater dam (Anderson *et al.*, 1998), the activity *First filling* was at the source of the failures; regarding

the Gibson dam (FEMA, 2014), Canyon Lake (USBR, 2015), Ulley (Charles, Tedd and Warren, 2011), the source of these failures was the *Natural environment* factor (*Rain)*. Table 4.2 presents the concepts related to external factors: External factor.

Main Concept	Sub-concept	Sub-subconcept
External factor	Activity	First filling, Filling, Drawdown, Tailings deposition, Soil placing, Bombing, Gate opening
	Natural environment	Gravity, Rain, Earthquake, Groundwater, Tailwater, Flooding, Temperature, Landslide

Table 4.2. Concept *External factor*

4.2.2. Concepts identifying the structural system

Structural system: A structural system is an assemblage of load-bearing components that interact to perform designated functions.

Component: It is a physical part that, in interaction with other parts, forms the system.

Material: It is a material that is used for the construction and operation of a system such as concrete, soil, rock.

Table 4.3, Table 4.4, and Table 4.5 present the concepts relating to the structural system, component, and material respectively. Concepts which need to decompose further will be presented in Appendix 6.

Main Concept	Sub-concept
Structural system	Dam system, Bridge system, Tunnel system, Building system

Table 4.3. The concepts related to *Structural system*

Main Concept	Sub concept	Sub-subconcept
Component	Reservoir	
	Dam	Concrete dam, Embankment dam, Tailings dam
	Appurtenant structures	Spillway, Bottom outlet
	Foundation	
	Abutment	

	Component of concrete dam	Gravity dam body, Arch dam body, Gallery drainage, Components of buttress dam
	Components of embankment dam and tailings dam	Homogeneous dam body, Horizontal blanket drainage, Rock toe drainage, Upstream protection, Downstream protection, Diaphragm embankment dam body, Diaphragm, Upstream blanket, Filter, Upstream shell, Downstream shell, Impervious core, Rais tailings dam body, Outlet pipe, Liner.
	Components of appurtenant structure	Intake structure, Approach channel, Control structure, Conveyance structure, Terminal structure
	Components of foundation	Bed foundation, Cut-off wall, Grouting
	Components of abutment	Abutment, Drainage, Thurst block

Table 4.4. The concepts relating to *Component*

Main Concept	Sub-concept
Material	Rock, Cyclopean concrete, Concrete, Blue-gray clay, Sand-clay, Tailings, Wearthered-gneiss rock, Sandstone, Water, Soil, Diluvia silty clay, Alluvium, Granite soil, Mine waste rock, Clay, Bassalt

Table 4.5. The concepts relating to *Material*

4.2.3. Concept to describe: Property

The term *Property* refers to attributes, properties, or characteristics that describe external factors, components, and materials. It is divided into three sub-types: External factor property, Component property, and Material property. Table 4.6, Table 4.7, and Table 4.8 present the concepts relating to *Property*, respectively. Concepts which need to decompose further will be presented in Appendix 6.

- **External factor property:** Concept *External factor property* refers to attributes to be considered in determining the influence of the external factors on the system. For example, earthquake has two properties to be taken into account when calculating the effect on the system: horizontal acceleration fraction and vertical acceleration fraction; heavy rainfall affecting the system by the inflow that can be determined by two properties: intensity and duration of rain.

The concept *External factor propery* is decomposed into different sub-concepts. They are all measurable attributes of the concept *External factor*. Different external factors may have the same property. For example, the concepts *First filling*, *Drawdown*, and *Rain* have the same characteristic *Duration*. Table 4.6 presents the concepts relating to external factor properties.

- **Component property:** The term *Component property* characterizes the properties which describe a component or subcomponent, such as size, geometrical shape, and surface. For example, length, width, level, area, slope are component properties.

  Table 4.7 presents the concepts relating to component properties.

- **Material property:** It is anything that describes a material; for example, the physical properties such as density, specific heat, melting and boiling point; mechanical properties such as strength, toughness, hardness.

  Table 4.8 presents the concepts relating to material properties.

Main Concept	Sub-concept	Sub-subconcept
Property	External factor property	Intensity, Duration, Acceleration of gravity, Horizontal gravity fraction, Vertical gravity fraction, Flood coefficient

Table 4.6. Concepts relating to *External factor property*

Main Concept	Sub-concept	Sub-subconcept
Property	Component property	Property of reservoir
		Property of dam
		Property of appurtenant structure
		Property of foundation

Table 4.7. Concepts relating to *Component property*

Main Concept	Sub-concept	Sub-subconcept
Property	Material property	Mechanical property
		Physical property

Table 4.8. Concepts relating to *Material property*

4.2.4. Concepts relating to function and performance:

Function: A function is what the system or component is intended to do, usually to a given performance. The sub-concepts of the function concept were defined by applying the functional analysis exposed in the previous chapter.

Performance: The performance is the capacity of a system or component to fulfill its function.

Performance parameter: It is measurable parameters used to evaluate the performance of a component or a system. For example, the factor of safety against sliding can be used to check the capacity of the dam body to resist sliding.

Expected level: It is the performance level designed to satisfy the function of a component or a system. Usually, it is based on standards or predefined criteria. For example, the factor of safety against sliding has an expected level at 1.5;

Measured level: It is a quantitative measure of the performance level of a component or a system that indicates the actual degree to which it performs the function.

Table 4.9 and Table 4.10 present the concepts relating to *Function* and *Performance parameter*. Concepts which need to decompose further will be presented in Appendix 6.

Main Concept	Sub-concept	Sub-subconcept
Function	Hydraulic function	
	Mechanical function	Resisting instability, Remaining durability, Resisting deformation

Table 4.9. Concepts relating to *Function*

Main Concept	Sub-concept
Performance parameter	Performance parameter of foundation
	Performance parameter of concrete dam
	Performance parameter of reservoir
	Performance parameter of appurtenance structure
	Performance parameter of embankment dam

Table 4.10. Concepts relating to *Performance parameter*

4.2.5. Concepts to identify flow

For a system, there are interactions between the system with its environment and between components of the system. For example, heavy rain increases the reservoir level, or the dam body by its weight impacts the foundation. These interactions are considered as flows (Pahl

et al., 2007), (Wainwright and Mulligan, 2013). The flows can be internal, endemic to the system, or external, entering the system from its environment. (Kravets, Bolshakov and Shcherbakov, 2020) formalized the flows into two types of flow: flows of energy and material.

- Energy flow involves the transfer of potential energy, kinetic energy, heat, constraints …, and so forth.
- Material flow: involves water, tailings, liquid, solid … (Haik and Shahin, 2015)

The processes inherent to the system can induce a conversion process of flows. The conversion process is a process of changing forms, states of energy, and material. For example, the hydraulic flow generated by rain increases the potential energy of water stored in the reservoir, which can be converted into kinetic energy (the movement of the generator's turbine) and generates hydroelectric power.

Figure 4.2. The conversion of energy, material (Pahl et al., 2007)

Figure 4.2 exposes a schematic representation of the conversion process, in which the system is symbolically represented as a black box. In many systems, some material and energy flow into the system is converted and produces output flows. In order to consider this conversion process and dynamically the flows, it is necessary to consider the time dimension (Kravets, Bolshakov and Shcherbakov, 2020), (Stone and Wood, 2000). **Flow is defined as a transfer of material and energy through the system with respect to time** (Stone and Wood, 2000), (Birta et al., 2015), (Nellis and Klein, 2009), (Arnold and Wade, 2015).

Functions of the system and its components are achieved via the flows. For a dam system, the interactions are mainly of two types: mechanical and hydraulic, to achieve the corresponding functions. In hydraulic interaction, a component exerts hydraulic load or transmit flows to another. Hydraulic interaction deals with two forms of fluids: fluid at rest (fluid statics) and fluid in motion (fluid dynamics).

Table 4.11 exposes the main concepts related to flow, which are formalized in the model.

Main Concept	Sub-concept	Sub-subconcept
Flow	Hydraulic flow	Outflow, Surface runoff, Peak runoff, Inflow, Seepage flow, Discharge flow, Piping flow, Overflow, Debris flow, Sediment flow, Jet flow, Dam-break outflow
	Load	Vertical earthquake inertia load, Earthquake hydrodynamic load, Horizontal earthquake inertia load,

		Tailwater load, Horizontal shear load P_f, Horizontal shear load P_u, Self-weight load, Tailwater load, Horizontal shear load P_d, Uplift load, Reservoir load

Table 4.11. Concepts relating to *Flow*

4.2.6. Concepts to identify time

The failure knowledge model describes the behavior of the system under the impacts of environmental factors. It includes the reactions and interactions of the components induced by its environment. These interactions will modify the state of the system through parameters, properties, and performance of the components (Furia *et al.*, 2012). Such changes in the system over time can lead to a failure process. Furthermore, the relations between the system elements can change dynamically over time, causing an evolution of the system (Parnell, Driscoll and Henderson, 2011). The model considers the time associated with each change of parameters. The evolution of the system is modeled as a sequence of "snapshots" of its state; each of these snapshots is characterized by a time that positions the snapshot against the temporal background (Furia *et al.*, 2012). For instance, we can consider the process of a failure consisting of a breach due to the heavy rain of an earthfill dam. It can be formalized as a set of snapshots providing a succession of states as the dam system undergoes interactions: the reservoir level increases due to heavy rain, then erosion occurs at the dam base, this forms a breach which develops, and finally, the dam collapses. Each "snapshot" is then described by time points and a collection of values of variables connected to parameters and properties of the system, environment, and components. The set of snapshots brings an overview of the progression of the failure process over time (Figure 4.3).

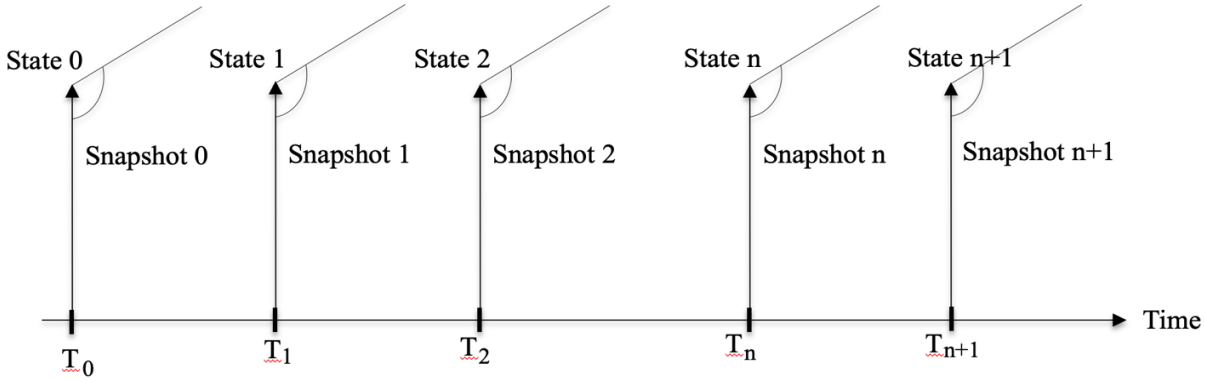


Figure 4.3. Timeline and the set of snapshots

The impacts and changes in the system form a sequence ordered in chronological order; this is consistent with the causal-ordering. The causal ordering is based on the well-known "happened before" realtion. (Lamport, 1978).

We want to draw attention to an essential point in this model. There is no concept of Failure. Failure is modeled through defects of functions. It has no existence in the model by itself. The model gives the failure a multifaceted and nuanced character, often composed of a set of unfulfilled functions.

4.3. Relations between concepts

As we exposed in Chapter 3, we can distinguish the relations according to their n-ary. We present the different relations used in our model in this section, according to their n-ary.

4.3.1 Quantitative relations (Relations with one argument)

Quantitative relations describe the attributes or states of a concept quantitatively (Figure 4.4). The model uses four different types of quantitative relations: relations that describe the attributes of the concepts *External factor*, *Component property*, *Material property*, and *Performance parameter*, relation that defines the attributes of the concept *Performance*; relations that identify the attributes of the concept *Hydraulic flow*, and relations that identify the attributes of the concept *Load.* Figure 4.4 illustrates the quantitative relations.

- The relations that describe the attributes of the concepts *External factor*, *Component property*, *Material property*, and *Performance parameter***: has value, has max value, has min value**.
- The relation that defines the attribute of the concept *Performance:* **has indicator**. For example, performance has an indicator of 0.
- The relations that identify the attributes of the concept *Hydraulic flow***: has quantity, has progress gradient, has critical velocity, has hydraulic shear stress, has stream power, has average velocity, has stream power density, has intial_gradient, has flow depth**. For instance, the seepage flow (*Hydraulic flow)* has a quantity of 0.24 m^3/day. These relations are inclusive but not exhaustive.
- The relations that identify the attributes of the concept *Load***: has moment** and **has magnitude**. For instance, horizontal earthquake load (*Load*) has a moment and has magnitude.

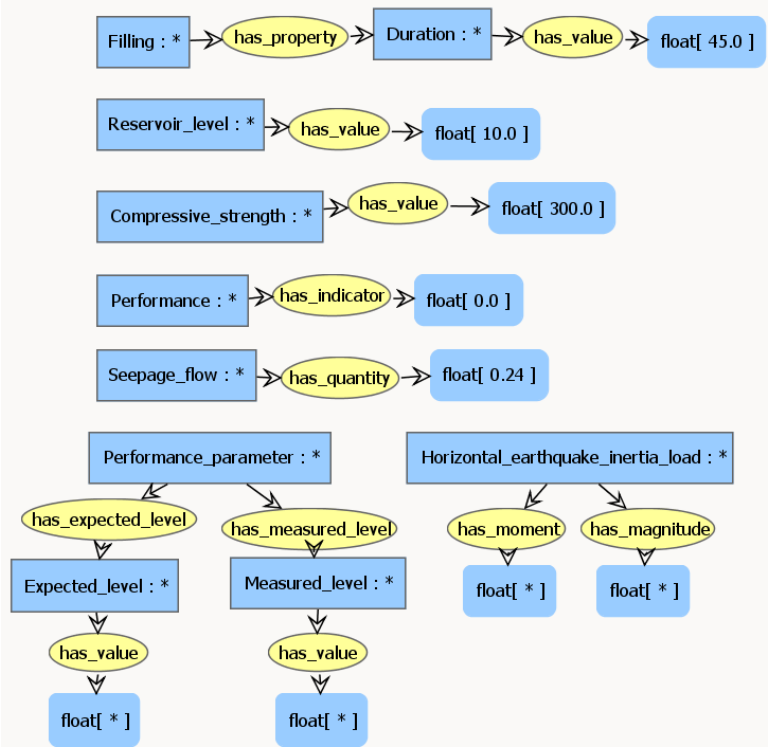


Figure 4.4. Quantitative relations

4.3.2 Binary relations

The binary relations of the knowledge model can be classified into five categories: partonomy relations, time relations, descriptive relations, Function – Performance relations, and influence relations.

a) **A partonomy relation** is a binary relation, which defines the relation between different levels in the system, such as between the system and its components, and between components and the lower-level components (Figure 4.5). It corresponds to a subdivision of an element into its different parts. The partonomy relation is represented by the relation: *is component of*.

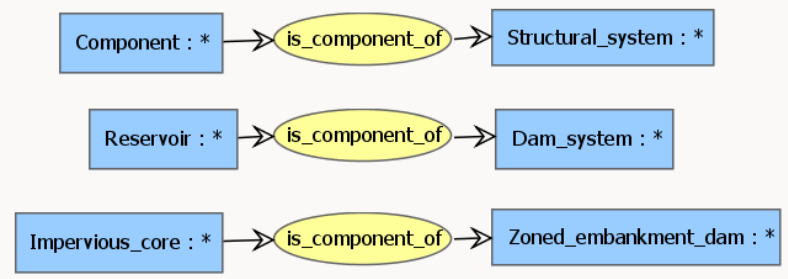


Figure 4.5. Partonomy relations

b) The **time relations** are binary relations, defining the point of time at which a state of the system exists. Figure 4.6 lists, for instance, some concepts which their value change with time and then use the "*exists at*" relation. The relation "*is before*" determines the chronological order between two effects/changes.

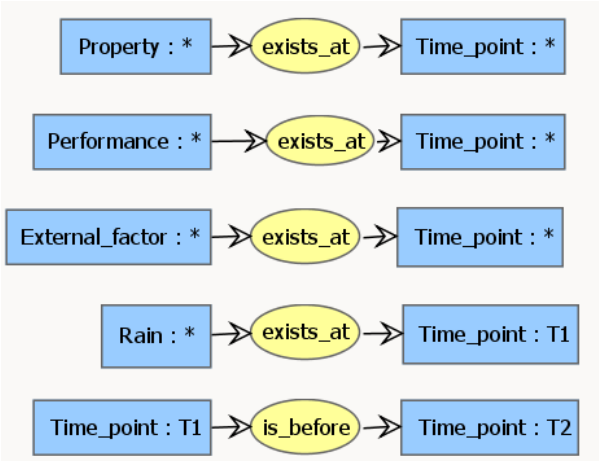


Figure 4.6. Time relations

c) **Descriptive relations** are binary relations, describing properties or characteristics of a component, a material, or an external factor (Figure 4.7). The model uses two descriptive relations: *has property* and *is made of*.

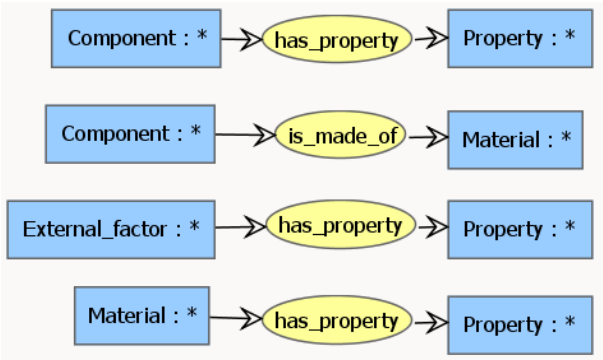


Figure 4.7. Descriptive relations

d) **Function – Performance relations** are binary relations, describing the relation concerning function and performance of a component, system (Figure 4.8).

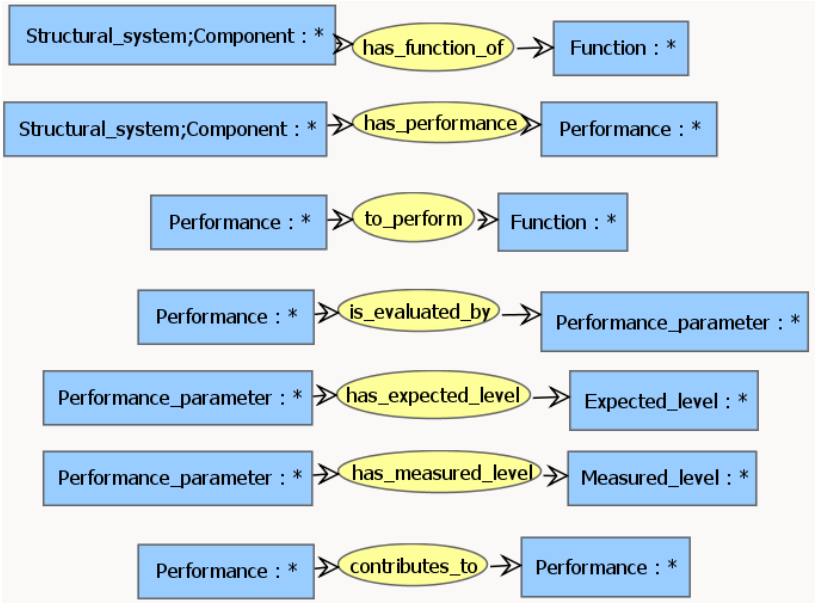


Figure 4.8. Relations related to function and performance

Figure 4.8 shows relations concerning function and performance. The relation **has function of** identifies the functions related to each *System, Component*, which also has a *performance* (using the **has performance** relation). In order to perform a function, a *component* (resp. *System*) must have a performance (the relation **to perform**). A *Performance* **is evaluated by** a *Performance parameter*. The *Performance parameter* **has expected level** *Expected level and* **has measured level** *Measured level*. A *Measured level* lower than the Expected level can be a source of failure. Furthermore, *Performance* **contributes to** *Performance,* which means that the performance of a component contributes to the performance of the higher-level component, and the performance of a component contributes to the performance of its system.

e) The **influence relation** describes the relationship between external factors and the system (Figure 4.9). For instance, Rain (external factor) can have an impact on the dam system.

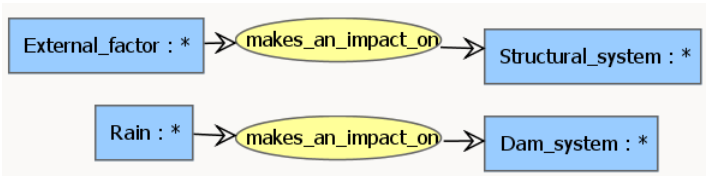


Figure 4.9. Influence relation

4.3.3 Ternary relation

The ternary influence relations used in the model are related to the flows. They expressed the transmission of a flow between two concepts (Figure 4.10).

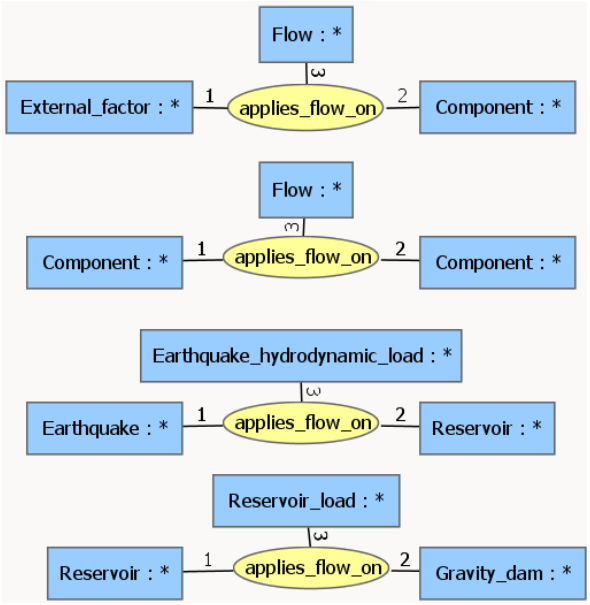


Figure 4.10. Ternary flowing relation

An *External factor* **applies flow** to a *Component*. For example, earthquakes (*External factor*) apply a hydrodynamic load (*flow*) to the reservoir (*Component*). In the same perspective, a *Component* **applies flow** to another *Component*. For instance, a reservoir (*Component*) applies a load (*flow*) on the dam (*Component*).

4.4. The knowledge model of dam system failure

4.4.1. Generic graph

Based on the concepts and relations exposed in the previous sections, we developed a generic knowledge model to describe and analyze dam failure. Figure 4.11 shows the generic model of the dam system; to ensure the readability of this figure, the sub-component level is not represented in this figure.

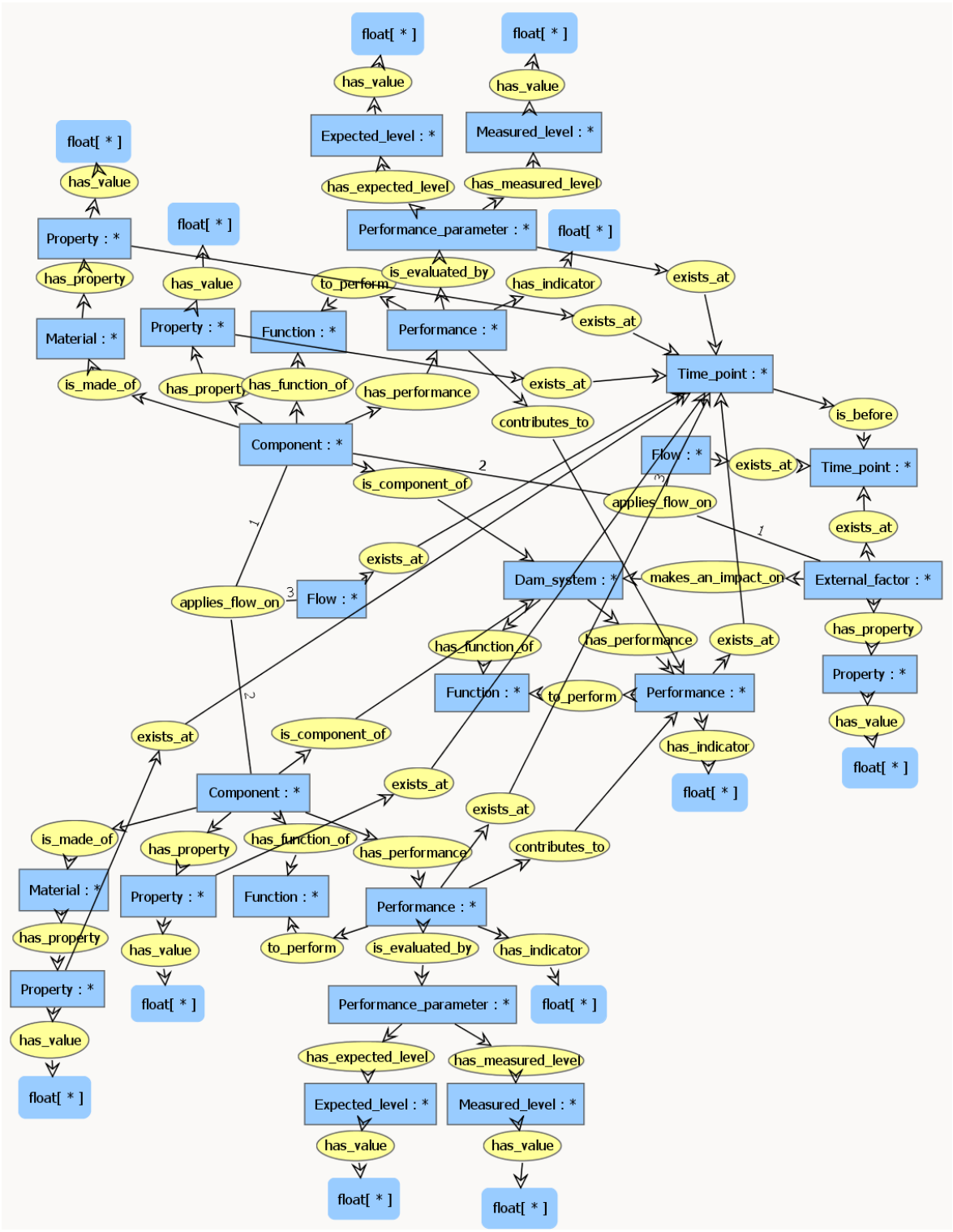


Figure 4.11. Generic model of the dam system at the component level

The generic model integrates:

(1) A modeling of the structure of the system:

- The structure of the dam system is presented with a partonomy hierarchy.
- The dam system is described by its function and performance;

- Each component is described by its property, material, function, and performance;
- The interaction between components is modeled by the ternary relation *applies_flow_on;*

(2) External factor:

- External factors are related to their properties;
- The interactions between the external factors and the system are modeled by the binary relation *makes_an_impact_on*
- The interactions between the external factors and the components are presented by the ternary relation: *applies_flow_on (Flow);*

(3) Time point:

- The state of the system at a time point is defined by the binary relation *exists_at*;
- The appearance of the external factor and its impact on the system at a time point is determined by the binary relation *exists_at*;
- The chronological order between the two time points is described by the binary relation *is_before*.

Figure 4.12 presents the generic model of the system at the sub-component level.

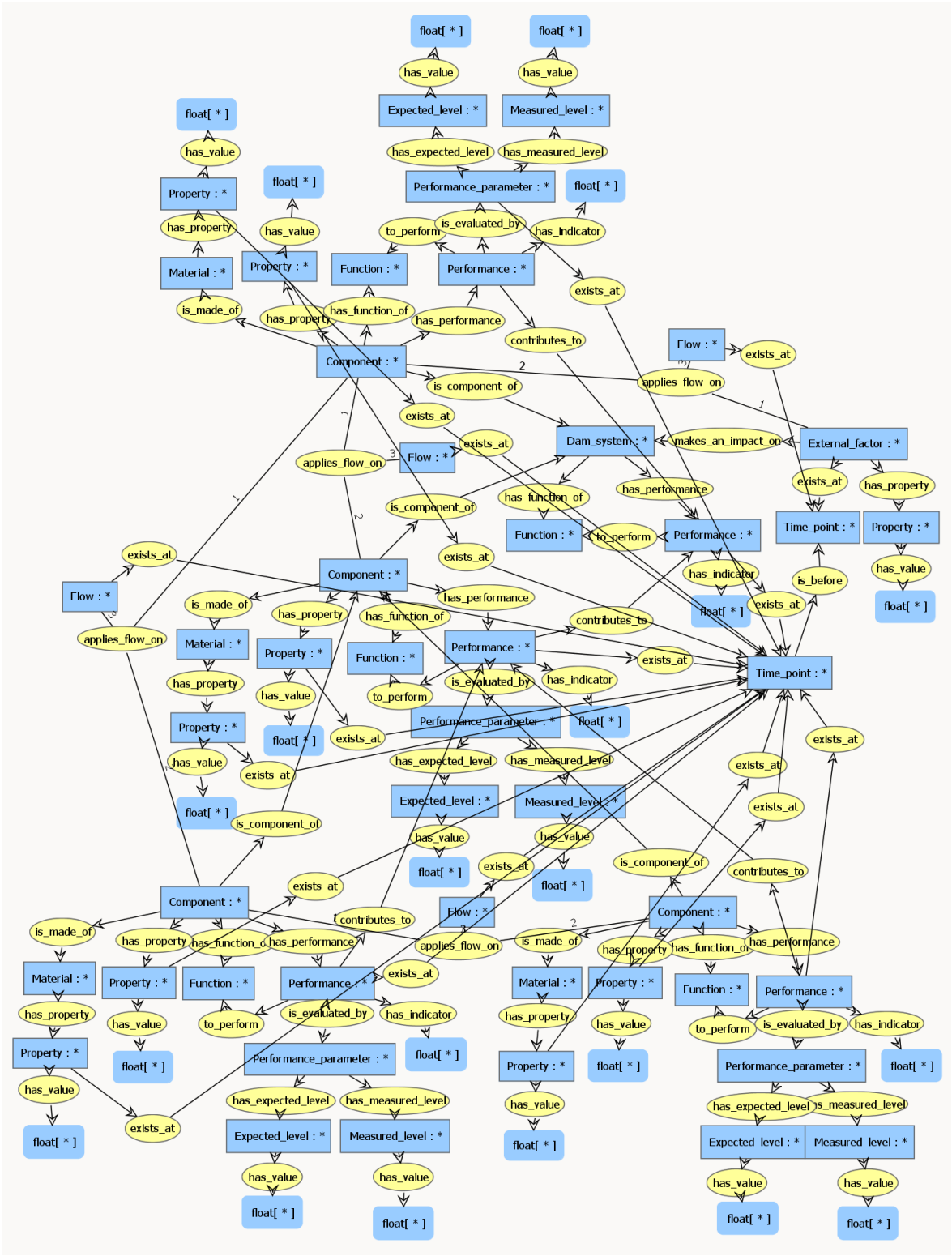


Figure 4.12. Generic model at sub-component level

In addition to the generic model at the component level, this model provides:

- The components are decomposed into lower-level components by the partonomy relation *is-component-of;*

- Each sub-component is described by its property, material, function, and performance;
- The performances of the sub-components are connected to the performance of the related higher-level component by the relation *contributes_to;*
- The interaction between the component and the sub-component is described by the ternary relation *applies_flow_on*;
- The interaction between the sub-components is described by the ternary relation *applies_flow_on*.

In order to describe with more details this knowledge model, the next parts will analyze individually some parts of it: the structural breakdown of the system, the description of a component,

4.4.2. Modeling the general structure of the system

The system is described using the partonomy relation at the component level and sub-component level. *Figure 4.13* and *Figure 4.14* describe the generic structure, respectively, for a not-specified structural system and a gravity dam system. The same type of model is available for all dam types (arch dam, etc.).

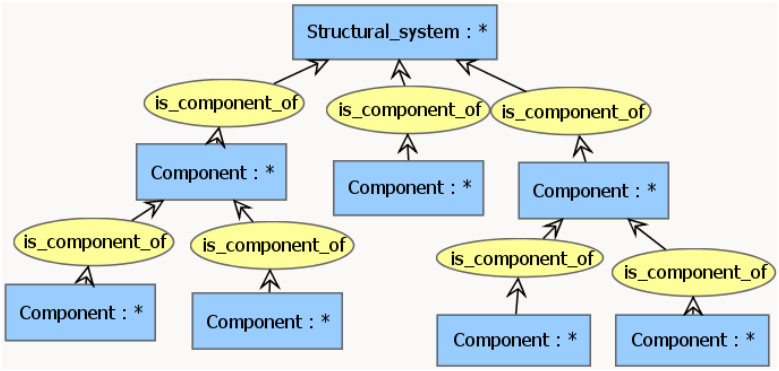


Figure 4.13. Model of a structural system

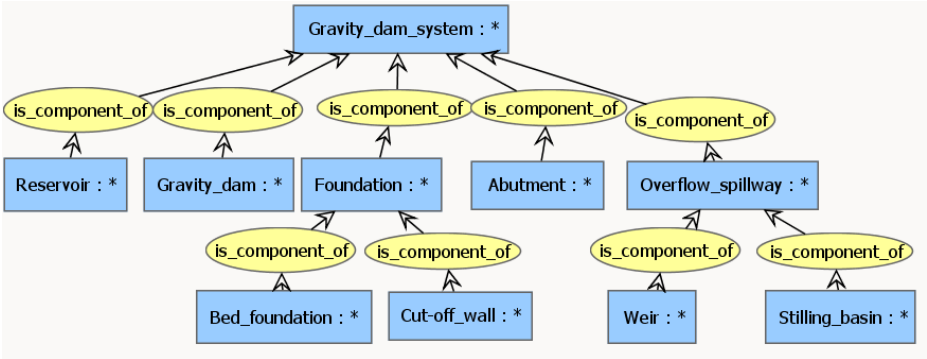


Figure 4.14. Model of a gravity dam system

With a partonomy hierarchy structure, it is possible to describe any type of structure at at any level.

4.4.3. Modeling a component

After organizing the structure of the system, each element is described in detail. A component is described by its properties, its material, its functions, and performance. Figure 4.15 exposes a conceptual graph that describes a typical component. The semantic related to this graph can be expressed as follow:

- A component is made of a material that has some properties;

- A component has properties that are quantified by values;

- A component has the performance to perform its function (described in the next section).

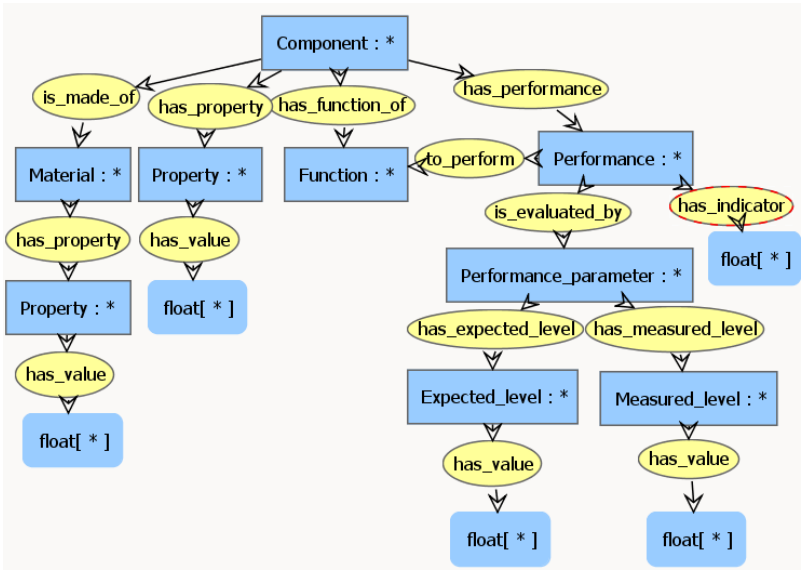


Figure 4.15. . Model of a component

4.4.4. Modeling a function

A system, a component, and a subcomponent are described by their functions and performance (Figure 4.16). The performance at the component and subcomponent levels is evaluated by performance parameters with the expected level and measured level, respectively. The performance has an indicator that evaluates the capacity of the system/component/subcomponent to perform its function.

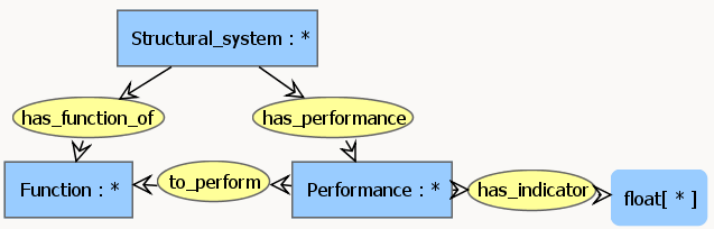


Figure 4.16. Model of function related to the structural system

4.4.5. Modeling an external factor

An external factor is modeled concerning its characteristics. Figure 4.17 exposes the model of an external factor and its application to rain (external factor) and its duration and

intensity (characteristic). The conceptual graph can be interpreted in natural language as follow:

- Rain has a duration property with its value is 48 hours;

- Rain has an intensity property with its value is 200 mm/hour.

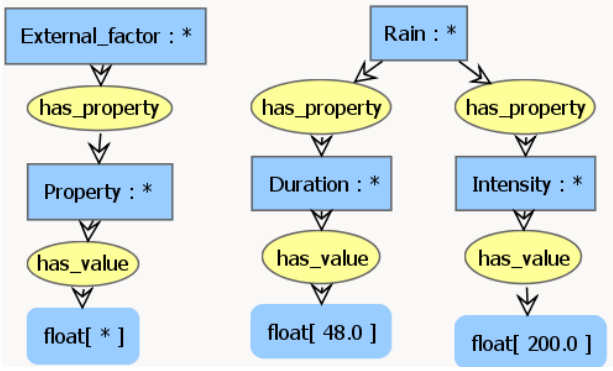


Figure 4.17. Conceptual graph of *External factor*

4.4.6. Modeling the Relations between performances at different levels

The performance of the components contributes to the performance of the system. In the same way, the performance of the sub-components contributes to the performance of the components. Figure 4.18 illustrates the relations between performances at different levels. These relations between performances will be used to identify the propagation of the failure process at the different levels of a system.

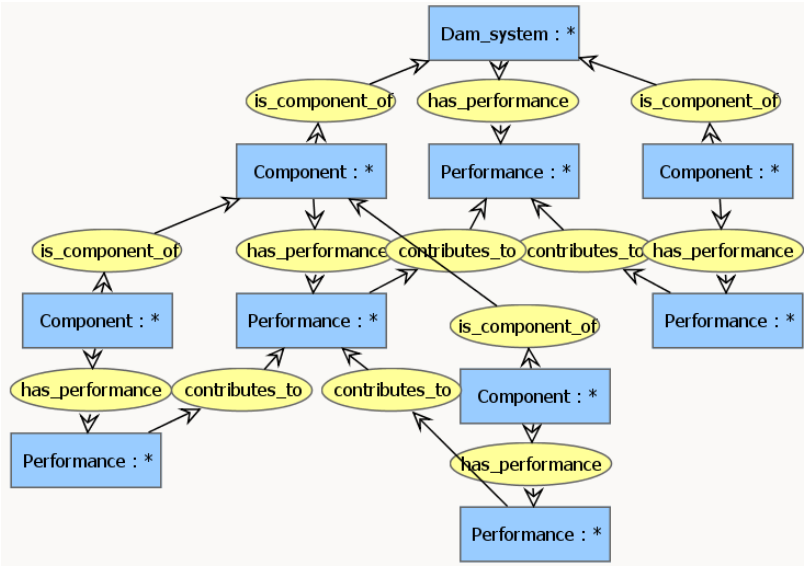


Figure 4.18. Model of Relations between performances at different levels

4.5. Method to instantiate a failure knowledge model

As we exposed in section 4.2.6, the progression of a failure of a dam system over time is a set of states of the system. Each state is a collection of values of variables connected to parameters and properties of the system, environment, and components. This state is

modeled as a “snapshot” and positioned by a time point. The sequence of “snapshots” will provide an overview of the failure process. Therefore, the instantiation of a failure knowledge model, indeed, is the development of the sequence of states or “snapshots” with the connection of time points.

In general, the sequence of states can be divided into three stages:

- The first stage describes the system's states at the initial time point (time point T0). The time point 0 identifies the time before the occurrence of external factors. The state shows the structure of the system, components with properties, functions, and performances. It also presents the interactions between components at this time.

- The second stage covers the subsequent states when the system is subject to the external factor's effects. The second stage shows interactions between the external factor with the system and interaction within the system. It also shows the changes in the system as it undergoes interactions. This stage connects with time points after T0, such as time point T1, time point T2.

- The final stage identifies the failure of the system.

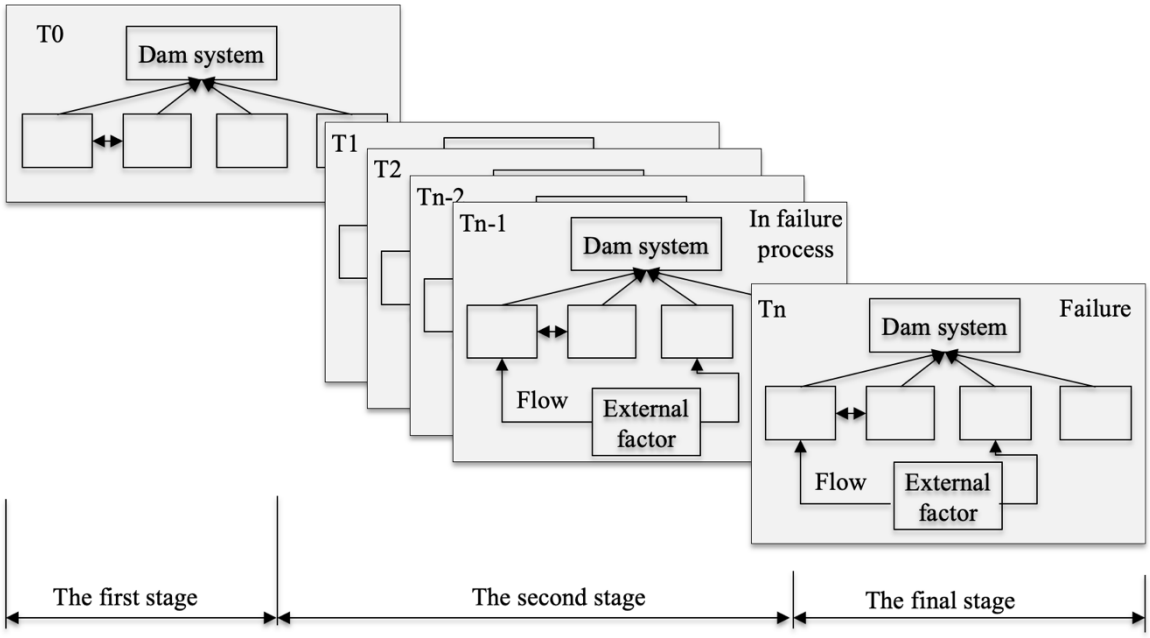


Figure 4.19. The sequence of states of the system

4.5.1. Describing the first state of the system

The first state of the system including describing the structure of the system, components, material constitued, functions, performance, interactions between the components. The time point positioned for the first state is T0.

Identifying system

A system is identified based on its components. For example, a raised tailings dam system is identified based on its components which are the tailings dam, foundation, and reservoir,

an earthfill dam system is determined based on its components which are the earthfill dam, foundation, reservoir, spillway, and abutment.

The rule identifying a system based on the type of the dam component, i.e., if there is a homogeneous embankment dam, then we have a homogeneous embankment dam system or if there is a zoned embankment dam, then a zoned embankment dam system is identified with its components.

Figure 4.20 shows an example of a rule identifying a homogeneous embankment dam system. The hypothesis graph includes two concepts: *Dam-system* and *Homogeneous embankment dam* which are linked by the relation *is-component-of*. The conclusion graph describes a typical structure of the homogeneous embankment dam system which composed by main components: Reservoir, Homogeneous embankment dam, Foundation, Abutment, Spillway, Bottom outlet.

Each component is described by the concepts: *Component*, *Property, Material, Function, Performance, Performance parameter, Expected level, Measured level*. The concept Performance is linked to the relation *has indicator*.

The concept *Dam-system* is described by the concepts: *Function* and *Performance.*

All components connect to the concept *Dam-system* by the partonomy relation: *is-component-of.* The concept *Performance* of each component is linked to the concept *Performance* of the system by the relation *contributes to*. It means that performance of component contributes to performance of system.

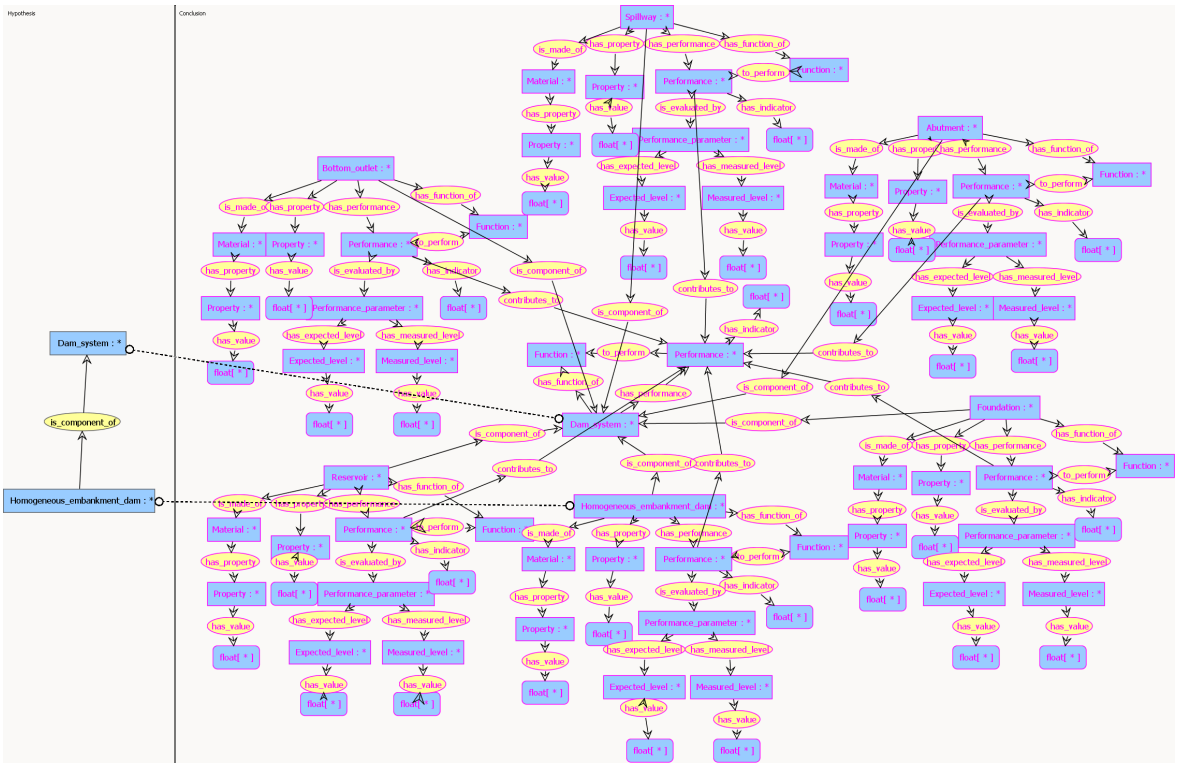


Figure 4.20. Example of rule identifying homogeneous embankment dam system

Identifying component

A component is identified based on its sub-level components. For example, a shaft spillway is identified based on its components which are the weir, gates, shaft, conduit; a fooundation is identified based on its components which are the bed foundation, cutoff-wall, grouting.

Figure 4.21 shows a rule to identify a spillway. The hypothesis graph shows the concept *Spillway*, the conclusion graph shows typical sub-components of the spillway including *Entrance structure, Discharge controlling structure*, *Conveyor structure*, *Terminal structure*.

It should be noted that in the case of a component which can be decomposed to the lowest level, then the lowest level of the concept type will be used. For example, the concept *Discharge controlling structure* can be decomposed by the taxonomy relation to the concept *Radial gate, i.e., Radial gate* is a type of *Discharge controlling structure,* then the concept *Radial-gate* will be used to replace *Discharge-controlling-structure*. Nevertheless, if we do not know the sub-type of a concept, we can keep the component.

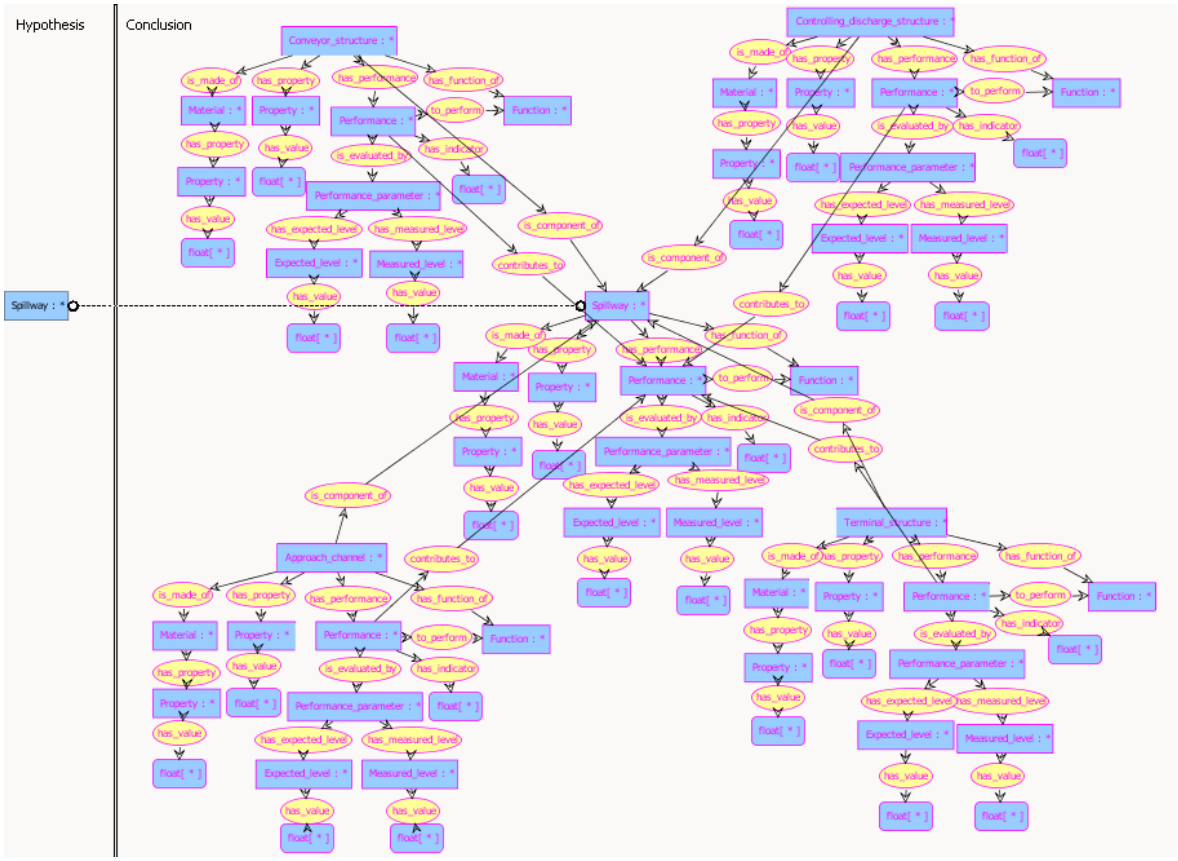


Figure 4.21. Rule to identify spillway

After determining the system and its components, in order to identify a specific dam system, we have to identify individual concepts and put all information relating to failure such as material, material property, the property of component and sub-component, function, performance parameter, performance indicator.

Depending on the behavior of the structure under loading or the number of available components of a real system, a structure can be considered at the component level or at the sub-component level. For example, for a gravity dam under the impact of an earthquake, with failures such as sliding, overturning, or tension crack, we can consider the structure at the component level because of the gravity dam's earthquake behavior as a whole. Another example is a homogeneous embankment dam without sub-components such as horizontal blanket drainage and chimney drainage. It can be considered at the component level.

The time point T0 is set for the beginning time, i.e., the time before the external factor's impact. The concepts containing values that can vary over time are connected with the concept Time-point by the relation *exist-at*. Figure 4.22 shows an example of the component Zoned-embankment dam.

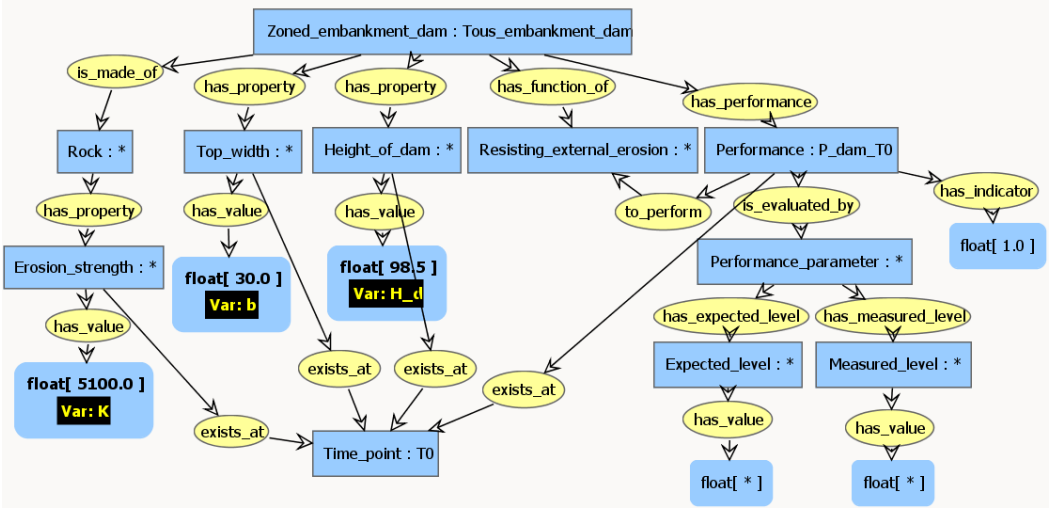


Figure 4.22. Graph of Zoned embankment dam

Figure 4.22 shows an example of the Tous zoned embankment dam. The individual concept is *Tous embankment dam.* The component is described with its properties, *Top-width* and *Height-of-dam*, its material, *Rock*, the material property is *Erosion-strength*. The values of the concept *Erosion strength* is *5100* assigned with the variable *K*. The values of the concept *Top width* and *Height of dam* are *30* and *98.5*, assigned with the variables *b* and *H_d*, respectively. The function considered is *Resisting-external-erosion*. At T0, the performance parameter and the values of *Expected-level* and *Measured-level* are undefined. Performance of the dam at the time point T0 is assumed to be 1, i.e., no failure. The property concepts and performance concept are connected with the concept *Time point: T0*.

Identifying interactions within the system at T0

At T0, there may be system interactions that need to be considered. An example is the hydraulic load of the reservoir acting on the dam. This load is generated due to the inherent water level in the reservoir.

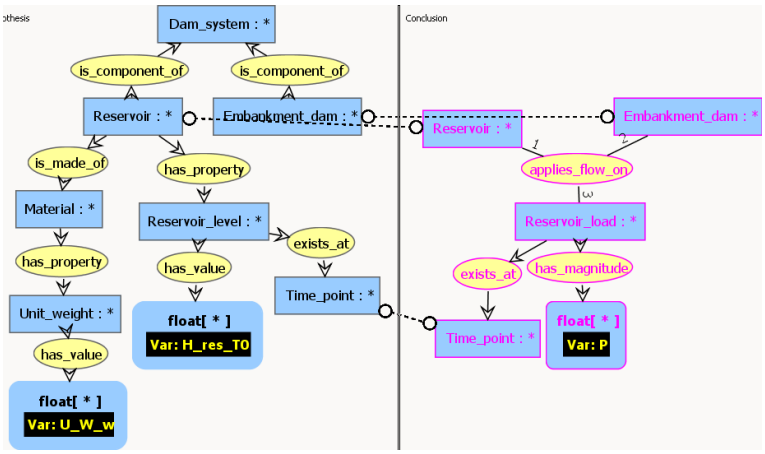


Figure 4.23. Rule identifying the reservoir load

Rule | Associated script

```
1  void after()
2  {
3      float value = U_W_w.getValue() * Math.pow(H_res_T0.getValue(), 2.0)/2;
4      P.setValue(value);
5  }
```

Figure 4.24. Script identifying the reservoir load

Figure 4.23 shows a rule identifying the reservoir load acting on the embankment dam. The rule said that **if** *Reservoir* and *Embankment dam* are components of *Dam system*, *Reservoir* is made of *Material* that has *Unit weight* defined by the variable *U_W_w*, and *Reservoir* has *Reservoir level* that its value is assigned to the variable *H_res_T0*, **then** *Reservoir* applies *Reservoir load* on *Embankment dam*. The reservoir load has a magnitude assigned to the variable *P*. The time point of the reservoir load is the time point of the water level. Figure 4.24 illustrates the script identifying the reservoir load.

4.5.2. Describing the subsequent states of the system

The subsequent states of the system are identified under the effects of external factors. Therefore, the external factor should be determined before.

Identifying external factor

The concept *External-factor* with its properties is added to the graph, with the time point that it happened. Figure 4.25 shows an example of an external factor that is *Rain.* The impact of *Rain* on the system is described by the relation *makes an impact on. Rain* has properties that are *Intensity* and *Duration* quantified by their values. Rain occurred at the time point T1, the date 19/10/1982 is added to clarify the real-time of the external factor.

The time point T0 is linked to T1 by the relation *is-before* in order to determine that the time point T0 is before the time point T1

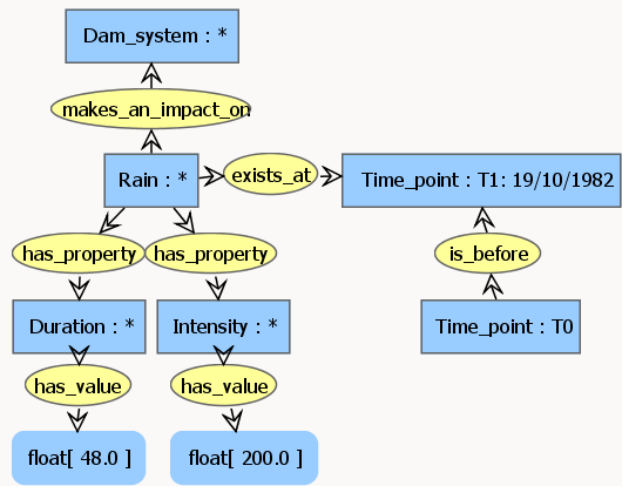


Figure 4.25. External factor

Identifying impacts of external factor to system

The impact of external factors on the system is the impact of the external factor on the components of the system. The impact is based on the rule as follow:

If [External_factor:*] → (make_an_impact_on) → [Structural_system:*]

[Component:*] → (is_component_of) →[Structural_system:*]

Then [External_factor:*] → (applies_flow_on) [Flow:*] →[Component:*]

The interpretation of the rule in natural language is: if an external factor makes an impact on the structural system, and the structure has a component, then the external factor will apply flow on the component.

Figure 4.26 shows a rule describing the impact of *Rain* on *Reservoir,* a component of *Dam system*. The hypothesis graph includes the concepts *Dam_system*, *Rain*, *Reservoir,* and other concepts describing properties of *Reservoir* and *Rain*. The relation *make_an_impact_on* links between *Rain* and *Dam_system*, the concepts *Reservoir* and *Dam_system* are connected by the relation *is_component_of*.

The conclusion graph includes *Rain*, *Reservoir,* and *Surface_runoff,* which are linked by a ternairy relation *applies_flow_on.*

The rule graph can be expressed as: **if** rain makes an impact on dam system, and reservoir is a component of the system, **then** rain applies a surface runoff to the reservoir. Knowledge is contained in the graph: if rain has intensity and duration, reservoir has runoff-coefficient and concentration coefficient, then the quantity of the surface runoff can be calculated.

Rain exists at the time point T1, concentration coefficient of reservoir exists at T0. The runoff flow exists at T2. The period from T1 to T2 is the interval time that rain forms the quantity of runoff and flows into the reservoir. Figure 4.27 illustrates the script describing the impact of rain on a reservoir.

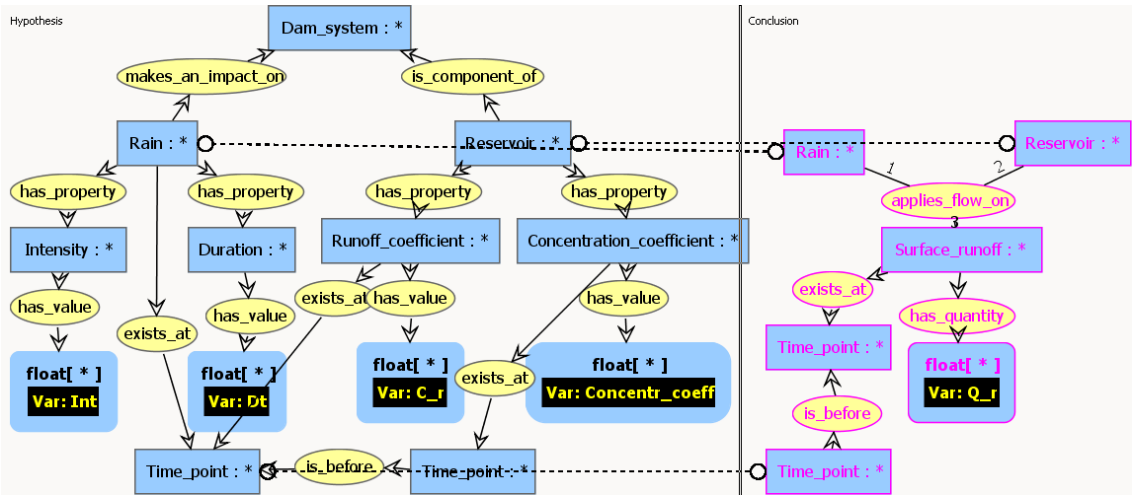


Figure 4.26. Rule describing the impact of rain on a reservoir

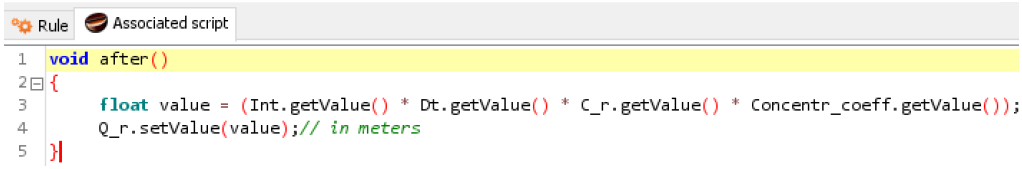


Figure 4.27. Script describing the impact of rain on a reservoir

Under the impact of the external factor, the state of the system will be changed. In the example above, when rain applies the runoff flow into the reservoir, the water level increases. A rule to describe this variation:

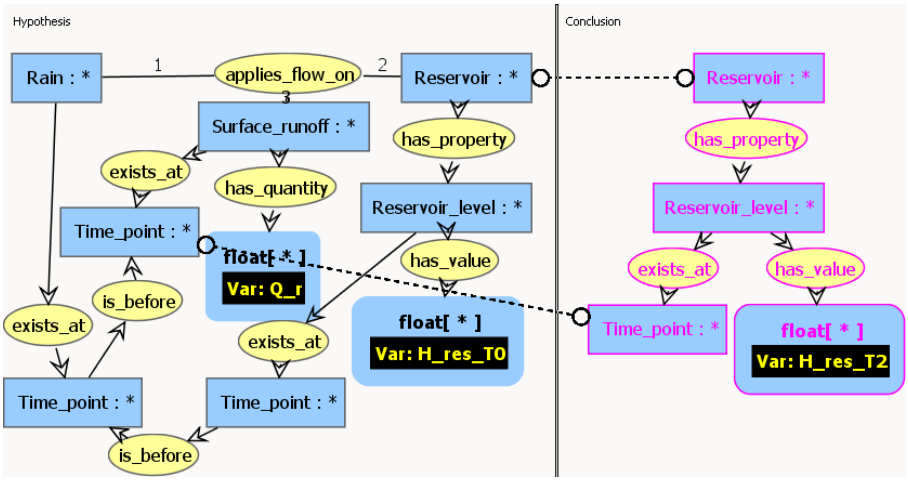


Figure 4.28. Rule of increasing of reservoir level

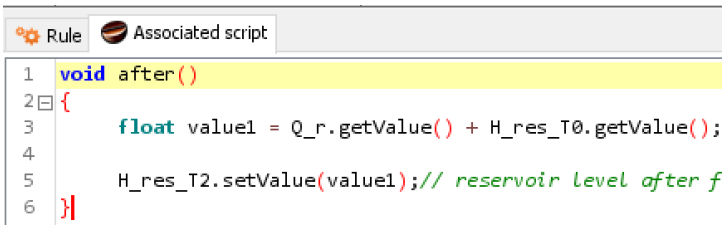


Figure 4.29. Script calculating increasing of reservoir level

The rule graph (Figure 4.28) shows the variation of water level. At the time point T0, water is at the level of *H_res_T0*. After a duration from T1 to T2, the reservoir increase to a level of *H_res_T2*.

The rule said that **if** *Rai*n applies *Surface runoff* on *Reservoir* and *Reservoir* has *Reservoir level* that its value assigned to the variable *H_res_T0*, **then** *Reservoir* has a new level that its value assigned to the variable *H_res_T2*. The *Surface runoff* has a quantity defined by the variable *Q_r*. The time point of the new reservoir level is the time point of the surface runoff. Figure 4.29 illustrates the script calculating increasing of reservoir level.

The knowledge in this rule is: if rain applies the runoff flow into a reservoir, the new water level can be computed based on the quantity of the runoff flow and the old level of the reservoir. Figure 4.30 shows the new level of a reservoir. The two levels placed next to each other show the change of the reservoir over time: at T0, the water level is 80 m; at T2, the water level is 357 m.

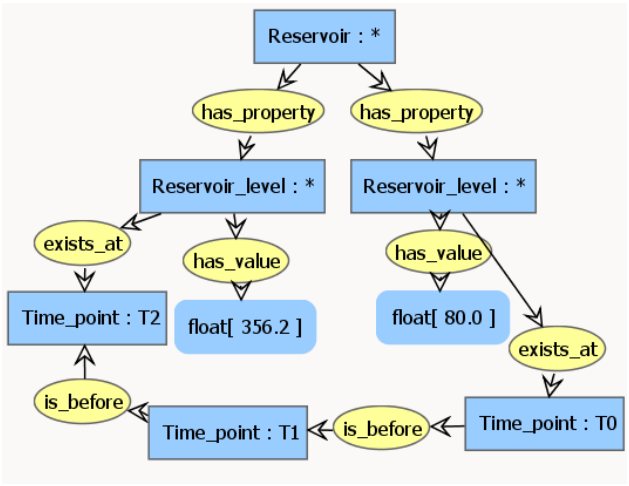


Figure 4.30. Two reservoir levels at two different time points

Interactions within the system

The change of a component under the impact of external factors will impact other components by their interactions within the system. Rule to identify this impact is:

If [Component:*] → (is_component_of) → [Structure_system:*]

[Component:*] → (is_component_of) → [Structure_system:*]

Then [Component:*] → (applies_flow_on) [Flow:*] →[Component:*]

The rule interpretation in natural language is: if a system has its components, then the components interact with each other.

For example, Figure 4.31 shows a rule graph describing the interaction between *Reservoir* and *Embankment dam*, two components of *Dam_system*. The rule graph said that **if** *Reservoir* and *Embankment dam* are components of *Dam system*, *Reservoir* has *Reservoir level* defined by the variable *H_res_T2*, *Embankment dam* has *Based width* and *Upstream slope* defined by the variable *B* and *s_u*, respectively, and *Embankment dam* is made of

Material that has *Permeability coefficient* defined by the variable *K_p*, **then** *Reservoir* applies *Seepage flow* on *Embankment dam*. The seepage flow is defined by the variable *Q*. The time point of the seepage flow is the time point of the reservoir level. Figure 4.32 illustrates the script identifying the seepage flow.

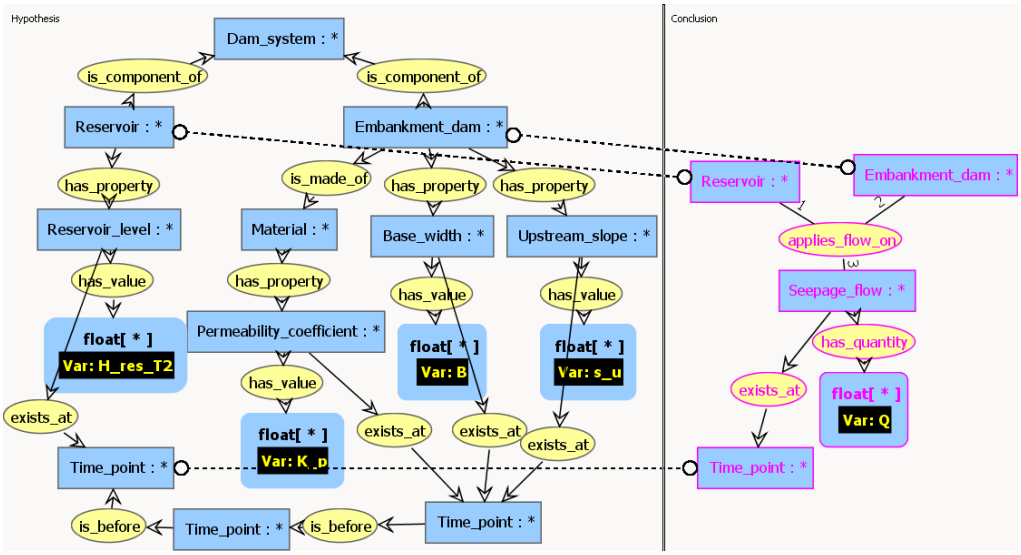


Figure 4.31. Rule identifying the seepage flow

Rule | Associated script

```
1  void after()
2  {
3      float value1 = H_res_T2.getValue() * s_u.getValue(); // value1 = L
4      float value2 = B.getValue() - (0.7*value1); // value2 = x_C
5      float value3 = (Math.sqrt(Math.pow(value2,2) + Math.pow(H_res_T2.getValue(),2))) - value2;
6      float value4 = K_p.getValue() * value3;// q = m3/s
7
8      Q.setValue(value4);//
9
10     }
```

Figure 4.32. Script identifying the seepage flow

Identifying performance

The change in component properties due to the influence of an external factor, or interaction in the system, leads to a change in the component's performance. For example, due to the runoff flow of rain, the reservoir water level increases. This causes the reservoir's performance to change. Another example is a concrete dam subjected to earthquake and other loads from the surrounding components, the combination of loads causing the dam to crack, i.e., the performance is not satisfied.

Performance can be computed in two ways:

(1) Performance is evaluated based on the Performance parameter:

This way includes two steps:

- Step 1: Identifying the measured level of the performance parameter

The measured level is estimated from the properties of the component or material properties.

Figure 4.33 shows a rule to calculate the measured level of freeboard. Freeboard is a performance parameter to evaluate the performance to perform the *Retaining_water* function.

Freeboard = Height of dam - Reservoir level

The hypothesis graph includes the conditions as follow:

- Reservoir and Dam are components of the Dam_system

- Reservoir level and Height of dam

The conclusion graph includes the components relating to performance and function: *Performance*, *Freeboard*, *Measured_level*, *Expected_level*, *Retaining_water*. Two concepts, *Reservoir* and *Retaining_water,* link with the same concepts in the Hypothesis graph by two coreference links.

The rule graph says that **if** a *Dam system* has two components: *Reservoir* and *Dam*, which has *Reservoir level* and *Height of dam* at a time point, **then** a new performance is created. The new performance is evaluated by *Freeboard* with the *Measured level*, computing by water level and height of the dam. The coreference link between two concepts *Retaining water* means that for one function, the performance to perform it can be changed at different time points. Figure 4.34 illustrates the script calculating the measured level of freeboard.

It should be noted that the reservoir level exists at T2 while the dam height exists at T0. It means that the dam's height does not change from T0 until T2, so we can use that dimension to calculate.

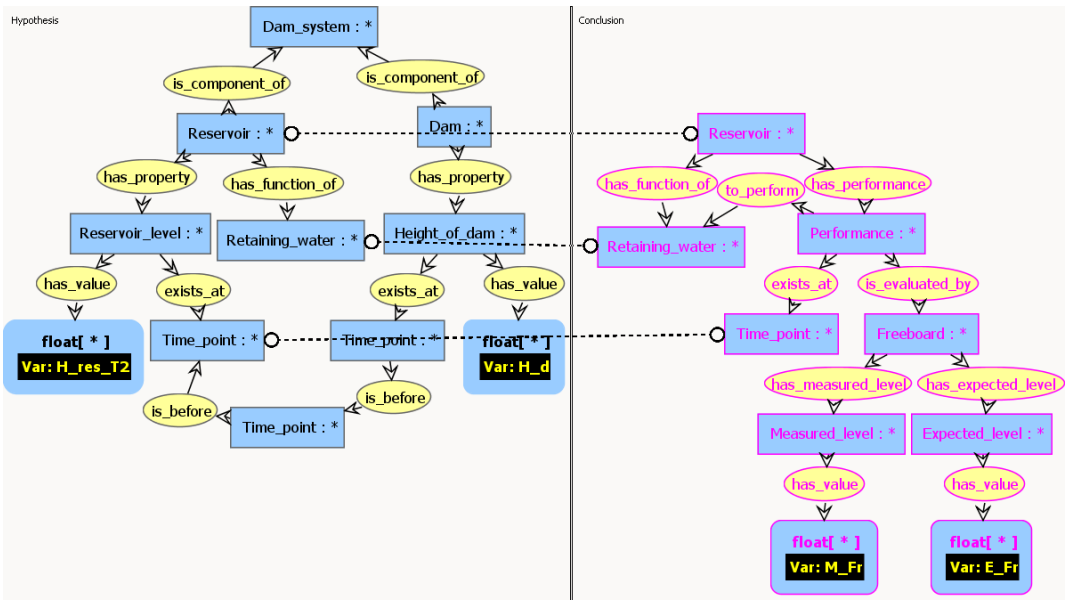


Figure 4.33. Rule calculating the measured level of freeboard

Rule | Associated script

```
1  void after()
2  {
3      float value1 = H_d.getValue() - H_res_T2.getValue();
4      M_Fr.setValue(value1);
5  }
```

Figure 4.34. Script calculating the measured level of freeboard

- ***Step 2:*** Evaluating performance

Performance is evaluating by comparing the measured level and the expected level of the performance parameter. The measured level indicates the actual value of the performance parameter at the time under consideration, and the expected level reveals the value the performance parameter needs to achieve. If the measured level is not as good as expected, the performance is unsatisfactory. This means that the component fails.

Figure 4.35 shows a rule calculating the performance of a reservoir. The graph says that **if** a *Performance* is evaluated by *Freeboard* and the *Freeboard* has a *Measured level* and has an *Expected level*, **then** the performance indicator can be calculated. Figure 4.36 illustrates the script calculating the performance.

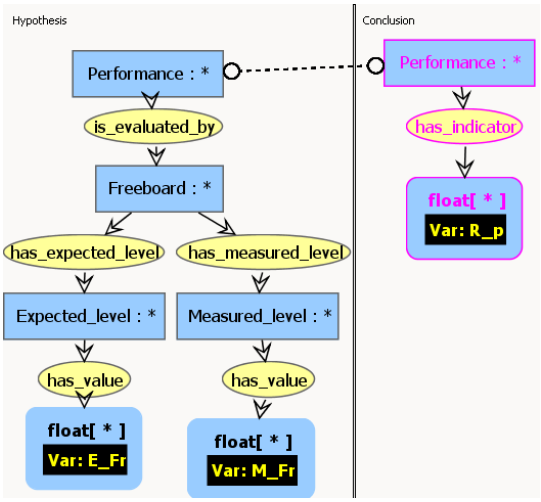


Figure 4.35. Rule calculating the performance relating to the freeboard of a reservoir

Rule | Associated script

```
1  void after()
2  {
3      if (M_Fr.getValue() < E_Fr.getValue()) {
4          R_p.setValue(0);
5      }
6      else {
7          R_p.setValue(1);
8      }
9  }
```

Figure 4.36. Script calculating the performance relating to the freeboard of a reservoir

(2) Performance is evaluated based on the relation "contributes to"

The performance of a system is considered based on the performance of its components. If a component of the system fails, then this failure contributes to the failure of the system.

Figure 4.37 illustrates an example of a gravity dam's failure that contributes to its system's failure. The graph says that **if** a *Dam system* has a *Gravity dam* component, and *Gravity dam* has *Performance* with the indicator is defined by the variable *T_c_p* at a time point, **then** the system has a new performance that contributed by the dam's performance at the same time point.

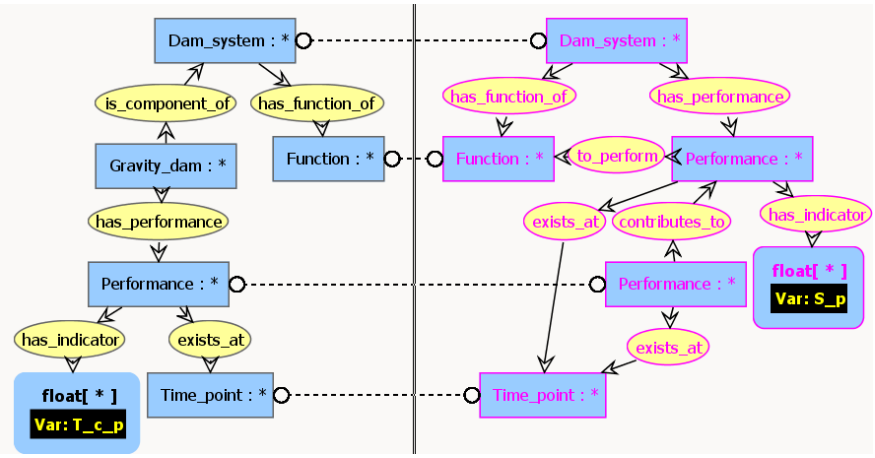


Figure 4.37. Rule identifying the performance of a dam system based on the performance of its gravity dam

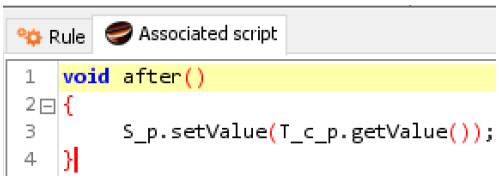


Figure 4.38. Script identifying the performance of a dam system based on the performance of its gravity dam

The resulting graph is:

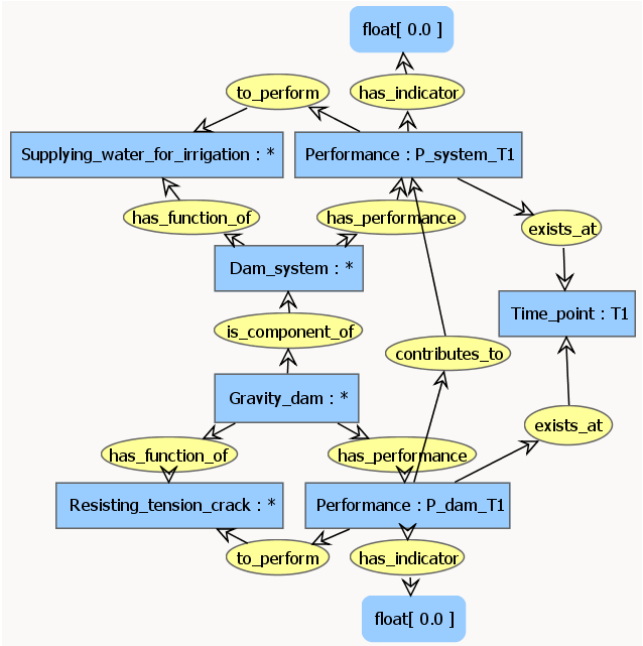


Figure 4.39. Resulting graph of system performance

The resulting graph (Figure 4.39) shows that a new performance of the system is created. It is contributed by the performance of the gravity dam component. Two performances exist at the same time. Also, it shows that the performance to resist tension crack of the dam can contribute to the performance to supply water for irrigation of the system.

4.6. Using the failure knowledge model

The instantiation of the failure model to structural failures composes a database of facts. This fact base can be used to acquire knowledge about failures of structural system, according to two objectives:

1. Similar request: to identify similar failure when a new failure occurs. The purpose is to find conditions or causes that can explain the failure based on similar facts (Breysse, Taillandier and Baudrit, 2018).

2. Inferring rules from facts: to propose failure processes, in order to identify associated risk.

4.6.1. Similar request

Based on the fact base, a similar request can be performed using a query-answering mechanism (Chein and Mugnier, 2008). A query contains information the user wants to retrieve; it can be information related to the structure of a system (components at risk, type of the structure, material), external factors (activity, environment), and the failure. Based on an homomorphism search provided by the CoGui solver, the model will provide all the previous similar cases. The information related to past cases is valuable to propose possible explanations about failure.

Figure 4.40 illustrates a request graph containing information about a failure case of a dam system subjected to drawdown activity. The system has components at risk, which are *Reservoir* and *Homogeneous embankment dam.* The failure is identified by the function of *Resisting sliding of upstream shell* that the performance needs to perform. The dam's state is identified by the performance indicator that has a value of 0.

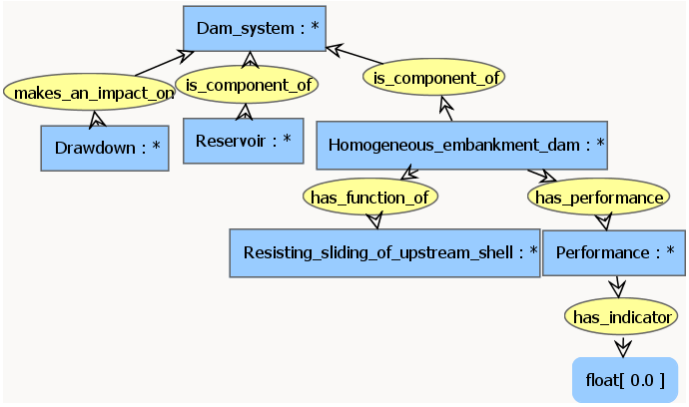


Figure 4.40. A request graph

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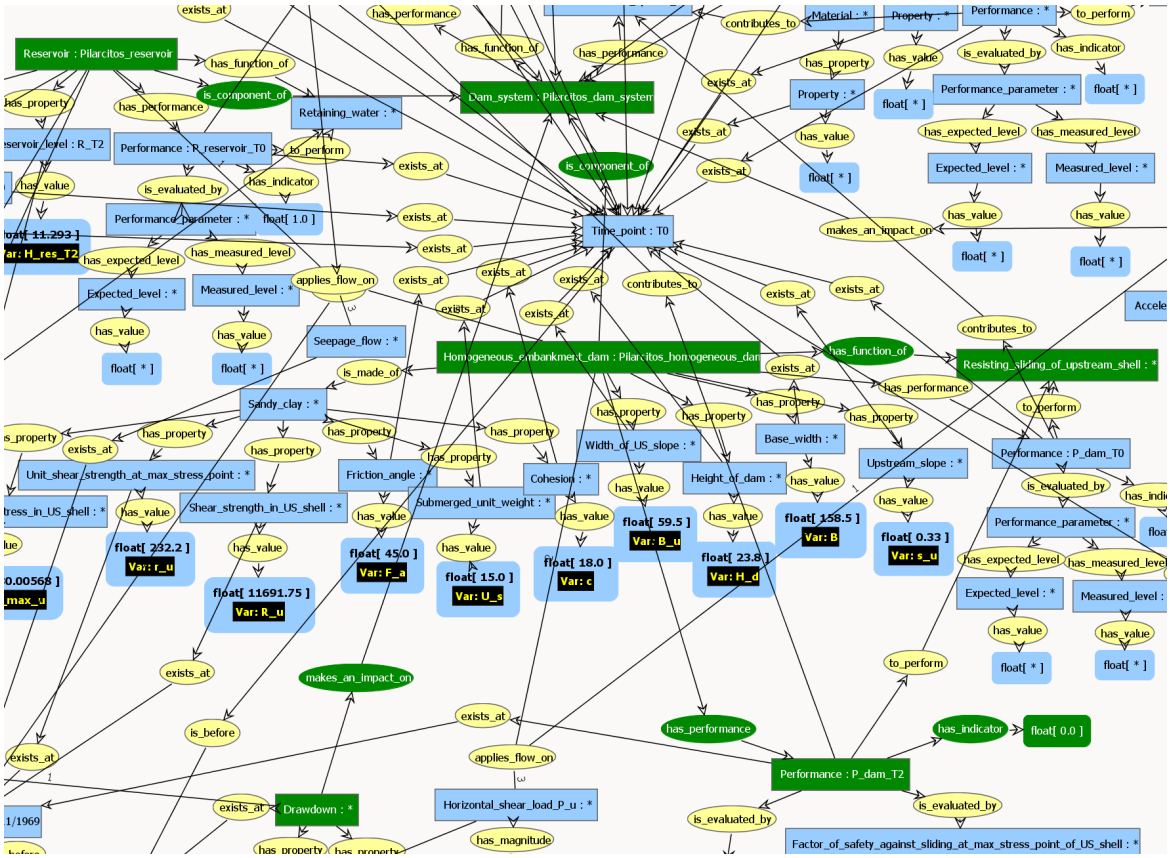

Figure 4.41. An answer to the request

Figure 4.41 illustrates an answer to this request. Elements of the query are highlighted in green. Information collected from the failure instance identifies the conditions relating to the failure. The graph shows that the homogeneous dam's failure results from a combination of the impact of the drawdown activity on the system and interactions within the system. The interactions were generated by associating many factors: high level of the reservoir, mechanical properties of soil, and geometrical parameters of the dam. The combination of all these factors leads to the sliding of the upstream shell suddenly.

4.6.2. Inferring rules from facts

The database of failure can be used as a source to build new rules that can be used to identify failure processes. Considering these processes, associated risks can be predicted, and action plans can be prepared.

Figure 4.42 shows a rule built from a failure case of an embankment dam system subjected to heavy rain. The failure process is started when the rain occurs, which causes an inflow into the reservoir. As the water level rises rapidly behind the dam, the reservoir becomes overflow, leading to external erosion of the embankment dam.

The hypothesis graph includes concepts relating to the system including *Dam_system, Reservoir and Embankment dam* and an external factor (*Rain)*. The conclusion graph describes the failure process and identifies a possible failure. The process shows the impacts of rain on the components: *Inflow* on *Reservoir* and *Overflow* that the reservoir applies on the embankment dam subsequently. These interactions lead to external erosion of the dam..

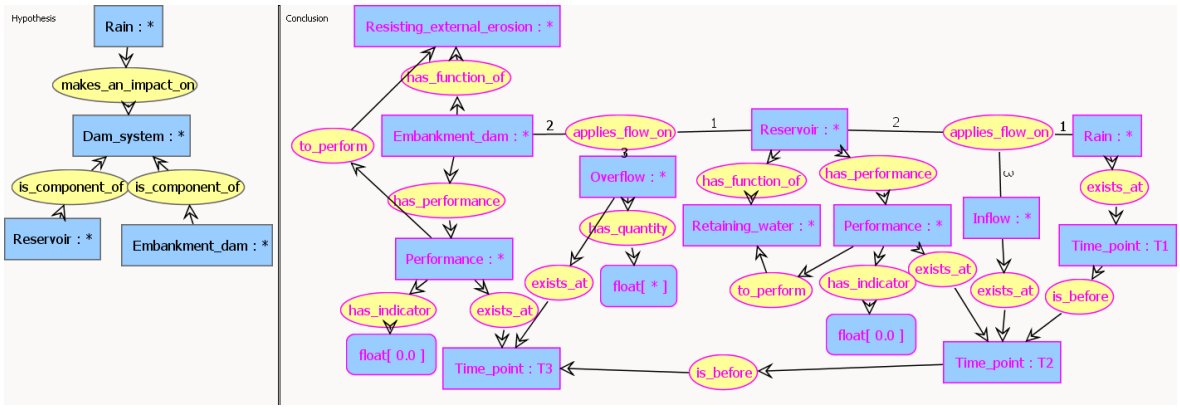

Figure 4.42. A rule inferring from the fact

Figure 4.43 describes a result when applying the rule inferring from fact. By applying this rule, a new graph will be created, showing that when an embankment dam system may be the subject of heavy rain, the interactions between the rain and the system may induce external erosion of the dam.

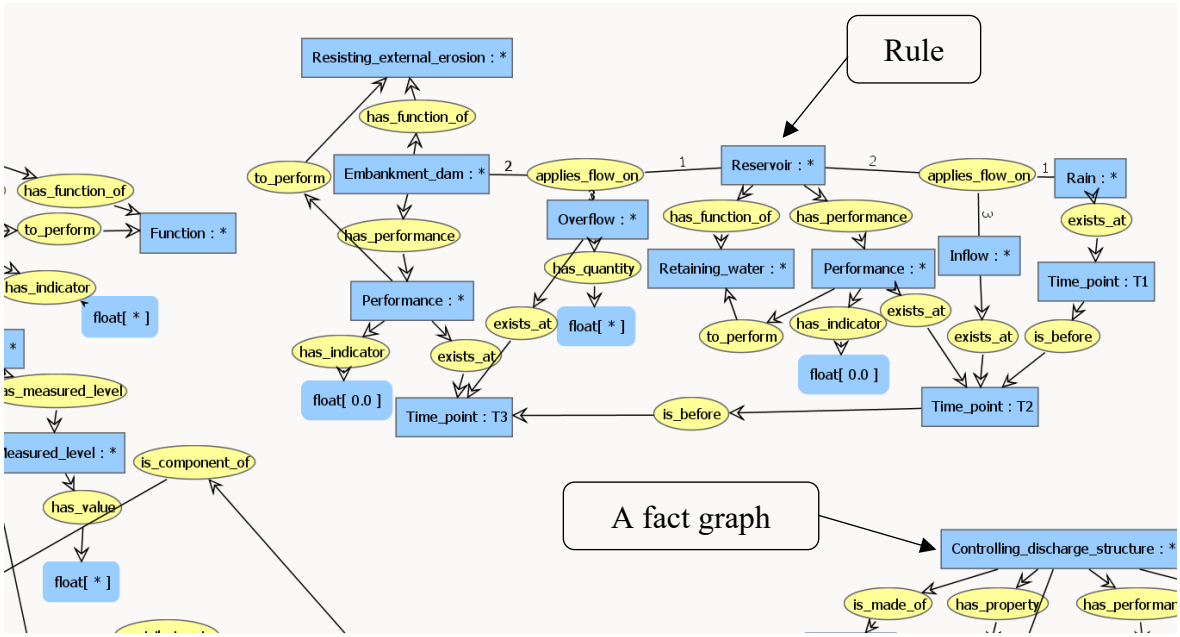

Figure 4.43. A result of the application of a rule inferring from the fact

4.7. Conclusion

In this chapter, we developed a generic knowledge model for dam failure. However, this model can be extended to any civil engineering structure. The model includes a hierarchy of the concepts and relations linking the concepts, describing the system and its behavior during a failure process. These concepts and relations are sufficiently generic to cover most of the structural systems. Nevertheless, a specific knowledge base was developed to describe dam systems and dam failures. Furthermore, the model structure allows adding new concepts for specific kinds of other structures such as bridges, tunnels, etc.

In the next chapter, based on this model, we will present how to use the model to describe failure and applications on actual failure cases.

Chapter 5
Application in case studies

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5.2.4. Failure process

5.3. Using the failure knowledge model

5.3.1. Similar request

5.3.2. Inferring rules from facts

5.4. Knowledge and Lesson learned from failures

5.5. Conclusion

5.1. Introduction

This chapter will provide an application of the failure knowledge model developed in chapter 4. In particular, this chapter serves two purposes:

- The first purpose is to instantiate the proposed model based on a real failure case. A fact graph of failure, formalizing the failure process of historic dam failure, will be created based on the vocabulary and the set of rules in the knowledge base. It will allow us to explain how to add new facts to the fact base.
- The second purpose is to use the fact base to infer new knowledge. Firstly, the set of failure instances can be used to identify similar past failure cases. It also enables creating a set of rules allowing to identify risks related to a dam.

In this perspective, we propose, in the first section, a case study to apply the proposed method: the failure of the Koyna dam in India. The Koyna dam's failure was the result of an earthquake. This failure case will illustrate how the combination of conditions may produce failures; they also show how the systems' effects and changes over time are implicated in the failure process. In the following section of the chapter, we will study how the failure knowledge model can be used, based on similar cases in the fact base, and how to propose rules from past cases. Finally, we will discuss, in a more general way, how to learn lessons from failures based on the proposed model.

5.2. Case study: Koyna dam system

5.2.1. Context of failure

The Koyna dam was built in India between 1954 and 1963. Its primary function is to ensure irrigation and provide hydroelectricity. The dam system includes six mains components: gravity dam body, reservoir, foundation, abutments, and spillway. Koyna dam was designed as a straight gravity dam that stands 103 m high and 853 m long. It measures 14.8 m thick at the crest and 70 m thick at the base, with a sharp slope change on the downstream face at the height of 66.5 m (Figure 5.1). It failed in 1967, December 11, due to an earthquake (Koyna earthquake).

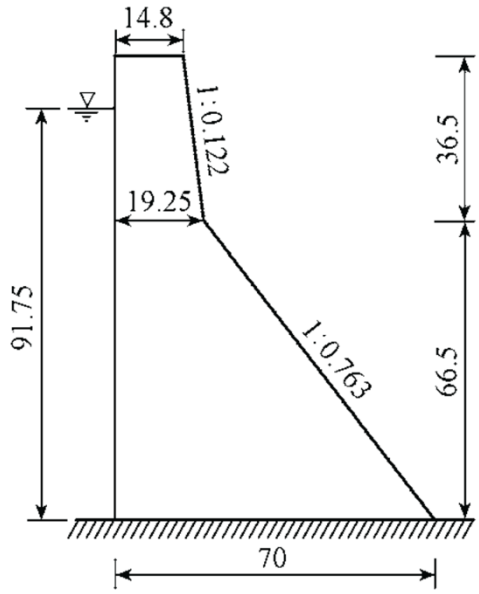

Figure 5.1. Cross-section of Koyna dam (unit: m) (Jiang and Du, 2012)

The dam was constructed primarily from cyclopean concrete, with a unit weight of 2642 kg/m3 (26.42 kN/m3), a compressive strength of 24.60 MPa, and a tensile strength of 2.46 Mpa (Jiang and Du, 2012). The reservoir has a maximum storage capacity of 3.1x109 m^3. At the time of the Koyna earthquake, the reservoir water level was 91.75 m. The overflow spillway is located at the center of the structure, 91.4 m wide. The foundation is primarily composed of basalt, which is very compact. It contains very thin cracks, which were consolidated grouted to support the structure. The foundation, which is 18m thick, is assumed to be fully rigid (Jiang and Du, 2012). The geology of the Indian Peninsula was considered stable and non-seismic when the dam was designed.

5.2.2. Failure presentation

Description of failure:

Koyna dam is one of the few concrete dams that have experienced a destructive earthquake. In 1967, the Koyna dam was shaken by a catastrophic earthquake that registered 6.5 on the Richter scale with a maximum acceleration measured at ten times the design value. Despite being subjected to high accelerations, the Koyna dam did not fail in the sense of uncontrolled discharge of water from the reservoir. However, the dam was significantly damaged with deep horizontal cracks formed throughout the upstream and downstream faces, and severe leakage was observed (USCOLD, 1992).

Analysis of failure

The identified factors which were related to the failure are:

+ Earthquake with the magnitude of Mw6.7.

+ Conditions of the dam: the dam was only designed to withstand seismic accelerations of 0.05g, whereas the acceleration of the earthquake was higher than 0.34g.

+ The water level of the reservoir was high during the earthquake, which is a dangerous condition for the dam.

The components at risk were the concrete dam, the reservoir, and the foundation. The Koyna dam failure results from interactions between the earthquake and reservoir, dam, foundation, and the interactions between these components. The combination of all the identified factors leads to severe damages to the dam in a short time.

5.2.3. Instantiation of the failure knowledge model

In order to formalize the failure of the Koyna dam, we consider two levels (system level and component level) and three time points (Figure 5.2).

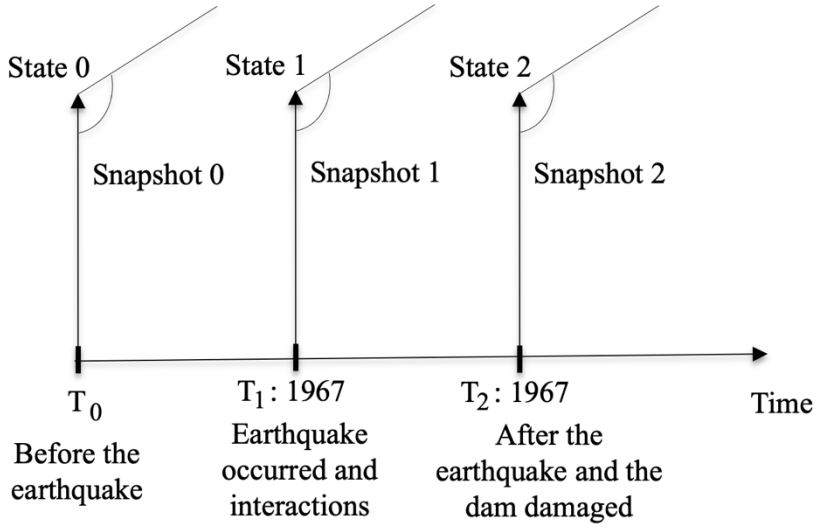

Figure 5.2. Timepoints of the failure process

The instantiation process follows six steps:

1. Identifying the dam system at T0

2. Identifying interactions within the dam system at T0

3. Identifying the external factors at T1

4. Identifying the impacts of the external factors

5. Performance of the concrete dam at T2

6. Performance of the system at T2

In the following section, we will detail these six steps.

5.2.3.1. Identifying the dam system at T0

In order to facilitate the instantiation, the model, thanks to the generic model presented in the previous chapter, a set of instantiating rules allows to automotize the instantiation process. Figure 5.3 shows a rule graph to identify the structure of the system. The rule can be expressed as **if** *Gravity_dam* is a component of *Dam_system*, **then** the main components of a gravity dam system will be created, including reservoir, gravity dam, foundation,

abutment, spillway, and bottom outlet. Each component is described with its properties, function, and performance. *Dam_system* is represented with its function and performance. It means that you only have to fill in the type of dam to obtain the complete model corresponding to this dam.

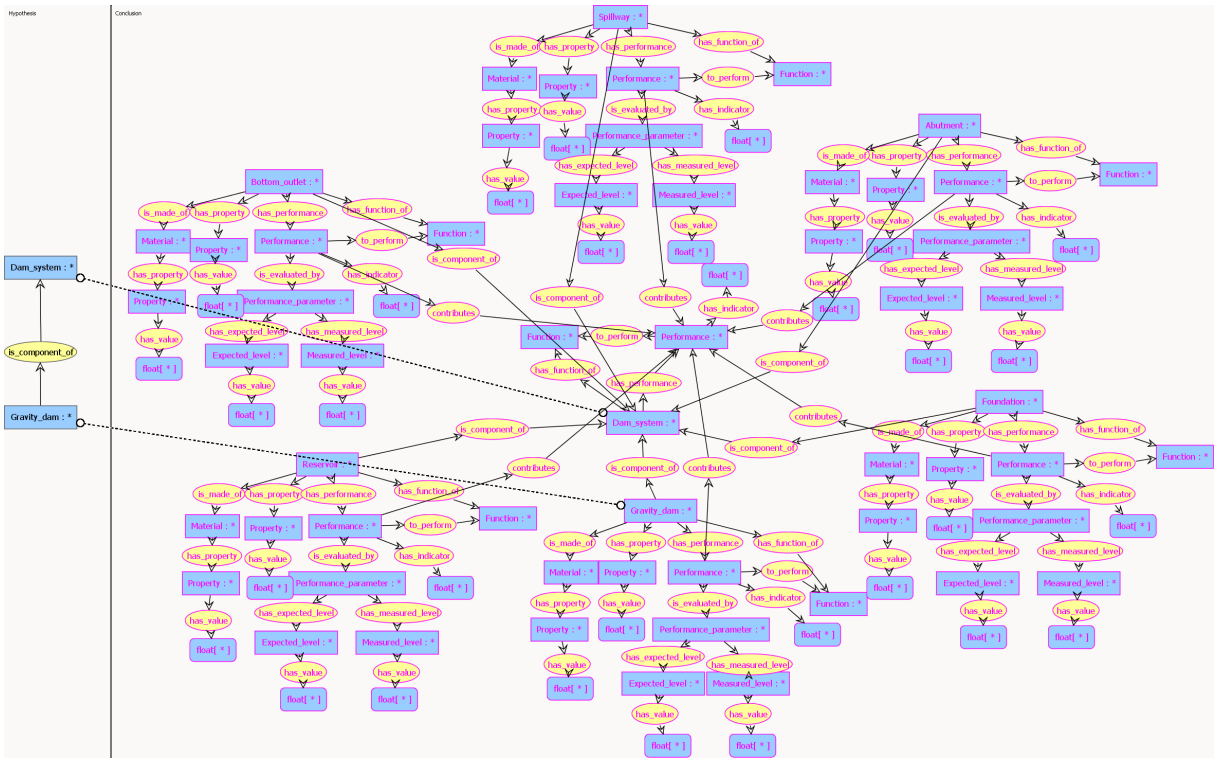

Figure 5.3. Rule identifying a gravity dam system

Resulting graph from the rule:

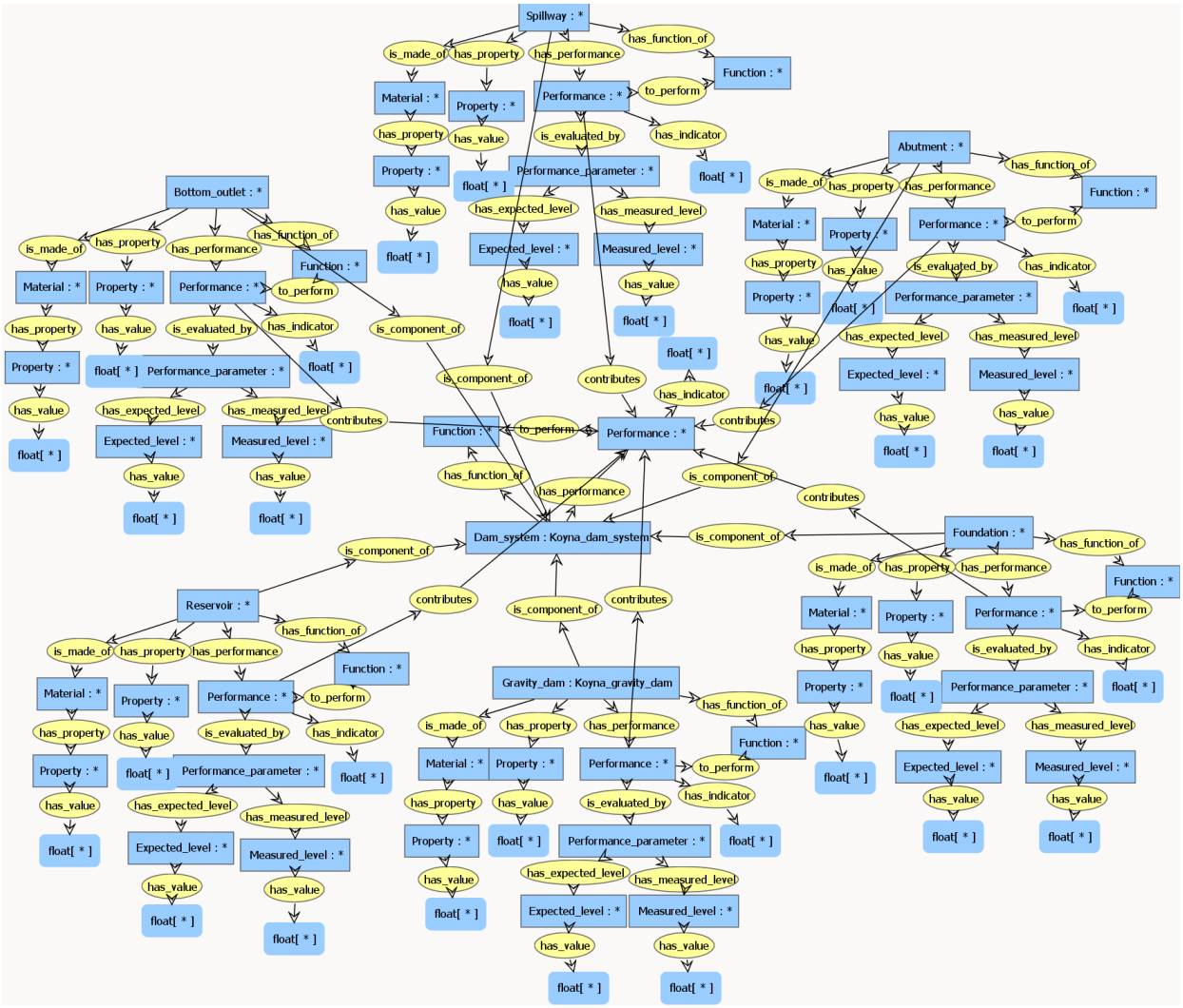

Figure 5.4. The resulting graph of the rule identifying the gravity dam system

The resulting graph (Figure 5.4) shows a typical structure of a gravity dam system with its main components. The concept types are generic concepts, noted *. Therefore all components of the structure need to be identified as individual concepts (i.e., instance) and filled with the necessary information to formalize the failure. For example, the concept *Reservoir* is instantiated as *Reservoir: Koyna_reservoir*. The gravity dam has a height of 103 m, a base width of 70 m, a top width of 19.25 m. The function is considered for the gravity dam is *Resisting_tension_crack* with the performance parameter *Factor of safety against tension crack.* The model was instantiated at the time point T0 (i.e., before the earthquake) for all parameters. Figure 5.5 and figure 5.6 describe the Koyna reservoir and Koyna gravity dam with all information.

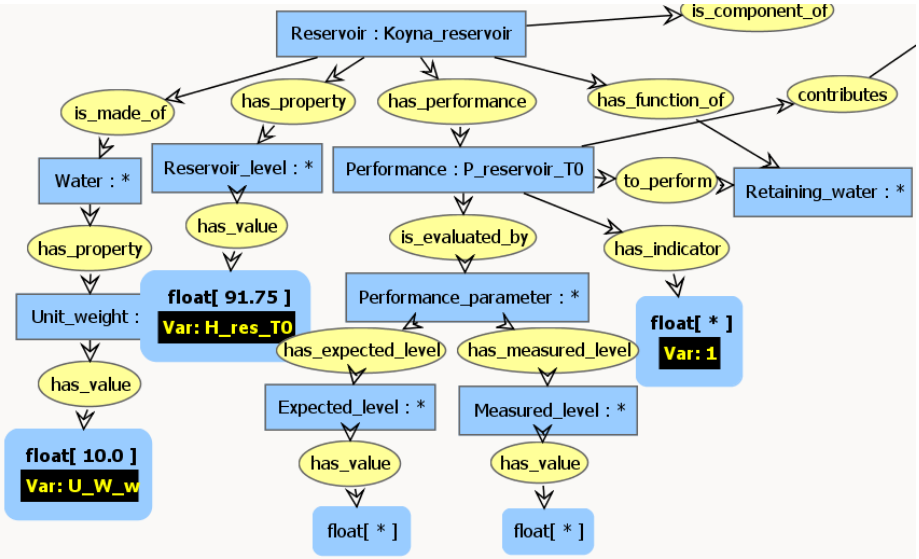

Figure 5.5. Reservoir component at T0

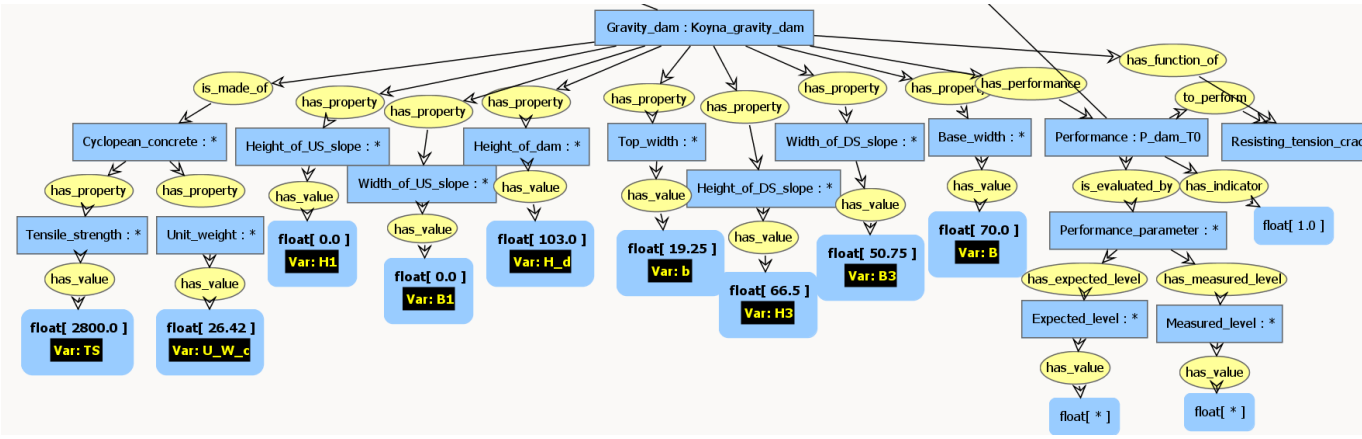

Figure 5.6. Koyna gravity dam component at T0

5.2.3.2. Identifying interactions within the dam system at T0

At T0, there exist interactions within the dam system. These interactions are generated by water in the reservoir and gravity. Gravity is a special external factor. It always exists and impacts the system at any time. Therefore, the self-weight load of the dam that gravity generated is considered at T0. Water seeps below the dam and exerts an uplift load on the base of the dam.

Interactions within the dam system at T0 include:

- Self-weight load of the gravity dam

- Reservoir load: the horizontal water load exerted by the weight of the water stored on the upstream side on the dam.

- Uplift load: the upward load exerting on the base of the dam.

Identifying gravity:

Figure 5.7 expose the graph with gravity impacting the dam system. The concept *Koyna dam system* is instantiated. Gravity exists at T0.

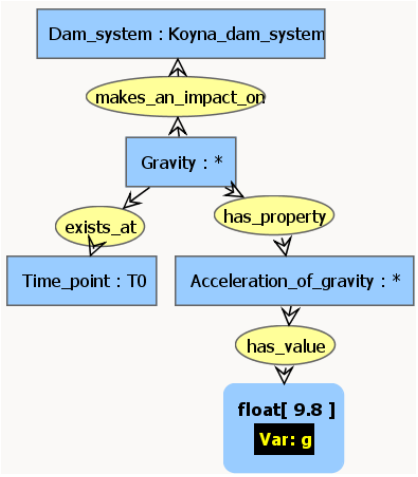

Figure 5.7. Gravity impacting the Koyna dam system

Self-weight load of gravity dam: Self-weight is attributable to gravity, and its magnitude is determined by the density of the materials that constitute the structure. The equation of self-weight load is:

$$W_c = \gamma_c * A$$

where,

W_c: self-weight load of gravity dam

γ_c is the unit weight of concrete, γ_c = 23.0 - 23.5 kN/m^3

A is the cross-sectional area of the structure.

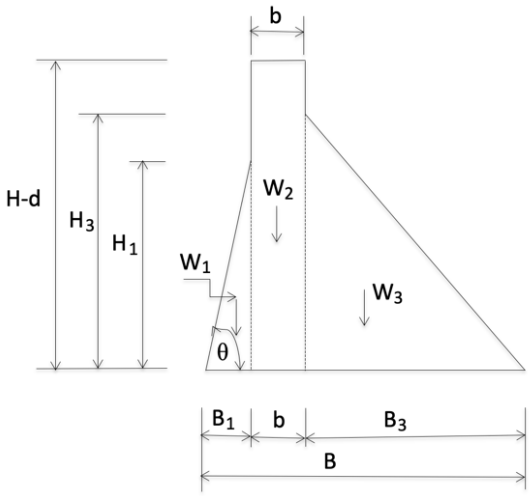

Figure 5.8. Typical cross-section of gravity dam

Figure 5.8 shows a typical cross-section of a gravity dam with a downstream slope face and an upstream slope.

$$W_c = W1 + W2 + W3$$

$$W1 = ½\ B_1 \,.\, H_1 \,.\, \gamma_c$$

$$W2 = b \,.\, H \,.\, \gamma_c$$

$$W3 = ½\ B_3\ .\ H_3\ .\ \gamma_c$$

where,

B: Base width of dam (m); b: Top width of dam (m); H_d: Height of dam (m); B_1: Width of the slope of the upstream face of the dam; H_1: Height of the slope of the upstream face of the dam; B_3: Width of the slope of the downstream face of the dam; H_3: Height of the slope of the downstream face of the dam.

The self-weight load of the gravity dam has to ensure the stability of the dam through the generated moment. The load is considered to act through the centroid of the cross-sectional area of the dam. The moment can be calculated by the equation:

$$\text{Moment of a load} = \text{load} * \text{moment arm}$$

where,

Moment (kNm)

Load (kN)

Moment arm (m): is the perpendicular distance between the line of action of the load and the center of moments.

The moment about the toe of self-weight load (Mwc) is composed of the moment of W1, W2, and W3:

$$M_{wc} = M_{wc1} + M_{wc2} + M_{wc3}$$

$$\text{Moment of W1: } M_{wc1} = (+)\ W1\ .\ \left(B - \frac{2}{3}B_1\right)$$

$$\text{Moment of W2: } M_{wc2} = (+)\ W2\ .\ \left(B_3 + \frac{b}{2}\right)$$

$$\text{Moment of W3: } M_{wc3} = (+)\ W3\ .\ \frac{2}{3}B_3$$

These equations were formalized as a rule in the knowledge model, allowing to calculate self-weight-load and its moment about the toe.

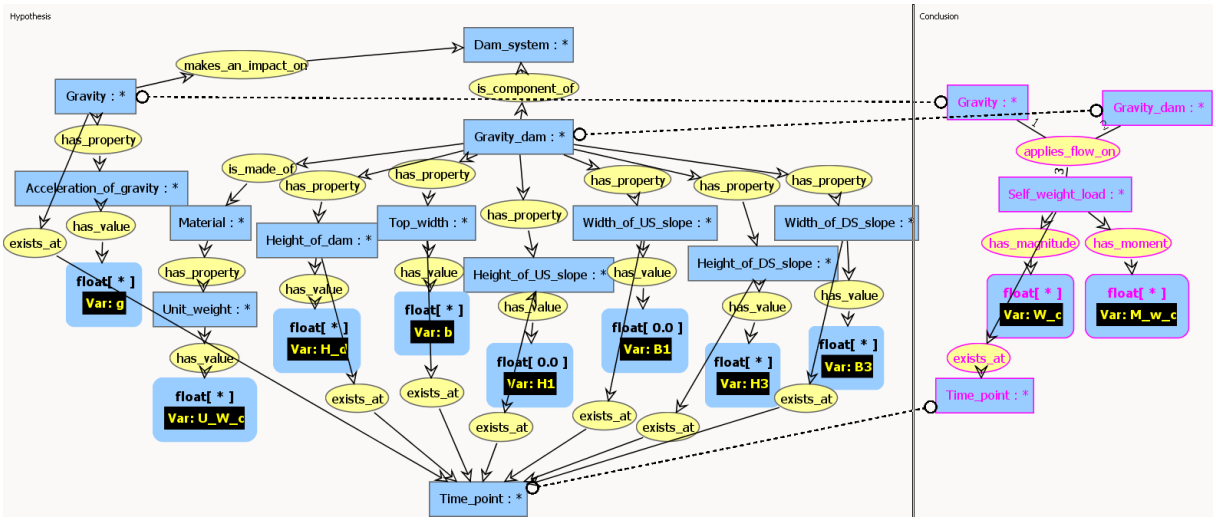

Figure 5.9. Rule calculating self-weight load and moment of gravity dam

Rule | Associated script

```
void after()
{
    float value1 = U_W_c.getValue() * H1.getValue() * B1.getValue() / 2; // valu
    float value2 = U_W_c.getValue() * H_d.getValue() * b.getValue(); // value2:
    float value3 = U_W_c.getValue() * H3.getValue() * B3.getValue() / 2; // valu

    float value4 = value1 * ((B1.getValue()/3) + b.getValue() + B3.getValue());/
    float value5 = value2 * ((b.getValue()/2) + B3.getValue()); //value5: moment
    float value6 = value3 * (B3.getValue() * 2/3); //value6: moment of W3 about

    float value7 = value1 + value2 + value3;// value7: self-weight load of dam-b
    float value8 = value4 + value5 + value6; // value8: moment of self-weight lo

    W_c.setValue(value7);
    M_w_c.setValue(value8);
}
```

Figure 5.10. Script calculating self-weight load of gravity dam

Figure 5.9 shows a rule graph calculating the self-weight load and the induced moment. The rule can be explained as **if** *Gravity* impacts *Dam-system*, and *Gravity_dam* is a component of *Dam_system*, **then** *Gravity* applies *Self-weight load* on *Gravity_dam*. Figure 5.10 shows a script allows calculating the self-weight load and its moment.

Reservoir load (P)

Reservoir load (P) is the most major external force acting on a dam. Water applies pressure with a linear variation with depth. The deeper the water, the more horizontal pressure it exerts on the dam. So at the surface of the reservoir, the water is exerting no pressure, and at the bottom of the reservoir, the water is exerting maximum pressure. The total force equals the integral of pressure, thus:

$$P = \frac{1}{2}\gamma_w H_{res}^2$$

where,

P : Reservoir load (kN)

γ_w : unit weight of water = 10 kN/m^3

H_{res} : Reservoir level (m)

The reservoir load acts at (1/3)H_{res} from the base.

The Moment of the reservoir load about toe is given as:

$$M_r = (-)\ P * H_{res}/3$$

where,

M_r: Moment of reservoir load about the toe of the dam (kNm)

P: Reservoir load (kN)

H_{res} : Reservoir level (m)

The rule to calculate the reservoir load and its moment about toe are given in figures 5.11 and 5.12.

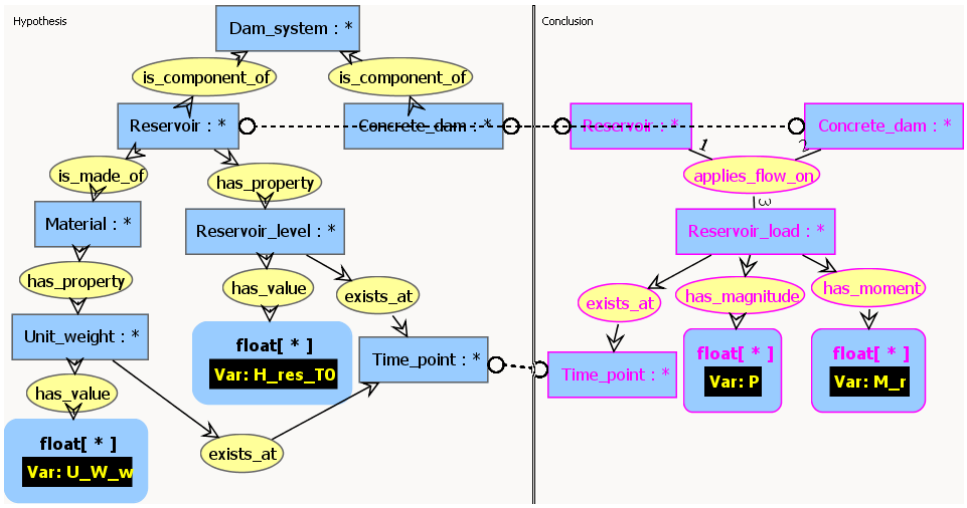

Figure 5.11. Rule to calculate reservoir load

Rule | Associated script

```
1  void after()
2  {
3      float value1 = U_W_w.getValue() * Math.pow(H_res_T0.getValue(), 2.0);
4      float value2 = value1 * H_res_T0.getValue()/3;
5
6      P.setValue(value1); // P: hydrostatic load
7      M_r.setValue(value2); // Moment of load
8  }
```

Figure 5.12. Script of the rule calculating reservoir load

The resulting graph (Figure 5.11) shows the interaction between the reservoir and the gravity dam. The rule graph can be expressed as **if** *Reservoir* and *Concrete dam* are components of *Dam_system*, **then** *Reservoir* applies *Reservoir_load* on *Concrete_dam*. The resulting load occurs at T0 (and for the following time point). Figure 5.12 illustrates the script calculating the reservoir load and its moment.

Uplift load (U)

The uplift load is the second significant load acting on a dam. Water penetrating along the cracks, fissures of the foundation material, or water seeping through the dam and then to the bottom through the joints between the dam and its foundation at the base exerts an uplift load the base of the dam. Such an uplift load reduces the self-weight load of the body of the dam and hence, acts against the dam stability (Garg, 2005).

The process of creating the uplift load is divided into two steps:

1. Water seeps into the foundation;

2. The seepage exerts a load on the base of the dam, which is considered as the interaction between the foundation and the dam.

The distribution of load through a horizontal section of the dam is assumed to vary linearly from a full hydrostatic head at the upstream face to zero at the downstream face, assuming the dam has no drains or unlined water passages.

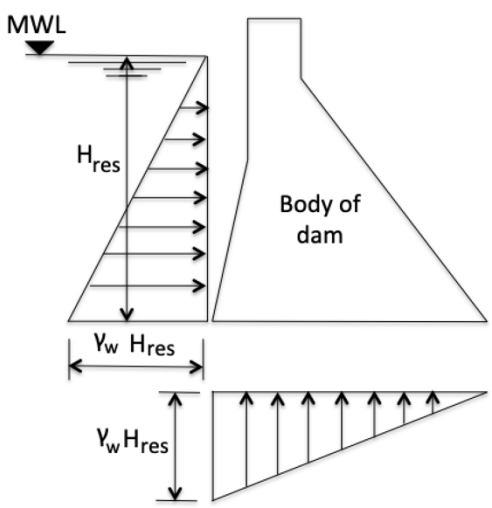

Fig (a) Uplift pressure diagram when no drainage gallery is provided

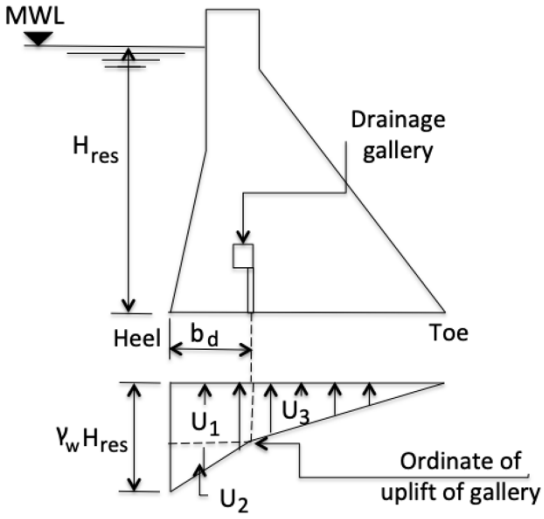

Fig (b) Uplift pressure diagram when drainage gallery is provided

Figure 5.13. Uplift pressure diagram

In the case of the Koyna dam system, there is no information related to the presence of a drainage gallery. Therefore, the equation to compute uplift load for dam without drainage gallery (Figure 5.13a) is used:

$$U = ½ \gamma_w * H_{res} * B$$

where, U : Uplift load (kN)

H_{res} : Reservoir level (m)

B : Base width of dam (m)

γ_w : unit weight of water = 10 kN/m^3

The moment of the uplift load about toe is:

$$M_u = (-) U * 2/3 B$$

where,

M_u: Moment of uplift load about the toe of the dam

U: Uplift load (kN)

B: Base width of dam (m)

The rule calculating the uplift load and its moment about the toe of the dam is exposed in figures 5.14, 5.15, and 5.16.

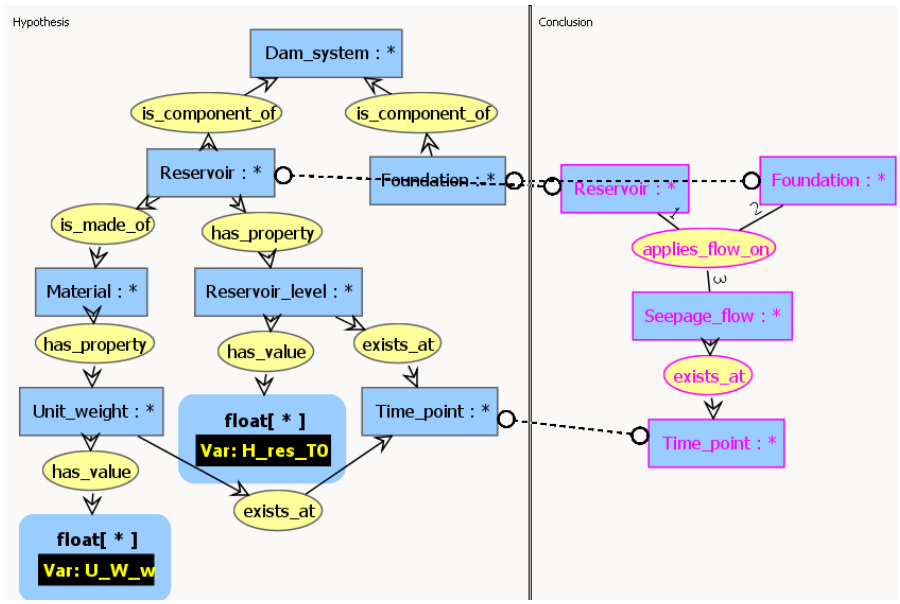

Figure 5.14. Rule identifying seepage flow in the foundation

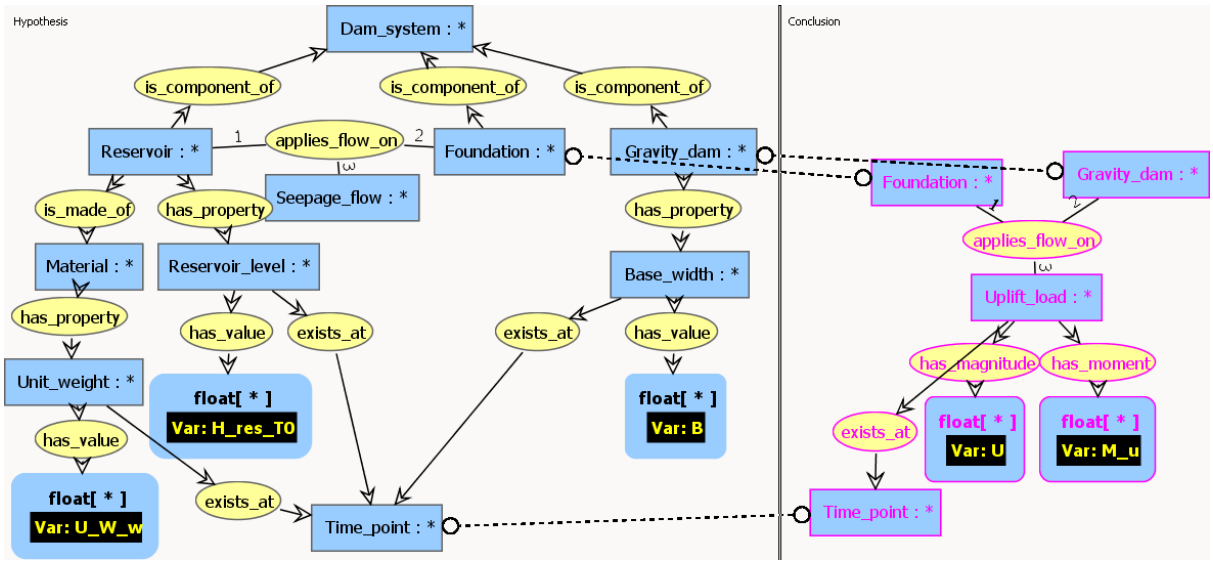

Figure 5.15. Rule computing the uplift load and its moment

Rule | Associated script

```
1  void after()
2  {
3
4      float value1 = U_W_w.getValue() * H_res_T0.getValue() * B.getValue()/2;
5      float value2 = value1  * (B.getValue() * 2/3);
6
7      U.setValue(value1);
8      M_u.setValue(value2);
9
10 }
```

Figure 5.16. Script computing the uplift load and its moment

Figure 5.14 describes the first step of the seepage flow into the foundation. The rule graph can be interpreted in natural language as **if** *Reservoir* and *Foundation*, with their properties, are components of *Dam_system*, **then** *Reservoir* applies a *Seepage flow* on *Foundation*.

The rule graph (Figure 5.15) shows an interaction between the foundation and the gravity dam, which is the next impact of the seepage flow in the foundation. The rule graph can be explained as **if** *Reservoir*, *Foundation*, and *Gravity_dam* are components of *Dam_system*, and *Reservoir* applies *Seepage flow* on *Foundation*, **then** *Foundation* applies *Uplift_load* on *Gravity_dam*. The reservoir is described with its relevant properties. Figure 5.16 presents the associated script.

5.2.3.3. Identifying external factors at T1

The second considered time, T1, corresponds to the day when the earthquake occurs (i.e., 11/12/1967). At this time, the instantiated concept Earthquake:*Koyna_earthquake* appears with its properties, which are also instantiated. Figure 5.17 exposes the graph with the earthquake.

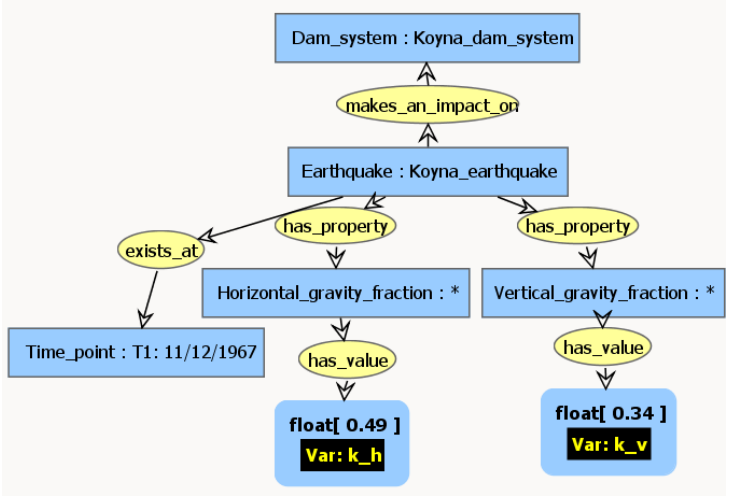

Figure 5.17. Koyna earthquake

5.2.3.4. Identifying impacts of the external factors

Impacts of the earthquake are considered.

An earthquake introduces momentary dynamic loads generated due to the inertia of the dam and the retained water. Two accelerations, i.e., one horizontal acceleration (α_h) (upstream or downstream) and one vertical acceleration (α_v) (upward or downward) characterize the earthquake interaction; they are generally expressed as a percentage of the acceleration due to gravity (g), i.e., α = 0.1 g or 0.2 g, etc. In the model, all the earthquake loads are set up at the time point of the earthquake, i.e., T1.

Horizontal inertia load E_h

Horizontal acceleration (α_h) causes horizontal inertia load, which exerts into the dam. The direction of this load will be opposite to the acceleration imparted by the earthquake. The amount of this horizontal inertial load is equal to the mass of the dam and its acceleration. The following equation gives this horizontal inertia load:

$$E_h = \left(\frac{W_c}{g}\right) \alpha_h = \frac{W_c}{g} * k_h * g = W_c * k_h$$

where,

E_h : is horizontal earthquake load

W_c: self-weight of concrete dam

k_h : is the fraction of gravity adopted for horizontal acceleration, such as 0.1 or 0.2, etc.

This load acts at the center of gravity of the dam.

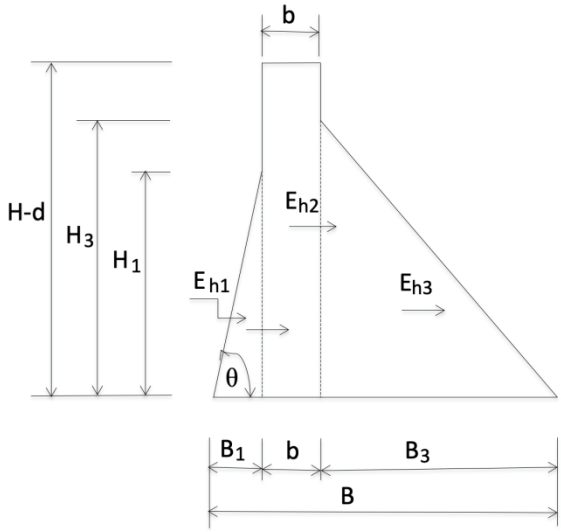

Figure 5.18. Typical cross-section of gravity dam to calculate horizontal earthquake load

The horizontal inertia load may be the sum of three loads (Figure 5.18):

$$E_h = E_{h1} + E_{h2} + E_{h3}$$

where:

$E_{h1} = W_1 . k_h$

$E_{h2} = W_2 . k_h$

$E_{h3} = W_3 . k_h$

This generates a moment called horizontal earthquake load, about the toe of the dam:

$$M_{e\text{-}h} = M_{e\text{-}h1} + M_{e\text{-}h2} + M_{e\text{-}h3}$$

where:

$M_{e\text{-}h1} = (-) E_{h1} . \frac{H_1}{3}$

$M_{e\text{-}h2} = (-) E_{h2} . \frac{H}{2}$

$M_{e\text{-}h3} = (-) E_{h3} . \frac{H_3}{3}$

As for the gravity load, the knowledge base provides a rule to calculate the horizontal earthquake load and its moment about the toe.

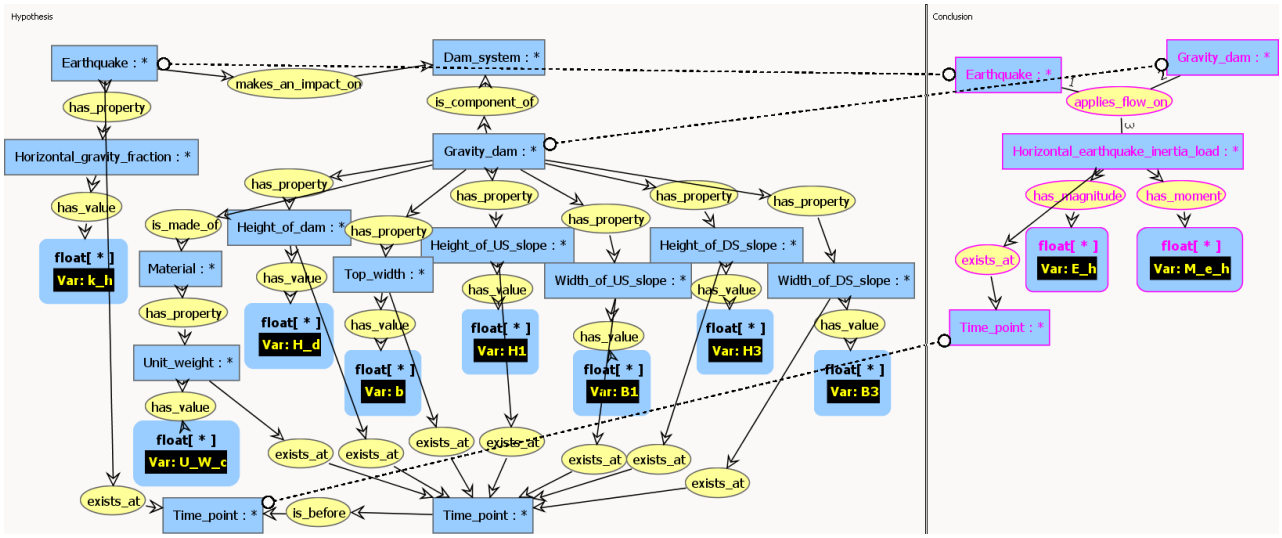

Figure 5.19. Rule calculating horizontal earthquake load and its moment about the toe of the dam

Rule | Associated script

```
1  void after()
2  {
3      float value1 = k_h.getValue() * U_W_c.getValue() * H1.getValue() * B1.getValue() / 2; //
4      float value2 = k_h.getValue() * U_W_c.getValue() * H_d.getValue() * b.getValue(); // val
5      float value3 = k_h.getValue() * U_W_c.getValue() * H3.getValue() * B3.getValue() / 2; //
6
7      float value4 = value1 * H1.getValue() / 3;//value4: moment of W1 about the toe anti-cloc
8      float value5 = value2 * H_d.getValue() /2; //value5: moment of W2 about the toe +ve in k
9      float value6 = value3 * H3.getValue() / 3; //value6: moment of W3 about the toe +ve in k
10
11     float value7 = value1 + value2 + value3;// value7: self-weight load of dam-body in kN
12     float value8 = value4 + value5 + value6; // value8: moment of self-weight load of dam-bo
13
14     E_h.setValue(value7);
15     M_e_h.setValue(value8);
16 }
```

Figure 5.20. Script calculating horizontal earthquake load and its moment about the toe of the dam

Figure 5.19 shows a rule graph calculating the horizontal earthquake load and its moment about the toe. The rule says that **if** *Earthquake* makes an impact on *Dam_system*, and *Gravity dam* is a component of *Dam system*, **then** *Earthquake* applies *Horizontal earthquake inertia load* on *Gravity dam*. *Earthquake* has *Horizontal gravity fraction* defined by the variable *k_h*. *Gravity dam* is described with *Height of dam*, *Top width*, *Height of US slope*, *Width of US slope*, *Height of DS slope*, *Width of DS slope*. Also, a script allows the computation of the required properties Figure 5.20.

Earthquake hydrodynamic load E_d

Furthermore, horizontal acceleration acting towards the reservoir causes a momentary increase in the water pressure, as the foundation and dam accelerate towards the reservoir and the water resists the movement owing to its inertia. The extra load exerted by this process is known as a hydrodynamic load. According to Von-Karman, the amount of this hydrodynamic load (E_d) is given by:

$$E_d = 0.555.k_h.\ \gamma_w.\ H_{res}^2$$

Where k_h is the fraction of gravity adopted for horizontal acceleration, such as 0.1, 0.2, etc.

γ_w: unit weight of water

It acts at the height of $\frac{4H_{res}}{3\pi}$ above the base, as shown in Figure 5.21.

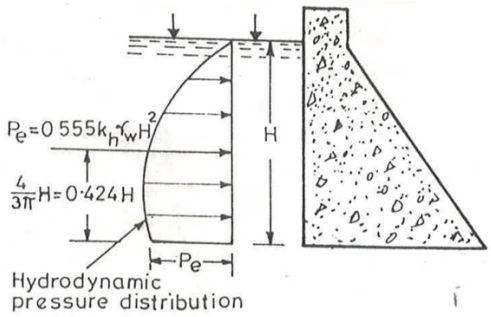

Figure 5.21. Earthquake hydrodynamic load (Garg, 2005)

The moment of the earthquake hydrodynamic load about the base is:

$$M_{e_d} = E_d \left(\frac{4H}{3\mu}\right) = 0.424.\ E_d.\ H_{res}$$

Figure 5.22 describes the impact of the earthquake on the reservoir. The rule graph can be expressed as **if** *Earthquake* makes an impact on *Dam_system*, and *Reservoir* is a component of *Dam_system*, **then** *Earthquake* applies *Earthquake hydrodynamic load* on *Reservoir*. The resulting hydrodynamic load is set at T1.

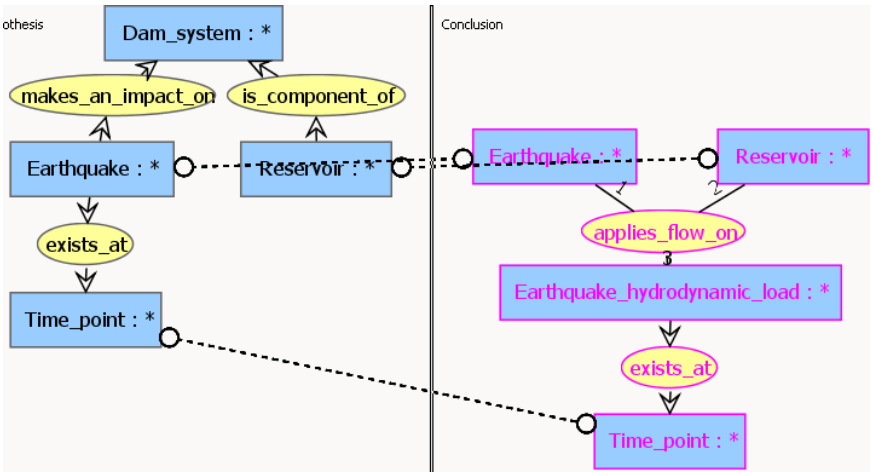

Figure 5.22. Rule to identify the impact of an earthquake on a reservoir

Figure 5.23 shows a rule to calculate the earthquake hydrodynamic load that the reservoir applies to the dam. The rule can be explained as **if** *Earthquake* applies *Earthquake hydrodynamic load* on *Reservoir*, and *Reservoir* and *Concrete dam* are components of *Dam_system*, then *Reservoir* applies *Earthquake hydrodynamic load* on *Concrete dam*. Figure 5.24 exposes the associated script.

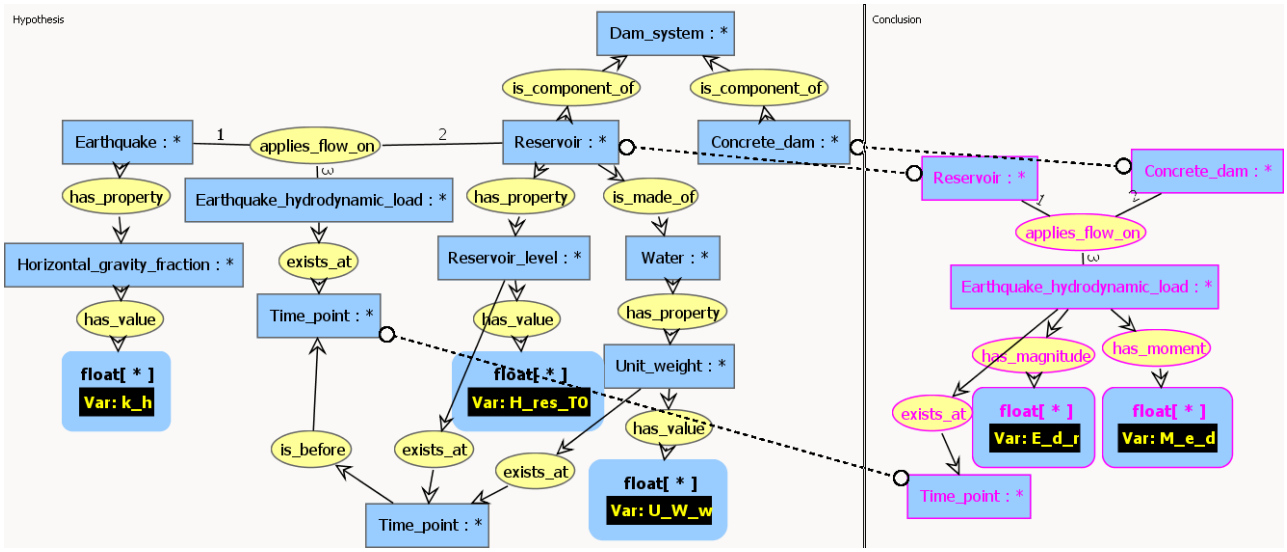

Figure 5.23. Rule to compute the hydrodynamic load and its moment at base

Rule | Associated script

```
1  void after()
2  {
3      float value1 = 0.555 * k_h.getValue() * U_W_w.getValue() * Math.pow(H_res_T0.getValue(),2.0);
4      float value2 = 0.424 * value1 * H_res_T0.getValue();
5
6      E_d_r.setValue(value1);
7      M_e_d.setValue(value2);
8  }
```

Figure 5.24. Script to compute the hydrodynamic load and its moment at base

Vertical earthquake load E_v

The vertical inertia load of the foundation due to the vertical acceleration (α_v) exert a load into the dam. The vertical earthquake load E_v, given by the equation:

$$E_v = \frac{W_c}{g}\alpha_v$$

where, E_v : Vertical earthquake load (kN)

g: Gravity acceleration = 9.81m/s^2

W_c: Self-weight load of the dam (kN)

α_v : Vertical acceleration

$$\alpha_v = k_v * g$$

$$\Rightarrow E_v = \frac{W_c}{g} \quad k_v\, g = W_c * k_v$$

where, k_v : is the fraction of gravity adopted for vertical acceleration, such as 0.1 or 0.2, etc.

The Moment of vertical earthquake load about toe is then:

$$M_{e_v} = (-)\, M_{w_c} * k_v$$

where,

M_{e_v}: Moment of vertical earthquake load about the toe of the dam

M_{w_c}: moment of self-weight load about the toe of the dam

k_v: is the fraction of gravity adopted for vertical acceleration, such as 0.1 or 0.2, etc.

The rules to calculate the vertical earthquake load and its moment are exposed in Figures 5.25, 5.26, and 5.27.

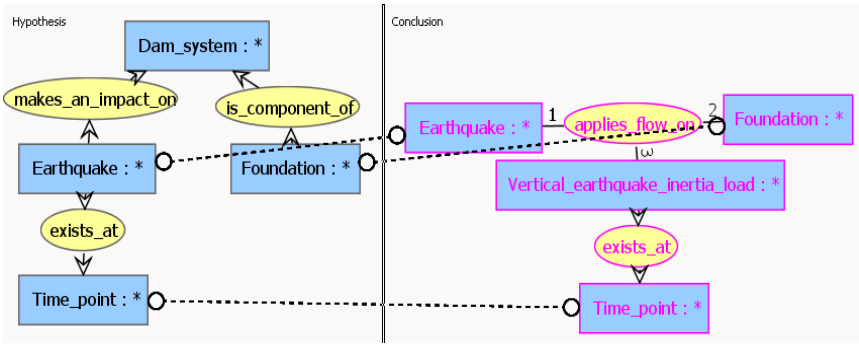

Figure 5.25. Impact of an earthquake on the foundation

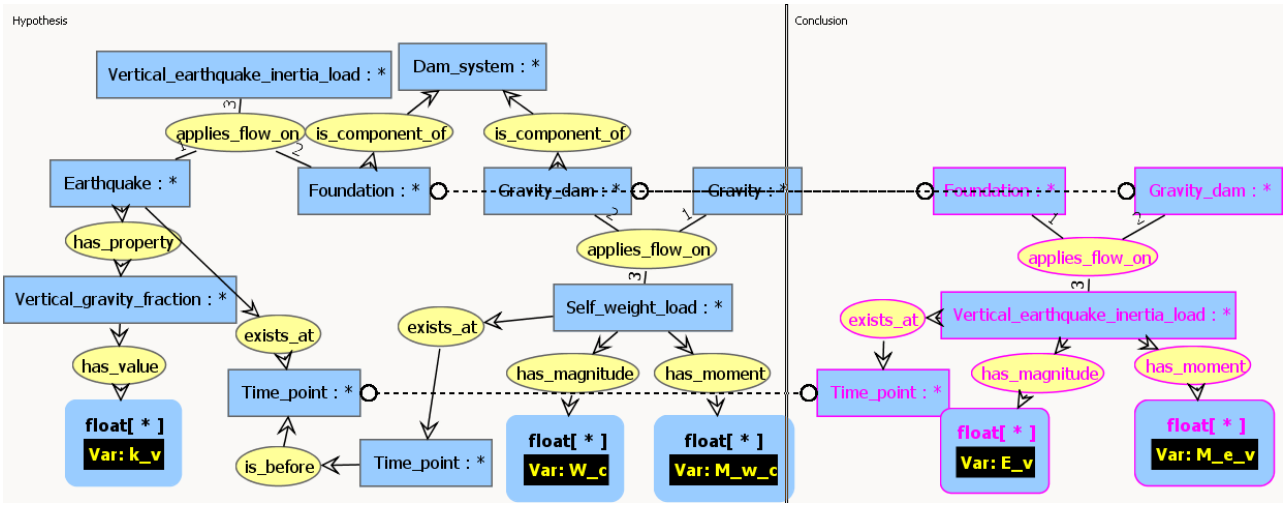

Figure 5.26. . Rule to compute the vertical earthquake load

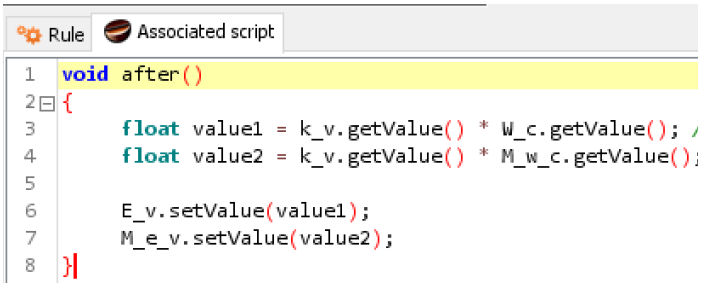

Figure 5.27. Script to compute the vertical earthquake load

Figure 5.25 and figure 5.26 describe the impact of the earthquake on the foundation and the impact of the foundation on the dam, respectively. These two rules can be explained as **if** *Earthquake* makes an impact on *Dam_system*, and *Foundation* is a component of *Dam_system*, **then** *Earthquake* applies *Vertical earthquake inertia load* on *Foundation*.

Next, if *Foundation* and *Gravity dam* are components of *Dam_system*, then *Foundation* applies *Vertical earthquake inertia load* on *Gravity _dam*. Figure 5.27 exposes the associated script.

Combination of the resulting loads and moments applying to the gravity dam at T1

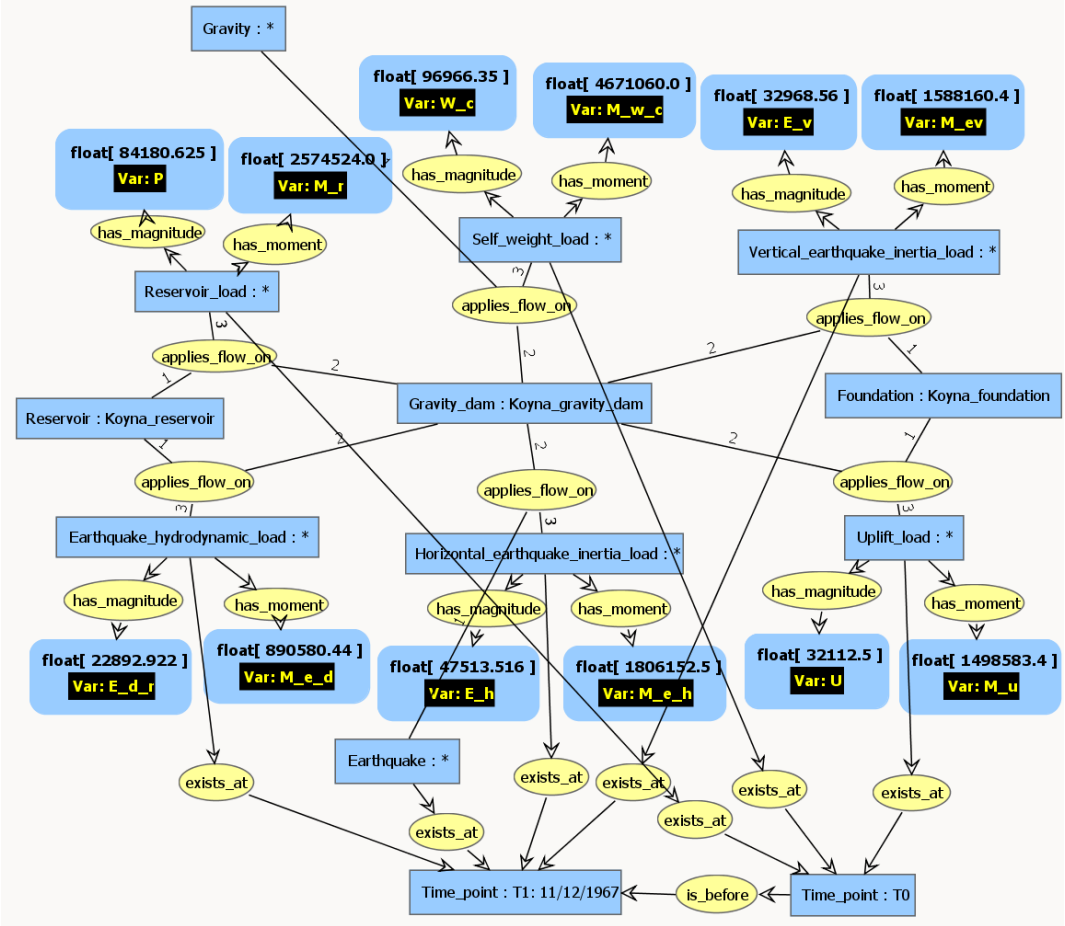

Figure 5.28. Loads affecting the Koyna dam

Figure 5.28 shows a combination of the resulting loads and moments applying to the gravity dam. The loads include:

- Loads which are interactions within the dam system at T0: reservoir load, self-weight load of gravity dam, and up-lift load of foundation;

- Loads are the impacts of the earthquake on the components at T1: hydrodynamic earthquake load, horizontal earthquake load, and vertical earthquake load.

Tension

Under this loading condition, vertical stress will be produced at the base. If the vertical stress is negative, tension will be produced in the dam, and materials may finally crack. Tension cracks reduce the effective width of the dam base, thus increase p_{max} at the toe. Simultaneously, due to crack formation, the uplift load increases, and the net effective downward load reduces. Therefore, the resultant will shift more towards the toe and further lengthening the crack due to further tension development. Finally, it may lead to the failure

of the toe by direct compression. Hence, a tension crack leads to the structure's failure by producing excessive compressive stresses (Garg, 2005).

The vertical direct stress distribution at the base, p, is given by the equation:

p = Direct stress + Bending stress

$$p_{\frac{max}{min}} = \frac{\sum V}{B}\left[1 \pm \frac{6e}{B}\right]$$

where, e: Eccentricity of the resultant load from the centre of the base

ΣV: Total vertical load

B: Base width

$$e = \frac{B}{2} - \underline{x}$$

where $\underline{x}$ is distance from the resultant load to the toe; it determines the location of the resultant load.

$$\underline{x} = \frac{\sum M}{\sum V}$$

where,

ΣM: The algebraic sum of the moments of all loads about the toe.

ΣV: The algebraic sum of all the vertical loads acting on the dam.

The maximum stres, i.e., p_{max} will be produced on the end which is nearer to the resultant load. When the reservoir is full, the resultant load is nearer the toe and hence p_{max} will be used for calculating vertical stress at the toe and p_{min} will be used for calculating vertical stress at the heel. If p_{min} comes out to be negative, tension shall be produced at the heel.

The vertical stress at the heel is

$$p_{\min} = \frac{\sum V}{B}\left[1 - \frac{6e}{B}\right]$$

The rule to calculate the vertical stress is given in Figure 5.29 and 5.30.

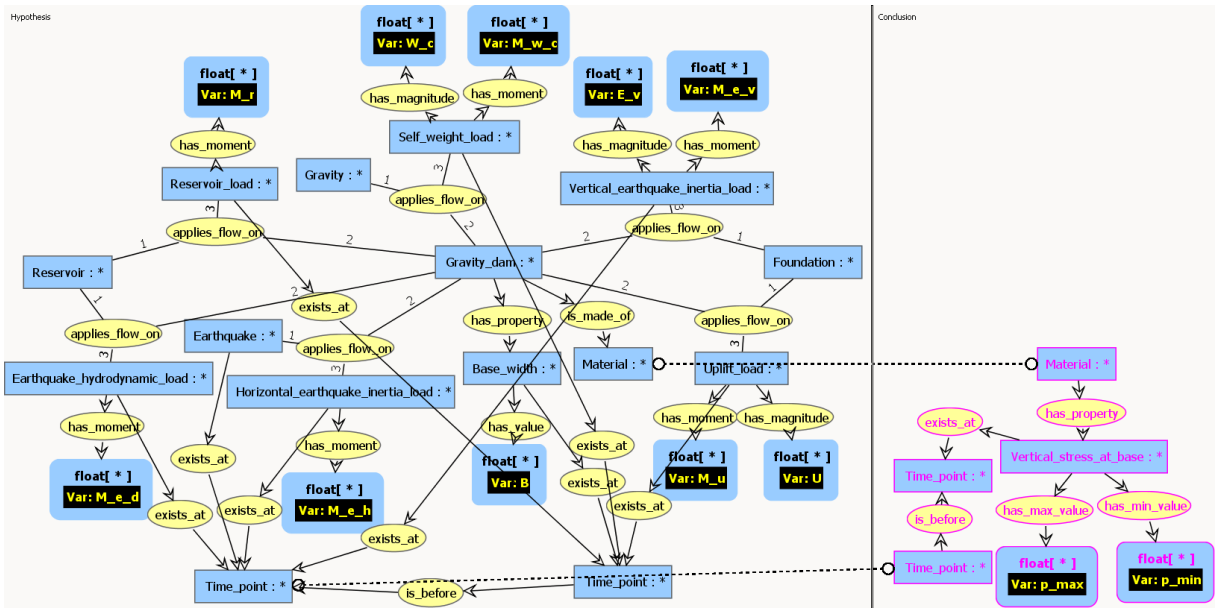

Figure 5.29. Rule to calculate vertical stress

Rule | Associated script

```
1  void after()
2  {
3      float M = M_w_c.getValue() - M_r.getValue() - M_e_d.getValue() - M_u.getValue() - M_e_v.getValue() - M_e_h.getValue();
4      float V = W_c.getValue()- U.getValue()-E_v.getValue();
5      float x = M/V;
6      float e = (B.getValue()/2)-x;
7
8      p_max.setValue(V/B.getValue()*(1+6*e/B.getValue()));
9      p_min.setValue(V/B.getValue()*(1-6*e/B.getValue()));
10 }
```

Figure 5.30. Script of rule calculating vertical stress

Figure 5.29 shows a rule to calculate the vertical stress at the base. The rule graph can be expressed as **if** *Reservoir* and *Foundation* apply the vertical loads to *Gravity_dam*, then *Vertical stress at the base* will be produced. The time point of the vertical stress is after the time point of the earthquake. Figure 5.30 exposes the associated script.

Principal stress at the heel

The vertical stress intensity, p_{max} or p_{min}, is not the maximum direct stress produced anywhere in the dam. The maximum normal stress will, in fact, be the major principal stress that will be generated on the major principal plane.

The principal stress at the heel is:

$$\sigma = p_{min}.sec_{\alpha}^{2} - (p + p_e)tan^{2}\alpha$$

where,

p: water pressure at base = $\gamma_w . H_{res}$

p_e: hydrodynamic pressure at base = $C_m k_h \gamma_w . H_{res}$

where C_m = maximum value of pressure co-efficient for a given constant slope = $0.735\left(\frac{90-\alpha}{90^o}\right)$; where α is the angle in degrees, which the upstream face of the dam makes with the vertical.

k_h: fraction of gravity adopted for horizontal acceleration

γ_w: unit weight of water

The rule to calculate the principal stress at the heel is exposed in figure 5.31 and 5.32.

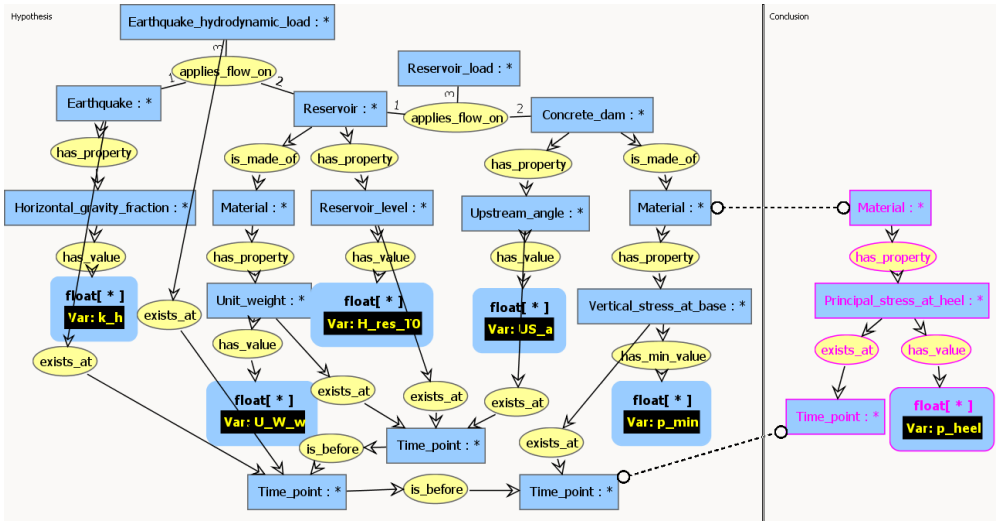

Figure 5.31. Rule to calculate the principal stress at the heel

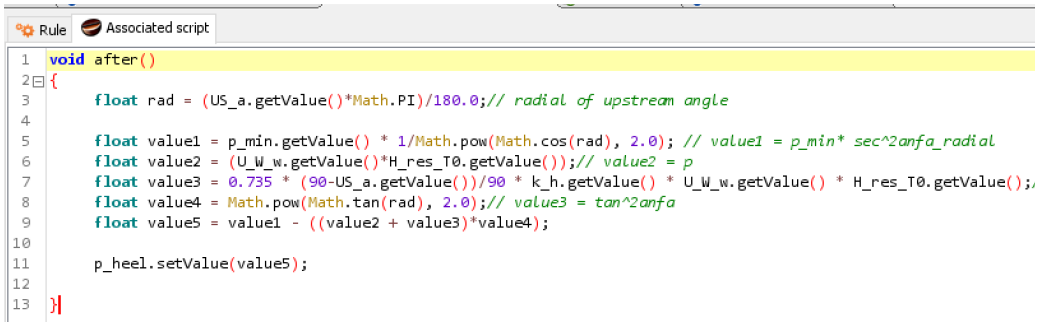

Figure 5.32. Script to calculate the principal stress at heel

The rule graph in Figure 5.31 computes the principal stress at the heel of the concrete dam. It can be explained as **if** *Earthquake* applies *Earthquake hydrodynamic load* on *Reservoir*, and *Reservoir* applies *Reservoir load* on *Concrete_dam*, **then** *Principal stress* will be produced at the heel of the dam. Figure 5.32 exposed the associated script.

If principal stress at the heel exceeds the tensile strength of the dam material, this material may finally crack.

5.2.3.5. Performances of the concrete dam at T2

Under the impacts of the earthquake and interactions within the system, a new performance of the dam will be produced. The new performance is evaluated by performance parameters. A performance parameter has two values:

- Measured level value: the value indicates the actual value of the performance parameter at the time considered.
- Expected level value: the value indicates the expected value that a component needs to perform its function.

Comparing these two values will let us know the performance indicator, which is an indicator identifying the state of the component's performance.

Therefore, determining a new performance includes two steps:

- Computing the measured level value of a performance parameter

- Determining the indicator value of the new performance

These two steps correspond with two rules to calculate the measured level value and the performance indicator.

The new performance of the Koyna dam is evaluated by a performance parameter that is the factor of safety against tension crack (FSC). The FSC can be computed by:

$$\text{FSC} = \frac{\text{Principal stress at heel}}{\text{Tensile strength}}$$

The first rule to calculate the measured level value of the FSC (Factor of safety against tension cracks) is exposed in figures 5.33 and 5.34. This rule also introduces a new performance to perform the function of *Resisting tension crack* at the time point *T2*.

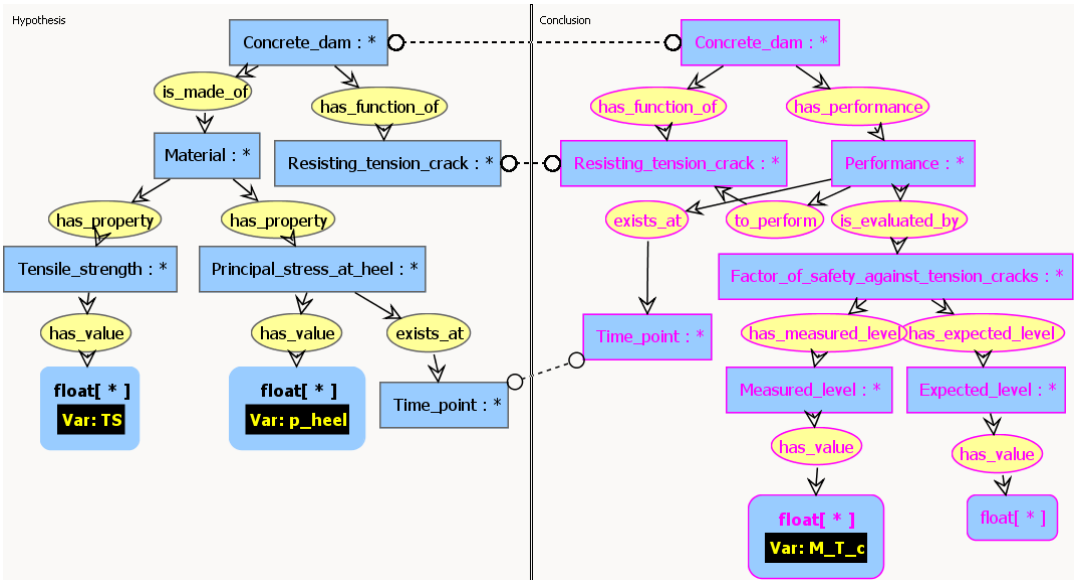

Figure 5.33. Rule to calculate the measured level of FSC

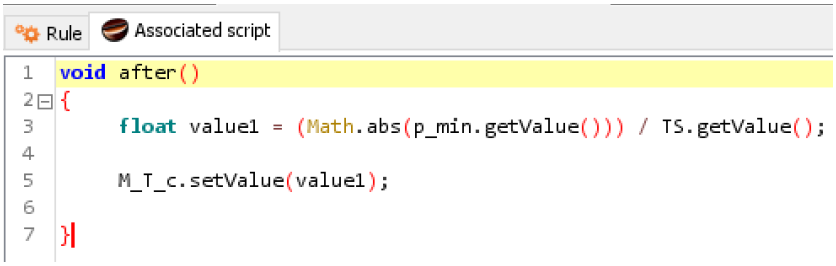

Figure 5.34. Script of rule calculating measured level of FSC

The rule graph (Figure 5.33) shows the rule relating to the computation of the new performance to perform the function of *Resisting tension crack*. The graph can be explained in the sentence as at the time point T2, **if** *Concrete dam* is made of *Material* with *Tensile strength* and *Principal stress at heel,* and it has a function of *Resisting tensile crack*, **then** *Concrete_dam* has *Performance* which is evaluated by *Factor of safety against tension cracks*. The factor of safety against tension cracks has two levels: *Measured level* and *Expected level*. The coref relation between two concepts *Resisting tension cracks* shows that with one *Resisting tension cracks* function, the dam can have different performances created at different time points to perform it. Figure 5.34 exposes the associated script

The second rule is to determine the new performance indicator value after the dam achieves the measured level value of the performance parameter. Figure 5.35 shows a rule identifying the new performance of the dam to resist tension crack.

If $p_{min} < 0$ and FSC > 1: the dam cracks.

If $p_{min} > 0$ and FSC < 1: no crack takes place.

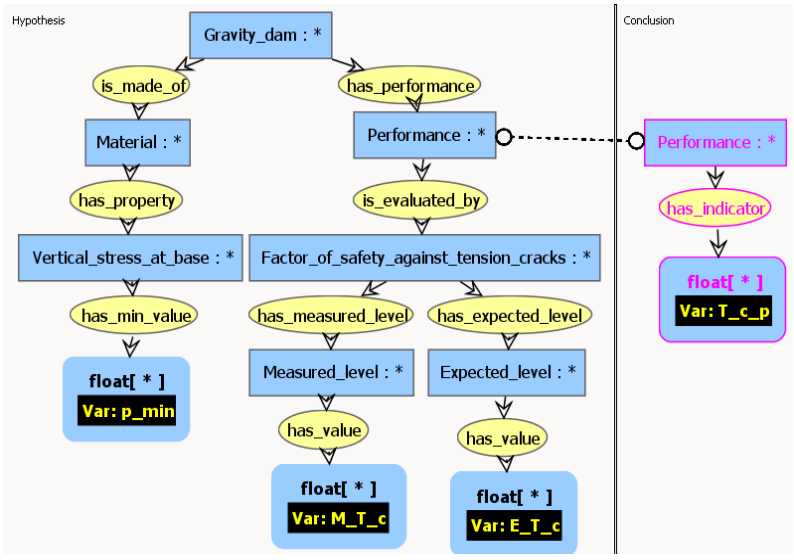

Figure 5.35. Rule calculating the indicator of the new performance of the dam

Rule | Associated script

```
1  void after()
2  {
3      if ( (p_min.getValue() < 0) && (M_T_c.getValue() > E_T_c.getValue()) ) {
4          T_c_p.setValue(0);
5      }
6      else {
7          T_c_p.setValue(1);
8      }
9  }
```

Figure 5.36. Script of the rule calculating the indicator of the new performance

The rule graph (Figure 5.35) exposes the necessary factors to determine a new performance indicator. They are properties of concrete material and the factor of safety against tension crack. The rule graph can be expressed as **if** *Gravity_dam* is made of *Material* with *Vertical stress at base*, and the dam has *Performance,* which is evaluated by *Factor of safety against tension cracks*, **then** *Performance* has an indicator defined by the variable *T_c_p*. Figure 5.36 exposes the associated script.

The resulting graph is exposed in Figure 5.37. It displays the new performance of the dam at T2.

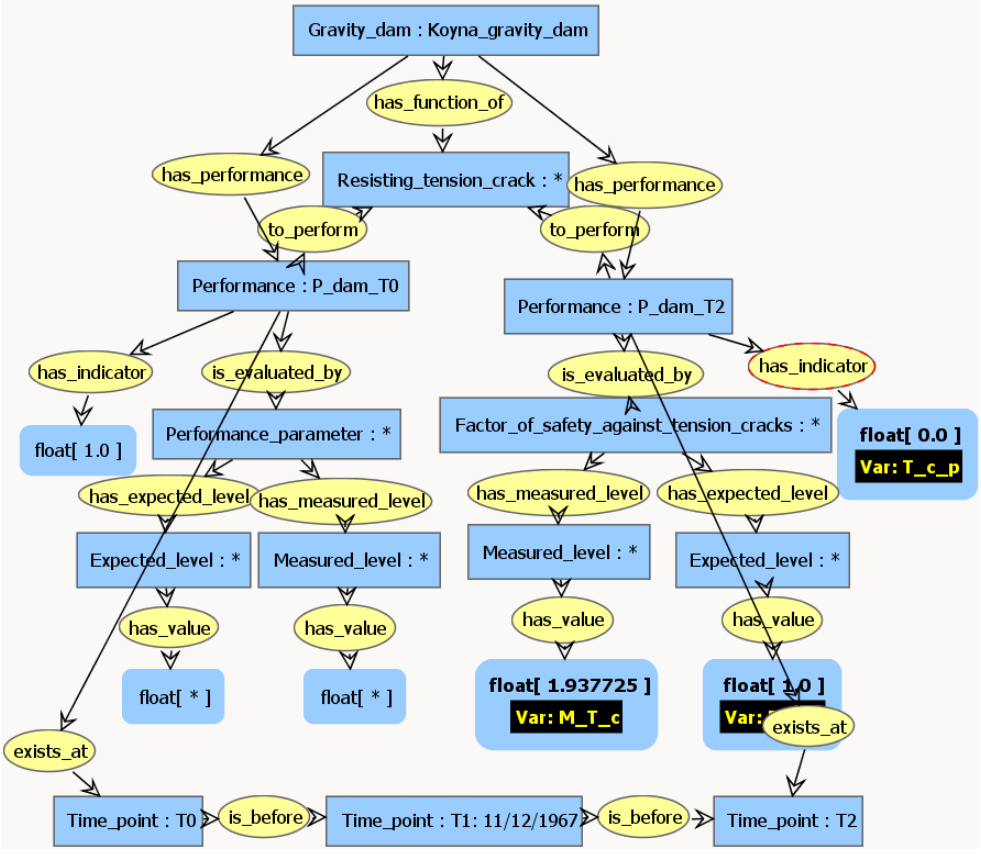

Figure 5.37. The performances of the Koyna dam

In order to make it easier to catch the evolution in the performances, the performance at T0 is also displayed. At the time point T0, the performance indicator is 1 (i.e., satisfied), and at the time point T2, this indicator changes to 0 (i.e., not satisfied, inducing a failure). The graph also shows the sequence relation between T0, T1, and T2.

5.2.3.6. Performance of the Koyna dam system at T2

The performance of a system is computed from the performance of its components. If the performance of one component of the system is not satisfied, then the performance of its system is not satisfied. In the case of the Koyna dam, the dam system's failure is produced by the Koyna dam's failure.

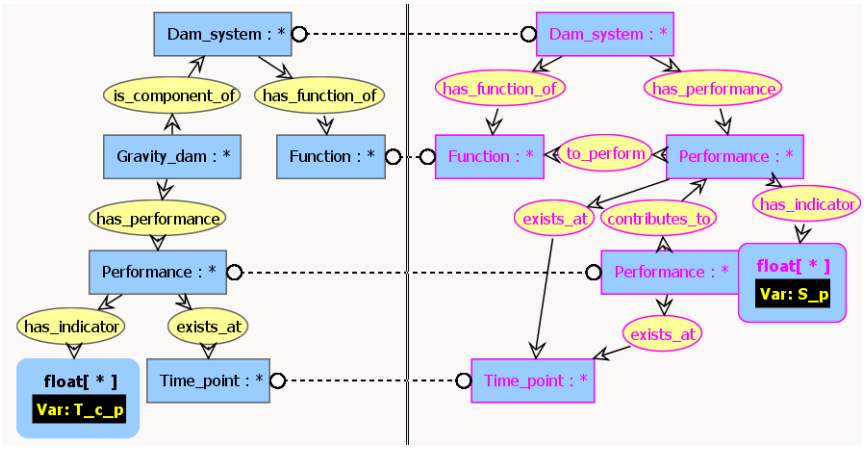

Figure 5.38. Rule to calculate the new performance of a dam system

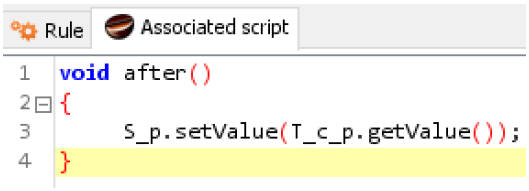

Figure 5.39. Script to calculate the new performance of a dam system

Figure 5.38 shows a rule computing the performance of the dam system based on the performance of the dam. The rule can be explained as **if** *Gravity_dam* is a component of *Dam_system*, and *Gravity_dam* has *Performance* at a time point, then *Dam_system* has a new *Performance*, which is contributed by *Performance* of the dam. The coref relation between two concepts *Function* shows that with one function, the dam system can have different performances created at different time points to perform it. Figure 5.39 exposes the associated script.

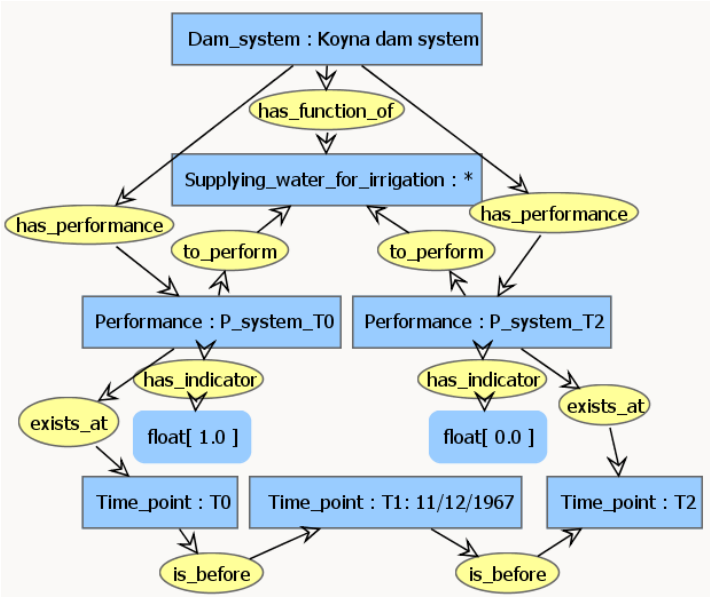

Figure 5.40. The resulting graph of the new performance of the Koyna dam system

The resulting graph (Figure 5.40) shows two Koyna dam system performances at two time points: T0 and T2. It can be seen that the capacity of the Koyna dam system to perform its function changes from the value of 1 (i.e., satisfied) at T0 to the value of 0 (i.e., not satisfied) at T2.

5.2.4. Failure process

The failure process of the Koyna dam system is described by three snapshots from the time point T0 to T2. Combining the three snapshots provides an overview of the failure's progression in a sequence of time.

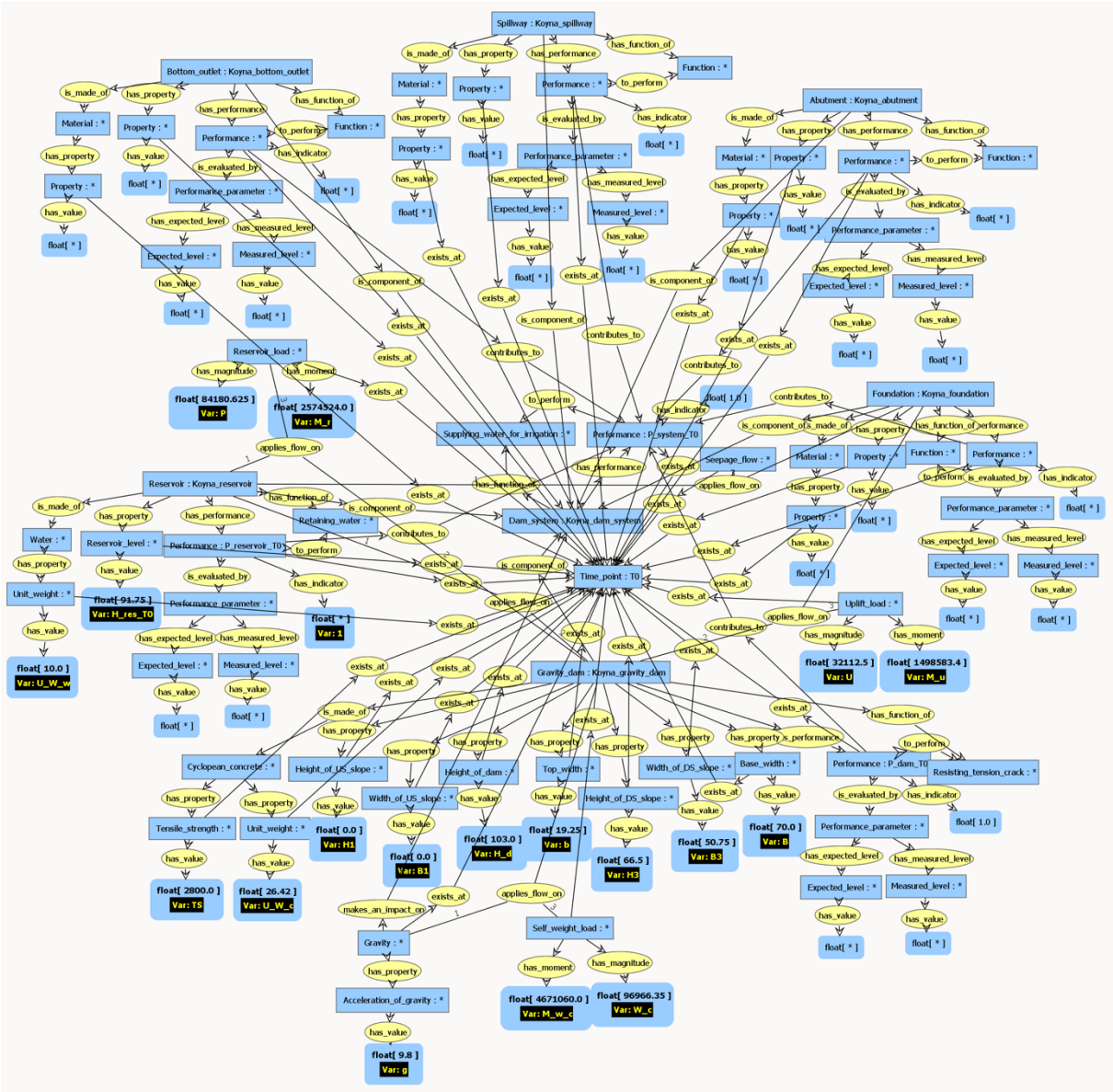

Figure 5.41. Snapshot at T0 of the Koyna failure

Figure 5.41 shows the snapshot at T0, the time before the earthquake. This snapshot describes the system's structure, including typical components of the system: gravity dam, reservoir, foundation, spillway, bottom outlet, and abutment, and relations connecting the concept types. At T0, there is the impact of gravity. The graph illustrates the interactions between the reservoir, the dam, and the foundation, which are the reservoir load, self-weight load, and uplift load, respectively. The concepts that can change their values over time are connected with *Time_point: T0*. At T0, the performance of the reservoir and the gravity dam are assumed as satisfied, and the performance indicator is for value 1.

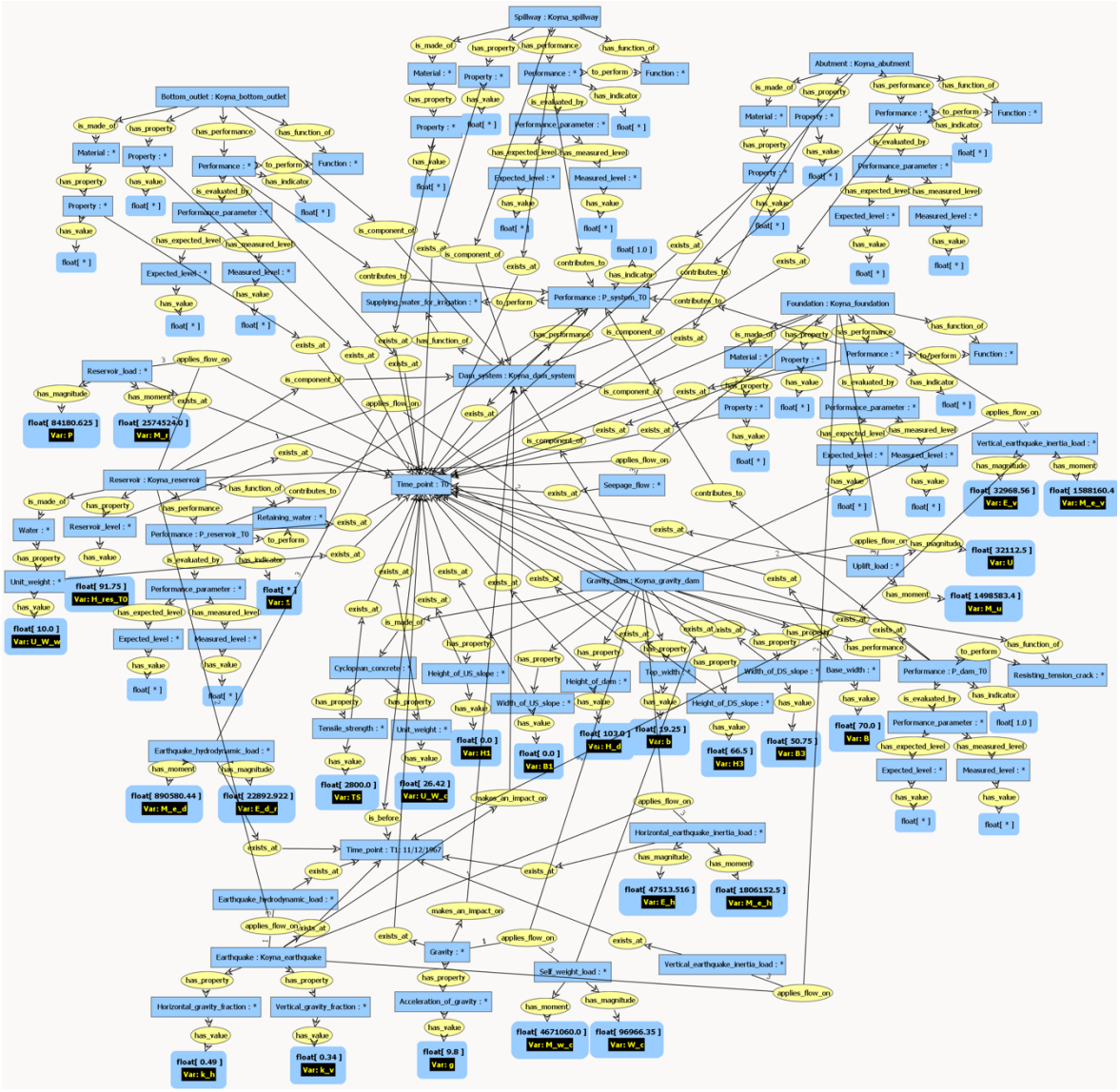

Figure 5.42. Snapshot of the Koyna dam failure at T1

Figure 5.42 shows the snapshot at T1 with the appearance of the Koyna earthquake. The impact of the earthquake on the system is described by the relation *makes_an_impact_on*. Two time points T0 and T1 are connected by the relation *is_before*. The interactive flows due to the earthquake are earthquake hydrodynamic load, horizontal earthquake inertia load, and vertical earthquake load. These interactions create different effects in the system: the earthquake hydrodynamic load that the reservoir applies on the dam and vertical earthquake load from the foundation to the dam. These interactions combine with the interactions at T0 create a combination load exerting the dam.

Figure 5.43 shows the snapshot of the failure at time point T2, which is the time after the earthquake. Under the impact of a combination of interactions, vertical stress and principal stress appear within the dam. The excessiveness of the principal stress compared to the strength of the concrete induces cracks on the dam faces.

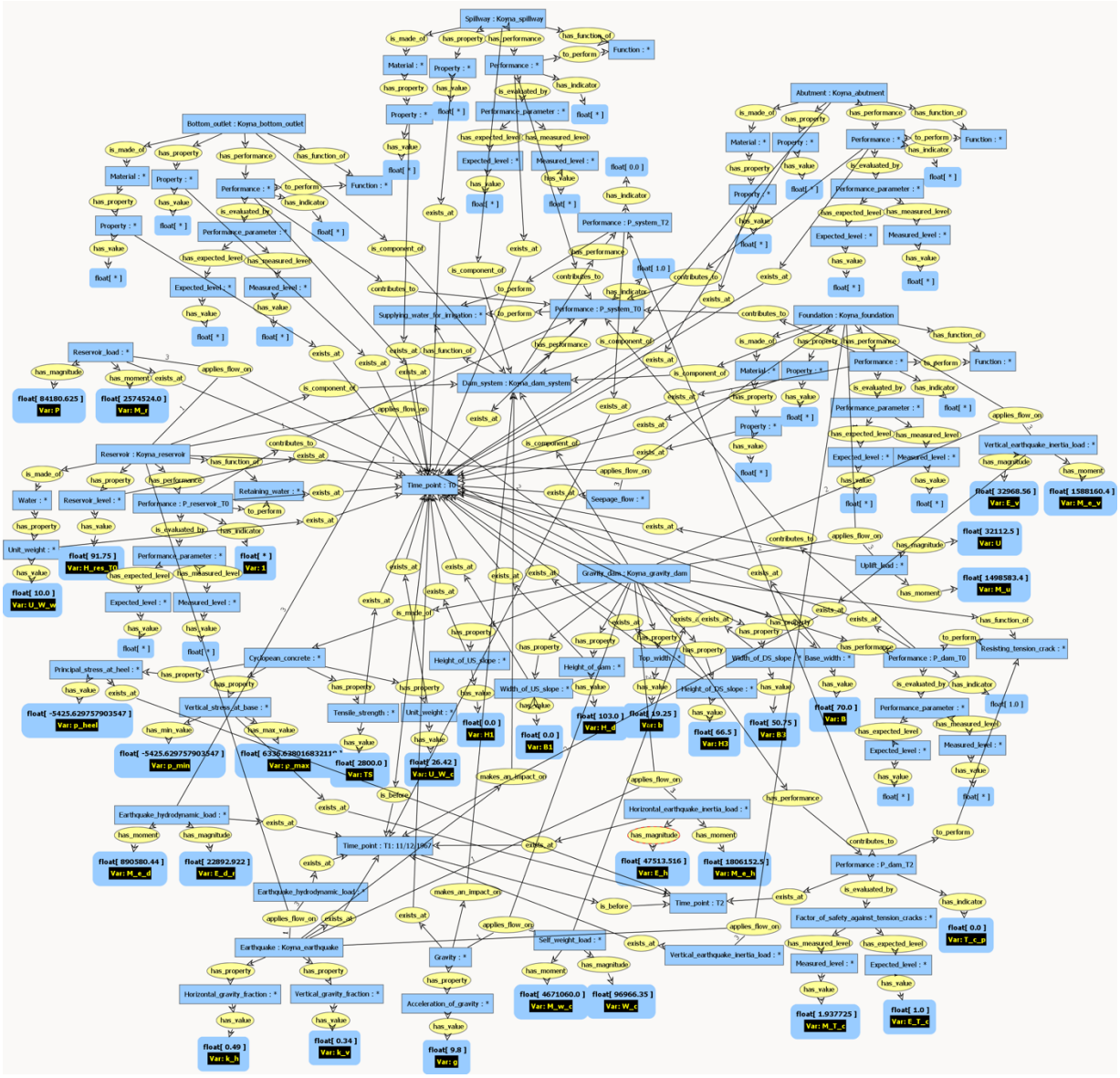

Figure 5.43. Snapshot of the Koyna dam failure at T2

In conclusion, the three snapshots provide an overview of the failure mechanism of the Koyna dam system. The first snapshot describes the state of the system before the earthquake occurs. The second snapshot shows the earthquake's occurrence and its impacts on the system, inducing different interactions in the system. The final snapshot shows the consequence of these interactions, which are the failure of the concrete dam.

5.3. Using the failure knowledge model

In the previous section, we present the instantiation of the failure model to a historic dam failure. The same process was performed regarding four other cases (Figure 5.44); the details of the modeling regarding these failures are provided in the appendix. These processes compose a first base of fact in the model.

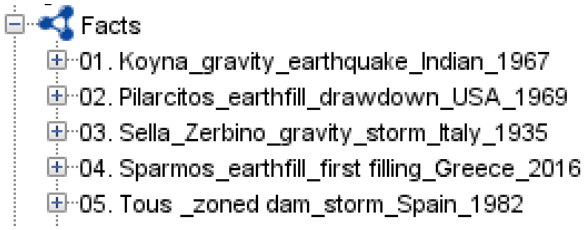

Figure 5.44. Database of dam system failure

This fact base can be used to acquire knowledge about the failure of the dam system, according to two objectives:

1. Similar request: to identify similar failure when a new failure occurs. The purpose is to find conditions or causes that can explain the failure based on similar facts (Breysse, Taillandier and Baudrit, 2018).

2. Inferring rules from facts: to propose failure processes in order to identify associated risk.

5.3.1. Similar request

In order to demonstrate the interest in searching for failure information from the previous similar cases, we will present three examples. They will illustrate how to acquire knowledge from past failures by the query-answer mechanism. Each case is analyzed to find possible causes or conditions contributing to the failure.

Request for *Gravity dam system – Earthquake – Crack*

With the CGs, the requests are expressed in a graphical format. Figure 5.45 shows an example of a request in the form of a graph. Figure 5.252 shows a request graph applied to a gravity dam system subjected to an earthquake. The system has components at risk, which are *Gravity dam* and *Reservoir.* The failure is identified by the function of *Resisting tension* crack that the performance needs to perform. The dam's state is identified by the performance indicator that has a value of 0.

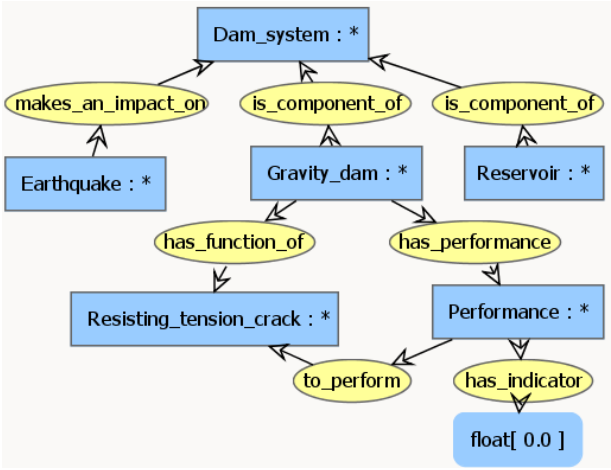

Figure 5.45. Request Graph for *Gravity dam – Earthquake – Crack*

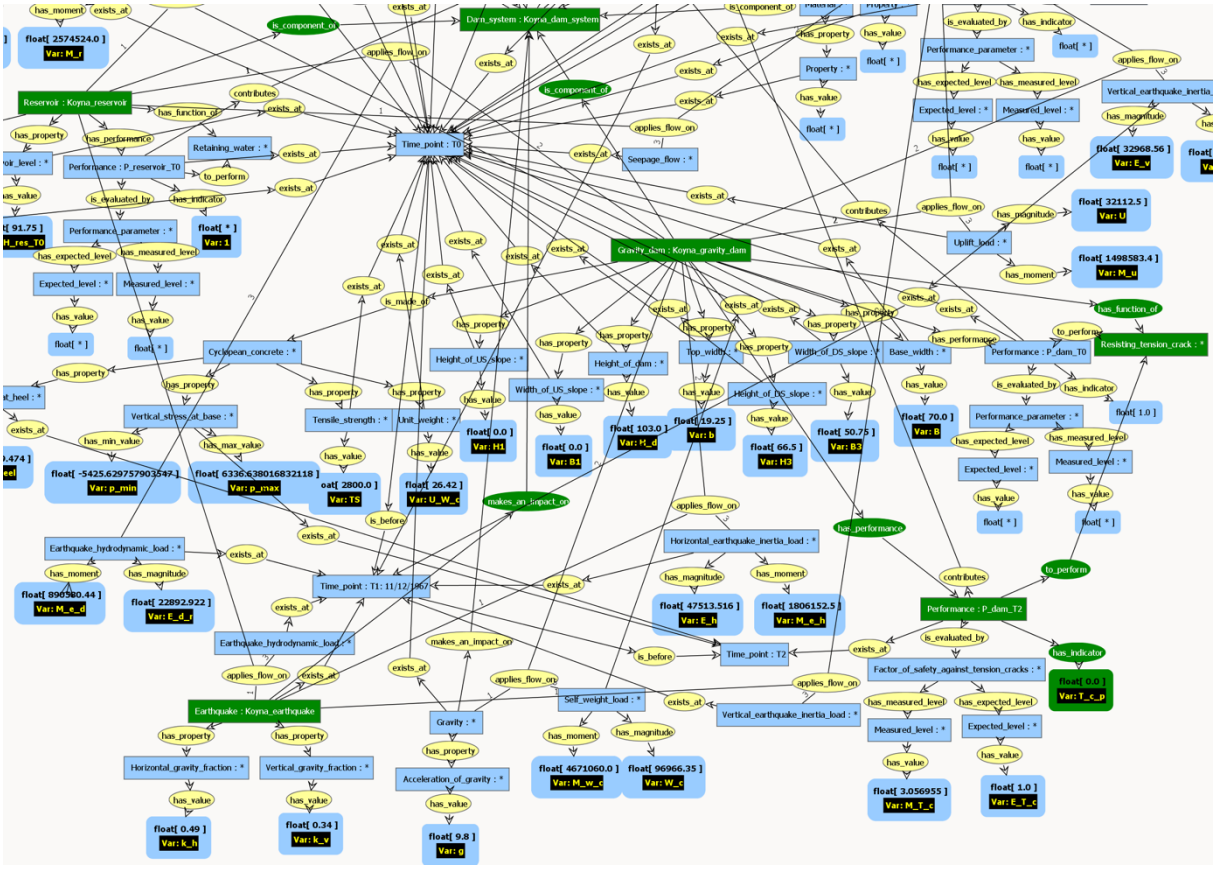

Figure 5.46. An answer to the query for *Gravity dam – Earthquake – Crack*

Figure 5.46 exposes an answer to this request. Elements of the query are highlighted in green. For this case, the only fact that corresponds to the request is the Koyna dam failure (see section 5.2 for the details).

Information collected from the Koyna failure instance identifies the conditions relating to the failure. The graph shows that the gravity dam's failure results from a combination of the impact of the earthquake on the system and interactions within the system. The interactions were generated by associating many factors: the magnitude of the earthquake, high level of the reservoir, mechanical properties of concrete, geometrical parameters of the

dam, and the foundation's structure. The combination of all these factors leads to serious damages to the dam in a short time.

Request for *Embankment dam system – First filling activity – Breach*

Figure 5.47 shows a request graph applied to an embankment dam system subjected to a first filling activity. The system has components at risk, which are *Embankment dam* and *Reservoir.* The function *Resisting breach* identifies the failure that the performance needs to perform. The dam's state is identified by the performance indicator with a value of *0*, which means "not satisfied".

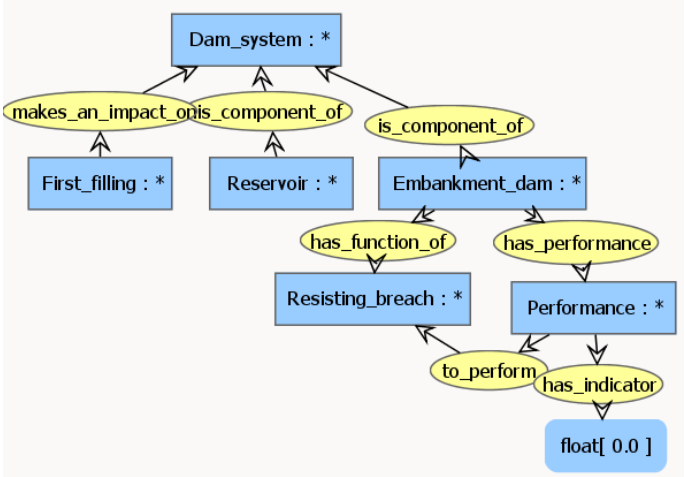

Figure 5.47. Graph request for *Embankment dam – First filling – Breach*

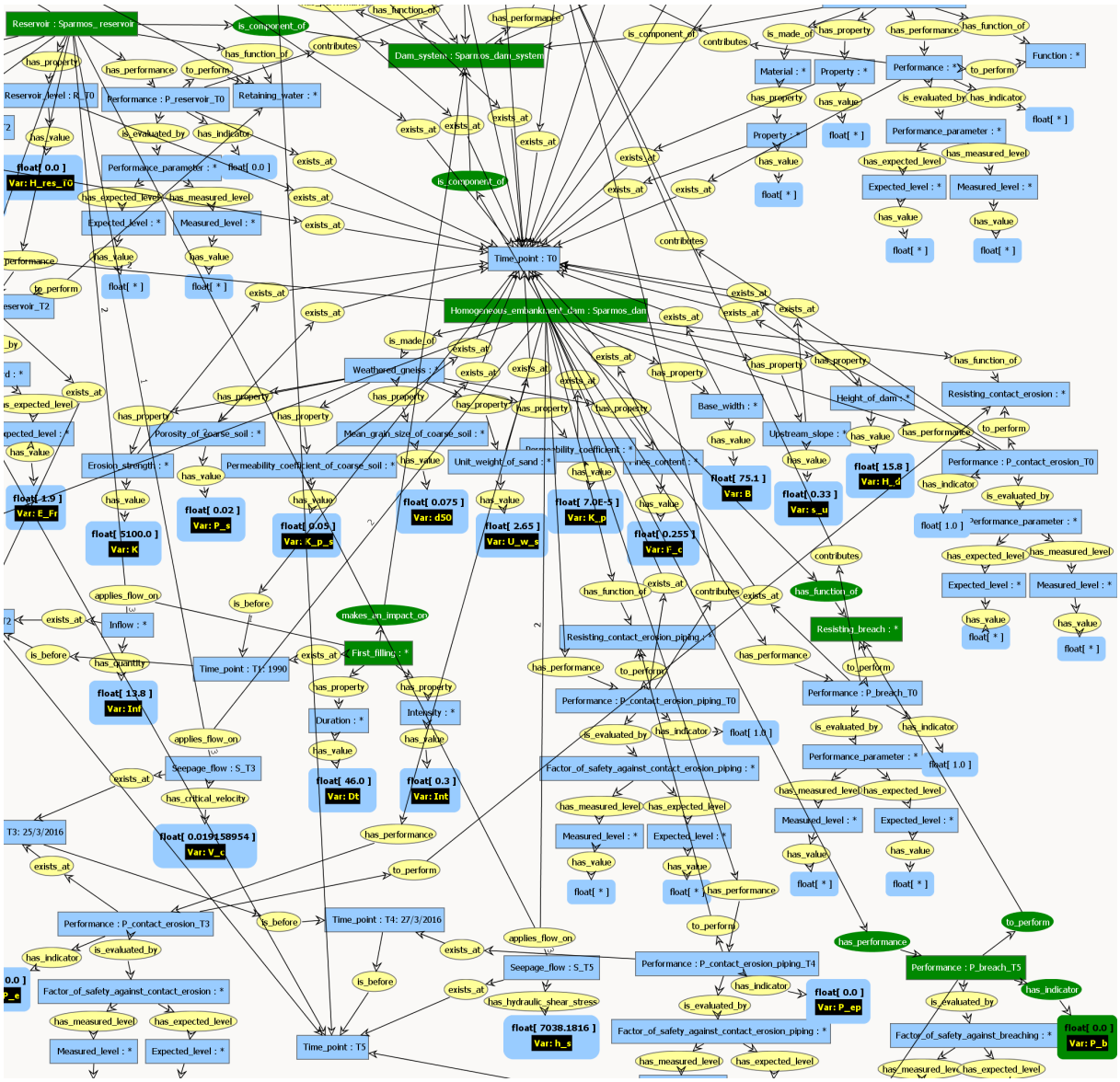

Figure 5.48. An answer to the query for *Embankment dam – First filling – Breach*

Figure 5.48 shows an answer to the query. The issue is to collect past cases with the characteristics common to the query: embankment dam, which the function *Resisting breach* is not satisfied during the first filling. In the fact base, only one case with these elements is referenced: the Sparmos failure (detailed in the appendix). Information collected from the Sparmos failure instance allows the user to identify examples of conditions relating to this kind of failure. It shows a combination of the impact of the first filling activity, the interaction between the reservoir and the dam, and the properties of the soil. It also presents the failure process from the seepage flow to erosion, the development of piping, and finally leading to the breach of the dam.

A failure process can be created by consecutive failures. For example, the failure process of the Sparmos dam is constituted from the erosion failure, then piping, and finally is a breach. Each failure in the failure process can be searched by a query.

Request for *Rock foundation – Heavy rain – External erosion*

The third example deals with a gravity dam system subjected to heavy rain, which causes external erosion (Figure 5.49).

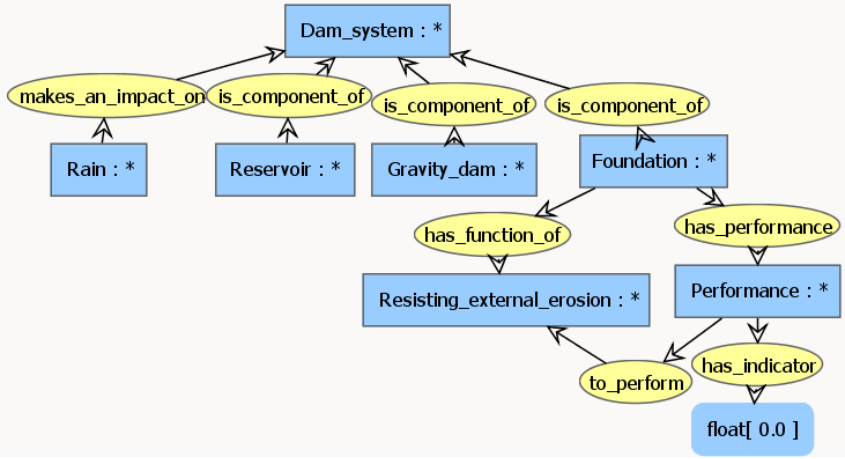

Figure 5.49. Graph request for *Rock foundation – Heavy rain – External erosion*

Figure 5.50 shows an answer to the query for rock foundation – heavy rain – external erosion based on the Sella Zerbino dam system failure. Information collected from the Sella Zerbino failure instance identifies the conditions which led to this: a combination of the impact of heavy rain, overflow of the reservoir, properties of the gravity dam, erosion strength of the bedrock. The failure process is triggered by the heavy rain, then the reservoir's overflow, and finally, erosion of the foundation.

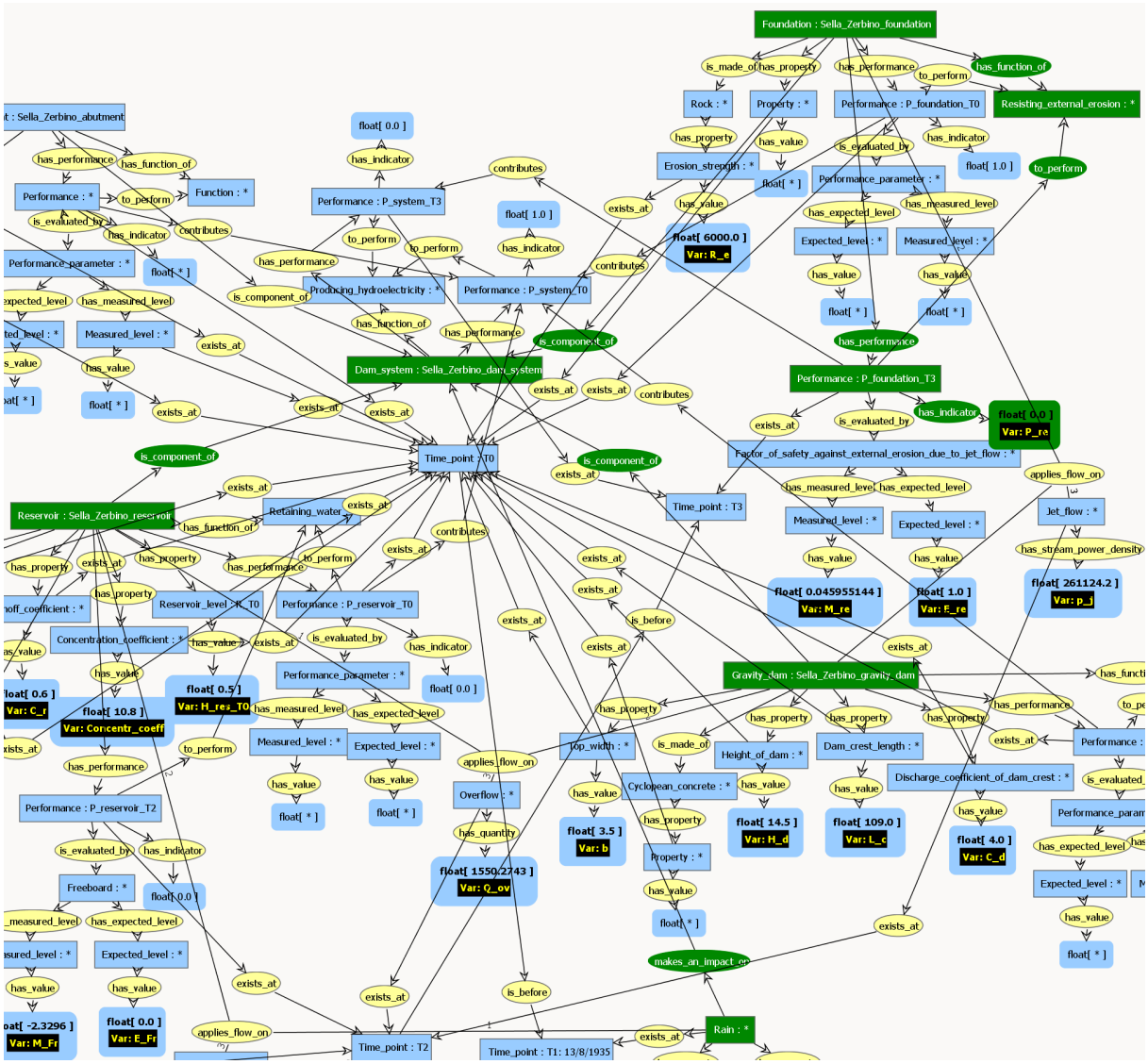

Figure 5.50. An answer to the query for *Rock foundation – Heavy rain – External erosion*

5.3.2. Inferring rules from facts

The database of failure can be used as a source to build new rules that can be used to identify failure processes. Considering these processes, associated risks can be predicted, and action plans can be prepared.

As an example, we present two rules built from the five failure instances of the fact base. They are also based on the homomorphism search provided by the CoGui solver. The hypothesis graph provides information about structures and external factors, and the conclusion graph shows possible failure scenarios.

Rule for *Gravity dam subjected to earthquake*

Figure 5.51 shows a rule applying for the case of a gravity dam system subjected to an earthquake. This rule is built from the Koyna failure instance.

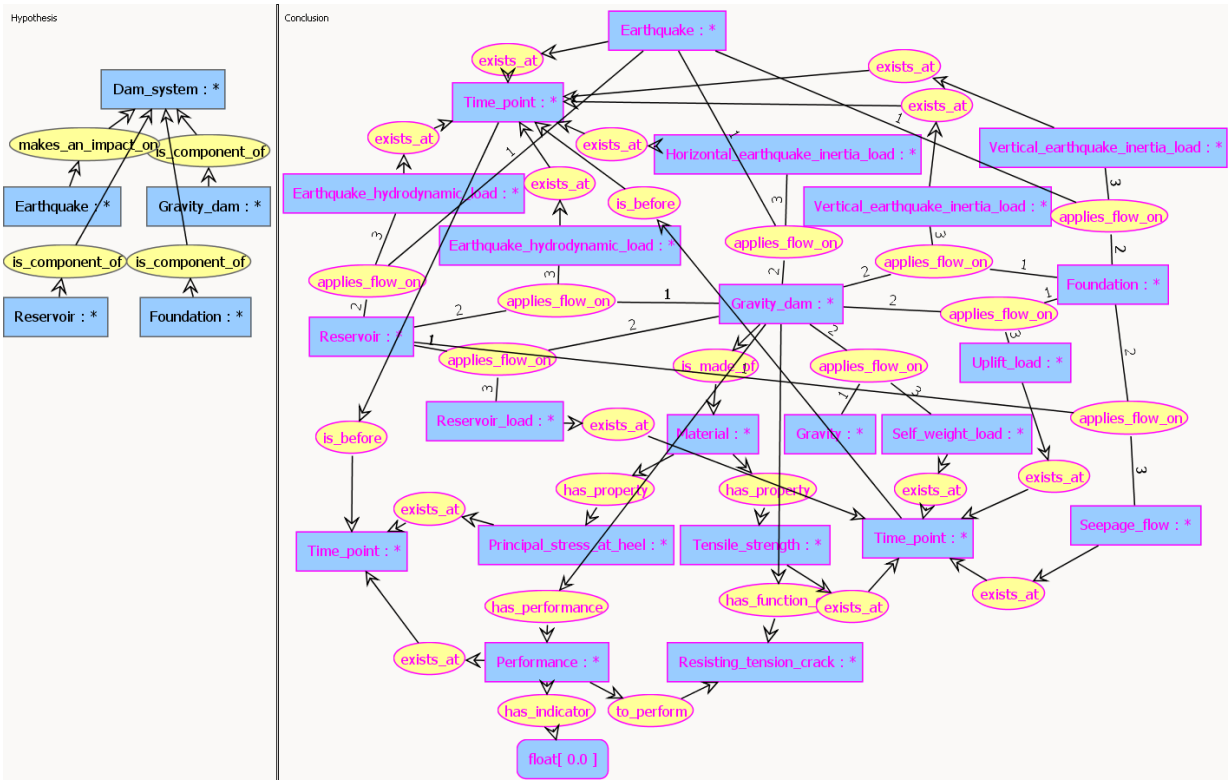

Figure 5.51. Rule for Gravity dam subjected to earthquake

The hypothesis graph includes concepts related to *Dam_system* components and an external factor (*Earthquake)*. The conclusion graph describes the failure process and identifies a possible failure. The process shows the impacts of the earthquake on the components: *Earthquake hydrodynamic load* on *Reservoir*, *Horizontal earthquake inertia load* on *Gravity dam*, *Vertical earthquake inertia load* on *Foundation*. Besides, the self-weight load that *Gravity* applies to the dam is also presented. Subsequently, the system's interactions are described, which are *Earthquake hydrodynamic load* and *Reservoir load* that *Reservoir* applies on *Gravity dam*, *Vertical earthquake inertia load,* and *Uplift load* that *Foundation* applies on the dam. Under these impacts, *Principal stress at heel* and *Tensile strength* of concrete are identified. These phenomena may lead to a failure of the dam. Thus, this rule can be used to build a potential scenario of failure; it could be a useful tool to perform a risk analysis.

For instance, figure 5.52 describes a result when applying the rule; by applying this rule, a new graph will be created, showing that when a gravity dam system may be the subject of an earthquake, the interactions between the earthquake and the system may induce cracks in the dam.

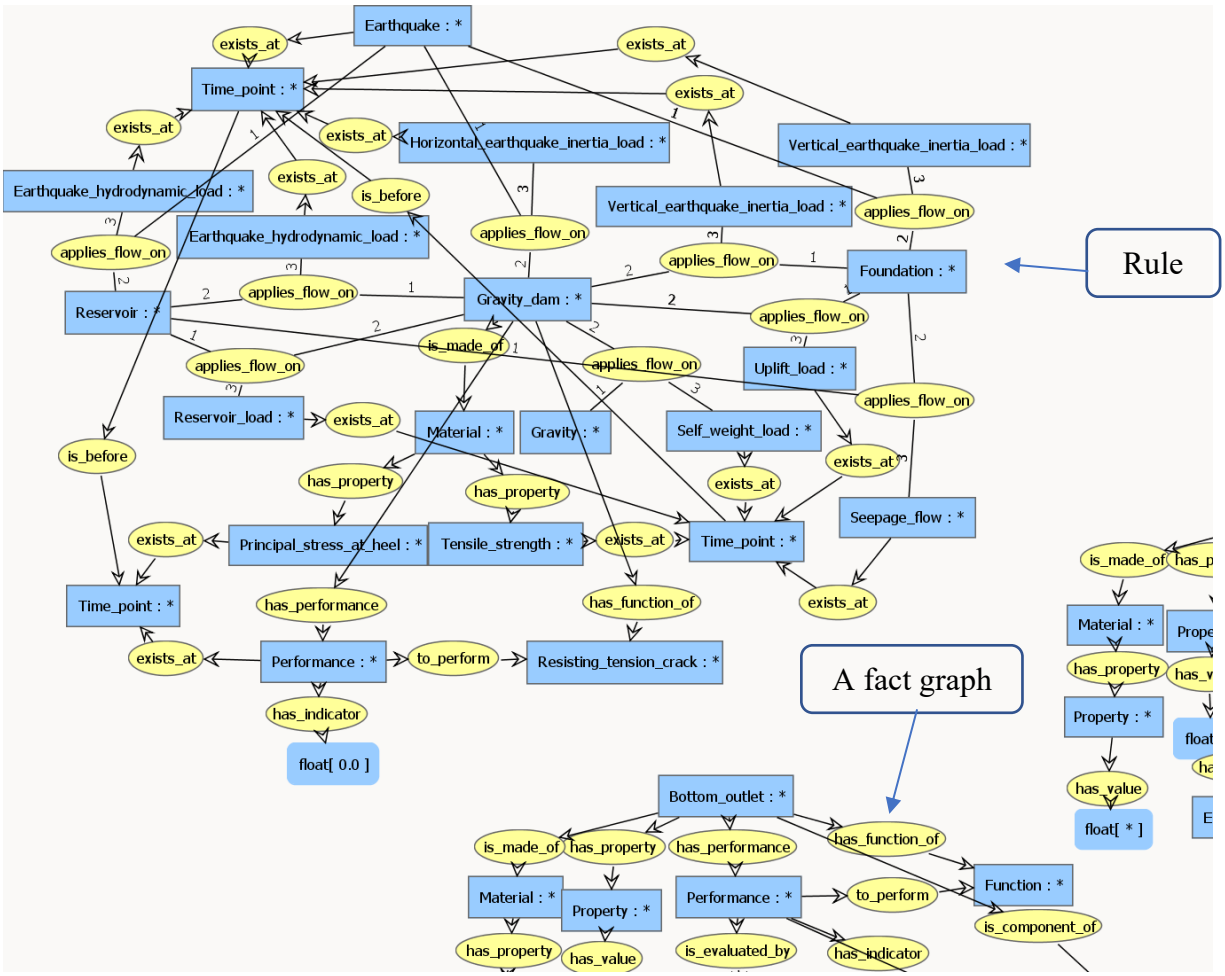

Figure 5.52. A result of the application of a rule for *Gravity dam subjected to earthquake*

Rule for *Homogeneous embankment dam subjected to Drawdown*

Figure 5.53 shows a rule applying for a case of a homogeneous embankment dam subjected to a drawdown activity. This rule is built from the Pilarcitos dam failure instance. The process shows the impacts of the drawdown on the reservoir (i.e., *Outflow),* which reduces the water level rapidly. The reduction of the water level has an impact on the balance of forces on the dam. It may lead to a combination of shear strength of the soil and P-u load that may lead to the sliding of the upstream shell.

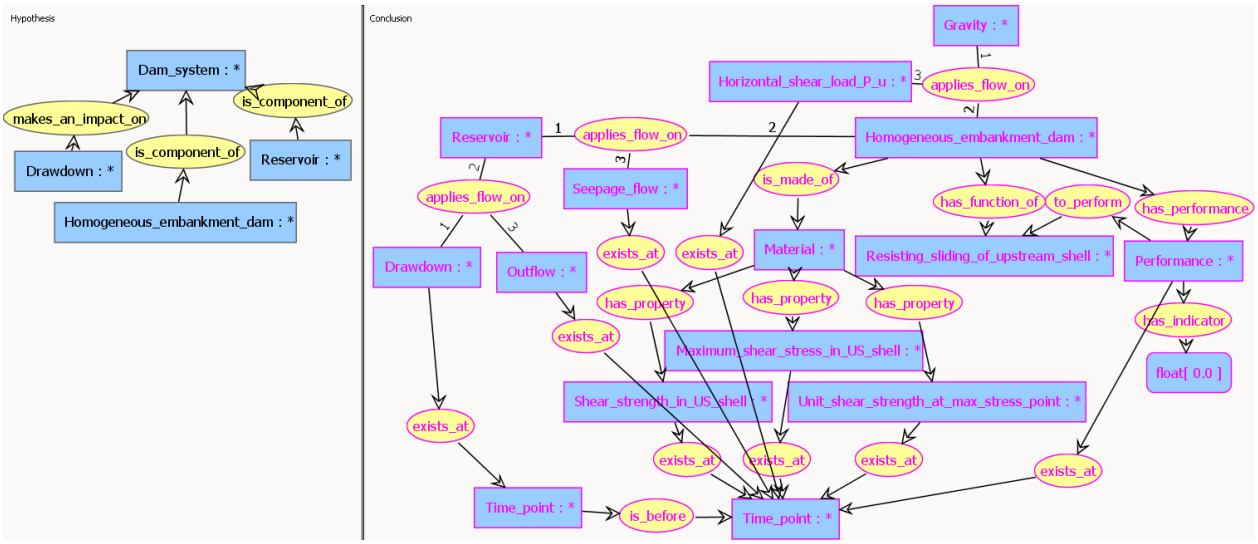

Figure 5.53. Rule for *Homogeneous embankment dam subjected to Drawdown*

Figure 5.54 describes a result of applying the rule for a *Homogeneous embankment dam subjected to Drawdown*. By applying this rule, a new graph will be created, showing what can happen when a homogeneous dam system is subjected to the drawdown activity. The associated risk is the sliding of the upstream shell.

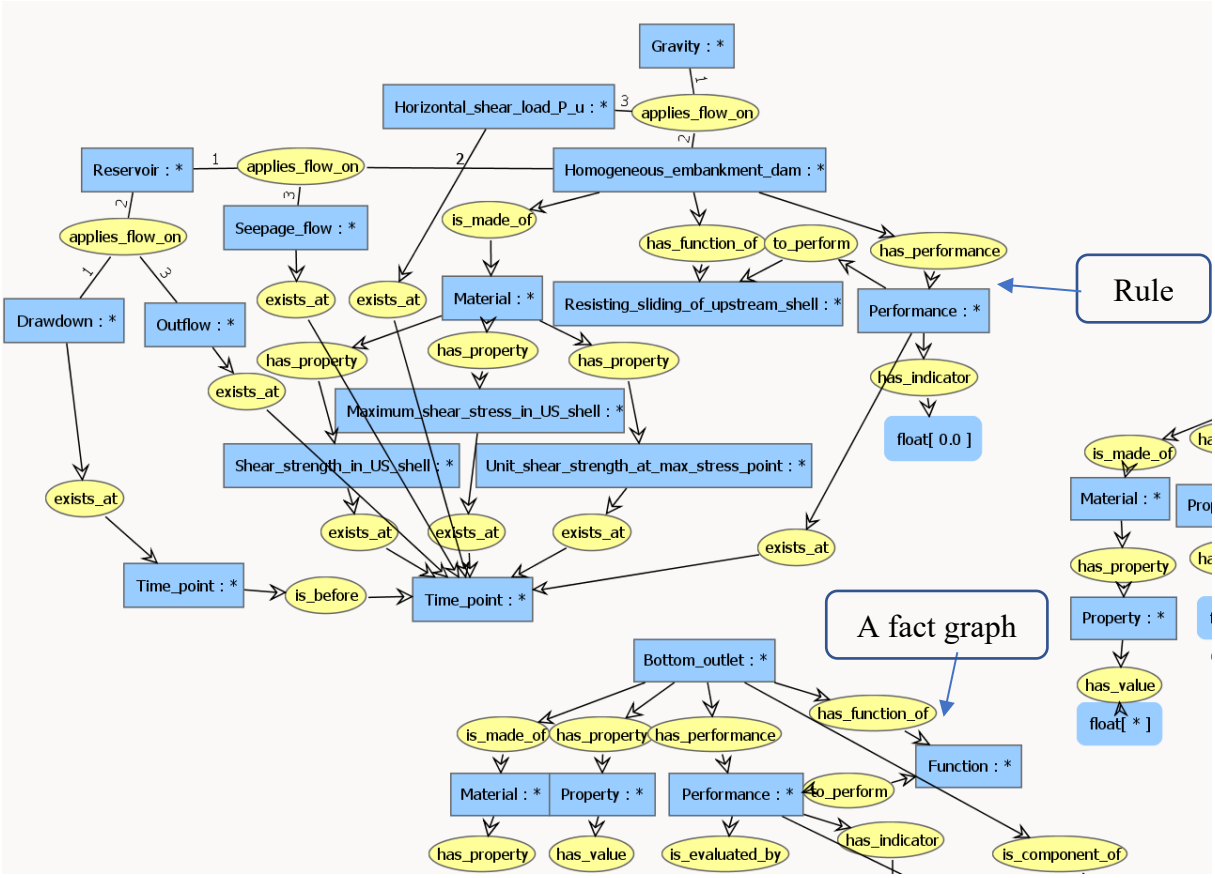

Figure 5.54. A result of the application of the rule for *Homogeneous embankment dam subjected to Drawdown*

5.4. Knowledge and Lesson learned from failures

The analysis of past failures can provide useful knowledge. For instance, each case from the fact base provides knowledge regarding some failure mechanisms and/or dam type. The failure of the Koyna dam system exposes how a failure may happen for gravity dam behavior under a catastrophic earthquake. Sliding failure of the Pilarcitos upstream shell presents a combination of horizontal shear load with a shear strength of soil in the dam due to a rapid drawdown activity and the absence of drains. In the Sella Zerbino dam case, a combination of the power stream of the jet flow and erosion strength of bedrock results in an external erosion of the foundation in the context of heavy rain and the lack of spillway and bottom outlet. Failure of the Sparmos dam began just during the first filling, whereas seepage occurred, causing a breach. In the Tous dam case, external erosion of the downstream shell results from the interactions of heavy rain and the inadequate capacity of the spillway and bottom outlet. The modeling of these failure cases allows enriching the knowledge base in order to provide new rules or to perform similarity requests. These two types of use of the fact base are really interesting regarding two objectives. The first objective is, facing a new dam failure to understand the causes of this failure (forensic investigation). For instance, if we consider an embankment dam that collapsed during the first filling, it is possible by a similarity request on the known elements to find past similar cases. Each of these past cases provides a scenario of failure that may correspond to our current case; at least, if none corresponds exactly, the past cases can enrich the reflection of the investigators. The second objective consists of analyzing, before a failure, the potential failure modes, and their consequences. The use of the rules deduced from the fact base can be very useful for this objective by proposing potential scenarios of failure. Furthermore, these failure scenarios can help the manager to propose action to prevent or mitigate failure. For example, the failure of the Pilarcitos dam and Sparmos dam demonstrated the necessity of the drainage system for the embankment dam.

Of course, the more the fact base is filled, and in particular, proposing a diversity of cases, the more interesting the use of this base will be, bringing more information. For example, by bringing more cases by similarity or by proposing several hypotheses of possible failures.

In addition, some other uses of the fact base may be considered. First of all, by imagining that many cases have been entered into the database, we could have a statistical return on failures. This would be very useful in the context of risk analysis to define the probability of failures; it would move from the qualitative logic of the model to possible quantitative use. It should be noted that the graphical structure of the model is particularly well suited to the propagation of uncertainties. Another use of the model and the fact base is for training and teaching purposes. By explaining the failure mechanisms, each fact of the fact base can be used to support teaching. For example, this can help to understand failure processes or the risks inherent in each activity. Reference can be made to work that has demonstrated the value of teaching based on case studies, notably in risk management teaching (Saleh and Pendley, 2012)

5.5. Conclusion

In this chapter, we presented an instantiation of the knowledge model to a case study. Through the archived results, it demonstrates the capacity of the model in describing a failure. The presented case study related to the Koyna dam failure in India shows the response of a concrete dam to an earthquake. Four other case studies are available in the appendix and demonstrate the capacity of the model to formalize different failure mechanisms for different types of the dam.

The instantiation of a new failure case requires a deep understanding of the failure process which occurred. It is firstly conducted with the analysis of the system and external factors in order to identify the structure of the system and its components. Subsequently, rules in the knowledge base are applied to construct the model, fastening the instantiation process. It is then necessary to formalize the failure at the different time points (e.g., before a hazard, during it, after it…). Each failure fact graph formalizes how conditions contribute to a failure and evolve over time, but a set of snapshots. Each snapshot shows the states of the system at a time point. The connection of the snapshot provides the process of failure.

The failure model instances from a database of failures can be used as a source to construct query graphs and inferring rules to acquire knowledge from failure. The request graphs can be used to identify similarities between past failure cases and a new one to find conditions or causes of similar facts. The inference rules from facts can be used to propose potential failure processes to identify associated risks. Knowledge acquired from failures can be used to diagnose causes relating to failure or predict risk. It is also valuable to make lessons in order to prevent failures from repeating in the future.

Conclusion and perspectives

Conclusion

Structural safety can be threatened by natural phenomena such as floods, rainfalls, earthquakes, or effects of human activities such as poor design, defects during construction and operation, and deterioration of materials. Structural failures can cause considerable losses in people, property, and the environment.

Forensic engineering is the application of engineering methods to deal with failure investigation. Its purpose is to determine and interpret causes of damage, or failure, of structure in order to draw lessons, prevent similar failure from repeating and improve structural performance in the built environment. However, this poses the problem of how the knowledge from these investigations is structured and shared. Indeed, the knowledge from the failure analysis is often not effectively communicated and used because the information collected from the failure investigation is not sufficiently structured.

In this context, this thesis proposes a generic failure knowledge model defining and describing structural systems' failure. The purpose is to formalize failures in order to capture knowledge and learn lessons from past failures. The model is based on conceptual graphs. It provides a structured vocabulary (concepts and relations) that allows formalizing a graph-based knowledge model. This model is able to simulate behaviors of the structural system under the impacts and produce new knowledge from a set of failure instances. In particular, the contributions of the proposed model as follow:

The first contribution of the model is to provide a generic model that can be applied to different kinds of structural systems. This model is based on:

+ A common vocabulary composed of the concepts and relations that provides basic knowledge on a specific application domain. In this study, the concepts and relations are derived from the theoretical analysis of dam system failures and the analysis of 20 real failure cases (in appendix 3). The set of concepts enables us to: (i) describe external factors that impact the system (*Environment, Activities*); (ii) describe the structure of the system (*Structural system, Component, Material, Property*); (ii) describe the impacts in/on the system (*Flow, Load*); evaluate the performance of the system and its component (*Function, Performance, Performance parameter*). The relations are able to formalize the interactions between the external factors and the system (*makes an impact on*) and between the components of the system (*applies flow on*). These concepts and relations allow covering all structure types. The model can be instantiated to any particular failure case.

+ A generic structure that allows to describe structural systems and understand how failure arises. The structure of the system is based on the common vocabulary. The system is composed of components, which can be decomposed into a further level of subcomponents. A component is described with its properties, material, function, and performance. The relations between function, performance, and performance parameter allow to characterize a failure and to evaluate its impact on the system performance at any time. It allows describing the failure at any detailed level.

+ A set of rules based on the common vocabulary allows simulating causal interactions between components of a system and describing the failure process. The rules are based on a visual reasoning mechanism (homomorphism), allowing the inference of new knowledge in a graphical way. In this study, efforts were devoted to developing a set of graph rules for dam systems to illustrate and simulate the behaviors of a dam system under different impacts. The rules are based on the fundamental theory of the dam system. The reasoning process is connected with the concept of time, and so a failure process can be described as a chronological sequence.

The second contribution of the model is its capacity to capture knowledge from past failure cases, i.e., instance failure facts. The instances of the failure model from the failure database can be used as a source to construct query graphs and inferring new rules. The request graphs can be used to identify similarities between past failure cases and a new one to find conditions or causes of similar facts. The inference rules from facts can be used to propose potential failure processes in order to identify associated risks. Knowledge acquired from past failures can be used to diagnose causes relating to failure or predict risk. It is also valuable to make lessons in order to prevent failures from repeating in the future.

Other contributions of the model come from the benefits that conceptual graphs offer:

+ The failure graph is a visual representation, providing an intuitive understanding and a semantic representation that can translate to natural languages. Therefore, the knowledge contained in the failure graph can be communicated friendly and easy to understand. It can be useful, for instance, to train or teach.

+ The capability to share and reuse a representation in the given domain. The formalized knowledge can be shared and reused to make lessons from previous experiences.

+ The model is flexible in use, and it can be easily adjusted and updated.

The model was applied to five case studies in order to illustrate the functioning of the model, how to instantiate it and how to infer new knowledge from instantiated cases. The failure case of the Koyna dam system was presented in chapter 5, and the other cases are presented in appendix 7. The five instantiations of the failure model expose how different conditions and their combination may result in failures; they also show how the systems' effects and changes over time form the failure process. Finally, they expose how request graphs and rules extracted from them can be used to generate new knowledge.

- Perspectives

This work opens up several perspectives:

+ The knowledge model was built to cover failures of the dam system. This knowledge is not exhaustive and should be enriched by other failure cases of the dam system. It should also be extended for other specific structural types such as bridges, tunnels. However, the procedures and methodology proposed in this work are compatible with any structural system.

+ Proposing an online tool to enrich the fact base and to consult the knowledge could be a useful improvement. It would help expand the approachability to users and enrich the database. The users could retrieve failure knowledge directly, learn lessons, and share information about the context of failures to enrich the database.

+ Data used to instantiate the model is gathered from various sources, such as design documents, specifications, witness interviews, and research analysis. It can be incomplete, inaccurate, and inconsistent. A coupling of the model with the BIM - Building Information Modeling (Autodesk, 2020) - data structure and software (via the IFC format standard) could take advantage of digital data of structural systems on design, construction, management to ensure data accuracy and improve work efficiency.

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Appendix

Appendix 1. Glossary

This Appendix defines terms using for the development of fact graphs of dam system failure.

Concept	Definitions/ Description
Component	A part that, in interaction with other parts, form a system.
Dam	A main component of all dam systems. It creates an obstruction or a barrier across a watercourse to impound water, tailings, or any liquid-borne material.
Concrete dam	A dam constructed of concrete.
Gravity dam	A concrete structure designed in such a way that its own weight resists the external forces in order to maintain its stability.
Arch dam	A dam which is curved both longitudinally and transversely, carriying a major part of its water load horizontally to the abutments by arch action.
Buttress dam	A gravity structure consisting of a solid, water-tight upstream side that is supported at intervals on the downstream side by a series of buttresses or supports.
Embankment dam	A dam constructed mainly by excavated natural materials such as soil, rock. Like gravity dams, embankment dams rely on their heavy weight to resist the force of the water.
Homogeneous embankment dam	A type of embankment dam made of a single kind of material.
Zoned embankment dam	A type of embankment dam made of more than one material. It consists of an impervious central core which is flanked by zones of material considerably more pervious called shells.
Diaphragm embankment dam	A modification of the homogeneous embankment type, in which the dam body of the embankment is constructed of pervious material and a thin diaphragm of impermeable material is provided to control the seepage
Tailings dam	The adams built of conventional materials or waste materials come from mining operations or mineral processing
Raised tailings dam	A dam constructed in phases as the need for additional disposal capacity arises

Water retention tailings dam	A type of tailings dam that constructed as a traditional zoned embankment dam
Component of concrete dam	
Concrete dam body	The portion of concrete material that fill up the volume of a dam.
Gallery drainage	The horizontal or sloping openings or passages left in the body of the dam to drain off the water which percolates through the foundation and serve inspection purpose.
Mat foundation	Foundation provides distribution of the pressure to the soil.
Concrete cutoff	The cutoff walls are constructed to reduce or prevent seepage
Deck-slab	The upstream slope membrane or deck which supports the water load and transmit it to buttresses
Buttresses	The buttresses are located at the certain intervals at right angle to the axis of the dam to support the deck to transfer the load to the foundation
Laterla braces	A system of cross bracing between buttresses is provided to effect lateral stiffness and resistance to buckling of buttresses.
Component of embankment dam	
Homogeneous dam body	The portion of material that fill up the volume of dam. It is available to contain internal structures within the dam body.
Raised tailings dam body	The portion of tailings material that fill up the volume of dam. It is available to contain internal structures within the dam body.
Liner	A barrier layer of asphaltic concrete, concrete, reinforced concrete, or shotcrete to provide watertightness, to prevent erosion, or to reduce friction
Upstream shell	Soil embankment located on the reservoir side; its mass provides stability to the dam.
Downstream shell	Soil embankment that, together with the upstream shoulder, provides stability to the structure.
Slope protection	Layers of material that protect the slopes against wave action or erosion.
Upstream slope protection	A layer of large uncoursed stone, precast blocks, bags of cement, or other suitable material, generally placed on the slope of an embankment

Downstream slope protection	A layer built by stone pitching or dumped riprap of around 0.3m thick, vegetative cover of 0.05 - 0.10 thick.
Dam core	A core in a zoned embankment dam consisting of impervious material.
Diaphragm	A water retention element that is thin compared to the surrounding embankment.
Horizontal blanket drainage	A layer of pervious material placed horizontally to facilitate seepage drainage of the embankment dam.
Upstream impervious blanket	A thin layer of impervious material (usually clay) laid out at the natural ground level on the upstream side of an embankment dam to reduce or eliminate seepage through or beneath the dam
Chimney drain	A vertical or inclined layer of pervious material in an embankment to facilitate and control drainage of the embankment fill.
Toe drain	A system of pipe and/or pervious material along the downstream toe of a dam used to transfer and discharge seepqge away from the dam.
Reservoir	A main component of all dam systems. It is the body of water impounded by a dam.
Foundation	A main component of all dam systems. It is the surface and the natural material beneath it on which a dam placed.
Component of foundation	
Grout curtain	Grouting of foundation materials to produce a barrier to seepage beneath a dam.
Cutoff wall	A wall of impervious material (e.g., concrete, as- phaltic concrete, steel sheet piling) built into the foundation to reduce seepage under the dam.
Bed foundation	The excavated surface or undisturbed material upon which a dam is placed.
Abutments	Main components of all dam systems. The abutments are the parts of the valley, to the right and to the left of the river bed, upon which the dam is supported.
Component of abutment	
Thurst block (for arch dam)	The part of the abutment of an arch dam against which horizontal thrust is exerted by the dam as the reservoir behind it is filled.

Drain channel	The layer of drainage material used in a proper place in downstream slope of abutments.
Appurtenance structure	Ancillary features which contributes to the operation of the dam and reservoir for its intended purposes.
Spillway	A hydraulic structure that passes normal (operational) and/or flood flows in a manner that protects the structural integrity of the dam and/or dikes.
Free overfall spillway	The simplest type of spillway which is constructed in the form of a flow height weir having downstream face either vertical or nearly vertical. Water drops freely from the crest.
Siphone spillway	A closed conduit in the form of an inverted U which uses the principle of siphonic action. The spillway is installed within the body of concrete dams when the valley is narrow and no space is available for constructing a separate spillway
Overflow spillway	The most common type spillway for gravity and buttress dam. It is characterized by control structures that consist of ogree shaped crests. The overflowing water remains in contact smoothly with the spillway surface from the top of the dam to the vicinity of its base.
Chute spillway	The spillway, used for earth or rockfill dam, and is placed either along a dam abutment and separated from the main dam. The surplus discharge through a steep sloped open channel, called a chute or trough.
Side chanel spillway	The spillway is placed on the side of the dam, suitable for earth or rockfill dams in narrow canyons and for other situations where direct overflow is not permissible. The control structure of the spillway is shaped as an ogee-crest spillway or else as a broad-crested weir, can be either controlled or free. The outlet part, most often in the form of a spillway chute or, more rarely, as a tunnel.
Shaft spillway	The spillway sits in the reservoir near the dam, it is used where there is inadequate space for other types of spillways. In a shaft spillway, water discharges down over the surface overflow crest, drops through a vertical or sloping shaft, and then flows to the downstream river channel through a horizontal or nearly horizontal conduit or tunnel.
Bottom outlet	The combinations of structures used to convey water from a reservoir to a discharge point downstream from a dam.

Component of appurtenance structure	
Entrance structure	The entrance channel convey water from the reservoir to the control structure.
Intake structure	The entrance of the conduit of the bottom outlet. An intake structure may vary from a simple concrete block supporting the end of the conduit pipe to huge concrete towers.
Discharge controlling structure	The structure regulates and controls the discharge flows from the reservoir.
Gate	A movable facility for controlling flow of water over a dam through a spillway.
Flashboards	Individual wooden panels supported by vertical pins that are expected to carry a certain predetermined head of water and bend and fail when that head is exceeded
Radial gate	A gate with a curved upstream plate and radial arms hinged to piers or other supporting structure.
Flap gate	A gate hinged along one edge, usually either the top or bottom edge.
Vertical lift gate	A simple timber or steel gate on the crest of a dam which span horizontally between the guide grooves in the supporting piers. The guides may be placed either vertically or inclined slightly downstream. The gate is raised or lowered by a host mounted on a bridge overhead.
Slide gate	A gate that can be opened or closed by sliding in supporting guides.
Weir	A low overflow concrete dam, with a spill-crest set up approximately parallel to the dam, can be gated or ungated.
Trash rack	A screen comprising metal or reinforced concrete bars located in the waterway at an intake so as to prevent the ingress of floating or submerged debris.
Valve	A device fitted to a pipeline or orifice in which the closure member is either rotated or moved transversely or longitudinally in the waterway so as to control or stop the flow.
Conveyor structure	The structure conveys water from the control structure to the terminal structure
Chute	A steeply sloping open channel, placed along a dam abutment or through a flank or a saddle, which connects the crest curve

	to the terminal structure to convey the surplus discharge from the reservoir to the downstream channel below.
Shaft	A vertical or sloping passage to discharge water.
Spillway surface	The upstream face of the crest is formed by smooth curves in order to minimize the separation and inhabit the cavitation.
Conduit	A closed channel to convey water through, around, or under a dam.
Terminal structure	The structure locates at the downstream end of the conveyor structure to dissipate or manage the kinetic energy of the flow, so it can be returned to the river or stream without significant scour or erosion that could damage or fail the dam and appurtenant structures.
Stilling basin	A basin constructed so as to dissipate the energy of fast-flowing water, e.g., from a spillway or bottom outlet, and to protect the river bed from erosion.
Material	Any material which is used for construction and operation of a system such as water, tailings, concrete, soil, rock.
Fine grained soils	Materials having at least 50 percent by weight of particles finer than 0.074 mm, or the openings of a U.S. Standard No. 200 sieve, according to the Unified Soil Classification System (USCS).
Clays	Fine grained soils with clay particles being defined as smaller than 2 microns.
Silts	Fine grained soils with sizes between 2 microns and the No. 200 sieve size.
Rock	A natural aggregate of minerals connected by strong and permanent cohesive bonds.
Cyclopean concrete	A type of concrete containing a mixture of a 60% plain concrete and 40% largestones (variable size between 10 and 25 centimeters).
Sandy clay	The coarse-textured soil, and clay-rich soil fine-textured.
Tailings	A waste product from mining activities
Coal refuse	Any waste coal, rock, shale, slurry, culm, gob, boney, slate, clay, and related materials, associated with or near a coal seam, that are either brought above ground or otherwise removed from a coal mine in the process of mining coal, or that are separated from coal during the cleaning or preparation operations.

Rubble concrete	Concrete in which large stones are placed and arranged roughly in courses. The stones are placed with not less than 15 cm of space between them so that the concrete may be properly rammed.
Sandstone	A sedimentary rock composed of sand-size grains of mineral, rock, or organic material. It also contains a cementing material that binds the sand grains together and may contain a matrix of silt- or clay-size particles that occupy the spaces between the sand grains.
Water	Liquid including solids or other matter therein that is or will be impounded.
Diluvial silty clay	A clay soil containing from 50 to 70 percent silt.
Alluvium	A deposit of sand, mud, etc., formed by flowing water.
Mine waste rock	The byproducts of the mining process.
Basalt	A fine-grained rock which is formed as an extrusive rock.
Coarse grained soils	The materials having more than 50 percent by dry weight of particles retained on the U.S. Standard No. 200 sieve, or 0.074 mm.
Gravels	Gravels are coarser than the No. 4 sieve and finer than 3 inches (76.2 mm).
Sands	Sands are defined as soils finer than the No. 4 sieve (4.76 mm) and coarser than the No. 200 sieve.
Property	The properties which describe a component and material such as size, geometrical shape, surface,
Property of reservoir	
Runoff coefficient	The proportion of rainfall which flows along the ground as surface runoff.
Concentration coefficient	The catchment-reservoir area ratio.
Reservoir level	Height to which the water rises behind the dam and is the difference between the lowest point in the original stream- bed at the axis of the dam and the maximum controllable water surface.
Minimum reservoir level	The lowest level to which the reservoir is drawn down under normal operating conditions. The lower limit of active storage.
Catchment area	The drainage area upstream of the dam that contributes to flow entering a reservoir when rain falls.

Maximum reservoir level	The highest elevation of the flood control storage.
Property of dam	
Upstream slope	The measure of how steep of the upstream face.
Width of downstream slope	The horizontal distance between the ends of the downstream shell.
Downstream slope	The measure of how steep of the downstream face.
Upstream angle	The angle which the upstream face of the dam makes with vertical.
Base width	The maximum width of the dam measured horizontally between upstream and downstream faces and normal to the axis of the dam.
Height of downstream slope	The vertical distance between the ends of the downstream slope.
Height of upstream slope	The vertical distance between the ends of the upstream slope.
Top width	The thickness or width of a dam at the level of the top of dam (excluding corbels or parapets).
Height of dam	Distance between the lowest point in the excavated foundation and the top of dam.
Width of upstream slope	The horizontal distance between the ends of the upstream face.
Length	The measured length of the component along its longest side.
Discharge face	The downstream portion from the point of intersection of the phreatic line with the downstream face to the toe of the dam.
Property of appurtenance structure	
Discharge coefficient	The coefficient to calculate the discharge passing over the spillway crest, which depends upn various factors such as relative depth of approach, relation of actual crest shape to the ideal nappe shape, slope of upstream face, downstream apron intereference, and submergence, etc.
Opening height	The height of the gate when open.
Flood design	The flood hydrograph used in the design of a dam and its appurtenant works particularly for sizing the spillway and outlet works and for determining maximum storage, height of dam, and freeboard requirements.
Opening width	The width of gate.

Height of gate	The distance from the bottom to the top of the gate.
Height of spillway crest	The lowest level at which water can flow over or through the spillway.
Property of foundation	
Thickness	The depth of foundation.
Depth of cutoff wall	The vertical distance that the cutoff penetrates into the foundation of dam
Width of cutoff wall	The width of the cutoff wall measured horizontally.
Material property	Anything that describes a material.
Mechanical property	The properties refer to components that react against an applied load.
Average shear strength	The average shear strength at the section, which assumed to be the same at each point located in the section. an ample safety margin
Shear stress	Shear stress (τ), on a surface is the result of force acting parallel to it, and is also defined as an internal resistance/load per unit area in the material, generated due to application of external load.
Shear stress in downstream shell	The internal resistance/load per unit area in the material of the downstream shell of embankment dam.
Shear strength	The maximum resistance of a soil or rock to shearing stresses.
Maximum shear stress	The shear stress occurs at a distance 0.6 of the base width of downstream shell from the toe of embankment dam (i.e. 0.4 downstream slope width from the top shell) and is equal to 1.4 times the average shear intensity.
Erosion strength	The energy absorbing capacity of the material per unit volume under the action of erosion loads.
Shear strength in upstream shell	Shear resistance of upstream shell portion of the embankment dam developed at base.
Tensile strength	The maximum stress that a material is capable of resisting under an axial tensile load.
Vertical stress at base	The vertical direct stress distribution at the base of a concrete dam, generated due to external vertical loads.
Average shear stress	The average shear stress at the base of the shell of an embankment dam, generated due to external horizontal loads.

Maximum shear stress in upstream shell	The maximum intensity of shear stress occurs at a distance 0.6 of base width of upstream shell of an embankment dam from the heel (i.e. 0.4 of base width of upstream shell from the top shell) and is equal to 1.4 times the average shear intensity.
Principal stress	The major principal stress that will be generated on the major principal plane of a concrete dam.
Unit shear strength at max stress point	The unit shearing resistance developed at the point of the maximum shear stress of dam shells.
Lane's coefficient	Values of Lane's safe hydraulic gradient for different types of soils.
Compressive strength	The maximum stress that a material is capable of resisting under an axial compressive load.
Physical property	The properties are those which can be observed without any change of the identity of material.
Permeability coefficient of coarse soil	The capacity of coarse soils, with normal conditions, to allow the passage of water or of another fluid through pore spaces.
Fines content	The portion of soil particles finer than the No. 200 sieve (0.075 mm), which was determined arbitrarily regardless of soil behavior.
Permeability coefficient	The capacity of a specific soil, with normal conditions, to allow the passage of water or of another fluid through pore spaces.
Mean grain size of coarse soil	The medium grain size of coarse soil (called D50%, for 50% of the cumulative frequency curve).
Cohesion	The relation and inter-connection between soil particles due to water polar molecules and soil polar particles.
Unit weight of sand	The weight per unit volume of sand.
Submerged unit weight	The weight of the solids in air minus the weight of water displaced by the solids per unit of volume of soil or rock mass.
Porosity of coarse soil	The ratio of the volume of voids to the total volume of the coarse soil.
Porosity	The ratio of the volume of voids to the total volume of the soil.
Dry unit weight	The weight of soil or rock solids per unit of total volume of soil mass.
Friction angle	A measurement of how well a material can take shear stresses and is defined as the angle (°) between the normal force (N)

	and the resultant force (R) attained when the material has failed due to shear stress.
Unit weight	The amount of mass contained in a unit volume.
External factor	All factors outside of the system that interacts with the system through a flow.
Activity	All activities performed by humans create a flow that interacts with the system.
Placing	The dumping and spreading of earthfill or rockfill.
Filling	Filling repeatedly over a period of time.
First filling	The increase in water level behind the dam from the time construction is complete until it reaches the desired operating level.
Drawdown	Reduction of the water level of a reservoir.
Tailings deposition	Tailings are discharged to form the tailings dam.
Bombing	The activity of attacking of dropping or detonating a bomb somewhere.
Environment	The natural environment around the dam site.
Tailwater	The water issuing downstream from tunnels, conduits, or spillways of a dam system.
Gravity	The load that attracts a body towards the centrer of the earth, or towards any other physical body having mass.
Temperature	The degree of hotness or coldness of air at a particular place and time.
Flooding	A temporary rise in water surface elevation resulting in inundation of areas not normally covered by water.
Rain	A type of liquid precipitation and is the result of water vapour condensing and precipitating.
Groundwater	The water below the earth's surface, mainly derived from rain or other water source that percolates (drains or seeps) from the surface.
Landslide	The movement of a mass of rock, debris, or earth fill down a slope under the direct influence of gravity.
Earthquake	A sudden motion or trembling in the earth caused by the abrupt release of accumulated stress along a fault.
Characteristic	Attributes to be considered in determining influences of external factors on the system.

Acceleration of gravity	The rate at which an object changes its velocity due to the gravity.
Intensity	The ratio of the total amount of precipitation falling during a given period to the duration of the period. It is expressed in depth units per unit time, usually as mm per hour (mm/hm)
Horizontal gravity fraction	The fraction of gravity adopted for horizontal acceleration.
Vertical gravity fraction	The fraction of gravity adopted for vertical acceleration.
Duration	The period of time during which rain falls.
Flow	The interaction that transfers material or energy through the system with respect to time.
Load	A measure of mechanical interaction between bodies.
Vertical earthquake inertia load	Load generated by the vertical inertia load of the foundation due to the vertical acceleration acting into the concrete dam.
Horizontal shear load P_d	The horizontal shear load P_d at base under the downstream shell of the embankment dam under steady seepage, is exerted by the saturated soil.
Tailwater load	The load exerted by the water depth at the tail of the dam.
Earthquake hydrodynamic load	The load generated by the resistance of water to its inertial movements due to the effect of horizontal acceleration on the reservoir.
Horizontal shear load P_f	The total horizontal shear load under a shell of the embankment dam.
Reservoir load	The load exerted by the water stored in the reservoir on the upstream.
Shelf weight load	The weight of the structure plus such appurtenances as gates and bridges, which acts through the centroid (center of gravity) of the cross-sectional area.
Horizontal shear load P_u	The horizontal shear load P_u developed at base under the upsptream slope of the embankment dam during rapid drawdown, is exerted by the saturated soil (i.e., by the doil as well as by water contained within the soil).
Horizontal earthquake inertia load	The inertia load generated by the horizontal acceleration acts into the concrete dam.
Uplift load	The upward load exerted by water penetrating through the pores, cracks and seams with in the body of the dam, at contact

	surface between the dam and its foundation, and within the foundation.
Hydraulic flow	The hydraulic interaction between objects.
Discharge flow	Tthe flow that releases from a dam into a downstream area to ensure that the water does not overflow and damage or destroy the dam or according to water demands in cities, farms, or industries.
Outflow	A flow that is transferred out of a system.
Surface runoff	A part of water from rain, snowmelt, or other sources, that flows over the land surface and flow into reservoir.
Seepage flow	The penetration and movement of water through the porous medium, under the action of the gravitational potential occurring after the construction of water-retaining structures and the filling of the reservoir.
Peak runoff	The maximum instantaneous discharge that occurs during a flood. It is coincident with the peak of a flood hydrograph.
Over flow	A water flow over the embankment from overtopping.
Inflow	A flow into a system.
Dam-break outflow	The uncontrolled flow of the reservoir due to dam breach
Function	Function is what the system or component is intended to do, usually to a given performance.
Mechanical function	The function that relates to the behaviors of a structure under mechanical loads.
Resisting instability	Resisting the non-equilibrium state of a structure.
Resisting sliding of upstream shell	Resisting the movement or sliding of the upstream shell during sudden drawdown in an earthen dam.
Resisting sliding of downstream shell	Resisting the movement or sliding of the downstream shell during steady seepage in an earthen dam.
Resisting overturning	Resisting the static loads that tend to induce overturning.
Resisting sliding	Resisting horizontal shear developed at the base of the dam
Providing support load	Providing support for structures, transferring their load to soil or rock layers that have sufficient bearing capacity and appropriate settlement characteristics.
Remaining durability	Remaining the condition of a structure or a mass of material when it is able to support the applied stress for a long time

	without suffering any significant deformation or movement that is not reversed by the release of the stress.
Resisting sloughing	Resisting the process when the downstream toe becomes saturated and continuously remains in the same state, causing the softening and weakening of the soil mass, leading to the sudden failure of the embankment dam.
Resisting erosion along conduit	Resisting the backward erosion piping due to the seepage along the interface between the conduit and surrounding soil.
Resisting internal erosion of hydraulic fracture crack adjacent to the conduit	Resisting the erosion of the soil in contact with the hydraulic fracture due to the differential settlement of an embankment dam.
Resisting head cutting	Resisting upstream movement and expansion of the scour hole after the erosion begins.
Resisting concentration erosion	Resisting the erosion occurred through an opening in plastic soil, and sometimes in unsaturated silt, silty sand and silty sandy gravel.
Resisting crushing	Resisting curshing of dam-material due to the excess of the compressive stresses to the allowable stresses.
Resisitng abrasion of conduit	Resisting the effect of scouring or grinding on the exposed surface of a conduit causing by water flow through the conduit at high velocities and contains silts, sands, gravels, or stones.
Resisting piping by flow from conduit	Resisting the failure of the high pressure flow exiting the conduit through defects and exerting hydraulic loads on the embankment soils.
Resisting piping of soils into conduit	Resisting the failure of seepage loads carrying soil particles into the conduit due to seepage occuring through the surrounding embankment.
Resisting deterioration of conduit	Resisting the deterioration of conduit caused by ageing.
Resisting breach	Resisting the formation of an opening through the dam that allows the uncontrolled release of the reservoir.
Resisting cavitation	Resisting the formation of bubbles or voids in low pressure zones within a liquid (spillway releases) due to flow surface irregularities and/or changes in flow surface geometry. The bubbles or voids pass into downstream higher pressure zones, rapidly collapse and issue high pressure shock waves. If the collapsing bubbles or voids are near a flow surface, high

	frequency impacts occur which result in fatigue and erosion of flow surface materials.
Resisting initation of piping	Resisting the detachment of particles at the exit (downstream end) of leakage paths through or under embankments.
Resisting spillway foundation erosion	Erosion of foundation materials due to excessive uplift underneath the spillway chute caused by stagnation pressures.
Resisting hydraulic jacking	Resisting damage resulting from hydrodynamic uplift on slabs (jacking).
Resisting external erosion	Resisting the physical process by which the soil particles on the surface of a dam are removed by the flowing water.
Resisting improper gate operation	
Resisting insufficient capacity	Resisting the exceesive of flood discharges to the design spillway capacity
Resisiting ball milling	Resisting a mechanism, where material trapped in a hydraulic jump stilling basin is circulated within the flow and abrades and erodes the stilling basin concrete due to a repetitive grinding process.
Resisting tension crack	Resisting cracking occurs in the concrete dam wherever vertical tensile stresses resulting from dynamic response of the structure to an earthquake exceed the tensile strength of the concrete.
Resisting abrasion of stilling basin	Resisting the mechanism in which the stilling basin concrete is ground down, with aggregate and concrete fragments also being loosened in the process.
Resisting erosion of stilling basin	Resisting the process in which abraded material and loosened concrete materials are removed from the concrete surface by flows that pass through the stilling basin.
Resisting contact erosion	Resisting erosion occurred where a coarse soil is in contact with a fine soil, and flow parallel to the contact in the coarse soil erodes the fine soil.
Resisting contact erosion piping	Resisting the formation of a “roof” in embankment after contact erosion occurs.
Resisting backward piping progression	Resisting the erosion upstream through material along the contact with a cohesive cover layer.
Resisting erosion of downstream toe	Resisting erosion of downstream toe of dam by tail water and cross currents that may come from the spillway buckets.

Resisting crack of embankment dam	Reisisting cracking due to frost action in the upper shell of the embankment dam.
Resisting saturation	Resisting the excessive seepage making the seepage line to cut the downstream face of the embankment dam.
Resisting clogging of trashcrack	Resisting blocking culverts due to debris.
Resisting deformation	Resisting the change of in geometry created when stress is applied.
Resisting liquefaction	Resisting the deformations caused by monotonic, transient, or repeated disturbance of saturated cohesionless soils under undrained conditions.
Resisting setllement	Resisting the vertical downward movement of a structure or its foundation.
Need	The human needs for water and water related services.
Supplying water for domestic and industrial use	Water may be released from a reservoir to provide adequate amounts of quality fresh water to residential, industrial facilities and mining sites.
Supplying water for irrigation	Water in a reservoir may be released and distributed over the land in the dry seasons to promote the growth of food crops.
Allowing recreation activity	Reservoir can be used for recreational activities such as swimming, boating, and fishing.
Controlling flood	Reservoir collects water at times of very high rainfall, then releases it slowly over the course of the following weeks or months.
Producing hydroelectricity	Electricity is generated from water by using the potential energy stored in reservoirs behind dams.
Hydraulic function	The functions related to flow movement in a dam system.
Retaining water	The retention of water in reservoir or delay of runoff either by planned operation.
Controlling seepage	To prevent, reduce, collect and carry away seepage that passes through and under the dam. seepage that passes through and under dams on rock foundations
Draining seepage	Collecting the seepage discharging from the embankment and foundation and conveying it to a free outlet.
Preventing seepage	Preventing, reducing seepage that passes through and under the dam.

Limiting hydraulic flow	Be watertight, impermeable or impermeable to prevent water from leaking out of the dam and and escape downstream.
Discharging water	Carrying surplus discharge over the spillway crest or below the dam, or to discharge water in case of need for repairs to the structures.
Regulating reservoir level	Controlling the water level of reservoir during the first impoundment, and rapid drawdown of reservoirs in emergency situations.
Controlling discharge	Regulating the rate of flow by operation of one or more gates to prevent sudden large releases that would happen if the dam were overtopped.
Withdrawing water from the reservoir	Withdrawing water from the reservoir over a predetermined range of pool levels
Conveying flow	Conveying flow from the control structure to the terminal structure through a discharge channel or waterway.
Performance	Performance is capacity of a system or component to fulfill its function.
Expected level	The level of performance parameter designed to satisfy function of a component or system. Usually, it is based on standards or pre-defined criteria.
Measured level	A quantitative measure of the performance level of a component or system that indicates the actual degree to which it performs the function.
Performance parameter	Measurable parameters which can be used to evaluate performance of a component or system.
Performance parameter of foundation	
Factor of safety against piping progression	The ratio of the fines content of the soil (% passing 0.075 mm) to 15% fines.
Factor of safety against shear at max stress point	The ratio of the unit shearing resistance developed at this point of maximum shear stress to the maximum intensity of shear stress occurs at a distance 0.6 of base width below downstream shell from the toe.
Factor of safety against sliding of foundation	The ratio of the average shear resistance to the average shear stress at the base of the shell.
Factor of safety against initiation piping	The ratio of the buoyant unit weight of the soil to the unit weight of water.

Performance parameter of concrete dam	
Factor of safety against tension crack	The ratio of the tensile strength of concrete to the maximum vertical stress.
Factor of safety agaisnt crushing	The ratio of the compressive strength of concrete to the maximum vertical stress.
Factor of safety against sliding	The ratio between all horizontal forces and vertical forces acting on the specific plane.
Factor of safety against overturning	The ratio of the stabilising moment to the disturbing moment.
Performance parameter of reservoir	
Flood retention	The water flow remaining in the reservoir during a flood, calculated by the subtracting of the inflow to the outflow.
Useful storage	The distance of water is stored in a reservoir between the minimum level and the level during normal operating conditions.
Freeboard	The vertical distance between the topt of the dam and the maximum reservoir water level.
Dam-break outflow retention	The water remains in reservoir after the breach of dam.
Performance parameter of appurtenance structure	
Opening capacity	The maximum opening capacity.
Opening capacity of spillway gate	The maximum opening capacity of spillway gate.
Opening capacity of bottom outlet gate	The maximum opening capacity of bottom outlet gate.
Discharge capacity	The maximum amount of water that can safely released from a given waterway.
Discharge capacity of spillway	The maximum discharge that can pass from the spillway.
Discharge capacity of bottom outlet	The maximum discharge that can pass from the bottom outlet.

Performance parameter of embankment dam	
Factor of safety agaisnt sliding at max shear f	The ratio of the unit shearing resistance developed at this point of maximum shear stress to the maximum shear stress.
Factor of safety against external erosion	The ratio of the stream power to the erodibility index of material.
Factor of safety against saturation	The value of discharge face.
Factor of safety agaisnt sliding of downstream shell	The ratio of the horizontal shear load P_d to the shear resistance (R_d) of downstream shell of embankment dam developed at base.
Factor of safety agaisnt sliding at max stress point of upstream shell	The ratio of the unit shearing resistance developed at the point of the maximum shear stress to the maximum intensity of shear stress occurs at a distance 0.6 base width below upstream shell from the heel.
Factor of safety against sliding at max stress point of downstream shell	The ratio of the unit shearing resistance developed at the point of maximum shear stress to the maximum intensity of shear stress occurs at a distance 0.6 base width below downstream shell from the toe.
Factor of safety agaisnt concentration erosion	The ratio of the critical shear stress to the hydraulic shear stress in a crack or pipe for the headwater level under consideration.
Factor of safety against sloughing	The ratio of tan of the internal friction angle to tan of the angle between downstream slope and the horizontal.
Factor of safety against overall sliding f	The ratio of the shear resistance of the dam at the base to the horizontal loads.
Factor of safety against contact erosion	The ratio of the critical velocity to the hydraulic conductivity (horizontal) of the coarse layer and seepage gradient for the reservoir level under consideration.
Factor of safety against backward piping	The ratio of the creep ratio for the reservoir level under consideration to the minimum (or safe) creep ratio for the piping material.
Factor of safety against contact erosion piping	The ratio of the fines content of the soil (% passing 0.075 mm) to 15% fines of the soil.
Factor of safety against breaching	The ratio of the hydraulic shear stress in the pipe to the erosion resistance of the soil.

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Appendix 2. Components of dam system

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This section presents knowledge about other components of dam system. We expose the reservoir, foundation, spillway, bottom outlet, their components and functions, material. This section serves for functional analysis and failure analysis.

2.1. Reservoir component

When a barrier is constructed across the valley of a water-course in the form of a dam, water is stored on the dam's upstream side. The dam creates a water body, generally called a reservoir (Chapman, 1996) (Figure 2.1).

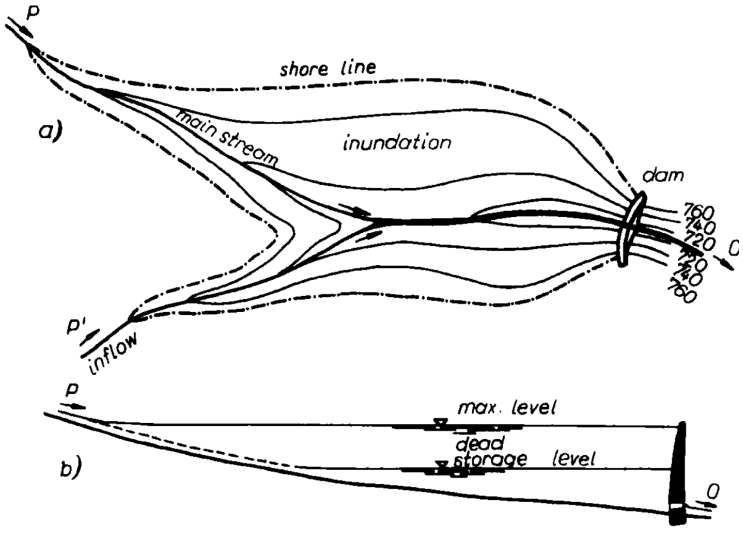

Figure 2.1. Schematic representation of a reservoir (Votruba and Broza, 1989)

(a) layout; (b) longitudinal section of the main stream

For tailings dams, which is a special type of hydraulic dam for containing fine mine waste, usually in the form of slurry (tailings), the dam is not constructed within the course of the river and formed by completely enclosed banks, creating a body of tailings.

A reservoir is, therefore, in the broadest sense of the word, the main component of all dams, which is defined as the body of fluid retained by a dam (Chapman, 1996), (Strom *et al.*, 2015), (USACE, 2004). The fluid can be water, in conventional dams, or tailings, in tailings dams.

The basic function of a reservoir is to store water or tailings. The water accumulated in the reservoir can be withdrawn for various purposes: industrial and cooling water supply, agricultural irrigation, power generation, flood control, drinking, municipal water supply, recreation, boating, and other aesthetic, recreational uses.

2.2. Foundation

Hydraulic structures, like other civil engineering structures, are built on construction ground, i.e., the foundation. The foundation is a critical element of any dam system. In general, the foundation must be sufficient strength to withstand the imposed loads from the dam and the reservoir. It also has to resist seepage to prevent excessive loss of water. It includes two parts:

2.2.1. Ground (Bed foundation) upon which the dam is supported. It is classified into three main kinds of widespread foundations in civil engineering: rock foundations, semi-rock foundations, and non-rock (soil) foundations.

+ Rock foundations (bedrock) have a compressive strength in a waterlogged state greater than 5Mpa (Tanchev, 2014). In general, rock foundations present no problem of bearing capacity and settlement. Nevertheless, the rock, as well as earth foundations, are heterogeneous, anisotropic, consisting of rocks of different properties and are divided by various cracks, i.e., foundations are never continuous.

+ Semi-rock foundations have been formed from rocks having compressive strength in waterlogged conditions less than 5MPa. They are characterized by noticeable deformability (marlstones, siliceous clays, etc.), lowered shearing resistance, and submissiveness to softening under water (gypsum, rock salt, gypsum-containing conglomerates, and others, which are unsuitable as foundations for dams).

+ Finally, soils are usually composed of sands, clays, peat, and similar materials.

2.2.2. Structures to control under seepage:

There are different techniques applied to the rock foundation and soil foundation to reinforce them. The rock foundation can be improved in two ways: grouting and backfilling fractures and tectonic zones. The foundation grouting is a process of injecting under pressure a fluid sealing material in appropriately positioned boreholes so that the grouting mixture is injected fractures, voids, and pores in the rock mass. There are three methods to improve the foundation by grouting: contact grouting, consolidation grouting, and curtain grouting:

- Contact grouting fills the possible gaps, voids, and fractures at the contact between the rock and the dam to obtain a monolithic bond between the concrete and the rock.
- Consolidation grouting is used to consolidate the entire foundation of the dam, aiming at increasing the strength of the rock below the foundation of the dam to reduce seepage through it (Figure 2.2).

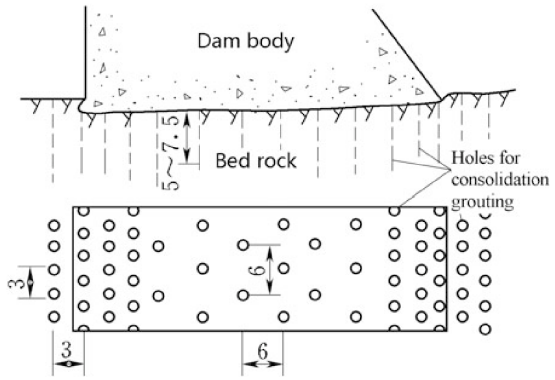

Figure 2.2. Typical layout of consolidation grouting (unit: m) (Chen, 2015)

- Grout curtains inject the grouting mixture into the fractures of the rock to form a curtain against the seepage through the foundation and thus reduce the uplift pressures (of concrete dams) (Figure 2.3).

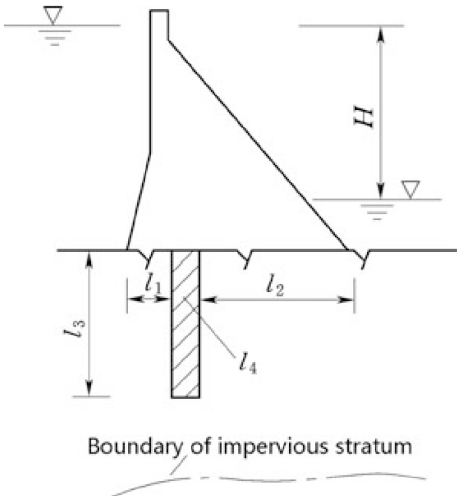

Figure 2.3. Diagram of the design of curtain grouting (Chen, 2015)

The second technique is the backfilling of fractures and tectonic zones. This method improves rock foundations by filling up fractures and tectonic zones with concrete or a solution of cement and sand by applying various procedures, depending on their size and the kind of material used to fill them.

Regarding the soil foundations, instead of using grouting, the water impermeability of soil foundations in hydraulic practice is more often achieved or improved with cut-offs. Cut-offs are impervious barriers placed in the foundation. They can be constructed by impervious soil (clay) in a cut-off trench; masonry (usually concrete) or steel sheet piling (limited to foundations of silt, sand, and fine aggregate) in a cut-off wall (P.Novak, A.I.B. Moffat, 2007), (Chen, 2015) (Figure 2.4).

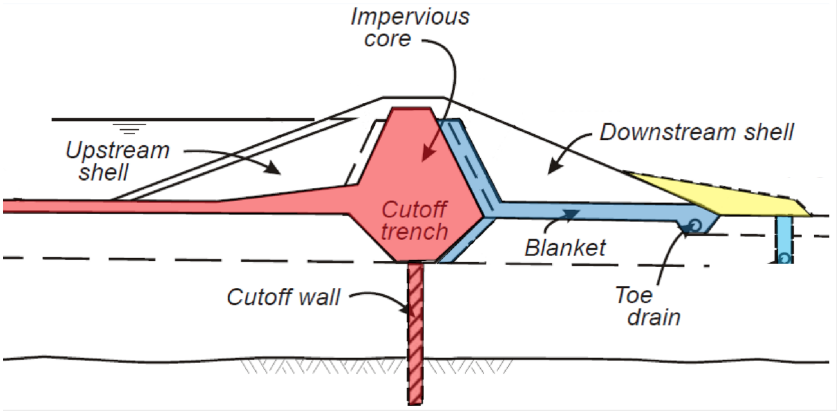

Figure 2.4. Cut-offs and control of under seepage (Rancier and Mills, 2017)

They are generally located directly under the core but can also be found at the upstream end of the embankment dam. Cutoff trench functions as extensions of the embankment core into the foundation. The cut-off wall should generally extend through the entire depth of the pervious foundation to effectively control the seepage. When the depth of the pervious foundation is considerable, a cut-off, up to a lesser depth, is called partial cut-off.

2.3. Abutments

Abutments are the parts of valley sides (wall), to the right and to the left of the river bed, upon which the dam is supported (Tanchev, 2014).

For an arch dam, which obtains its stability by both the self-weight and by transmitting the imposed loads by arch action into the valley walls, abutments have sufficient strength to support the arch thrust. On special occasions, artificial abutments - thrust blocks - may be used in the absence of suitable natural abutment(s).

Parts of abutment can be:

(1) Abutment

(2) Thrust block (abutment block) (for the arch dam)

(3) Drainage: can be drain pipe or drain channel (filled by drainage materials) used properly in the downstream slope of the abutments.

2.4. Appurtenant structures

Appurtenant structures are structures used for flood control and/or reservoir level management without affecting the dam's safety. These include spillways, outlet works, gates, valves, trash racks, power plants, diversion works. They can be of considerable importance to the project because they are necessary to the operation of the dam system (NRC, 1983), (Yazdandoost and Attari, 2004). The spillways and outlet works are two critical types of appurtenant structures associated with storage and/or multipurpose dams.

2.4.1 Spillway

The spillway is among the most important hydraulic structures of a dam system. A spillway is in the overflow portion of a dam, allowing discharging overflows from the reservoir to the downstream. The size and location of the spillway are determined by the size and kind of dam, local topography, geology, and a careful review of the history of stream flow at the site of the dam. A spillway can be located either within the body of the dam or outside the dam’s body. The main elements of the spillway are:

(1) Approach channel: it is an entrance structure to draw water from the reservoir and convey it to the control structure. It is not required for the free overfall spillway and overflow spillway.

(2) Control structure: it consists of a weir and gates to regulate and control the outflow from the reservoir, i.e., a low overflow concrete dam, with a spill-crest set up approximately parallel to the dam, can be gated or ungated.

(3) Conveyance structure (Discharge structure): it conveys the water to the terminal part of the structure, except in the case of a free overfall spillway. It may include conduits, tunnels, and chutes, and a combination of these elements.

(4) Terminal structure: may be a hydraulic jump stilling basin, flip bucket, or plunge pool. At the downstream end of the discharge structure, flow manifests itself in the form of high velocities enough to cause scour, erosion, and subsequent damage to an

adjacent structure. A stilling basin is provided to dissipate the energy of the water current and to ensure a steady flow in the river channel downstream of the works.

A spillway can be controlled (gated) or uncontrolled (ungated):

(1) Controlled (gated) spillway: the outflow of water over a spillway may be controlled by installing gates over the spillway crest. The spillway crest is the highest horizontal surface of the spillway.

(2) Uncontrolled (ungated) spillway: with this type of spillway, the crest permits water to escape automatically as the water level in the reservoir rises above the crest.

Spillway comes in a variety of forms and configurations. The choice of a spillway depends on the characteristics of the site, proposed use for the dam, and economic constraints (Taiao, 2017). The different types of spillway are: free overfall or straight drop spillway, ogee or overflow spillway, chute or trough spillway, side-channel spillway, shaft spillway, and siphon spillway

2.4.1.1 Free overfall or straight drop spillway

Free overfall spillway is the simplest type of spillway, constructed in the form of a flow height weir having downstream face either vertical or nearly vertical. Water drops freely from the crest, and the underside of the falling nappe is ventilated sufficiently to prevent a pulsating, fluctuating. Occasionally, the crest is extended in the form of an overhanging lip (similar to that provided in notch falls) to direct the small discharge away from the face of the overfall section (Figure 2.5). The components of a free overfall spillway are the spillway crest, the gates, and the stilling basin.

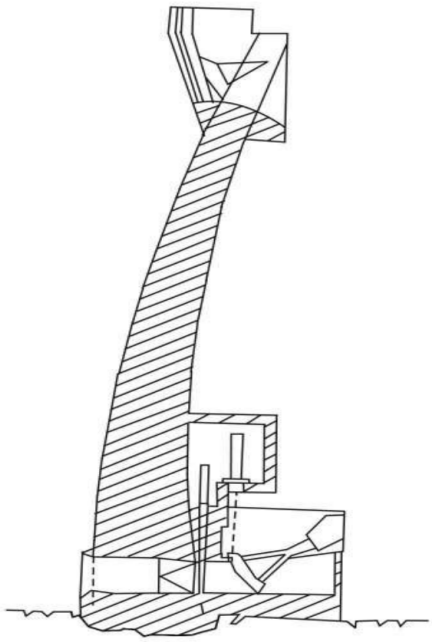

Figure 2.5. Free overfall spillway for an arch dam (Sharma, 2017)

2.4.1.2. Ogee or overflow spillway

Overflow spillway is the most common type of spillway for gravity and buttress dams. The spillway section is lower than the other sections of the dam, allowing water to flow over its top and down downstream. Ogee spillway is characterized by control structures that consist of ogee shaped crests (crest that is ogee or s-shaped when viewed in profile). The overflowing water remains in contact smoothly with the spillways surface from the top of the dam to the vicinity of its base so that the overflow water does not break contact with the spillway surface (Figure 2.6).

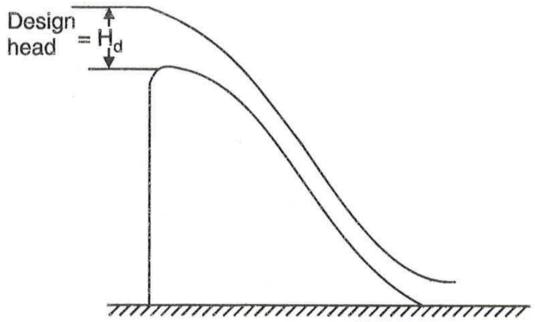

Figure 2.6. *Section of overflow spillway* (Punima *et al.*, 2009)

2.4.1.3. Chute (open channel or trough) spillway

A chute spillway is a spillway that transmits the surplus discharge through a steep sloped open channel, called a chute or trough, placed along a dam abutment. Generally, this type of spillway is used for earth or rockfill dam and is separated from the main dam (Figure 2.7).

Chute spillways benefit from the simplicity of their design and construction, their adaptability to almost any type of foundation, and the overall economy often obtained using large amounts of spillway excavation in the dam embankment.

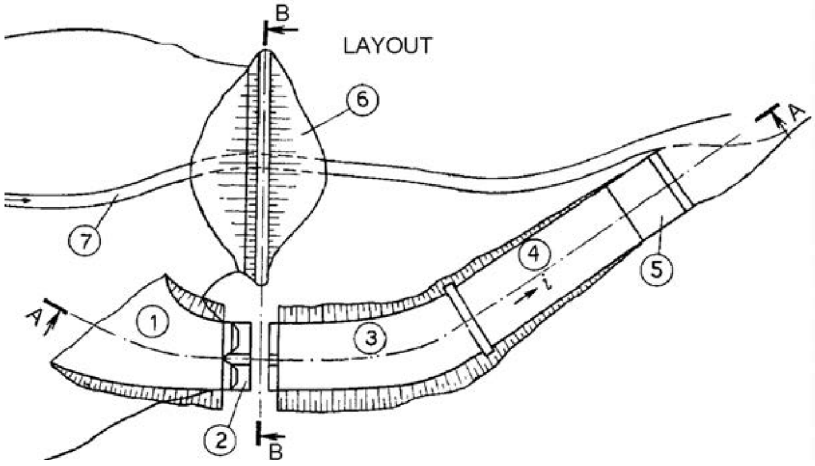

Figure 2.7. *Plan of a chute spillway* (Tanchev, 2014)

(1) approach channel; (2) spillway; (3), (4) outlet parts; (5) terminal part; (6) embankment dam; (7) river bed (channel).

2.4.1.4. Side-channel spillway

A side channel spillway is a spillway in which the flow, after passing over an ogee crest, is carried away by a channel running parallel to the crest. It is placed on the side of the dam and is suitable for earth or rockfill dams in narrow canyons and for other situations where direct overflow is not possible (Punima *et al.*, 2009).

The control structure of the spillway is shaped as an ogee-crest spillway or as a broad-crested weir and can be either controlled or free. The outlet part is the most often, in the form of a spillway chute or, more rarely, as a tunnel (Figure 2.8).

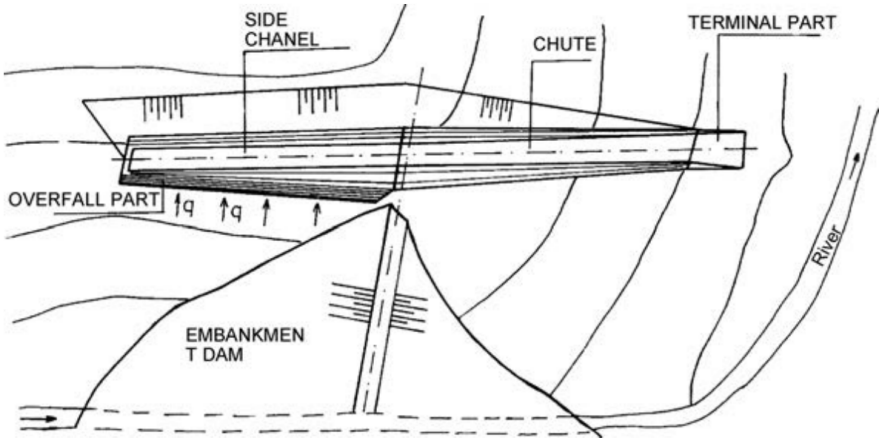

Figure 2.8. *Plan of a side-channel spillway (Tanchev, 2014)*

2.4.1.5. Shaft spillway

In a shaft spillway (Figure 2.9), the water discharges down over the surface overflow crest, drops through a vertical or sloping shaft, and then flows to the downstream river channel through a horizontal or nearly horizontal conduit or tunnel. The shaft sits in the reservoir near the dam. It is used when there is inadequate space for other types of spillways. The shaft spillway structure is used to evacuate large quantities of water (up to 6000m3/s) within medium and high head hydraulic schemes over a rock foundation (Tanchev, 2014).

For a shaft spillway, the surface overflow part is in the form of a circle, an incomplete circle, or a tunnel. The discharge structure is a vertical or slightly inclined shaft.

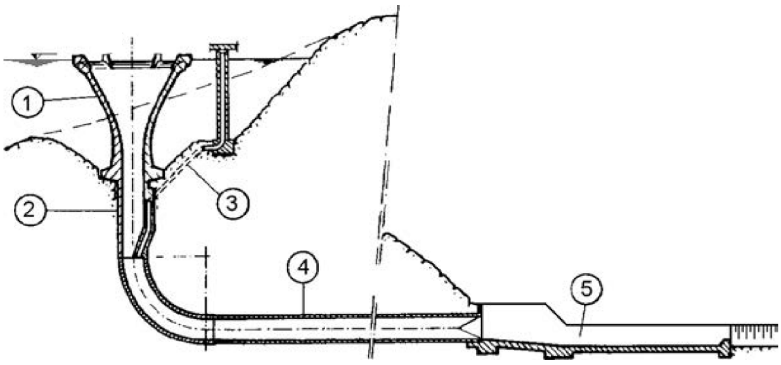

Figure 2.9. Section of a shaft spillway (Tanchev, 2014*)*

(1) funnel; (2) shaft; (3) air inlet; (4) outlet tunnel; (5) terminal part

2.4.1.6 Siphon spillway

A siphon spillway is a closed conduit in the form of an inverted U, which uses the principle of siphonic action (Figure 2.10). In a siphon spillway, one end is kept on the upstream side and is in contact with the reservoir, while the other end discharges water on the downstream side. For very low flows, air enters the siphon through the vent, and siphonic action cannot occur. Once the reservoir level rises, the velocity in the siphon increases, and the flow in the lower leg begins to exhaust air from the top of the siphon until this primes (*i.e.,* the siphon is filled with water) and begins to flow full as a pipe.

Siphon spillways can be either constructed of concrete or formed of steel pipe. They are installed within the body of concrete dams when the valley is narrow, and no space is available for constructing a separate spillway (Asawa, 2008).

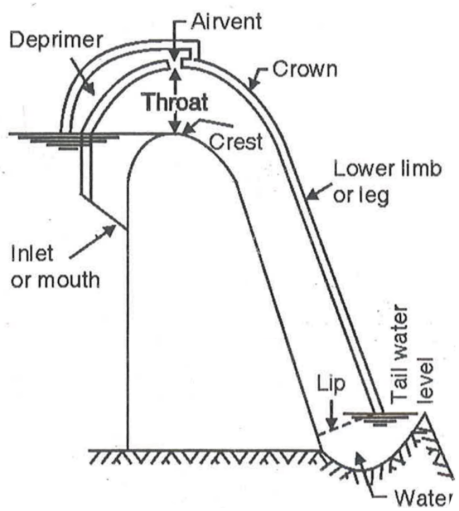

Figure 2.10. Section of a siphon spillway (Punima *et al.*, 2009)

2.4.2. Bottom outlet works or sluiceways

Bottom outlet works are a combination of structures used to convey water from a reservoir to a discharge point, downstream from a dam (Jansen, Scherich and Regan, 1988) (Figure 2.11). They aim to facilitate the lowering of the reservoir or supply water to irrigation channels or for a combination of multipurpose requirements (Tanchev, 2014).

An outlet work may consist of the following components:

(1) Conduit or sluiceway: in the form of a pipe or tunnel that passes directly through the dam or the abutment.

(2) Control devices: such as gates, valves, are installed at the entry of the conduit.

(3) Intake structure: it forms the entrance into the outlet work. It supports trash racks, fish screens, bypass devices, and accommodates the control device. It can be submerged when trash cleaning is ordinarily not required; in that case, it only serves as an entrance to the outlet conduit. A trash rack is a structure provided at the entrance to

the conduit to prevent entrance to debris. A tower intake is provided if an operating platform is needed for trash racking, maintaining and cleaning fish screens, or installing stop logs.

(4) Stilling basin: A basin constructed so as to dissipate the energy of fast-flowing water, e.g., from bottom outlet, and to protect the river bed from erosion.

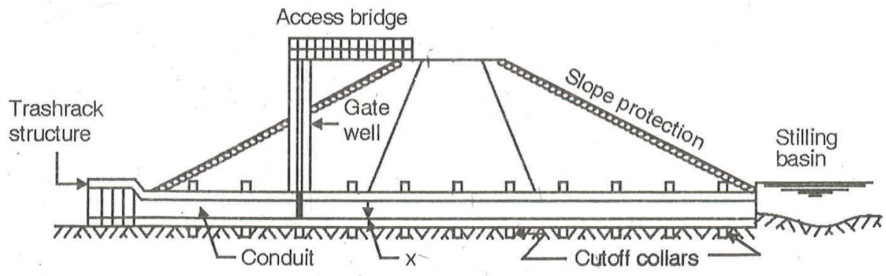

Figure 2.11. Outlet structure through the dam (Punima *et al.*, 2009)

2.5. Drainage

The water seeping through the body of the earthen dam or the foundation can impact the stability of the dam by causing sloughing and piping either through the body or through the foundation, and thus resulting in the failure of the dam.

2.5.1. Upstream blanket

It is a layer of impervious soil placed on a pervious foundation, located upstream and tying into the impervious core. It increases the length of the seepage path through the pervious foundation and thus reduces the hydraulic gradient and the quantity of seepage.

2.5.2. Downstream drainage system

The drainage consists of a graded coarse material in which the seepage is collected and moved to a point where it can be safely discharged. The draining material is graded from relatively fine on the periphery of the drain to coarse near the center to prevent the movement of particles of the foundation or embankment due to seepage forces.

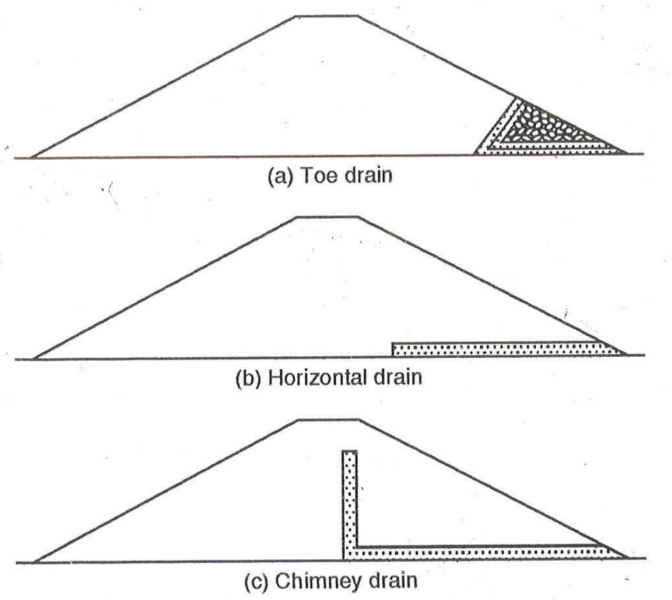

Figure 2.12. Drains in earth dam (Punima *et al.*, 2009)

Generally, three types of drains are provided in the earth dams (Figure 2.12):

(1) Toe drain: a system of pipe and/or pervious material along the downstream toe of a dam used to collect seepage from the foundation and embankment and convey it to a free outlet.

(2) Horizontal blanket: a layer of permeable material to permit free flow without loss of fine soil particles (internal erosion) can lead to failure (Rubertis, 2018).

(3) Chimney drains: an inclined or vertical chimney drain in order to prevent stratification and intercept seepage water before it reaches the downstream slope.

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Appendix 3. Database of historic failure of dam system

Failure No. 1: Nishinotani-Ike dam system

1. General information

- Location: Japan
- Failure: Collapse of dam due to backward erosion piping
- Fatalities: 0
- Year of failure: 2011
- Year of construction: No information
- Function of the dam system: No information

2. External factor

- Heavy rainfall by Typhoon No. 15

  Intensity: 71.0 mm/hr, 390.0 mm/day

  Duration: No information

3. Description of the site, structure and materials:

The Nishinotani-ike dam, a 4.0m high, 3,7 m of crest width, 41.5 m of crest length, 1:1.2 of upstream slope and 1:1.4 downstream. It is a homogeneous type without filters and drains, and is composed of diluvial silty clay of low plasticity (Cheng, Draper and An, 2014).

The reservoir is 1.560 m^3 total reservoir capacity.

4. Description of failure:

The embankment dam collapsed on 21 st September 2011. This failure is attributed by piping erosion due to heavy rains and an increase in storage water level.

Piping erosion: is the formation of piping holes in embankment when the forces resisting erosion are less than those which tend to cause it, the soil particles are washed away and piping commences.

5. Analysis

- Elements involved in the failure process:

  + External factor that is the heavy rain due to Typhoon No.15. The external factor with its characteristics those are intensity and duration creates a runoff flow which increase the reservoir level.

  + The reservoir level which created the highest hydraulic gradient of 0.516 on the toe of the slope. This value is more than the value of 0.5 for stable embankment. Thus, the dam has the possibility of piping.

  + Components at risk are the reservoir and the embankment dam.

  + The time factor is manifested in the intensity and duration of heavy rain, durations of the formation and developing of piping erosion.

- The failure is consequences of interactions of factors. The first interaction was the inflow runoff from heavy rain flowing into the reservoir, causing an increasing of water level. As the water level rose behind the dam, the interaction of the seepage flow and soil within the embankment increased which developed piping erosion. Eventually, collapse of the dam was resulted from a combination of hydraulic stress in the pipe and property of the safety level for piping of soil.

Reference:

Cheng, L., Draper, S. and An, H. (2014) 'Scour and Erosion', in *Proceedings of the 7th international conference on scour and erosion, the university of Western Australia, Perth, Australia, 2-4 december 2014*. London: CRC Press Taylor & Francis Group, p. 834.

Failure No. 2: Takayama-ike dam system

1. General information

- Location: Japan
- Failure: Collapse of dam due to sloughing
- Fatalities: 0
- Year of failure: 2011
- Year of construction:
- Function of the dam system: No information

2. External factor

- Heavy rainfall by Typhoon No. 12

  Intensity: no information

  Duration: no information

3. Description of the site, structure and materials:

The Takayama-ike dam is 10.4 m high, 4.0 m of crest width, 1:2.3 of upstream slope and 1:2.2 downstream. The dam is homogeneous-type, composed of decomposed granite soil (SM) (Cheng, Draper and An, 2014).

The reservoir is 25,000 m^3 total reservoir capacity.

4. Description of failure:

The dam collapsed on 2nd September 2011, about two weeks before heavy rain due to the Typhoon No.12. This failure is attribued by progressive backward sloughing.

Sloughing is the process of slumping of the downstream face when the toe becomes saturated by the seepage from the reservoir.

5. Analysis

- Elements involved in the failure process:

  + Heavy rain due to the Typhoone 12 which fill the reservoir.

  + The increasing of reservoir level causing the phreatic line to cut the downstream face, the sign of saturation of the embankment.

  + The contribution of material that is friction angle of material compared with the downstream angle of the embankment dam.

  + Components at risk are the reservoir and embankment dam.

  + The time factor are manifested in the intensity and duration of the heavy rain, the interval for development of sloughing to collapse of the dam.

- Failure of Takayama-ike dam system was the failure of the downstream shell of the embankment dam, which was resulted from a combination of hydraulic interactions with the downstream shell. The first interaction was the runoff from the Typhoon No. 12 flowing into

the reservoir, causing the increasing of water level. Subsequently, the interactions within the embankment (i.e., the interaction between the seepage flow and soil in the dam) induced the saturation and development of the sloughing of the downstream slope. With the combination of the time factor, i.e., two weeks for developing of the sloughing, the dam came to collapse.

Reference:

Cheng, L., Draper, S. and An, H. (2014) 'Scour and Erosion', in *Proceedings of the 7th international conference on scour and erosion, the university of Western Australia, Perth, Australia, 2-4 december 2014*. London: CRC Press Taylor & Francis Group, p. 834.

Failure No. 3: Gibson dam system

1. General information

- Location: Montana, USA
- Failure: Erosion of downstream face due to overtopping and the failure of spillway
- Fatalities: 0
- Year of failure: 8/6/1964
- Year of construction: 1926 - 1929
- Function of the dam system: supplying water for irrigation

2. External factor

- Heavy rainfall

  Intensity: 203 – 406 mm/h

  Duration: 30 hours

3. Description of the site, structure and materials:

The Gibson dam system includes components as follow:

- A high concrete thick arch dam 60.6 m high with a crest length of 292.6 m, the dam crest width is 4.6 m and the base width is 35.7 m.

- A drop-inlet spillway discharging into a shaft and 9.0 diameter tunnel in the left abutment, controlled by six 10.4 m by 3.7 m radial gates. It has a capacity of 850 m^3/s.

- An outlet works providing a capacity of 86 m^3/s.

- The foundation is crystalline limestone in regular beds.

- The reservoir has a capacity of $122x10^6$ m^3 with catchment area is 1489 km^2.

4. Description of failure:

On 8th June 1964, an extreme storm developed in the area which made the water level reached "unimaginable" levels. Under this condition, the gates, components of the spillway, couldnot be fully opened and leads to failure of spillway to discharge the flood flow. The arch dam was overtopped and huge volumes of water fell on the abutment which caused erosion.

5. Analysis

- Elements involved in the failure process:

  + Rainstrom producing 30 hours rainfall amount from : 203 – 406 mm/h

  + Gates of spillway cannot be fully opened

  + The failure of spillway to discharge the flood flow

  + Reservoir level rises to a maximum overtopping .

  + The abutment rock which was eroded

+ Components at risk are: the reservoir, the arch dam, gates of spillway, the spillway, the abutment.

+ Time factor is expressed in the duration of rainstorm, time for rising water level, duration of the overflow to erode the abutment.

The failure of the Gibson dam system was result of a series of interactions. Firstly, the interaction between rainstorm and the reservoir made the water level to increase. The inreasing of water level accompained with the malfunction of spillway gates, causing overtopping of the reservoir. This condition in turn associated with the erodibility of material in the downstream face generated erosion at the downstream. The failure process also interpretes the contribution of a component to the failure of its higher level component, i.e., the failure of spillway to discharge is contributed by the malfunction of its gates.

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Failure No. 4: Buffalo Creek dam system

1. General information

- Location: West Virginia, USA
- Failure: Breach of dam
- Fatalities: 125
- Year of failure: February 26, 1972
- Year of construction: 1968-1971
- Function of the dam system: retaining mine refuse from mining activities

2. External factor

- Precipitation from heavy runoff and melting snow, heavy runoff from locally intense cloudburst rainfall in any of the streams tributary to Buffalo Creek Storm

Intensity: 93.98 mm/h

Duration: 72 hours

3. Description of the site, structure and materials:

The main dam, known as Dam No. 3, is a part of a network that includes three tailings dam on Buffalo Creek, includes components as follow:

- Dam No. 3 was constructed by end dumping coal waste from trucks in closely spaced piles from 1.2 to 2.1 m high and then graded in layers 0.6 to 1.2 m thick. The dumping was done in the form of a single lift (level of material) which ranged up to 18.28 m thick.

- By early February, 1972, dam No. 3 extended 141.7 m across the valley along the downstream, was 137,16 m wide at the rear, and up to 167,64 m wide along the center. It was 109,72 m thick on the right and 146,30 m thick on the left (looking downstream). On the right, the compacted crest rose 13,41 m, and on the left, it rose 18,28 m above the level of the sludge in pond No. 2. The downstream face of the dam sloped 37 (degrees), and the upstream face sloped 32 (degrees).

- The reservoir was created by dumping the sludge steadily ranging between 12.2 and 30.48 m in thickness. A year before the February 26 failure, the reservoir level was 6.1 m below the crest at that time.

- A 60cm emergency spillway was installed on Dam No. 3.

- The foundtion was fine-grained coal sludge wastes 12 to 30.48 m in thickness.

4. Description of failure:

On February 26, 1972, the main coal refuse dam on Buffalo Creek failed near Saunders, West Virginia. In the three days preceding the failure, a storm of rain fell in the area. The surface runoff caused the reservoir behind the third dam to rise at a rate of 1,8 to 2,4 m per hour. The increased water level due to the rain exacerbated action of piping through the base of the dam, resulting in further weakening of the already unstable foundation. As the water

level rose rapidly behind Dam No. 3, the dam was becoming super-saturated, thus increasing its weight and adding to the load on the foundation. The increased weight of the downstream portion of the dam in combination with the weakening of the foundation resulted in a large rotational shear failure of the downstream shell and liquefaction of the dam. This leads to the near-zero shear strength of the material within the dam caused sudden total collapse of the dam.

5. Analysis

- There is a number of elements involving in the failure process:

+ The foundation material sludge is a weak material having negligible shear streng that were extremely detrimental to the long-term stability of these dams.

+ Within a year prior to the failure of Dam No. 3, piping occurred to some extent in the dam foundation, which would have contributed significantly to the weakening of an already unstable foundation

+ The spillway 60 cm diameter is insufficient capacity to handle the water increase at the

time of failure.

+ Poor standard in earth-dam construction, the foundation was not prepared and the fill material was not compacted. This could affect the surface erosion capacity of the dam and overall stability.

+ Properties of coal wastes material used to construct dam is low unit weight increasing liquefaction probability.

+ No adequate means were provided for safely controlling internal seepage through the embankment and foundation.

+ Components at risk are: the reservoir, the coal waste dam, the emergency spillway, and the foundation.

+ Time factor is involved with all processes as the duration of precipitation, the increasing of water level, the weakening state of foundation and the tailings dam, the liquefaction of tailings dam.

- The disaster failure of the coal refuse dam on Buffalo Creek manifestes a combination of various factors, from external factors that was precipitation from heavy runoff and melting snow to the unstable state of the dam itself and its foundation. The interactive flow from the precipitation in the combination with the insufficient capacity of the emergency spillway increased the water level of the reservoir. Then, the other interactions within the system, i.e., the interactions between the reservoir and tailings dam, and the foundation, and the property of coal waste material, caused the sliding of the downstream shell and resulted in liquefaction of the dam. Eventually, the rising water level contributed to the liquefaction leading to collapse of the dam. This case failure shows a chronology time of all effects.

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Failure No. 5: Canyon Lake dam system

1. General information

- Location: Rapid City, South Dakota, USA
- Failure: Breach of dam
- Fatalities: 238
- Year of failure: 1972
- Year of construction: 1938
- Function of the dam system: Recreation

2. External factor

- Two thunderstorms

  Intensity: 63 mm/h

  Duration: 6 hours

3. Description of the site, structure and materials:

- Canyon Lake Dam was a 6 m high earth dam, 152.4 m long, earthfill dam located 11.3 km up the meandering Rapid Creek that flows through Rapid City.
- Reservoir has a total capacity of 236,828 m^3.
- Catchment area was 25,9 km^2.

4. Description of failure:

On June 9, 1972 a tragedy occured for Rapid City, South Dakota along the eastern slopes of the Black Hills mountain range. The two isolated thunderstorms that struck the area produced a total of 381 mm of rain in just 6 hours. The flash flood within the catchment of the reservoir carried debris-laden water down into Canyon Lake reservoir where it accumulated. The dam spillway gates were opened to avert the rising water levels but they soon became clogged so that the water level continued to rise until the dam was overtopped. Water flowed over the earthfill embankment for about 45 minutes before complete breaching of the dam occurred.

5. Analysis

- There is a number of elements involving in the failure process:

  + Two intense thunderstorms: the heavy sustained rainfall averaged about four times the 6-hours amounts that are to be expected once every 100 years in the area.

  + The spillway gates were clogged by debris.

  + The volume of water normally stored behind Lake Canyon dam was relatively small.

  + The dam was constructed by earthfill.

  + Components at risk are: the resevoir, the earthfill dam, spillway gates

+ Time factor is expressed in the duration of rainfall, time for increasing of water level, time for developing the breach of the dam.

- The breach of Lake Canyon dam shows the contribution of various factors to the final failure and a process of interactions. In which, the external factor are two intense thunderstorms which generate the interactive flow, i.e., the flood runoff, with the dam system. This interaction instigates a series of subsequent interactions: each interaction is contributed by many factors: the rising of water level which contributed by the failure of spillway gates, i.e, clogging. Then, the interaction between the reservoir and the earthfill dam creates the overflow and leads to breach of the dam. It also shows the effect of spillway gates to discharge capacity of spillway.

References:

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Failure No. 6: Upper Stillwater dam system

1. General information

- Location: Northern Utah, USA
- Failure: Foundation movement
- Fatalities: 0
- Year of failure: Summer 1988
- Year of construction: 1985 - 1987
- Function of the dam system: Regulating the flows in the area.

2. External factor

- First filling activity

  Intensity: No information

  Duration: No information

3. Description of the site, structure and materials:

- Upper Stillwater dam is a 88.4 m high straight gravity structure. It's crest is approximately 816.9 m long and 8.9 m wide at an elevation of 2492.50 m.

- The reservoir behind the dam has a total capacity of approximately 40.84×10^6 m^3.

- The spillway, a central overflow spillway, consists of a 182.9 m long uncontrolled ogee crest, a slip-formed concrete stepped chute, and a hydraulic jump basin. The design discharge capacity is 424.8 m^3/s.

- The outlet works consists of a single 1.8 m diameter conduit beneath the dam from a free-standing intake tower.

- Foundation includes layers:

  + A thick argillite layer is present near the base of the dam at both abutments.

  + A lower sandstone unit, with nearly horizontal bedding structure, forms most of the foundation.

  + A continuous 0.61 m thick argillite interbed, labeled Unit L, lies beneath the dam within the lower sandstone foundation.

- Blanket grouting was performed over the entire foundation to a depth of 9.1 m.

4. Description of failure:

Beginning in June 1988, the reservoir was filled up to a height of 71.4 m for the first time, providing the downstream hydrostatic load. This load provoked the foundation to move at discrete locations as the yields along Unit L argillite far exceeded the expected values.

5. Analysis

- Factors related to the failure process:

+ First filling activity which provided an inflow to increase water level of the reservoir.

+ Hydrostatic load created due to the inreasing of water level

+ Foundation structure with three layers of different materials

+ Properties of the materials within the foundation

+ Components at risk are reservoir, foundation, and buttress dam

+ The contribution of time factor to failure is expressed in the duration of first filling, the interval for action of hydrostatic load within the foundation.

- This failure is the excessive horizontal movement of the foundation. It is triggered by the interaction of the activity with the dam system, i.e., the inflow. Additional, another interaction between components of the system, i.e., the hydrostatic load of the reservoir acting on the foundation, combines with the properties of foundation materials causing the sliding of the foundation rock mass.

Reference:

Anderson, C. *et al.* (1998) *Concrete dams - Case histories of failures and nonfailures with back calculations*, *Dso-98-05*. USBR - Dam safety office.

Failure No. 7: Acude da Nacao dam system

1. General information

- Location: Bom Conselho, in the state of Pernambuco, Brazil
- Failure: Piping leading to breach of dam
- Fatalities: 0
- Year of failure: June 2010
- Year of construction: 1980s
- Function of the dam system: irrigation and providing drinking water to local communities.

2. External factor

- Extreme rainfall

  Intensity: no information

  Duration: no information

3. Description of the site, structure and materials:

The Acude da Nacao dam system includes components as follow:

- Acude da Nacao dam was a homogenous compacted earth fill, 12m high, 240m long and resting on bedrock. The crest was protected by a pavement layer.

- Upstream slope: 2.5(H):1(V) protected by a layer of riprap;

- Downstream slope 2(H):1(V) addition of a granular filter and drainage layer, 1.5m thick, covering the bottom half of the slope.

- The embankment fill material was a non-dispersive soil.

- The dam was equipped by a 30m long uncontrolled spillway with four rectangular openings with approximate dimensions of 1.0m x 1.5m.

4. Description of failure:

In 2010, the reservoir was filled rapidly by intense rain in the area. The spillway gates were not capable of discharging the excess water, causing the increase of the reservoir and overtopping. Higher reservoir result in higher hydraulic gradients within the dam. The piping action was developed and ensued by breaching of the dam.

5. Analysis

- Factors related to the failure process:

  + External factor: the extreme rainfall which caused the reservoir level reaches its peak and the phreatic line in the dam rises.

  + The inability of the spillway to discharge excess water, which contributes significantly to the failure.

+ The slope protections: to protect the dam from external erosion of the overflow.

+ Earthfill material composed the dam: the maximal gradient exceeds the critical gradient of the material: this criterion identifies the initiation of piping erosion.

+ Components at risk are reservoir, foundation, spillway, earthfill dam.

+ Time factor is presented in the duration of rainfall, process of internal erosion until the development of breach of the dam.

This failure is the result of a combination of various factors. The inreasing of water level was contributed by the interaction of rainfall to the reservoir. Then, the overtoping was contributed by the combination of excessive water level and the inability of the spillway to discharge the surplus water. Also, the combination of the seepage load and earthfill material caused the development of the piping which resulted in the collapse of the dam.

References:

Borela, R. and Melo, D. de (2017) 'Acude da Nacao dam failure: Insights and prospects on resilient structure design', in *PGS Workshop 2017 | Climate Change and Geotechnical Engineering April 21st , West Lafayette, IN*.

Moura, D. de M. *et al.* (2017a) 'Failure of the Acude da Nacao earth dam: A probabilistic perspecive', in *Proceedings of the 37th US Society of Dams Conference, Anaheim, CA, April 3-7, 2017*, pp. 1689–1699. doi: 10.1017/CBO9781107415324.004.

Moura, D. de M. *et al.* (2017b) 'It's a Small World: Managing Our Water Resources', in *37th Annual USSD Conference Anaheim, California, April 3-7, 2017*. United States Society on Dams.

Failure No. 8: Movi dam system

1. General information

- Location: Morvi, Saurashtra region, India
- Failure: Collapse due to overtopping
- Fatalities: about 1,500 – 15,000
- Year of failure: 11 August 1979
- Year of construction: completed August 1972
- Function of the dam system: irrigation scheme

2. External factor

- Rain storm: rainfall over Saurashtra region was more than 7 times the normal for this period

Intensity: 447 mm/h

Duration: 12 days

3. Description of the site, structure and materials:

The Morvi dam system includes components as follow:

- The Morvi dam was 22.56 m high and 3,905 m long and consisted of a masonry spillway in river section and earthen embankments on both sides. The embankment had a 6.1 m top width, with slopes 1 V : 3 H and 1 V : 2 H respectively for the upstream and downstream slopes and a clay core extending through alluvium to the rocks below. The upstream face had a 61 cm small gravel and a 61 cm hand packed riprap. The embankments were structured by a central clay core, transition zones and gravel upstream and downstream shells.

- The central concrete gravity section included masonry work on the exterior as well as 18 massive radial arm gates, two of which failed to open during the flood.

- The embankment material consisted of clayey silt, sand, and rock fragments taken from excavations and burrow areas of the river's canyon area.

- The spillway do not have enough spillway capacity.

- Reservoir storage: 1.1×10^8 m^3

- The catchment area: 1900 km^2

4. Description of failure:

On 11 August 1979, the Machhu-2 earth dam failed due to excessive rain and insufficient spillway capacity.

5. Analysis

- Factors related to the failure process:

+ External factor: the extreme rainfall which caused the reservoir level reaches its peak.

+ The inability of the spillway to discharge excess water: designed capacity was 5.7 x 10^3 m^3/s while the actual observed peak flood exceeding 1.6 x 10^4 m^3/s, three times of what the dam was designed for.

+ The central clay cores of embankment dams are resistant to erosion but are still at risk of failure.

+ Components at risk are reservoir, spillway, central clay cores, embankment dam.

+ Time factor is presented in the duration of rainfall, process of overflow until the collapse of the dam.

The failure of Morvi dam was consequence of a combination of several factor and its interactions. The first interaction was the runoff flow from the extreme rainfall flowing into the reservoir. This flow accompanied with the inadequate capacity of the spillway causing the increasing of water level and leading to overtopping of the reservoir. At this stage, a combination of the overflow and erodibility of material of downstream leading to the collapse of the embankment dam.

References:

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Failure No. 9: Ulley dam system

1. General information

- Location: Rotherham, England
- Failure: Erosion of downstream shell
- Fatalities: 0
- Year of failure: 26 June, 2007
- Year of construction: completed 1973
- Function of the dam system: Recreational facility

2. External factor

- Rain:

  Intensity: 92.4 mm/h

  Duration: 18 hours

3. Description of the site, structure and materials:

The Ulley dam system includes components as follow:

- Ulley dam, which is a diaphragm embankment structure, has a puddle clay core, a crest length of 205 m and a maximum height of 16 m.
- The reservoir has a capacity of 580,000 m^3, and a surface area of 0.12 km^2.
- The catchment area: is 11.86 km^2
- The dam is located on sandstones of the area.
- The dam has three spillways:

  + Two narrow cascades spillways down both mitres with masonry retaining walls on either side. These spillway have a series of plunge pool type stilling basins to dissipate energy.

  + A concrete spillway was constructed at the south end of the dam to discharge, via a chute, to a short stilling basin adjacent to the stream.

- Total outflow in the spillways during the incident was about 10.1 m^3/s.
- There is a low level outlet with the capacity is 18,000 m^3/day

4. Description of failure:

In the evening of 25 June 2007, after a day of heavy rain, the older masonry spillway along the left mitre of the embankment suffered from out of bank flows. The hydraulic pressure of the channel flow exceeded the retaining wall threshold causing it to collapse and the subsequent erosion of the embankment fill material.

5. Analysis

- Factors related to the failure process:

+ External factor: the heavy rain which rose the reservoir to 1.62 m above top water level.

+ The arrangement of the design meant that the older, stepped masonry spillway always operated preferentially so that flood water reverted to the original masonry stepped spillway in the left mitre of the main earth embankment.

+ Condition of the masonry retaining walls at the time of failure: the masonry had lost much of its pointing and had little bedding mortar between the blocks.

+ Earthfill material of embankment dam

+ The size of the outlet was rather low to lower reservoir levels, which constituted an increase in the water level.

+ Components at risk are: reservoir, embankment dam, masonry spillway, masonry retaining wall.

+ Risk factor is expressed in duration of rainfall,

- Failure of the Ulley dam system in June, 2007 was a combination of many factors and interactions. The first interaction is the inflow which created by heavy rain fell into the reservoir. As the reservoir increases due to the inflow, subsequent interactions appears including the overflow running down the older spillway, hydraulic load acting on the masonry retaining wall and downstream shell. These interactions associated with properties of the components such as the arrangement of the spillways, condition of the masonry wall, earthfill material of downstream shell causing a sequence of failure those were the deterioration of the channel, the collapse of the wall, and the following erosion of the downstream shell.

References:

Charles, J. A., Tedd, P. and Warren, A. (2011) *Lessons from historical dam incidents*.

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Failure No. 10: Maich dam system

1. General information

- Location: Renfrewshire, Scotland
- Failure: Erosion of downstream shell
- Fatalities: 0
- Year of failure: 1 August, 2008
- Year of construction: in the second half of the 19th century
- Function of the dam system: public water supply

2. External factor

- Heavy rain:

  Intensity: 10.4 mm/h

  Duration: 2 hours

3. Description of the site, structure and materials:

The Maich dam system includes components as follow:

- The dam was a small diaphragm embankment about 9 m high and 35 m long, with a central clay core. The top of the dam had settlement of about 200 mm relative to its ends.

- The bypass channel about 4 m wide with a 25 m long section collapsed a few years previously.

- An overflow spillway about 6 m long was located on the right abutment discharging into the bypass channel.

- The reservoir has capacity about 24 300 m^3, and water level of 6.34 m.

- The catchment area of 5.4 km^2 located in hilly ground.

- An overflow weir about six metres long was located on the right abutment,

- The outlet consisted of a 150-mm pipe through the dam, but it was inoperable.

4. Description of failure:

In the early hours of 1 August 2008, a heavy rain fell in west central Scotland causing local flooding which went into the reservoir and caused overtopping. The overtopping had eroded away a large part of the downstream fill.

5. Analysis

Factors related to failure of Maich dam system

+ Fine screens for fish which restrict flow and allow debris to inhibit flow

+ The collapsed part of the bywash channel wall leading the flood flow into the reservoir

+ Long-term settlement of the crest

The interaction betweet heavy rain and the reservoir generated an flood inflow which in combine with the collapse part of the bypass channel wall leading the flood flow going into the reservoir. This, together with the settlement of the dam and placing of screens partially blocking the discharge inducing overtopping of the dam. The overflow associated with earthfill material causing erosion of the downstream shell.

References:

Charles, J. A., Tedd, P. and Warren, A. (2011) *Lessons from historical dam incidents*.

Mann, R. and Mackay, A. (2009) 'Maich dam overtopping emergency, Renfrewshire – engineering and emergency response aspects', in *Dams & Reservoirs*. ICE Publishing 2020, pp. 35–42. doi: https ://doi.org/10.1680/dare.2009.19.1.35.

Failure No. 11: Moihne dam system

1. General information

- Location: Germany
- Failure: Bombing
- Fatalities: 1300
- Year of failure: May 17, 1943
- Year of construction: 1913
- Function of the dam system: public water supply

2. External factor

- Bombing activity

3. Description of the site, structure and materials:

The Möhne dam system includes components as follow:

- The Möhne dam was a curved gravity dam and was 40.3 m high and 650m long.
- The reservoir has capacity of $134x10^6$ m^3.and was full when failure occurred.

4. Description of failure:

On May 17, 1943, bombers attacked the Moihne dam. The bombing occurred at a time when the Moihne reservoir was filled to its capacity, generated a breach 77 m long and 22 m deep. $116x10^6$ m^3 of water flowed through the breach within 12 hours.

5. Analysis

Factors related to failure of Moihne dam system

+ Bombing activity

+ Water level was full at the time of failure

The failure of the Moihne dam shows a combination of the bombing activity with condition of the reservoir which together exacerbate the failure.

References:

Jansen, R. B. (1983) *Dams and Public Safety: A Water Resources Technical Publication*. Denver, Colorado: Bureau of Reclamation.

Mason, A. (2018) *The Incredible Story Of The Dambusters Raid | Imperial War Museums*. Available at: https://www.iwm.org.uk/history/the-incredible-story-of-the-dambusters-raid (Accessed: 25 April 2020).

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Failure No. 12: Sgorigrad dam system

1. General information

- Location: Western Bulgaria
- Failure: Collapse of tailings dam
- Fatalities: 107
- Year of failure: 1st May, 1966
- Year of construction: 1958
- Function of the dam system: Retaining the residual waste produced by the flotation process.

2. External factor

- Heavy rains

  Intensity: no information

  Duration: 3 days

3. Description of the site, structure and materials:

The Sgorigrad dam system includes components as follow:

- The Sgorigrad dam, a 12-meter high sand embankment structure.
- The reservoir attained the approximate height of 60 m in 1966.
- The decant structure with spillway to discharge the decanted water.
- The concrete pipes for discharging the decanted water were placed at the bottom of the valley and the basin were connected to the decant structure.

4. Description of failure:

On 1st May 1966 the failure of the tailings dam occurred after days of heavy rains. The reservoir was high level and the tailings were saturated. The dam became unstable and then the waste liquefied and failed suddenly.

5. Analysis

Factors related to failure of Sgorigrad dam system:

+ Heavy rains
+ Condition of the dam: fissures at the downstream base of the dam due to water infiltration inside the reservoir which had not been detected before.
+ The decant towers had a low spillway capacity leading to the increasing of water level dangerously and causing the submersion of the beach.
+ Components at risk: the reservoir, the tailings dam, spillway
+ Time factor was shown in the duration of heavy rain and liquefaction time leading to dam collapse.

Failure of the Sgorigrad dam system is the result of a combination of the interactive inflow due to heavy rain, with the inadequate capacity of spillway which lead to the inreasing of reservoir and the submersion of the beach. As the beach submersion, leading to the change of tailings material which was the process of liquefaction and eventually collapse of the dam.

References:

Jansen, R. B. (1983) *Dams and Public Safety: A Water Resources Technical Publication*. Denver, Colorado: Bureau of Reclamation.

Lucchi, G. and Tosatti, G. (1985) 'Lessons learnt from the Sgorigrad and Stava disasters'.

Stava1985 (2020) *The Sgorigrad tailings dam failure, 1966*, *International Alexander Langer Award 2010*. Available at: https://www.stava1985.it/the-disaster-of-sgorigrad-in-bulgaria/?lang=en (Accessed: 25 April 2020).

Failure No. 13: Kasho dam system

1. General information

- Location: Japan
- Failure: Some structures were cracked
- Fatalities: 0
- Year of failure: October 6, 2000
- Year of construction: 1989
- Function of the dam system:

2. External factor

- Earthquake

Accelerations: 2.09g (N-S), 1.43g (E), and 0.90g (V)

3. Description of the site, structure and materials:

The Kasho dam system has characteristics as follow:

- Kasho Dam is a concrete gravity dam with a structural height of 46.4 m, a crest width of 7.5 m at elevation 124.4 m, a base width of 35.6 m, and a crest length of 174 m.

- The reservoir has a normal elevation of 118 m and was at elevation 112.2 m during the earthquake.

4. Description of failure:

On October 6, 2000, a magnitude Mw 6.7 earthquake occurred in the Western Tottori Prefecture in Japan. Despite large accelerations of the earthquake, the dam survived the earthquake without serious damage. However, the water level dropped suddenly by 6 cm, and the walls and base of the control house, a cantilever structure projecting upstream from the dam crest, were cracked.

5. Analysis

Factors related to failure of Kasho dam system:

+ Earthquake with the magnitude of Mw6.7.

+ Condition of the dam: concrete gravity dam

+ Conditions of other components: water level of the reservoir during the earthquake, structures of other components.

+ Components at risk: the concrete dam, the reservoir, other structures.

The case of Kasho dam system is the failure under earthquake of a gravity dam system type. The interactions between the earthquake with components of the system generated different damages, depending properties of components and materials composing them.

References:

NS Energy (2011) *Lessons learned from the earthquake performance of concrete dams - NS Energy*. Available at: https://www.nsenergybusiness.com/features/featurelessons-learned-from-the-earthquake-performance-of-concrete-dams/ (Accessed: 1 May 2020).

Ohmachi, T. *et al.* (2003) 'Near Field Effects of Hidden Seismic Faulting on a Concrete Dam', *Journal of Natural Disaster Science*, 25(1), pp. 7–15.

USSD (2014) *Observed Performance of Dams During Earthquakes*.

Failure No. 14: Oroville dam system

1. General information

- Location: Feather River in California, USA

- Failure: Overtopping and failure of main spillway

- Fatalities: 0

- Year of failure: February 7, 2017

- Year of construction: completed in 1967

- Function of the dam system: flood control, water provision to southern California, and hydroelectric power generation.

2. External factor

- Earthquake

  - Intensity: 136 mm/h

  - Duration: from 2/2/2017 - 11/2/2017

3. Description of the site, structure and materials:

The Oroville dam system has characteristics as follow:

- Oroville dam is the highest earthfill dam in the United States. It is a zoned-earth-rock dam with a structural height of 226.16 m, comprising an inclined impervious core on a concrete foundation.

- The reservoir has a maximum operating storage of 4364 hm^3, area of 63.96 km^2, flood control level of 259.08 m.

- The Oroville dam includes a main spillway and an uncontrolled emergency spillway:

  + Main spillway is a concrete chute spillway located on the right abutment, composed of an unlined approache channel, a set of gates controlling by radial gates with dimensions of 17.78 cm thick and 5.18 m wide by 10.06 m high, and a concreted lined chute approximately 929m in length. The main spillway has discharge capacity of 4250m^3/s.

  + Emergency spillway is an ungated spillway with a concrete weir. The design capacity is 9910.90 m^3/s, crest elevation is 274.62 m. The emergency spillway is "activated" when the reservoir level exceeds weir height

- A gated flood control outlet was not used in 2017.

- The catchment area is approximately 9.342 km^2

4. Description of failure:

At the beginning of 2017, heavy rains required an increase of outflows from the reservoir to compensate for the rapidly rising water level. On 7 February 2017, during the reservoir release, the main spillway's concrete slab was completely damaged in one section. In order

to avoid erosion of the spillway structure, the main spillway gates were closed. Meanwhile, inflows to the reservoir continued to increase due to rainfall. Eventually, heavy rains resulted in the activation of the ungated spillway for the first time in history. Water flowed down the natural terrain downstream of the crest structure and caused extensive erosion. In response to the erosion caused by the use of the emergency spillway, on February 12, the main spillway was re-opened rapidly to release water to relieve. The reservoir was lowered, but the main spillway was severely damaged (Figure A-3.1).

Figure A-3.1. Damaged main spillway

5. Analysis

Factors related to failure of Oroville dam system:

+ Heavy rain

+ High water level of the reservoir before flood

+ Conditions the main spillway:

- Insufficient thickness of the main spillway's concrete slab for the design hydraulic conditions
- Cracks and joint displacements under the base slabs caused water stagnation and cavitation pressure intrusion
- Damaged concrete: possibly caused by cavitation or erosion due to irregularities or rough surface.
- Lifted slab panels: possibly caused by poor drainage under slabs, and/or inadequate anchoring of slab to foundation.

- Geological conditions below the spillway chute: the foundation rock is comprised of the metavolcanic materials which is highly fractured and heterogeneous.
- Possible damage due to encroaching vegetation around the main spillway chute.

+ Malfunction of the outlet work

+ Components at risk: the embankment dam, reservoir, main spillway, emergency spillway, chute slab of the main spillway, downstream face of the abutment, outlet work.

The Oroville dam system's failure resulted from a combination of multiple interactions in chronological order. The first interaction was generated by the association of three factors: the flood inflow from rainfall, the malfunction of the outlet work, and the water level of the reservoir, which induced the increase of water level. The water level changing led to subsequent interactive flows between the reservoir with the main spillway and the emergency spillway, resulting in failures of the spillway chute slab and the downstream face of the abutment. These interactions also showed the contribution in performance of a component to its high-level component. For example, the failure of the concrete slab led to the closure of the main spillway.

References:

FERC (2005) *Oroville Facilities - FERC Project No. 2100*.

France, J. W. *et al.* (2018) *Independent Forensic Team Report: Oroville Dam Spillway Incident*.

Hollins, L., Eisenberg, D. and Seager, T. (2018) 'Risk and Resilience at the Oroville Dam', *Infrastructures*, 3(4), p. 49. doi: 10.3390/infrastructures3040049.

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Stork, R. *et al.* (2017) *The Oroville Dam 2017: Spillway Incidents and Lessons from the Feather River Basin*, *Friends of the River*. California.

Failure No. 15: Stave dam system

1. General information

- Location: Dolomite Mountains, North-Eastern Italy
- Failure: The dam collapses due to soil liquefaction due to static loading
- Fatalities: 268
- Year of failure: July 19, 1985,
- Year of construction: completed in 1961
- Function of the dam system: storing and decanting the fluorite tailings

2. External factor

- Tailings deposit

3. Description of the site, structure and materials:

The Stave dam system has characteristics as follow:

- The tailings dam was built on a hill-slope, and consisted of two basins corresponding two separate tailings dams, one above the other.(Luino, Tosatti and Bonaria, 2014). When collapse took place, the upper dam was 28 m high and the second basin was 23 m high. The two Stava tailings dams were raised by means of a hydrocyclone; this equipment allows the coarser part -i.e., the sand - to be separated from the finer one. The difference of altitude between the base of the lower basin and the top of the upper basin was over 50 m. (Figure A-3.2).

- The dam of the upper basin had been built with an excessive slope (over 80%) and did not allow water drainage or consolidation of the tailings therein contained.

- The area of the dam system was scattered with water springs, since the foundation ground was made up of a thick layer of high-permeability glacio-fluvial deposits. Intense groundwater circulation, often reaching the ground surface, considerably hindered silt consolidation inside the dams, since dissipation of pore-water pressures was not possible.

- The high acclivity of the natural slope, with an average inclination of 25%, should have discouraged the construction of tailings dams on this site.

4. Description of failure:

On July 19, 1985, the tailings dams of the Prealpi Mineraria mine, located on the Porcellini Creek, Italy, failed. The dam of the upper basin collapsed, also causing the failure of the lower one. Failure of the dams occurred suddenly and was accompanied by a 180,000 m3 flow slide of semi-fluid slime.

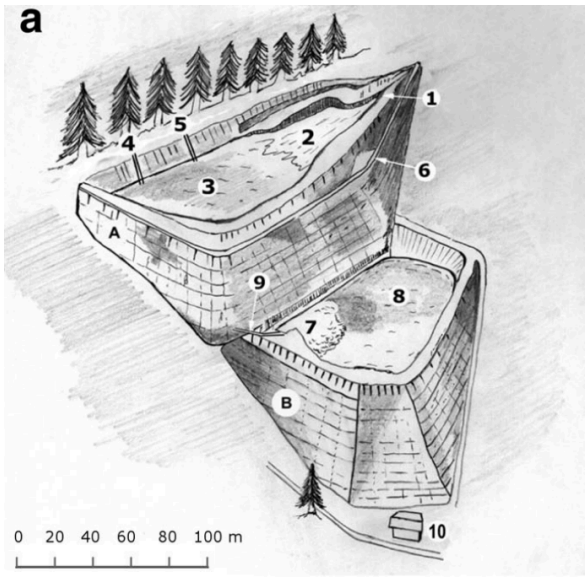

Figure A-3.2. Sketch of the Stava tailings dams (Pirulli *et al.*, 2017)

5. Analysis

Factors related to failure of the Stave dam system:

- The construction operations of the embankments were inadequate

- Overloading due to the additional elevation of the embankment that was under construction.

- Insufficient separation between the reservoir and the embankment

- The upper basin has a rather inhomogeneous soil composition, with negative feedback on the shear strength parameters and horizontal and vertical hydraulic conductivity.

- The area where the basins stood was marshy and poorly drained and, as such, unstable and unsuitable for supporting these geotechnical constructions.

- The overflow and drainage pipes had been wrongly placed inside the upper basin, and they sagged under the increasing weight of the silt deposits. This caused significant leaks inside the reservoir.

Failure of the Stave tailings dam system is a result of a combination of several factors. The construction operation increases the self-weight of the dam, associated with the conditions within the system: incorect installation drainage pipe, homogeneous soil material, instability of the area, and the high slope of the dam.

References:

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Appendix 4. Functional block diagrams

Functional block diagram relating to hydraulic flows

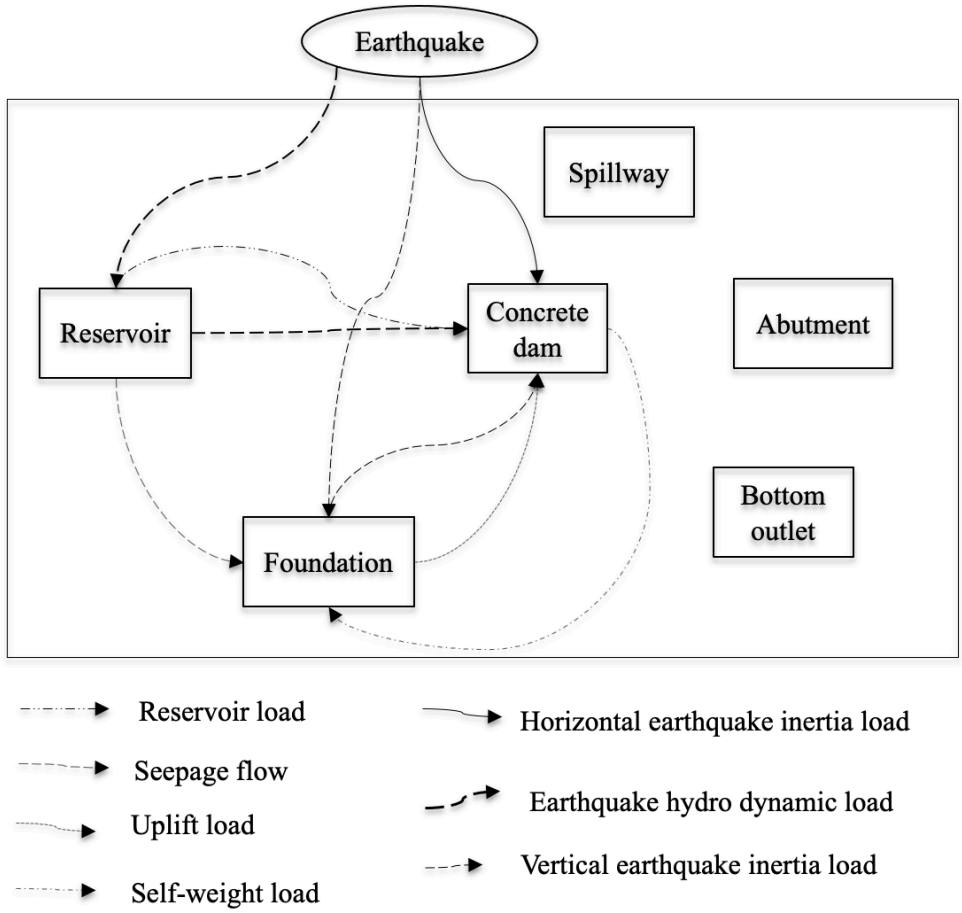

Figure A-4.1. Functional block diagram relating to the earthquake factor (Concrete dam system)

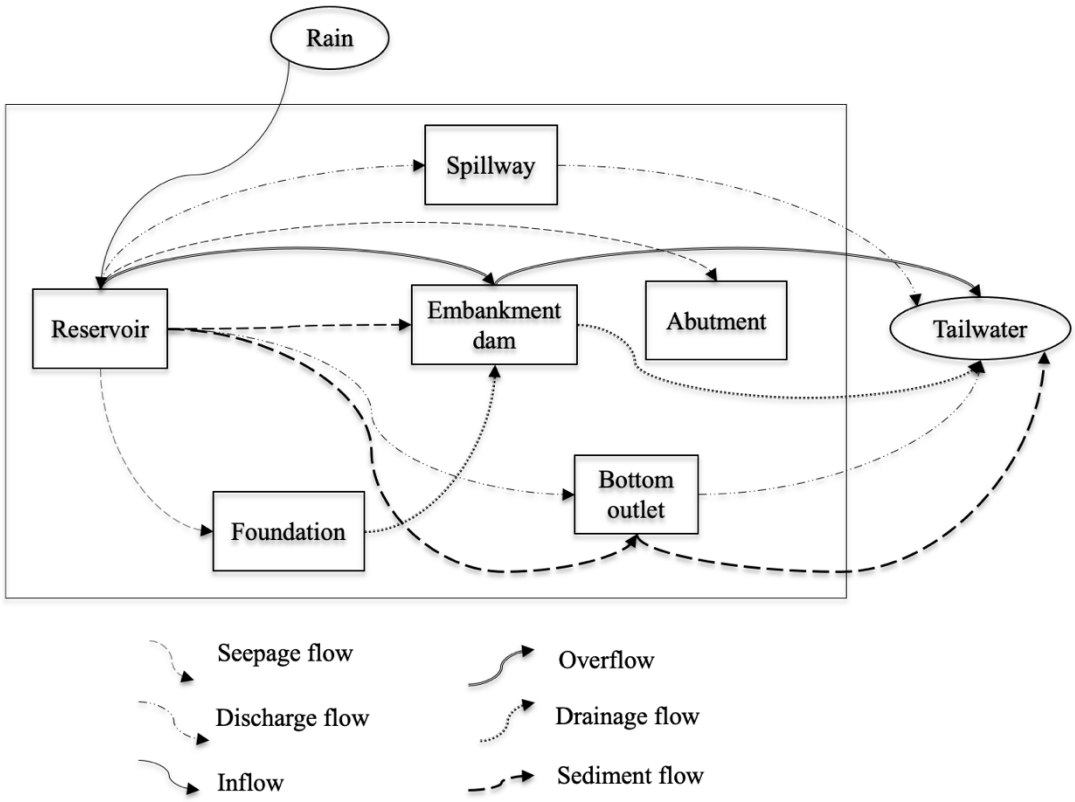

Figure A-4.2. Functional block diagram relating to hydraulic flows (Embankment dam system)

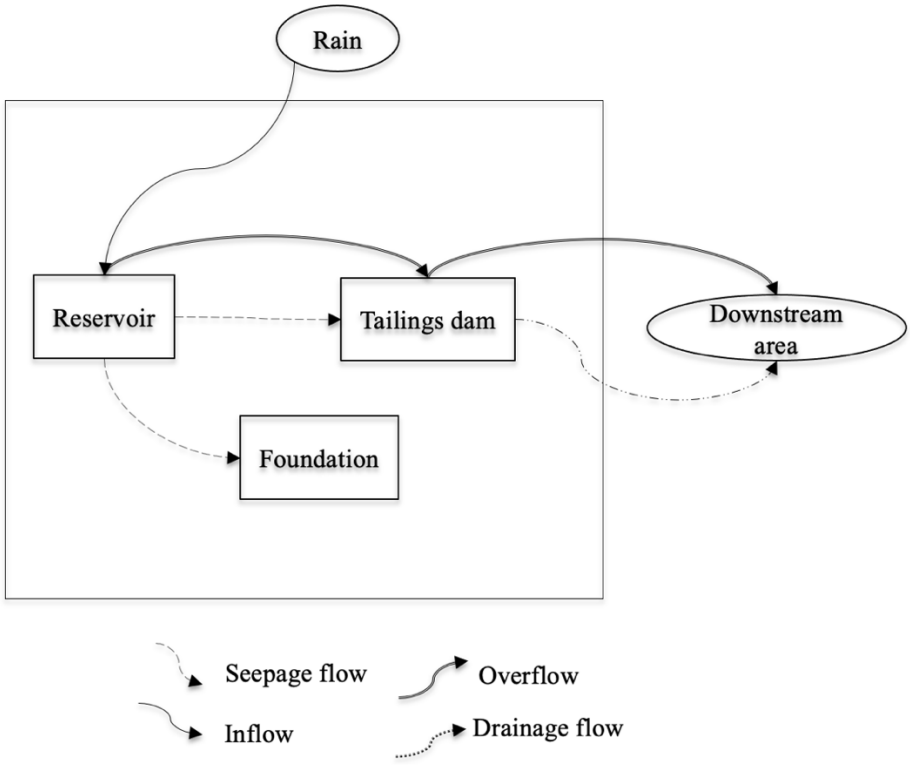

Figure A-4.3. Functional block diagram relating to hydraulic flows (Raised-tailings dam system)

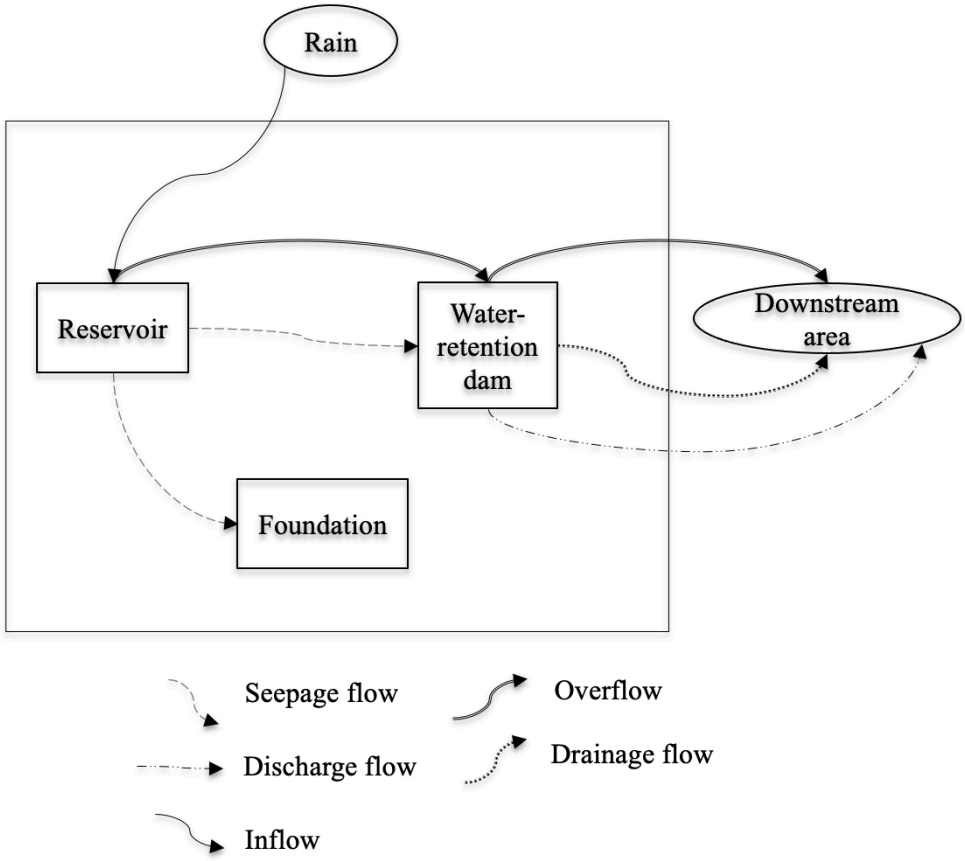

Figure A-4.4. Functional block diagram relating to hydraulic flows (Water-retention dam system)

Appendix 5. Functional analysis of dam system at sub-component level

Table A-5.1. Primary functions and technical functions at the sub-component level:

Component	Primary functions		Technical function	
	Hydraulic function	Mechanical functions	Hydraulic function	Mechanical functions
Components of gravity dam				
Gravity dam body	Retaining water		Limiting flow from the reservoir	- Resisting sliding - Resisting crushing - Resisting overturning
Gallery drainage	Draining seepage			
Components of arch dam				
Arch dam body	Retaining water in the reservoir		Limiting flow from the reservoir	- Resisting sliding - Resisting crushing - Resisting overturning
Gallery drainage	Draining seepage			
Components of buttress dam				
Deck		- Supporting the water load - Transmitting the water load to the buttresses	Limiting flow from the reservoir	- Resisting sliding - Resisting crushing - Resisting overturning
Buttresses		- Supporting the deck		- Resisting sliding - Resisting crushing

		- Transmitting the water load to the mat foundation		- Resisting overturning
Concphrete cutoff	Preventing seepage	Supporting the deck		- Resisting sliding - Resisting crushing - Resisting overturning
Mat foundation		- Supporting the buttresses - Distributing the water load to the foundation		- Resisting sliding - Resisting crushing - Resisting overturning
Components of homogeneous embankment dam				
Homogeneous dam body		- Imparting stability	Preventing seepage	- Resisting internal erosion - Resisting external erosion - Resisting upstream sliding - Resisting piping - Resisting sloughing - Resisting breach - Resisting settlement - Resisting erosion along the conduit
Horizontal blanket drainage	Draining seepage			
Rock toe drainage	Draining seepage			- Resisting erosion of the downstream toe
Upstream protection		Protecting the slope	Draining seepage	- Resisting external erosion - Resisting piping - Resisting breach

				- Resisting settlement - Resisting sliding of US shell
Downstream protection		Protecting the slope	Draining seepage	- Resisting external erosion - Resisting piping - Resisting sloughing - Resisting breach - Resisting settlement - Resisting sliding of DS shell
Components of diaphragm embankment dam				
Upstream protection		Protecting the slope	Draining seepage	- Resisting sliding of US shell - Resisting piping - Resisting sloughing - Resisting breach - Resisting settlement
Downstream protection		Protecting the slope	Draining seepage	- Resisting sliding of DS shell - Resisting external erosion - Resisting piping - Resisting sloughing - Resisting breach - Resisting settlement
Diaphragm embankment dam body		- Imparting stability - Protecting the diaphragm		- Resisting internal erosion - Resisting external erosion - Resisting piping - Resisting sloughing

				- Resisting breach - Resisting settlement - Resisting erosion along the conduit
Diaphragm	Preventing seepage			- Resisting piping - Resisting breach - Resisting cracking - Resisting settlement
Horizontal blanket drainage	Draining seepage			
Upstream blanket	Preventing seepage			
Toe drain	Draining seepage			Resisting erosion of the downstream toe
Filter	Draining seepage			
Components of zoned embankment dam				
Upstream protection		Protecting the slope	Draining seepage	- Resisting sliding of US shell - Resisting piping - Resisting sloughing - Resisting breach - Resisting settlement
Downstream protection		Protecting the slope		- Resisting sliding of DS shell - Resisting external erosion - Resisting piping - Resisting sloughing - Resisting breach

				- Resisting settlement
Upstream shell		Protecting the impervious core, drainage, filter	Draining seepage	- Resisting sliding of US shell - Resisting internal erosion - Resisting piping - Resisting sloughing - Resisting breach - Resisting settlement
Downstream shell		Supporting the impervious core, drainage, filter	Preventing seepage	- Resisting sliding of DS shell - Resisting internal erosion - Resisting external erosion - Resisting piping - Resisting sloughing - Resisting breach - Resisting settlement
Impervious core	Preventing seepage			- Resisting piping - Resisting breach - Resisting cracking - Resisting settlement
Horizontal blanket drainage	Draining seepage			
Upstream blanket	Preventing seepage			
Filter	Draining seepage			
Toe drain	Draining seepage			Resisting erosion of the downstream toe

Components of water-retention tailings dam				
Upstream protection		Protecting the slope	Preventing seepage	- Resisting sliding of US shell - Resisting sloughing - Resisting breach - Resisting settlement
Downstream protection		Protecting the slope		- Resisting sliding of DS shell - Resisting external erosion - Resisting piping - Resisting sloughing - Resisting breach - Resisting settlement
Upstream shell		Protecting the impervious core, drainage, filter	Preventing seepage	- Resisting sliding of US shell - Resisting internal erosion - Resisting sloughing - Resisting breach - Resisting settlement
Downstream shell		Supporting the impervious core, drainage, filter	Preventing seepage	- Resisting sliding of DS shell - Resisting internal erosion - Resisting external erosion - Resisting sloughing - Resisting breach - Resisting settlement
Impervious core	Preventing seepage			- Resisting piping - Resisting breach

				- Resisting cracking - Resisting settlement
Horizontal blanket drainage	Draining seepage			
Upstream blanket	Preventing seepage			
Filter	Draining seepage			
Toe drain	Draining seepage			Resisting erosion of the downstream toe
Liner	Preventing seepage			
Components of raised tailings dam				
Rais tailings dam body	Retaining tailings			- Resisting external erosion - Resisting internal erosion - Resisting liquefaction - Resisting piping - Resisting settlement - Resisting breach - Resisting erosion along the conduit
Outlet pipe	Draining seepage			
Liner	Preventing seepage			
Components of foundation				
Bed foundation		- Supporting weight load of the dam		- Resisting sliding - Resisting piping - Resisting liquefaction

		- Supporting the reservoir load exerted on the US side of the dam		- Resisting settlement
Cut-off wall	Preventing seepage			- Resisting sliding - Resisting piping - Resisting settlement - Resisting cracking
Grouting	Preventing seepage			
Components of spillway	Controlling floodwater from the reservoir		- Discharging surplus flows from the reservoir	- Resisting cavitation - Resisting head-cutting - Resisting erosion at spillway base
Approach channel	Conveying water from the reservoir to the control structure			
Control structure (Weir, Gates)	Controlling discharge		Resisting insufficient capacity	- Resisting improper gate operation
Conveyance structure (Chute, Shaft, Conduit, Tunnel)	Conveying the water to the terminal part.			- Resisting cavitation - Resisting head-cutting - Spillway foundation erosion - Hydraulic jacking
Terminal structure (stilling basin, flip bucket, or plunge pool)	Dissipating the energy of the water current.			- Resisting ball milling - Resisting abrasion of stilling basin - Resisting erosion of stilling basin
Components of bottom outlet				

Intake structure	Withdrawing water from the reservoir			- Resisting clogging of trash rack
Radial gate	Controlling discharge		Resisting insufficient capacity	- Resisting improper gate operation
Conduit	Conveying the water to the terminal part.			- Resisting piping along the outside of conduit - Resisting piping by flow from a conduit - Resisting piping of soils into a conduit - Resisting deterioration - Resisting cavitation of conduit - Resisting abrasion of conduit
Stilling basin	Dissipating the energy of the water current.			- Resisting ball milling - Resisting abrasion of stilling basin - Resisting erosion of stilling basin
Components of abutment				
Abutment		Providing stability for the dam		- Resisting piping - Resisting sliding - Resisting external erosion
Drainage	Draining seepage			
Thurst block		Supporting the arch thrust		- Resisting sliding

Appendix 6. Hierarchy of concepts and relations

This Appendix presents the hierarchy of concepts and relations proposed in chapter 4. The hierarchy is implemented in CoGui, a conceptual graph editor.

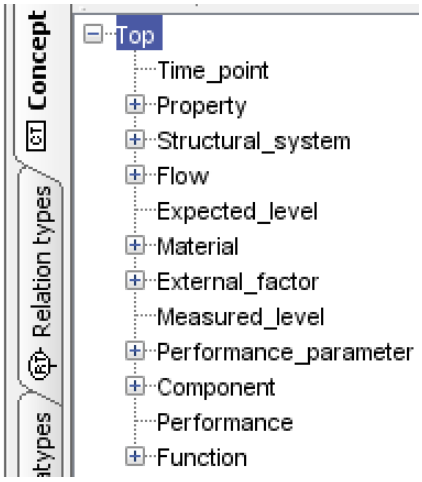

Figure A6.1. Hierarchy of the main concepts

Figure A6.1 shows the main concepts of the failure model. The highest level is the concept *Top*, which is *the* universal concept. The next lower level includes main concepts of the failure model: *Time_point*, *Property*, *Structural system*, *Flow*, *Expected level*, *Material*, *External factor*, *Measured level*, *Performance parameter*, *Component*, *Material property*, *Performance*, and *Function.*

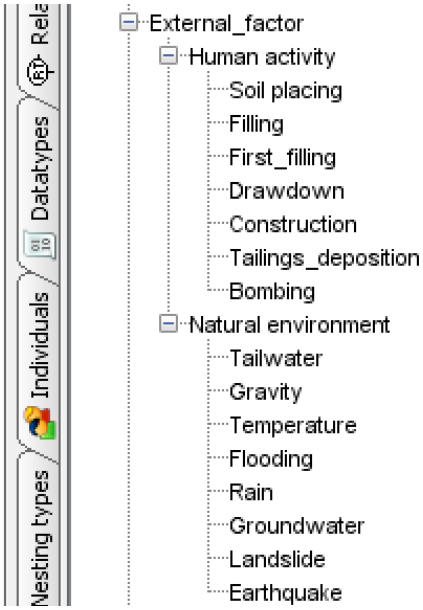

Figure A6.2. Hierarchy of the concept External factor

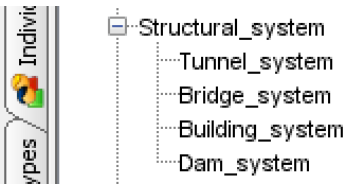

Figure A6.3. Hierarchy of the concept *Structural system*

Figure A6.3 shows the hierarchy of the concept *Structural-system*. The concept is decomposed into one lower-level including *Dam system*, *Building system*, *Bridge system*, *Tunnel system* concept. The number of sub-concepts can be increased during the process of applying the model to different types of structural systems

Figure A6.4. Hierarchy of the concept Component

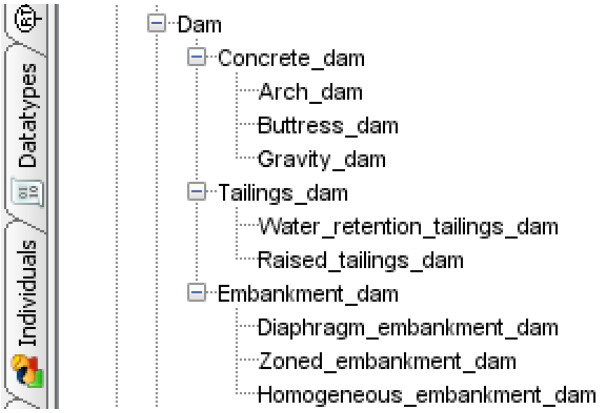

Figure A6.5. Hierarchy of the concept Dam

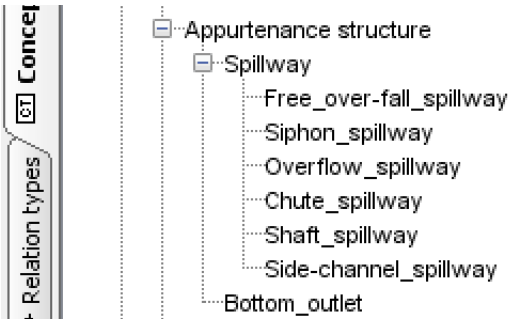

Figure A6.6. Hierarchy of the concept *Appurtenant structure*

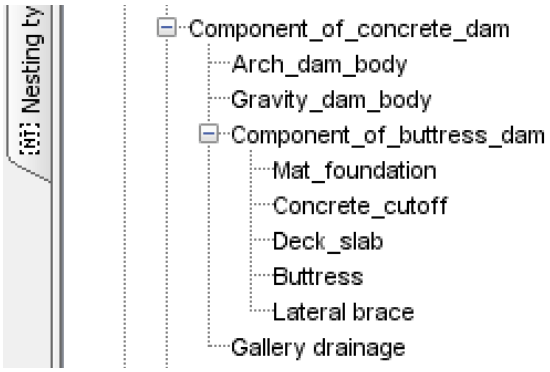

Figure A6.7. Hierarchy of concept concrete dam

Figure A6.8. Hierarchy of the concept *Embankment dam* and *Tailings dam*

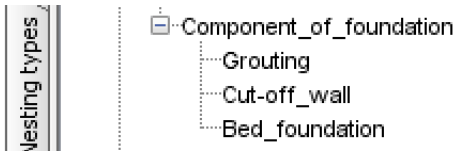

Figure A6.9. Hierarchy of the concept *Foundation*

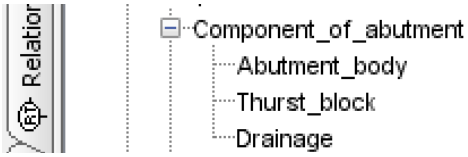

Figure A6.10. Hierarchy of the concept *Abutment*

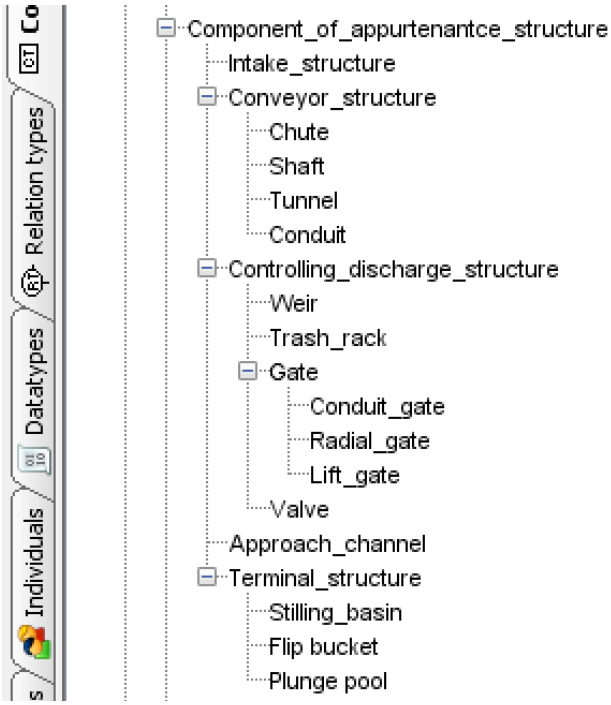

Figure A6.11. Hierarchy of the concept *Appurtenant structure*

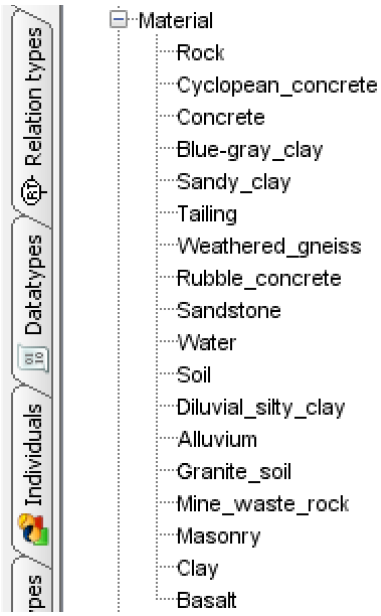

Figure A6.12. Hierarchy of the concept *Material*

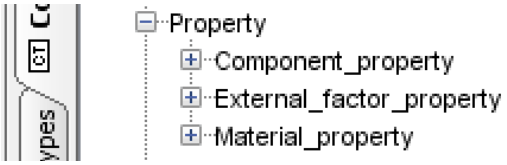

Figure A6.12. The first sub-level of the hierarchy of the concept *Property*

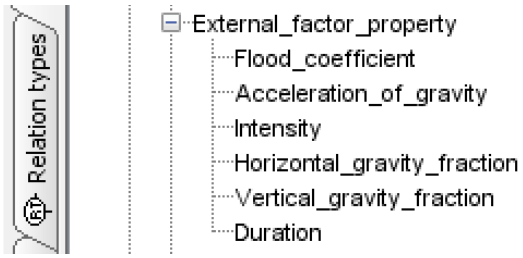

Figure A6.13. Hierarchy of the concept *External factor property*

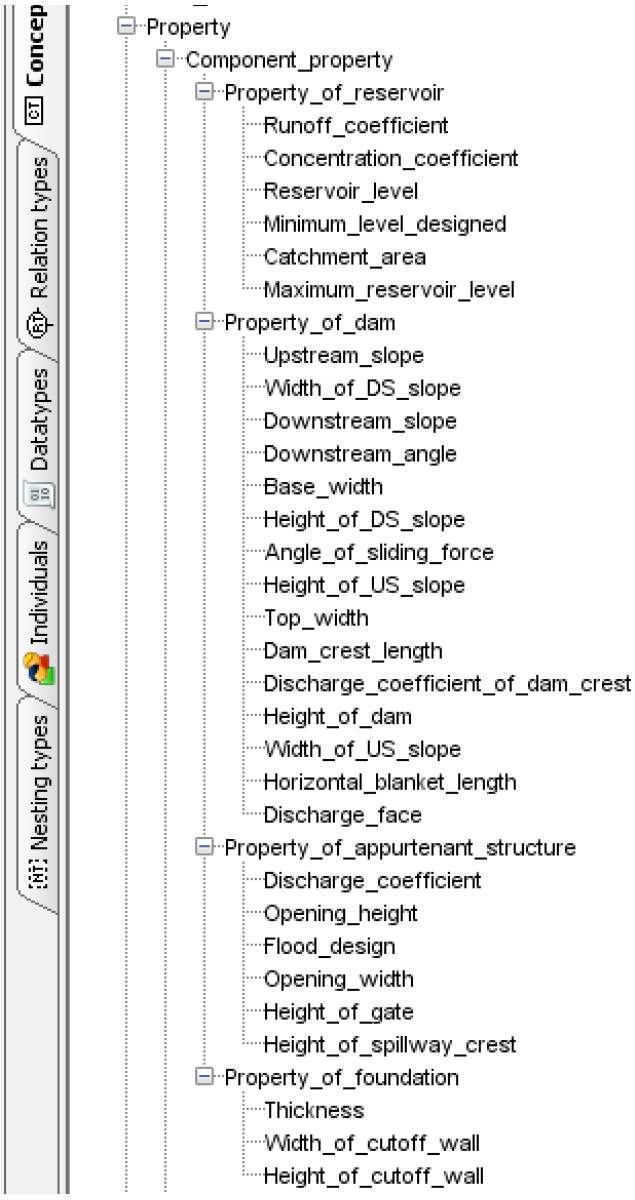

Figure A6.14. Hierarchy of the concept *Component property*

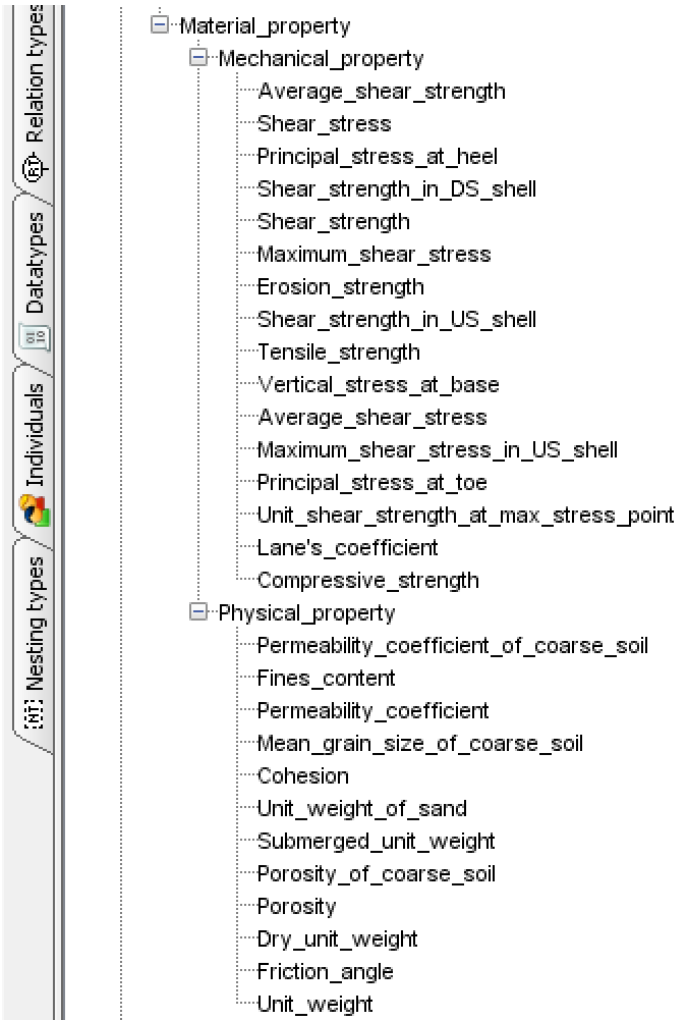

Figure A6.15. Hierarchy of the concept *Material property*

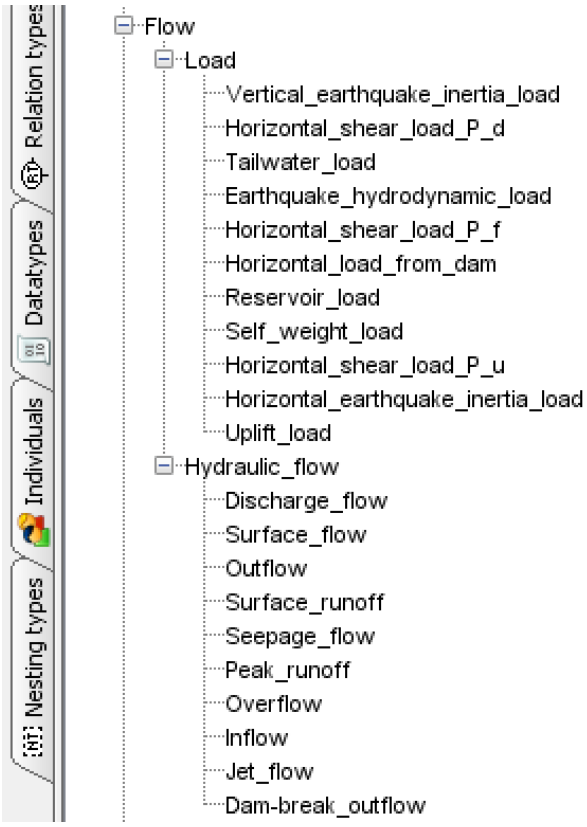

Figure A6.16. Hierarchy of the concept *Flow*

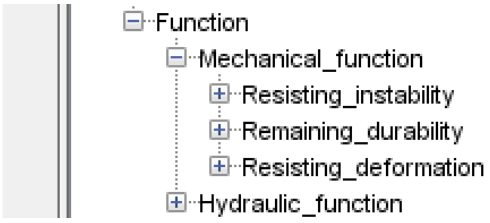

Figure A6.17. Hierarchy of the concept *Function*

Figure A6.18. Hierarchy of the concept *Resisting instability*

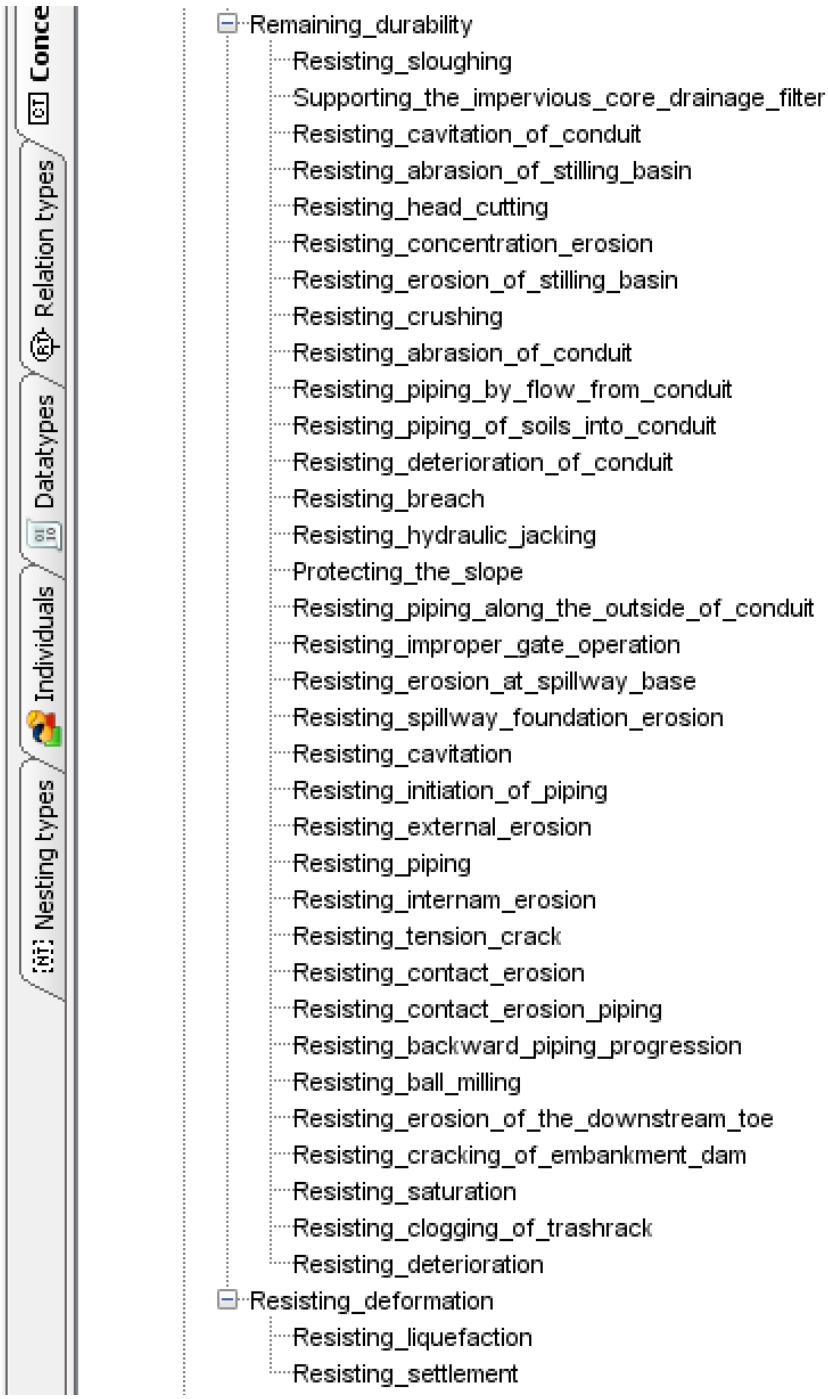

Figure A6.19. Hierarchy of the concept *Remaining durability* and *Resisting deformation*

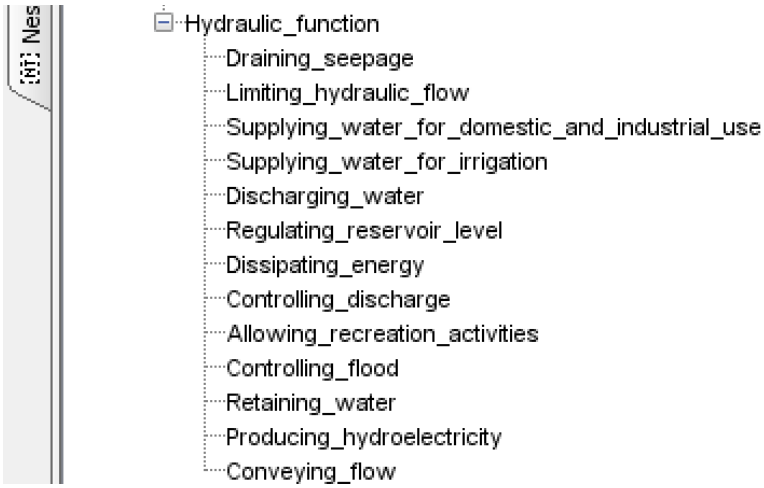

Figure A6.20. Hierarchy of the concept *Hydraulic function*

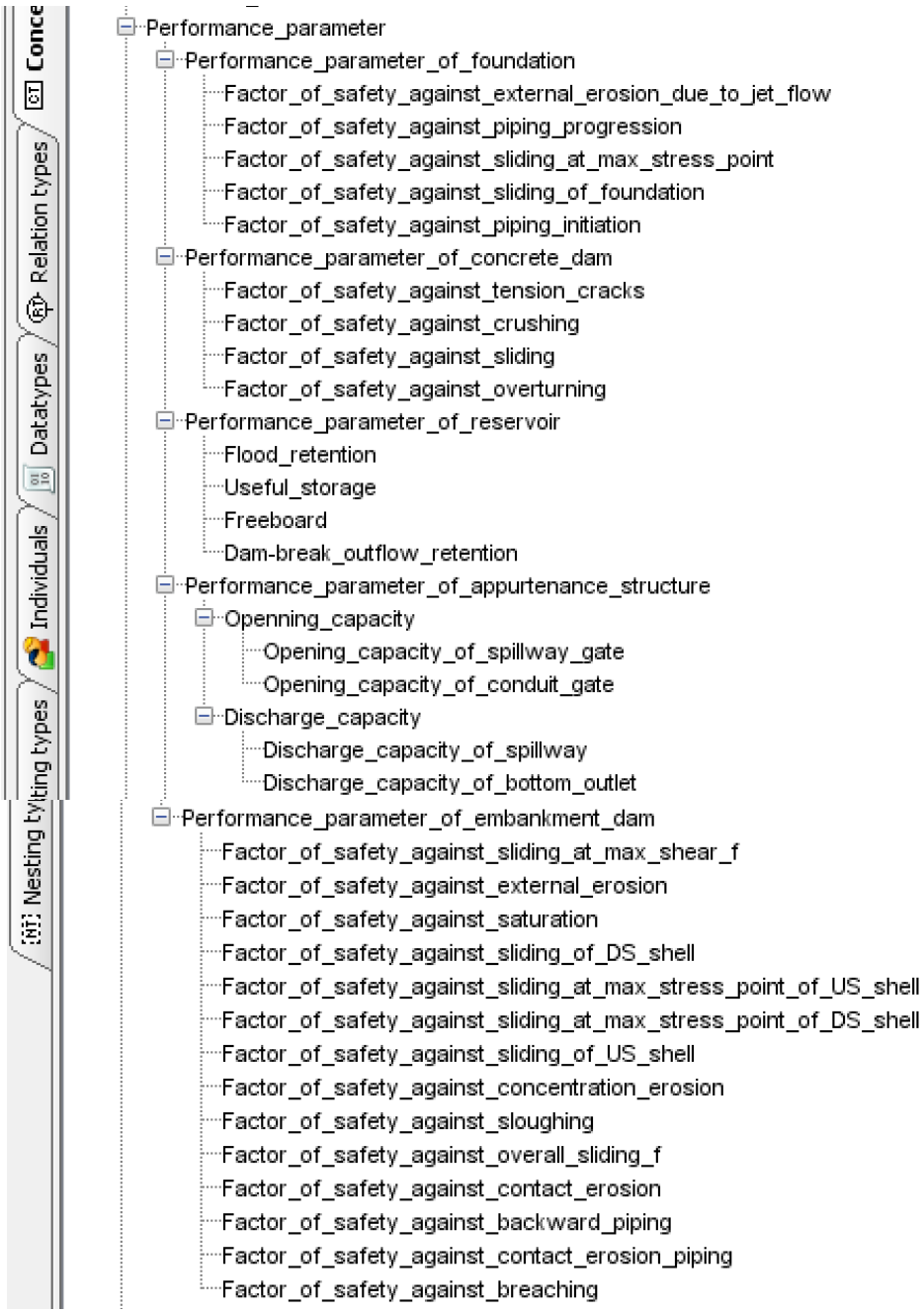

Figure A6.21. Hierarchy of the concept *Performance parameter*

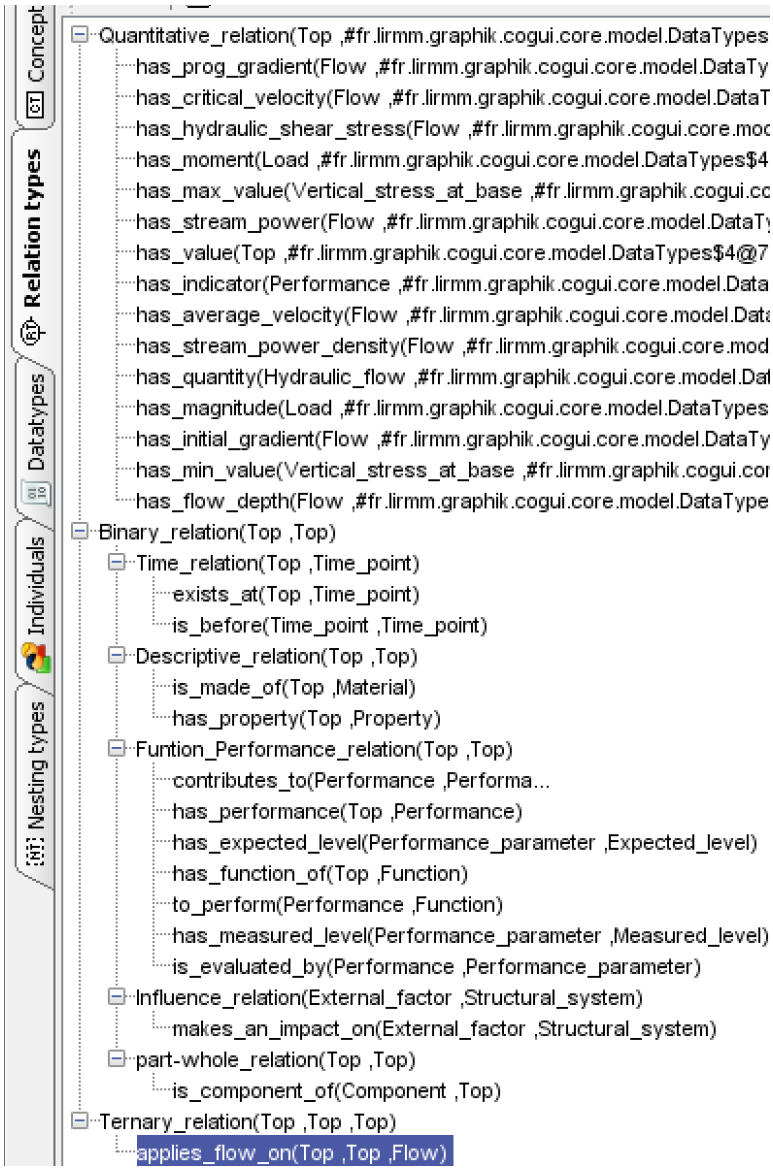

Figure A6.22. Hierarchy of the relations

Appendix 7. Application in case studies

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7.1. Case study 1 application - Pilarcitos dam system failure

7.1.1. Context of failure

General information

- Location: San Francisco, USA
- Failure: Sliding of upstream shell`
- Fatalities: 0
- Year of failure: 1969
- Year of construction: 1864 - 1866
- Function of dam system: Supplying water

External factor :

Rapid drawdown activity

Intensity: 0.52 m/day

Duration: 43 days

Description of site, structure and materials

Pilarcitos Dam is a homogeneous dam with a height of 23.8 m and a long-term water level that was 1.8m below the crest. The upstream slope inclination varies from 2.5H:1V up to El. 206.7 m and at 3H:1V above that point (VandenBerge, Duncan and Brandon, 2013). The dam was built from compacted sandy clay with a total unit weight of 21.2 kN/m^3. A cross-section of the dam's upstream slope is shown in Figure A-7.1.

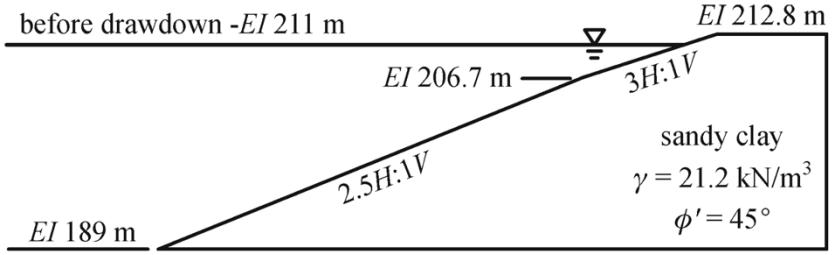


Figure A-7.1. Geometry of the upstream slope of Pilarcitos Dam (Vandenberge, 2014)

7.1.2. Failure presentation

Description of failure

In 1969, a rapid drawdown slide occurred after the reservoir level was suddenly lowered 10.7 m over the course of 43 days. The failure process is described with the external factor being the drawdown activity, which leads to the reduction of reservoir level. The development of excess pore pressures combined with the increase of shear stresses within the embankment upstream induced failures. (Fig A-7.2).

Rapid drawdown is known as one of the most dangerous conditions for the upstream slope (VandenBerge, Duncan and Brandon, 2013). The rapid drawdown condition occurs when the water level adjacent to the slope drops quickly after a long period at the normal reservoir

level. In such a case, the pore-water pressures present in the soil do not have enough time to dissipate due to small permeability of the soil. The shear stresses in the slope increase during drawdown as the stabilizing effect of the water load acting on the slope is removed. As a result, the water's weight within the soil tends to slide the upstream slope along a circular arc, leading to failure of the upstream shell.

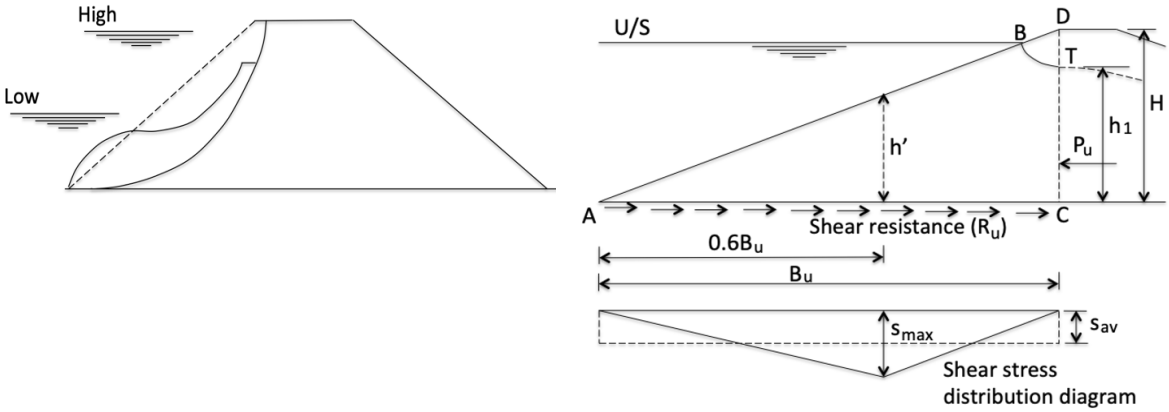


Figure A-7.2 The rapid draw-down slide

Analysis of failure

Factors related to failure of Pilarcitos dam system **:**

+ Rapid drawdown activity

+ High reservoir level before the failure

+ Conditions of the dam:

- Homogeneous earthfill dam is made of the sandy clay with the permeability of the soil was 4x10-8 cm/sec which is low relative to the rate of drawdown;
- Upstream slope was 3H:1V
- The dam was design without drainage

+ Components at risk: embankment dam, reservoir.

Failure of the Pilarcitos dam system results from a combination of the interactive outflow due to the drawdown activity with the earthfill dam. The conditions of the earthfill dam, such as the permeability of the soil, the slope of the upstream, the absence of drains, lead to the excess of pore pressure and the reduction of shear strength in the dam, causing sliding of the upstream slope.

7.1.3. Instantiation of the failure knowledge model

Pilarcitos dam is a homogeneous structure without any obvious filters or drains. Therefore, the system is describe in two levels: system and component level.

The external factor: Rapid drawdown activity

The failure process is described with 3 time points: from the time point T0 to the time point T2 (Figure A-7.3):

- Time point T0: Before the rapid drawdown activity, the dam system was in a normal state; the reservoir water level was 22 m, the foundation was stable.
- Timepoint T1: On October 7, 1969, the drawdown activity occurred.
- Timepoint T2: On November 19, 1969, the drawdown activity finished, and the upstream slid. The performance of the reservoir was satisfied.

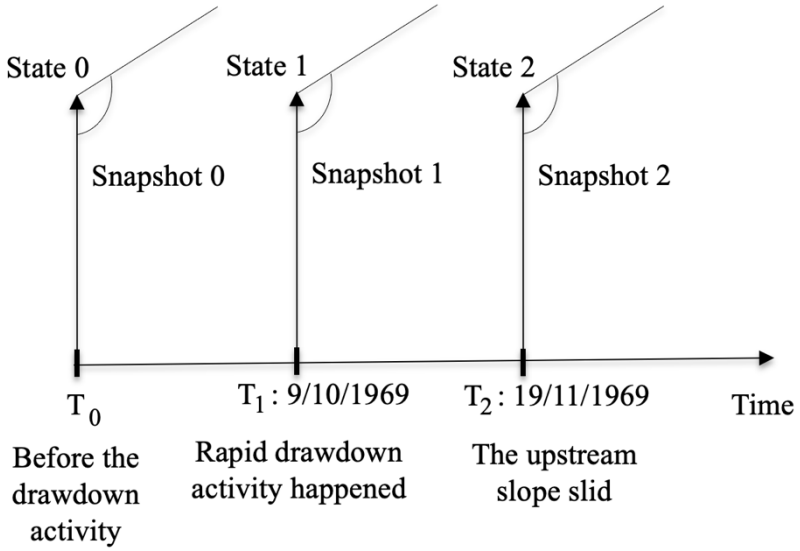


Figure A-7.3. Timepoints of the failure process

Steps to instantiate:

1. Identifying the dam system

2. Identifying the external factors

3. Identifying impacts of the external factors at T1

Performance of the reservoir at T2.

4. Interactions and performance of the embankment dam at T2

7.1.3.1. Identifying the dam system

Figure A-7.4 shows a rule graph to identify the structure of the homogeneous embankment dam system. The rule can be expressed as **if** *Homgeneous_embankment_dam* is a component of *Dam_system*, then the main components of a homogeneous embankment dam system will be created; *Dam_system* is also described with its function and performance. A homogeneous embankment dam system's main components include reservoir, homogeneous embankment dam, foundation, abutment, spillway, and bottom outlet.

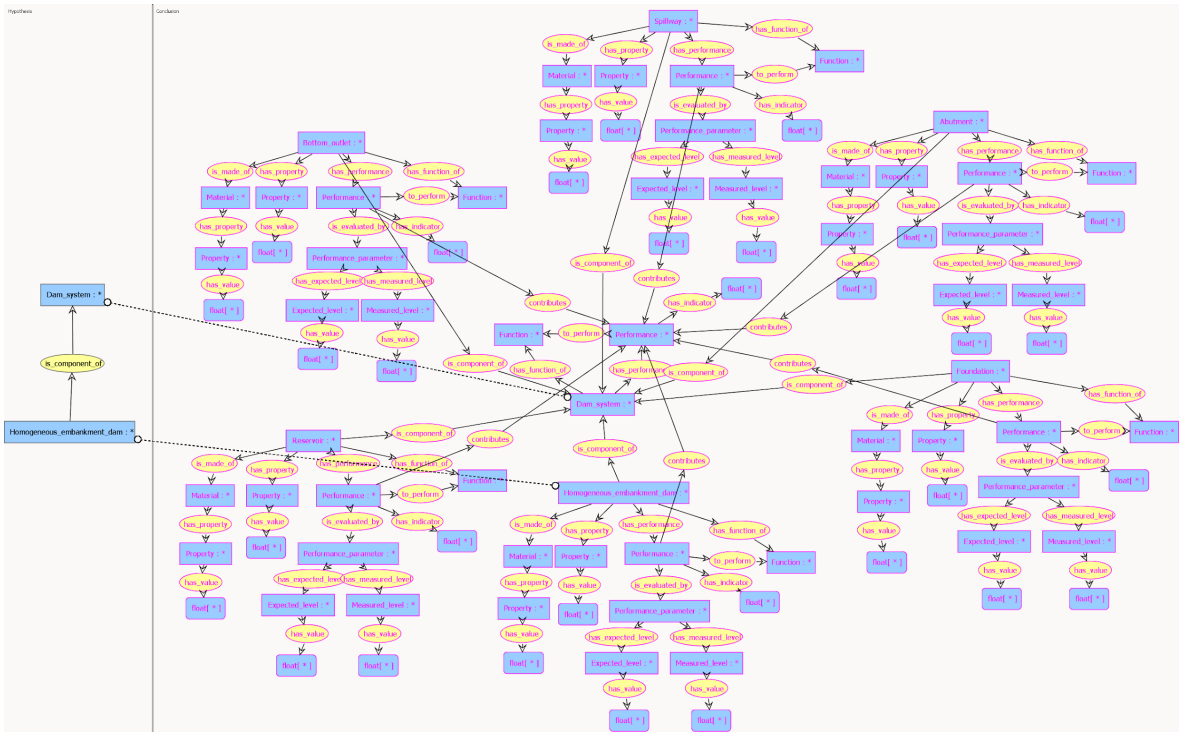


Figure A-7.4. Rule identifying the structure of homogeneous embankment dam system

After applying the rule above, all components of the structure need to be identified as individual concepts in the resulting graph. For example, the concept type *Reservoir* is presented as *Reservoir: Pilarcitos_reservoir*. Information necessary for the model representational is filled with their values. For example, the homogeneous dam is made of sandy clay, with a friction angle is *45°*, submerged unit weight is *15*, cohesion is *18*. The dam has a height of *23.8* m, a base width of *158.5* m, a width of the upstream slope is *59.5* m, and an upstream slope is *0.33*. The function is considered for the dam is *Resisting_sliding_of_upstream_shell*, with the performance indicator is assumed as 1 (i.e., satisfied) (Figure A-7.5).

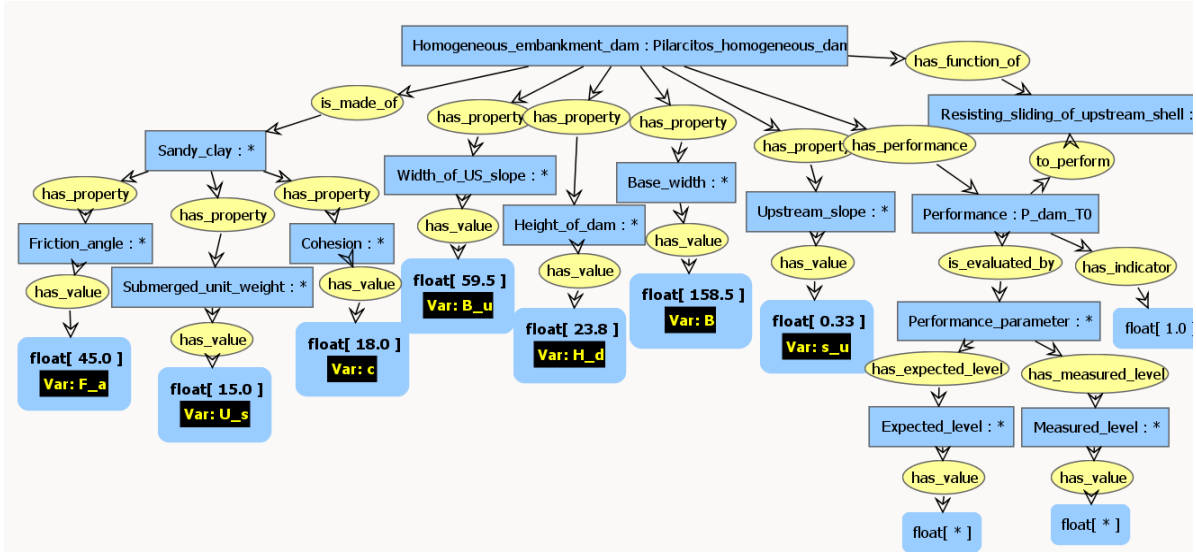


Figure A-7.5. Homogeneous embankment dam at T0

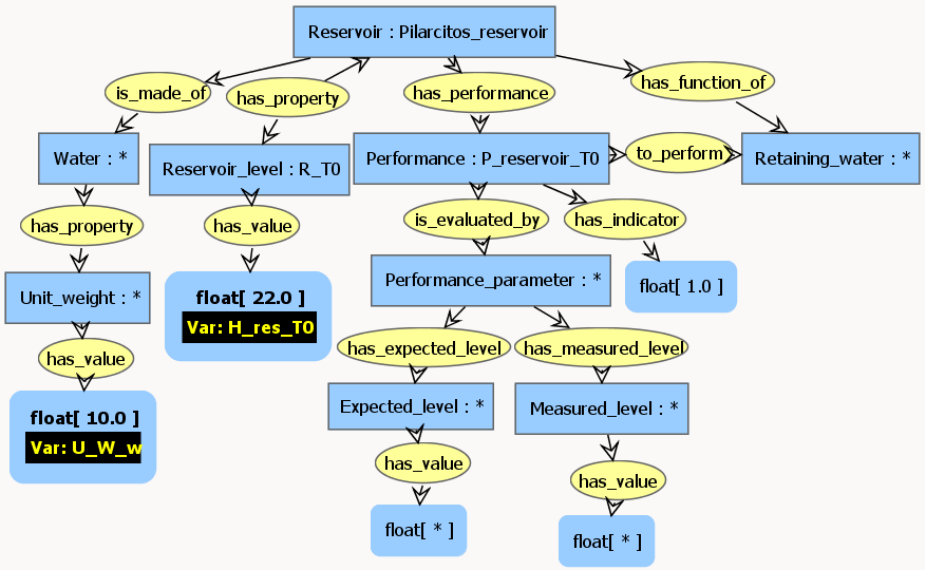


Figure A-7.6. Pilarcitos reservoir at T0

Figure A-7.6 shows a resulting graph of the Pilarcitos reservoir at T0. The reservoir is described with material constituted that has a value of unit_weight is 10, reservoir level at T0 that has a value of 22 m. The function considered of the reservoir is retaining water, and it has performance at T0 is assumed as 1, i.e., satisfied.

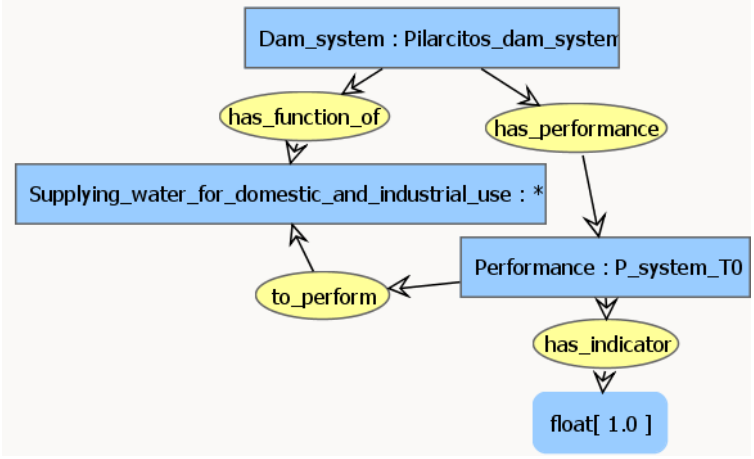


Figure A-7.7. Pilarcitos dam system at T0

Figure A-7.7 describes the Pilarcitos dam system with the function is *Supplying water for domestic and industrial use*; the performance at T0 is *P_system_T0*, which is assumed is satisfied, the value of the indicator is 1.

7.1.3.2. Identifying the external factors

There are two external factors: drawdown and gravity (Figure A-7.8).

The time point of the drawdown activity is named as T1: 7/10/1969, i.e., 7/10/1969 is the day that the drawdown happens.

The time point of gravity is determined as T0.

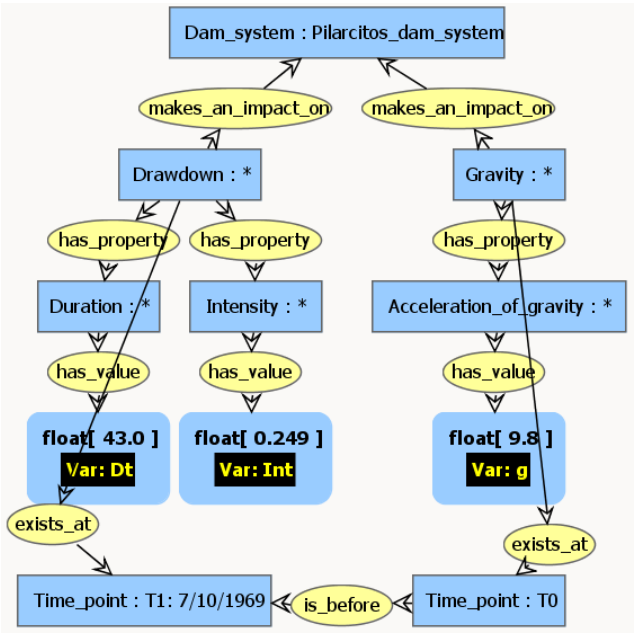


Figure A-7.8. External factors of Pilarcitos dam system

Figure A-7.8 shows two external factors of the Pilarcitos dam system: *Drawdown* activity has two properties *Duration*: 43 days, and *Intensity*: 0.249 m/day; *Gravity* with acceleration is 9.8 m/s^2. Time point of Drawdown is T1, time point of Gravity is T0. Two time points is connected by the relation *is_before*.

7.1.3.3. Identifying impacts of the external factors at T1

Outflow of the reservoir due to rapid drawdown activity

The outflow of sudden drawdown activity = Duration * Intensity

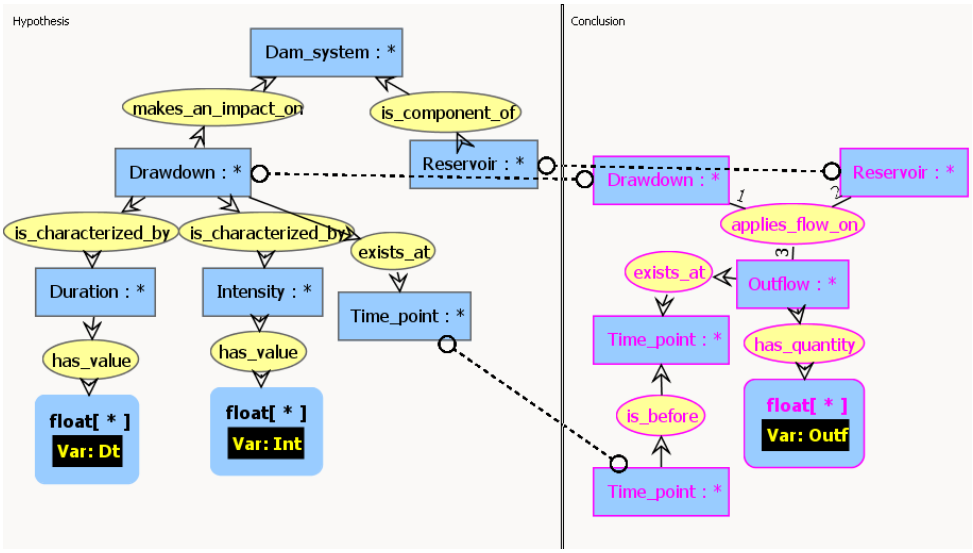


Figure A-7.9. Rule calculating outflow of drawdown activity

Rule | Associated script

```
1  void after()
2  {
3      float value1 = Dt.getValue() * Int.getValue();
4      Outf.setValue(value1);
5  }
```

Figure A-7.10. Script calculating outflow of drawdown activity

Figure A-7.9 illustrates calculating the outflow of drawdown activity. The rule can be explained as **if** *Drawdown* makes an impact on *Dam_system*, and *Reservoir* is a component of *Dam_system*, **then** *Drawdown* applies *Outflow* on *Reservoir* at a time point after the time point of Drawdown. Drawdown is described with *Duration* and *Intensity*; those have variables *Dt* and *Int* respectively. Figure A-7.10 illustrates the associated script.

Reduction of reservoir due to rapid drawdown

When the reservoir is affected by an outflow, the water level will drop.

New water level (Reservoir level at T2) = Reservoir level at T0 – Outflow

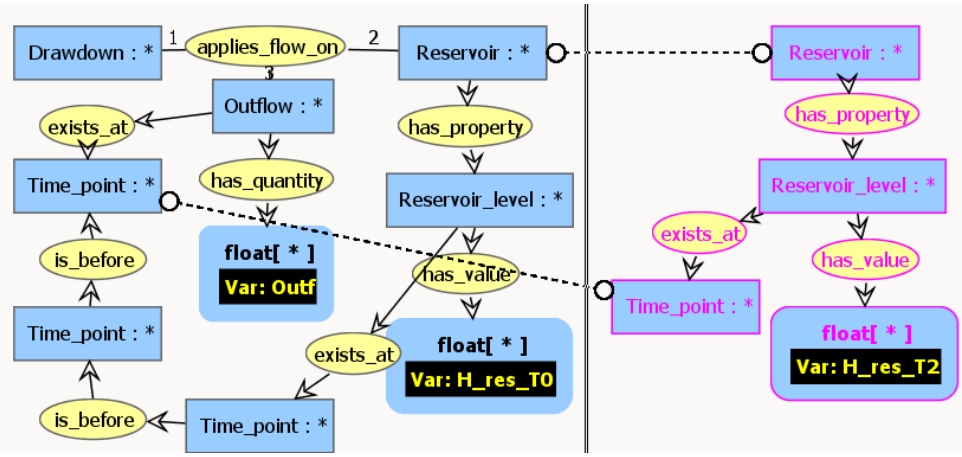


Figure A-7.11. Rule calculating the reduction of reservoir due to rapid drawdown

Rule | Associated script

```
1  void after()
2  {
3      float value1 = H_res_T0.getValue() - Outf.getValue();
4
5      H_res_T2.setValue(value1);// reservoir level after fi
6  }
```

Figure A-7.12. Script calculating the reduction of reservoir due to rapid drawdown

Figure A-7-11shows a rule calculating the new reservoir level at T2. The rule can be expressed as **if** *Drawdown* applies *Outflow* on *Reservoir*, **then** *Reservoir* has *Reservoir level*. The quantity of the outflow is represented by the variable *Outf*. *Reservoir level* in the hypothesis graph is represented by the variable *H_res_T0* and exists at T0. *Reservoir level* in the conclusion graph is represented by the vatiable *H_res_T2* and exist at T2. Figure A-7.12 exposes the associated script.

Resulting graph of new reservoir levels:

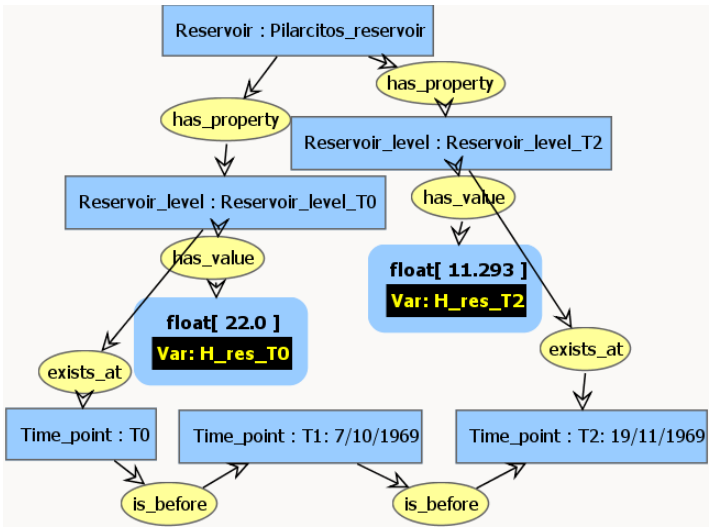


Figure A-7.13. Two reservoir levels at two different time points

Figure A-7.13 shows two reservoir levels: the original level at time point T0 represented by variable *H_res_T0* with the value of 22 m, and the new level at time point T2, which results from the drawdown activity, at 11.293 m.

7.1.3.4. Performance of reservoir at T2:

As the water level decreases, the reservoir's performance is considered based on the parameter of useful storage. Useful storage is the distance of water stored in a reservoir between the minimum and water surface during normal operating conditions.

Useful storage = Water level during normal operating conditions – Minimum water level

$$= H_{res_T2} - H_{min}$$

If useful storage < 0: not satisfied

useful storage > 0: satisfied

Rule to calculate the measured level of useful storage of the reservoir:

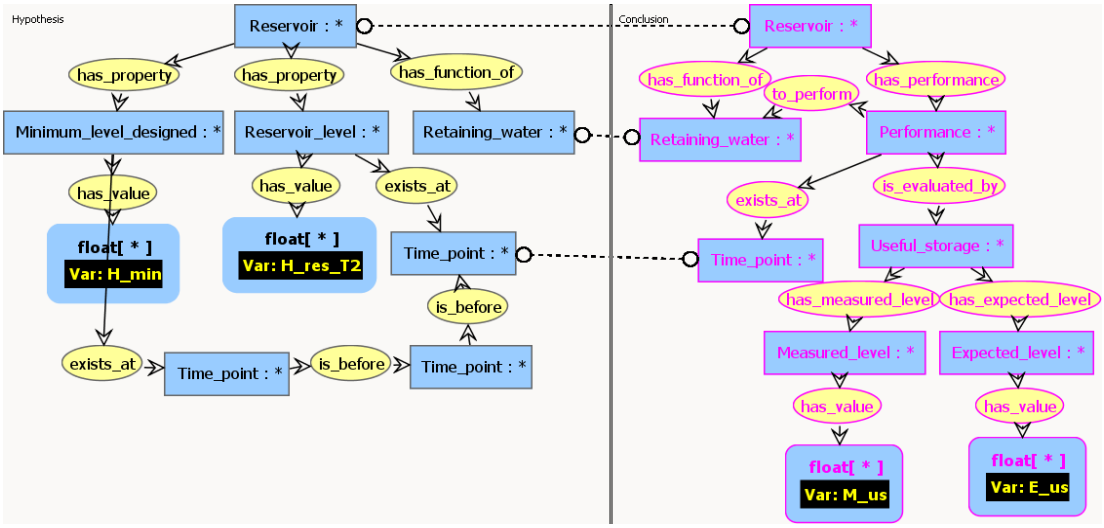


Figure A-7.14. Rule calculating measured level of useful storage of reservoir

Rule | Associated script

```
1  void after()
2  {
3      float value1 = H_res_T2.getValue() - H_min.getValue();
4      M_us.setValue(value1);
5  }
```

Figure A-7.15. Script calculating measured level of useful storage of reservoir

Figure A-7.14 illustrates a rule calculating the measured level of useful storage of the reservoir. The rule can be explained as **if** *Reservoir* has *Minimum_level_designed* and *Reservoir level*, **then** *Reservoir* has a new *Performance* to perform function *Retaining_water*, evaluated by *Useful storage*. The useful storage parameter has *Measured level* and *Expected level*, represented by two variables *M_us* and *E_us*, respectively. Figurre A-7.15 exposed the associated script.

Performance of reservoir at T2:

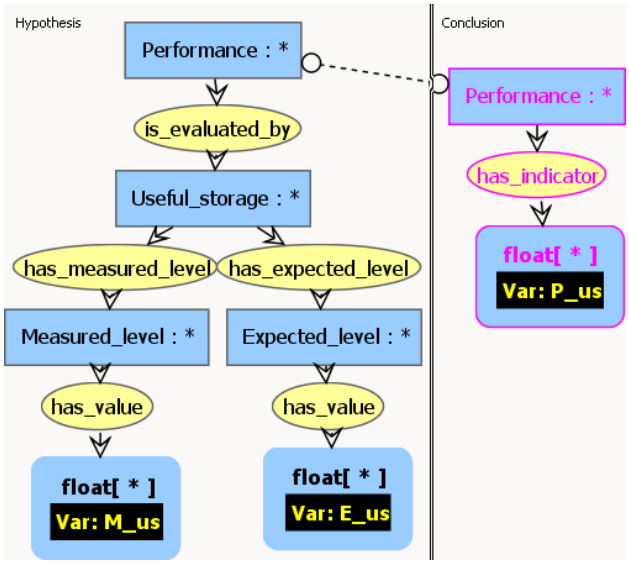


Figure A-7.16. Rule calculating performance of reservoir

Rule | Associated script

```
1  void after()
2  {
3      if (M_us.getValue() < E_us.getValue()) {
4          P_us.setValue(0);
5      }
6      else {
7          P_us.setValue(1);
8      }
9  }
```

Figure A-7.17. Script calculating performance of reservoir

Figure A-7.16 illustrates the calculating of reservoir performance at T2. The rule can be expressed as **if** *Performance* is evaluated by *Measured level* and *Expected level*, **then** *Performance* has an indicator represented by a variable *P_us*. Figure A-7.17 exposes the associated script.

The resulting graph of the new performance of the reservoir:

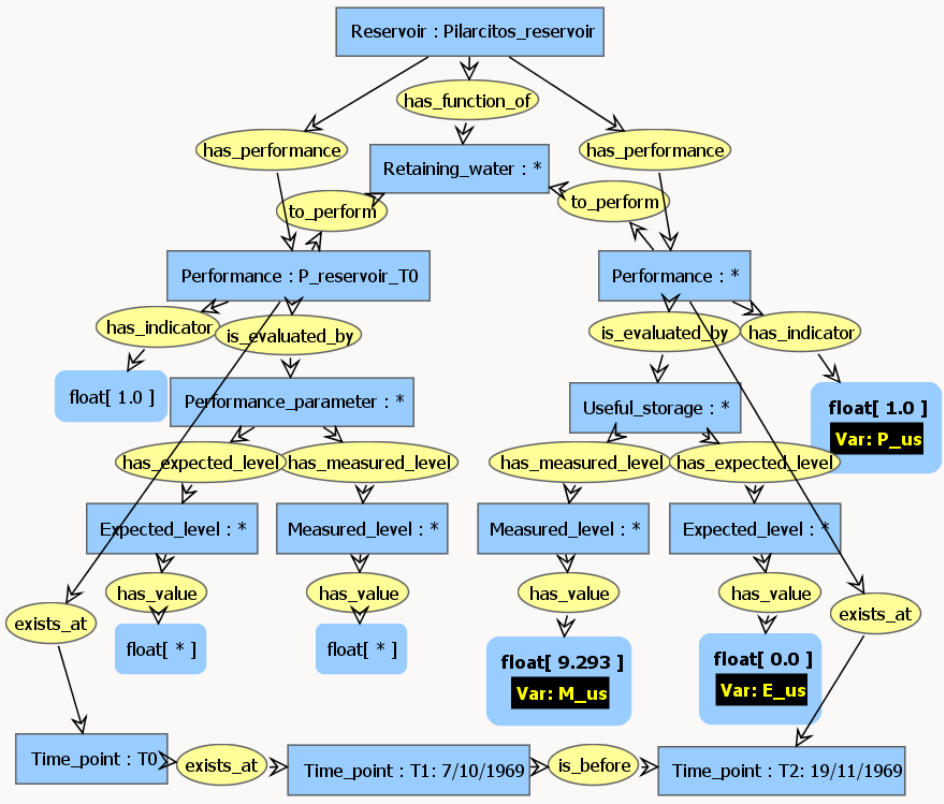


Figure A-7.18. Two performances of reservoir at two different time points

Figure A-7.18 shows two performances of the reservoir at two different time points: T0 and T2. The performance at T0 is assumed as satisfied, with the indicator has a value of 1. The performance at T2 has the same value as the indicator, i.e., 1; this means that the performance is satisfied.

7.1.3.4. Interactions and performance of the embankment dam at T2

Applying an approximate method for checking the stability of the u/s slope against sudden drawdown. It is based on the simple principle that a horizontal shear load P_u is exerted by the saturated soil. The resistance to this force (call R_u) is provided by the shear resistance developed at the base of the soil mass, contained within the u/s triangular shoulder ADC (Figure A-7.19)

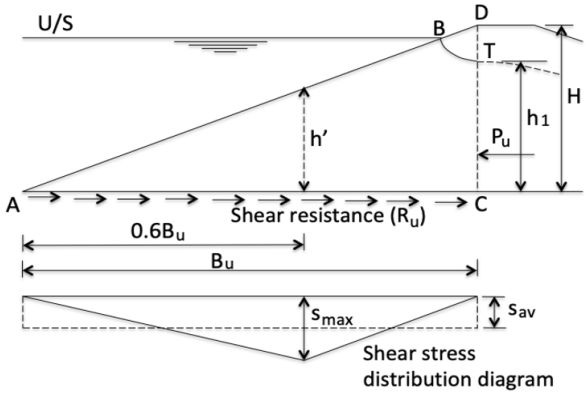


Figure A-7.19. Shear stress distribution diagram

Horizontal load P_u

Considering a unit length of the dam, the horizontal load P_u is given by the equation

$$P_u = \left[\frac{\gamma_1 H^2}{2}\left(45 - \frac{\phi}{2}\right) + \gamma_w \frac{h_1^2}{2}\right]$$

where γ_1 is the weighted density at the centre of triangular shoulder upstream and is given by

$$\gamma_1 = \frac{\gamma_{sub}.h_1 + \gamma_{dry}.(H - h_1)}{H}$$

γ_{sub} : Submerged unit weight of the soil in the dam (kN/m^3)

γ_{dry} : Dry unit weight of the soil in the dam (kN/m^3)

H: height of dam body (m)

φ: Angle of internal friction of soil in the dam

Rule to calculate the horizontal force P_u in case of the embankment dam without horizontal blanket drainage:

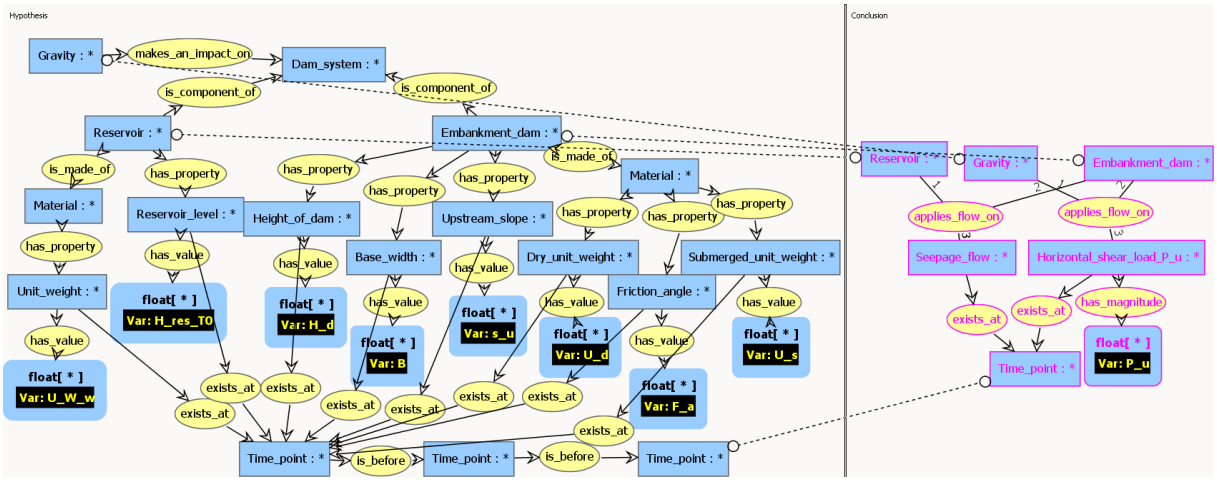


Figure A-7.20. Horizontal load P_u

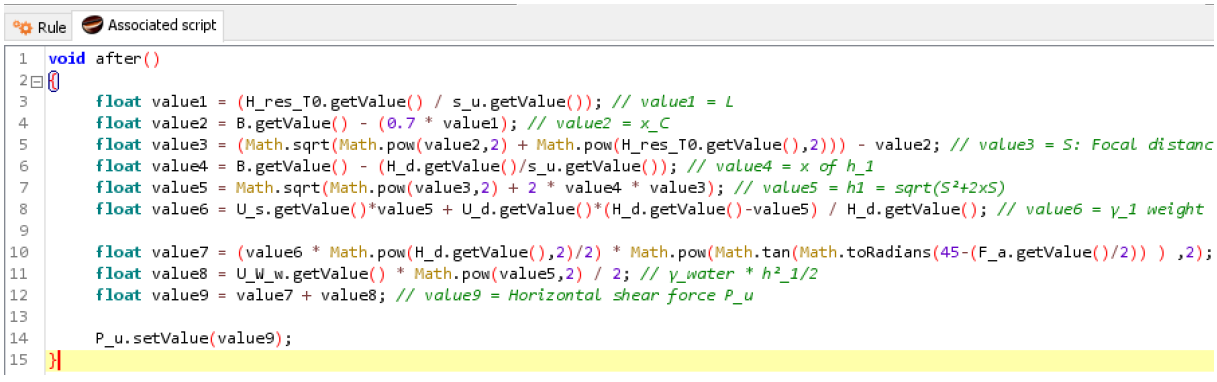


Figure A-7.21. Script calculating horizontal P-u

Figure A-7.20 shows a rule calculating horizontal load P_u. The rule graph can be expressed as **if** *Reservoir* and *Embankment_dam* are components of *Dam_system*, and *Gravity* makes an impact on *Embankment_dam*, **then** *Reservoir* applies *Seepage flow* on

Embankment_dam, and *Gravity* applies *Horizontal _shear_load_*P_u on *Embankment_dam*. The reservoir is described with *Unit_weight* of water, and *Reservoir_level* at T0. *Embankment_dam* is described with its relevant properties as *Height_of_dam*, *Base_width*, *Upstream_slope*, properties of material as *Dry_unit_weight*, *Friction_angle*, and *Submerged_unit_weight*. Time point of P_u is at T2. Figure A-7.21 exposes the associated script.

Shear resistance (R_u) of u/s slope portion of the dam

Shear resistance (R_u) of u/s slope portion of the dam developed at base AC is given by

$$R_u = C + W \tan \varphi$$

where W = the weight of the u/s triangular shoulder of dam

C = The total cohesive force developed at base AC

If c_{dam} is the unit cohesion of the dam soil, then C = c_{dam} * (B_u * 1) where B_u = length AC.

The weight W of the u/s slope portion of dam will be computed as the entire area taken as submerged.

In such a case,

$$W = [\text{Area of } \Delta ADC] \,.\, \gamma_{sub} = \gamma_{sub} \,.\, \left(\frac{1}{2}.AC.H\right)$$

$$\text{or } R_u = C + W \tan \varphi = c_{dam} \,.\, (AC \times 1) +. \left(\gamma_{sub}.\frac{1}{2}.AC.H\right) \tan \varphi$$

Rule to calculate shear strength (R_u) at upstream base:

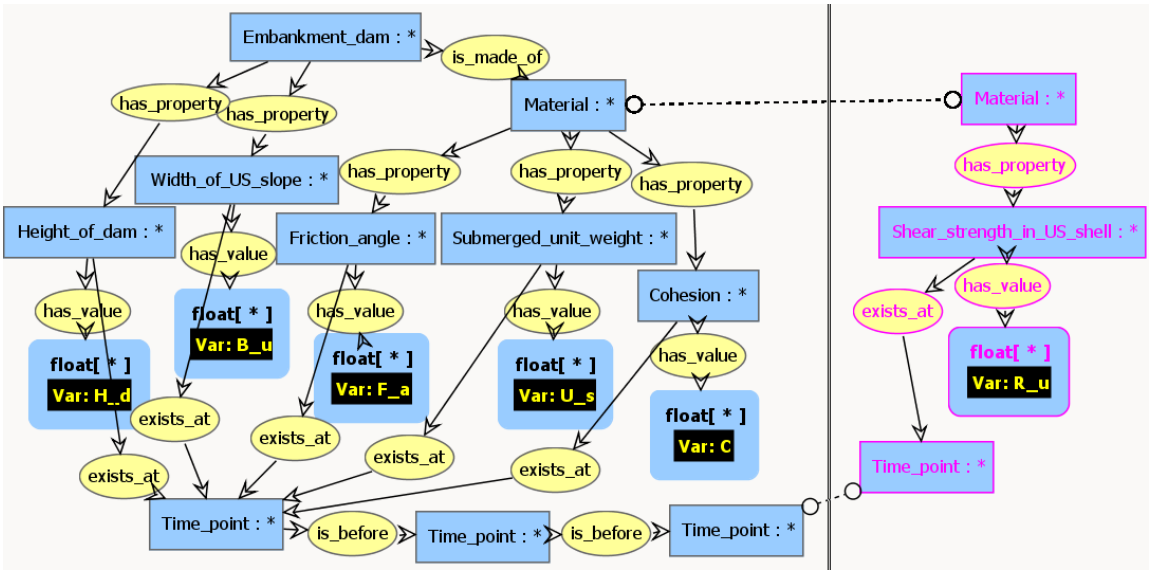


Figure A-7.22. Rule of shear strength (R_u) at upstream base

Rule | Associated script

```
void after()
{
    float value1 = C.getValue() * B_u.getValue(); // value1 = c.B_u.1
    float value2 = U_s.getValue() * B_u.getValue() * H_d.getValue() * Math.tan(Math.toRadians(F_a.getValue())) / 2;

    float value3 = value1 + value2;
    R_u.setValue(value3);
}
```

Figure A-7.23. Script of shear strength (R_u) at upstream base

Figure A-7.22 illustrates the calculating shear strength R_u at upstream base. The rule can be expressed as **if** *Embankment_dam* has properties as *Height_of_dam* and *Width_of_US_slope*, and *Material* has properties of *Friction_angle*, *Submerged_unit_weight*, and *Cohesion*, **then** *Material* has *Shear_strength_in_US_shell*. Time point of shear strength is the time point T2. Figure A-7.23 illustrates the associated script.

Factor of safety against sliding at base

The factor of safety against sliding can be calculated, using

$$\text{Factor of safety against sliding of upstream shell } = \frac{R_u}{P_u}$$

Limit condition for sliding stability at base of u/s slope portion:

if $\frac{R_u}{P_u} >$ Limit factor of safety = 1.5 : no sliding take place

if $\frac{R_u}{P_u} <$ Limit factor of safety = 1.5 : u/s slope slid

Factor of safety against sliding with the maximum intensity of shear stress

The maximum intensity of shear stress occurs at a distance 0.6 AC from the heel (i.e. 0.4 AC from the top shoulder) and is equal to 1.4 times the average shear intensity.

The average shear intensity is

$$\tau_{av} = \left(\frac{P_u}{AC.1}\right)$$

Maximum shear stress induced

$$= \tau_{max} = 1.4 \left(\frac{P_u}{AC}\right) (\text{kN/m}^2)$$

which is developed at the distance 0.6 AC.

Rule to calculate the maximum shear stress induced

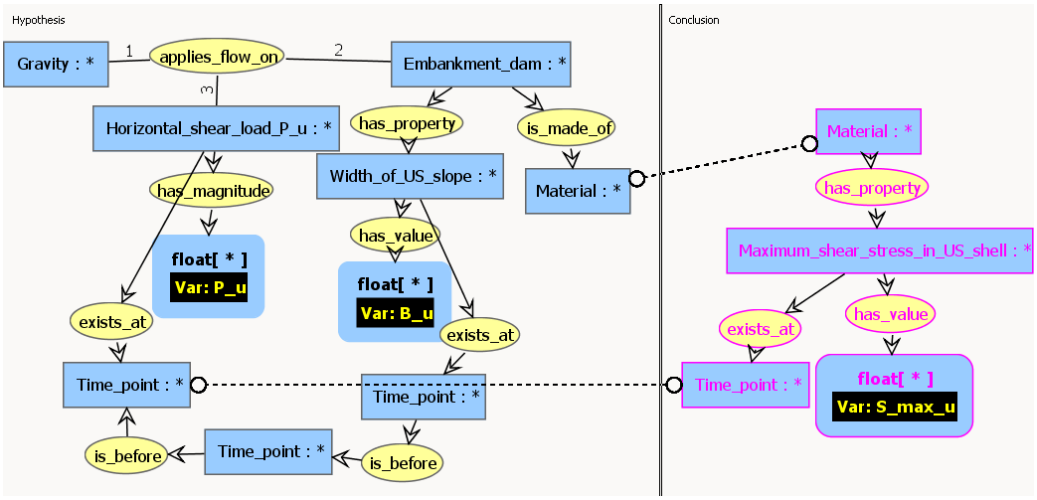


Figure A-7.24. Rule calculating maximum shear stress

Rule | Associated script

```
1  void after()
2  {
3      float value = 1.4 * (P_u.getValue() / B_u.getValue());
4      S_max_u.setValue(value); // kN/m²
5  }
```

Figure A-7.25. Script of maximum shear stress

Figure A-7.24 shows a rule computing the maximum shear stress in the upstream shell. The rule can be interpreted as **if** *Gravity* applies *Horizontal shear load P_u* on *Embankment dam*, **then** *Material* has *Maximum_shear_stress_in_US_shell*. The embankment dam is described with *Width_of_US_slope*. The time point of maximum shear stress is the time point load P_u. Figure A-7.25 illustrates the associated script.

The unit shearing resistance developed at the point of the maximum shear stress is given by

$$\tau_f = c + h'\gamma_{sub}.tan\ \phi$$

$$= \text{c} + 0.6\ \text{H}\ .\ \gamma_{sub}.tan\ \phi$$

Rule to calculate the unit shearing resistance at the maximum shear stress:

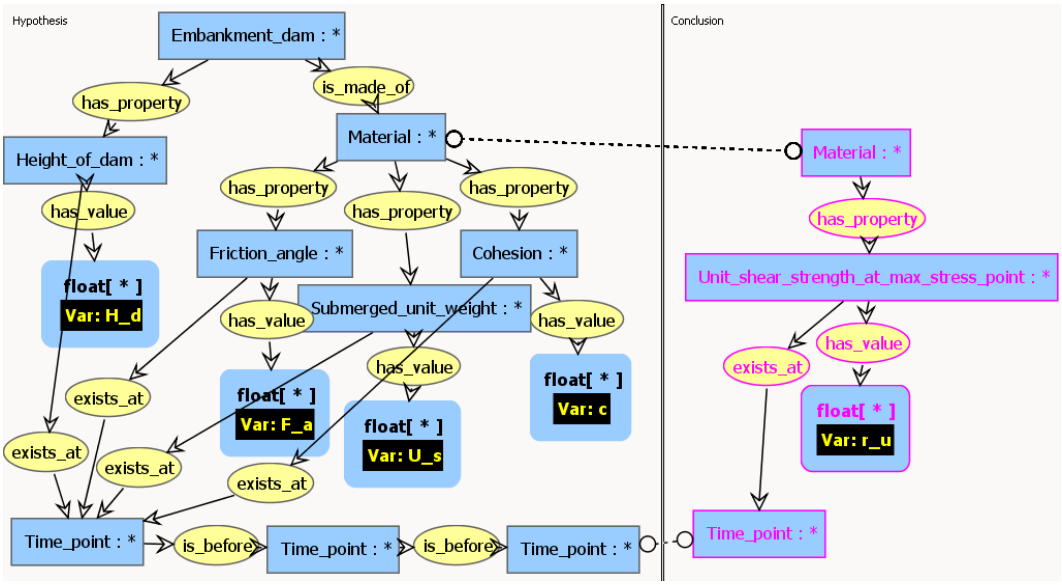


Figure A-7.26. Rule to calculate unit shearing resistance at the maximum shear stress

Rule | Associated script

```
1  void after()
2  {
3      float value = c.getValue() + (0.6 * H_d.getValue() * U_s.getValue() * Math.tan(Math.toRadians(F_a.getValue())));
4
5      r_u.setValue(value); // kN/m²
6  }
7
```

Figure A-7.27. Script to calculate unit shearing resistance at the maximum shear stress

Factor of safety against sliding at the point of the maximum shear $= \frac{\tau_f}{\tau_{max}}$

Limit condition for sliding stability at the point of the maximum shear stress:

if $\frac{\tau_f}{\tau_{max}} >$ Limit factor of safety = 1 : no sliding take place

if $\frac{\tau_f}{\tau_{max}} <$ Limit factor of safety = 1 : u/s slope slid

The performance of sliding stability of the u/s slope portion of the dam is evaluated based on two conditions:

- Limit condition for sliding stability at base of u/s slope shell
- Limit condition for sliding stability at the point of the maximum shear stress

If either of these conditions is not assured, performance of sliding stability of the u/s slope portion will not be assured.

Rule to calculate the measured level of the factor of safety against sliding at the point of the maximum shear and base:

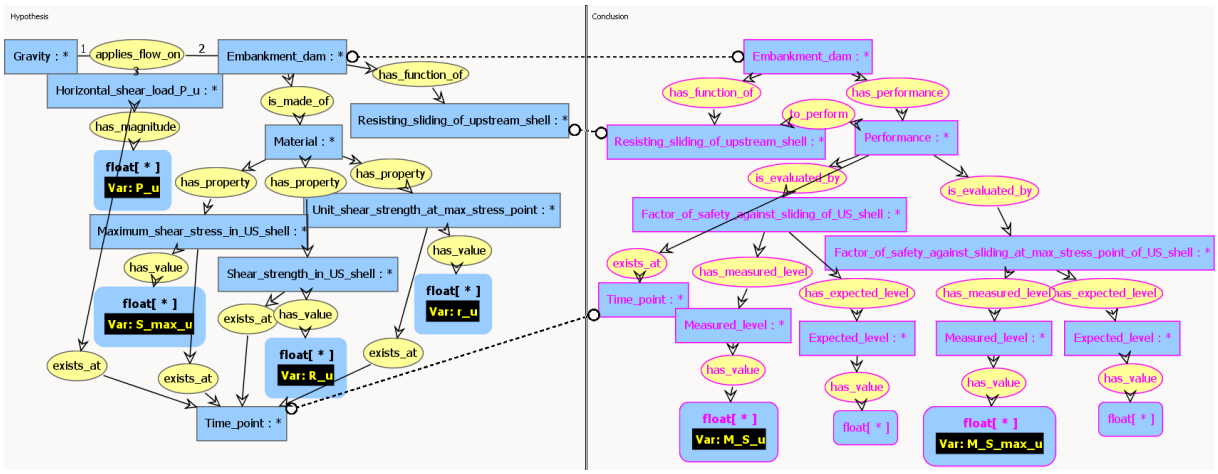


Figure A-7.28. Rule of measured levels of factor of safety agaisnt sliding at the point of the maximum shear and base

Rule | Associated script

```
1  void after()
2  {
3      float value1 = R_u.getValue() / P_u.getValue();
4      float value2 = r_u.getValue() / S_max_u.getValue();
5
6      M_S_u.setValue(value1);
7      M_S_max_u.setValue(value2);
8
9  }
```

Figure A-7.29. Script to calculate measured levels of factor of safety agaisnt sliding at the point of the maximum shear and at the base

The rule graph in Figure A-7.28 shows a calculation of measured levels of the factor of safety against sliding of upstream shell and at the point of maximum stress of upstream shell. The measured level of two factors are computed based on Horizontal shear load P_u and the values of properties of embankment material. The rule graph can be expressed as **if** *Gravity* applies *Horizontal shear load* P_u on *Embankment dam*, **then** *Performance* to perform the function of *Resisting sliding of upstream shell* is evaluated by *Factor of safety against sliding of upstream shell* and *Factor of safety against sliding at max stress point of upstream shell*, with their *Measured level* and *Expected level*. The time of performance is the time of load P_u. Fugure A-7.29 shows the associated script.

Rule to calculate performance of sliding stability of the u/s slope portion of the dam during sudden drawdown:

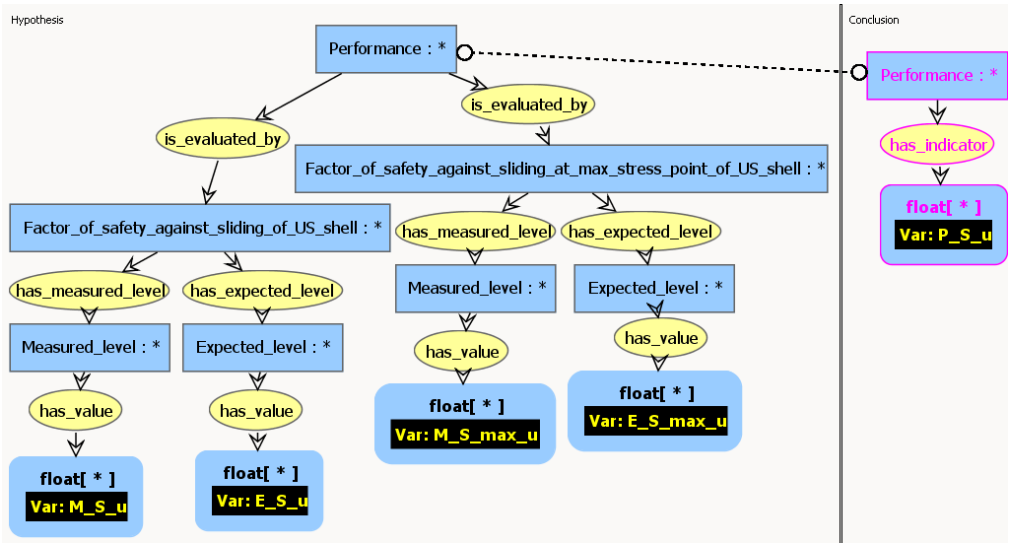


Figure A-7.30. Rule of the sliding performance of upstream shell

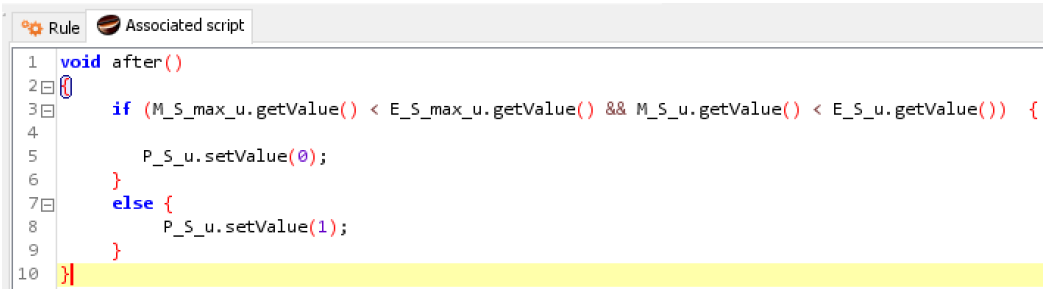


Figure A-7.31. Script of the sliding performance of upstream shell

Figure A-7.30 shows a rule graph to calculate the indicator of the performance to resist sliding of the upstream shell. The rule graph can be expressed as **if** *Performance* is evaluated by *Factor_of_safety_against_sliding_of_US_shell* and *Factor of safety against sliding at max stress point of US shell*, then *Performance* has an indicator. Figure A-7.31 shows the associated script.

Performances of the embankment dam in two different time points T0 and T2

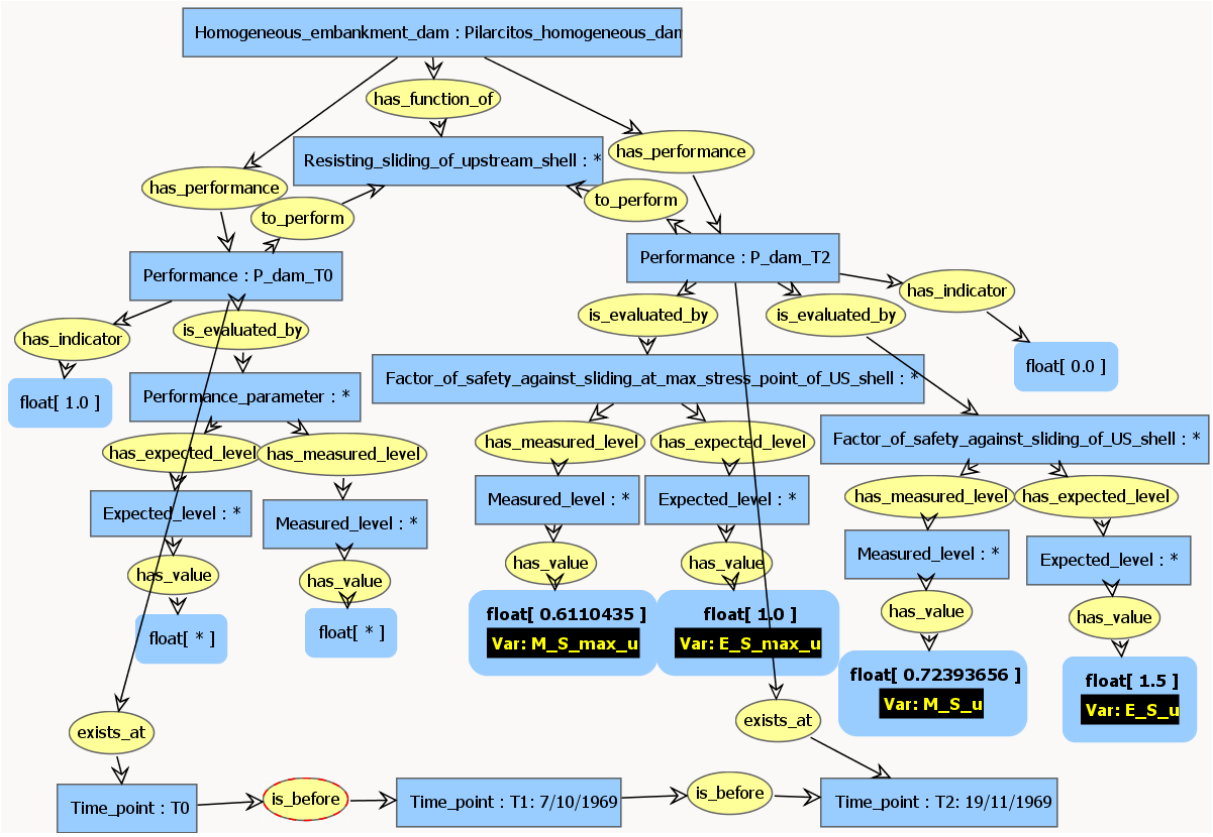


Figure A-7.32. Performances of dam in two time points

Figure A-7.32 show the resulting graph of performances of the dam. There are two performances at two different time points, T0 and T2. The performance at T0 is described by the individual concept *Performance: P_dam_T0*. It is assumed that satisfied, i.e., the indicator has a value of 1. The performance at T2 is presented by the individual concept *Performance: P_dam_T2*. It is evaluated by two performance parameters, and its indicator has a value of 0. It is apparent that from the time point T0, i.e., before 7/10/1969, to the time point T2, i.e., 19/11/1969, the dam changed its performance.

7.1.3.5. Performance of the dam system at T2

The performance of the dam system is contributed by the performance of the embankment dam. Therefore, if the dam's performance is not satisfied, it leads to the dam system's failure.

Rule to identify the performance of the dam system:

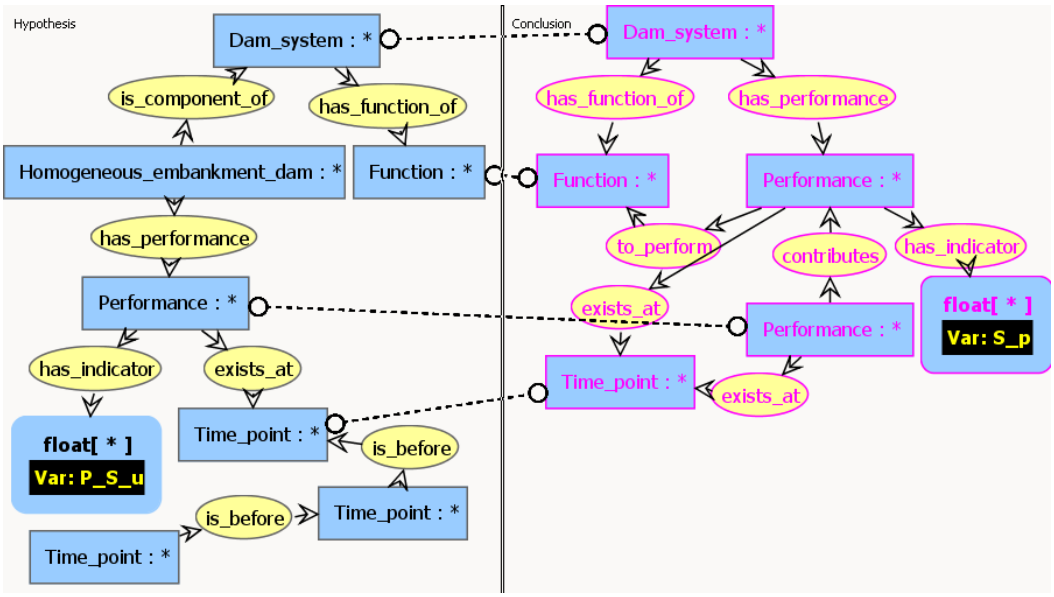


Figure A-7.33. Rule identifying performance of dam system

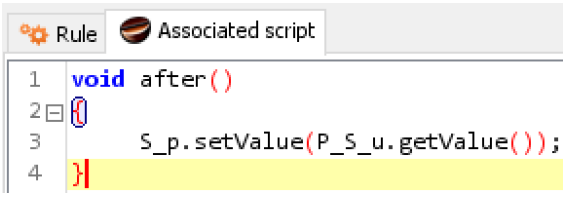


Figure A-7.34. Script identifying performance of dam system

Figure A-7.33 shows a rule identifying performance of dam system. The rule can be explained as **if** *Homogeneous_embankment_dam* is a component of *Dam_system*, and the dam has *Performance* exist at *Time_point*, **then** *Dam_system* has a new *Performance* which is contributed by *Performance* of the dam. The performance of the dam is represented by a variable *P_S_u*, the performance of the system is represented by a variable *S_p*. The time point of the system's performance is the time point of the dam's performance. Figure A-7.34 shows the associated script.

Resulting graph of the performance of dam system

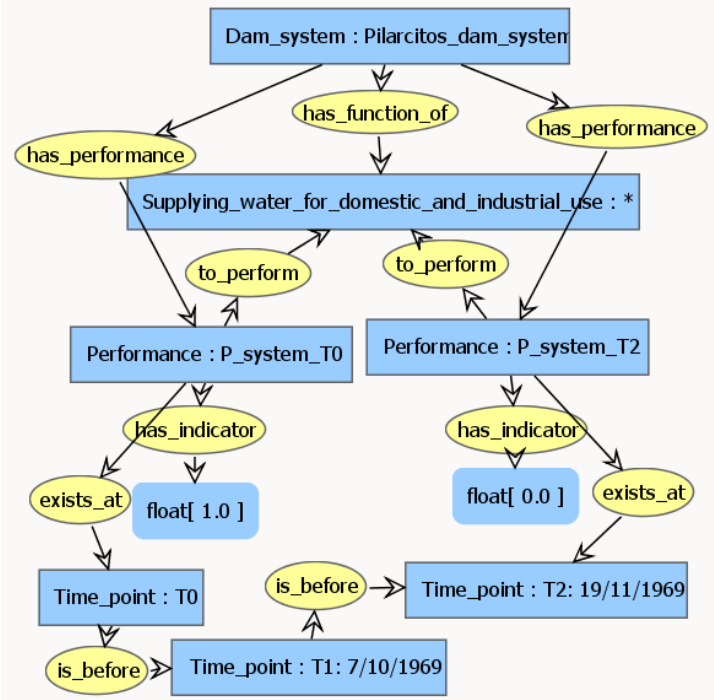


Figure A-7.35. Two performances of dam system at two different time points

Figure A-7.35 illustrates a change in the performance of the dam system over time. The graph shows two performances of the system at two different time points, T0 and T2. The first performance is assumed as satisfied, with the value of the indicator is 1. The second performance has a value of the indicator is 0, i.e., the system failed to supply water for domestic and industrial use.

7.1.4. Failure process

The failure process of the Pilarcitos dam system is described by three snapshots from the time point T0 to the time point T2. Each snapshots present interactions, changes in the state of the system, and results of interactions at each time point. Combining the three snapshots provides an overview of the failure's progression in a sequence of time.

- Snapshot at the time point T0

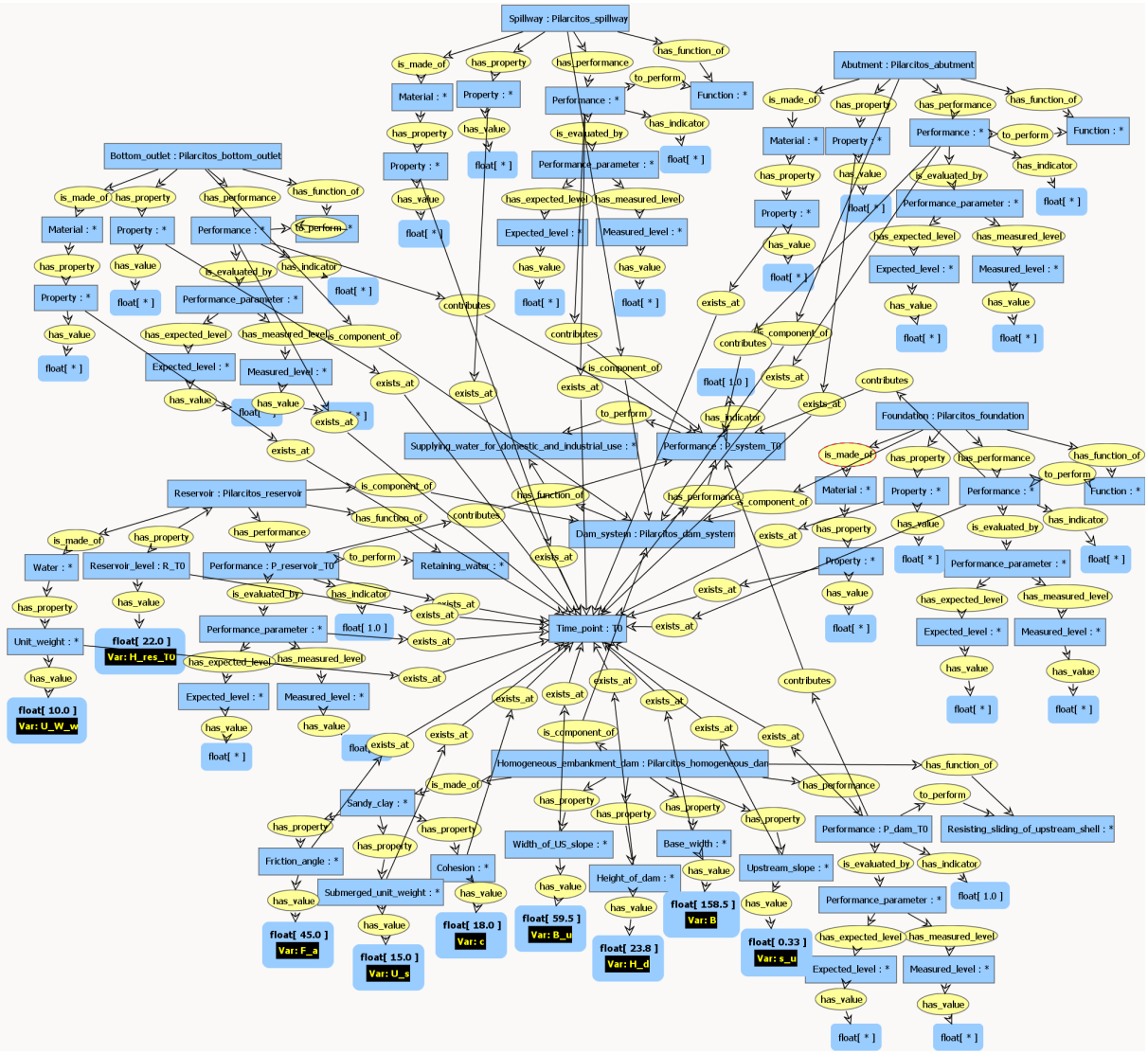


Figure A-7.36. Snapshot of the Pilarcitos dam failure at T0

Figure A-7.36 shows the snapshot at T0, the time before the drawdown activity, of the Pilarcitos dam failure. This snapshot describes the system's structure, including typical components of the system: homogeneous dam, reservoir, foundation, spillway, bottom outlet, and abutment, and relations connecting the concept types. It also shows relations connecting the concepts. The concepts that can change their values over time are connected with the concept *Time_point: T0* to identify their values and states at T0. At T0, the performance of the reservoir and the homogeneous embankment dam are assumed as satisfied, and the performance indicator values have values of 1.

- Snapshot at the time point T1

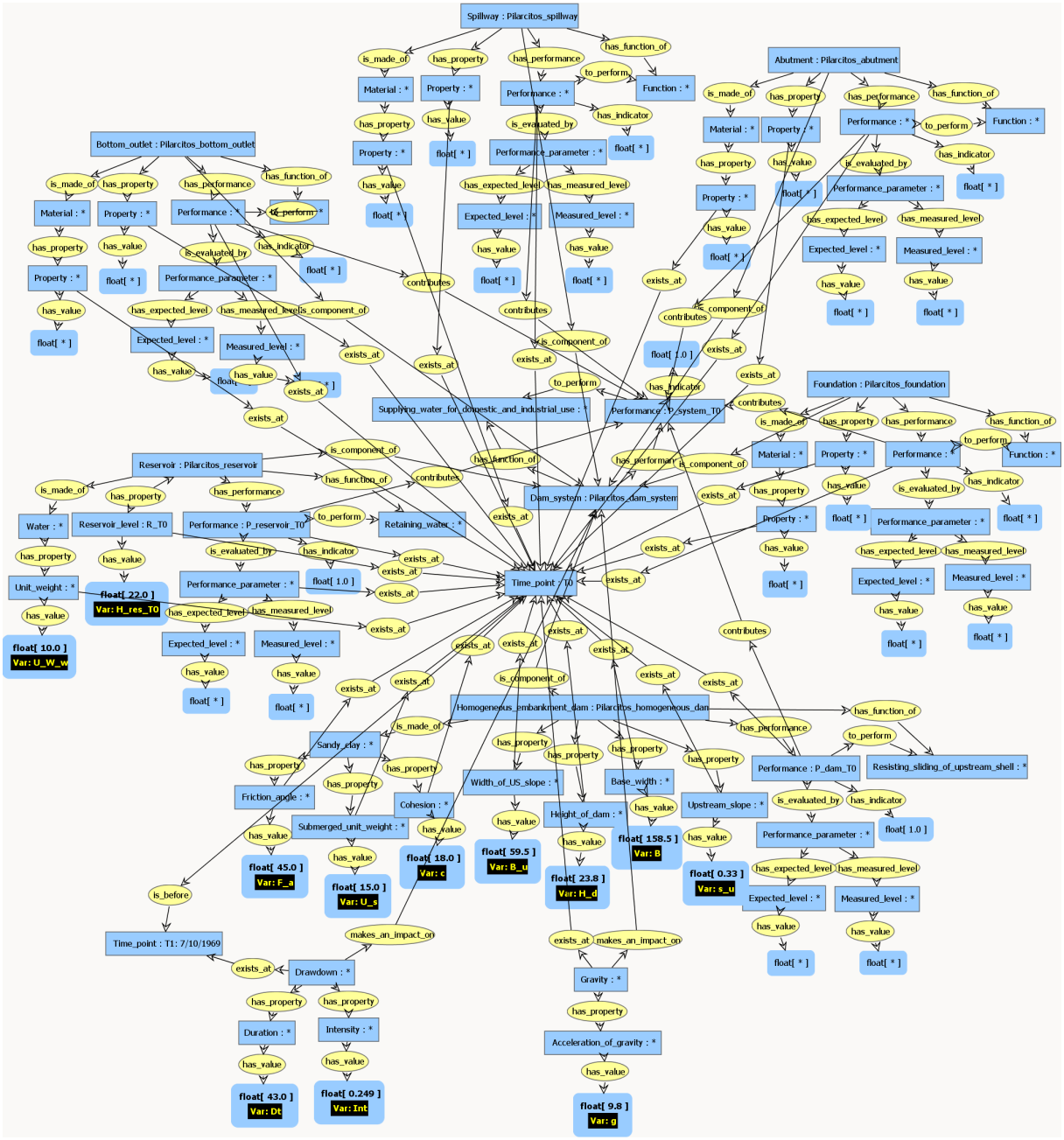


Figure A-7.37. Snapshot of the Pilarcitos dam failure at T1

Figure A-7.37 shows the snapshot at T1 of the Pilarcitos dam failure. It describes the appearance of external factors. There are two external factors: drawdown and gravity. The relations between the external factors and the system are described by the relation *makes_an_impact_on. Drawdown* is identified at T1, and gravity is identified at T0. Two time points are connected by the relation *is_before*.

- Snapshot at the time point T2

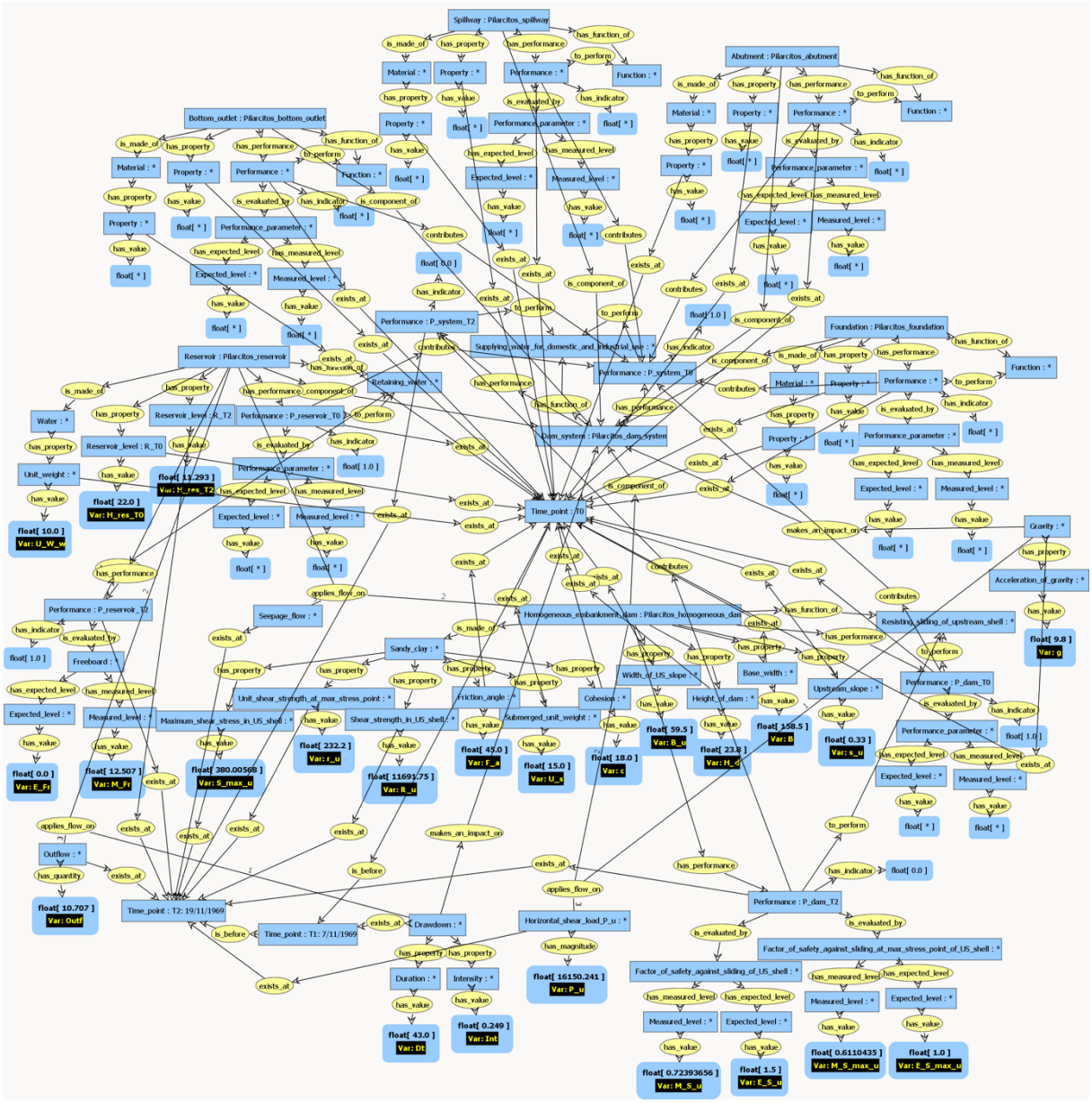


Figure A-7.38. Snapshot of the Pilarcitos dam failure at T2

Figure A-7.38 shows the snapshot of the failure at time point T2, which is the failure's time. This snapshot describes the impacts of the external factor on the system and interaction within the system. The interactive flow due to the drawdown activity is outflow causing the rapid drawdown of the reservoir. The horizontal shear load is created due to a combination of the impact of gravity and properties of the embankment dam and the reservoir. These conditions induce the appearance of shear strength and shear stress within the embankment dam. The excesses of the shear stress and the horizontal shear load lead to sliding of the upstream shell. The failure exists at the time point T2. The relation *is_before* connects the time T1 and the time T2. The interval time between T1 and T2 is an important factor contributing to the sliding of the upstream shell.

In conclusion, the three snapshots provide an overview of the failure of the Pilarcitos dam system in a sequence of time. The first snapshot shows the state of the system before the impact of the external factors. The second snapshot shows the appearance of the drawdown activity. Subsequently, the third snapshot describes the interactions between the external factors with the system, and the sliding of the upstream shell is the result of these interactions.

7.2. Case study 2 application – Sella Zerbino Secondary dam

7.2.1. Context of failure

General information

- Location: Molare, Italy

- Fatalities: 111

- Year of failure: 1935

- Year of construction: 1925

- Function of the dam system: Producing hydroelectricity

External factor:

Heavy rainfall

- Duration: 9 h

- Intensity: 40.7 mm/h

Description of site, structure, and materials

- The Sella Zerbino dam was one of two dams that competed in 1925 to form the Ortiglieto reservoir on the Orba River, in South Piedmont, Italy. It was a straight dam built in cyclopean concrete, with a crest elevation of 325.5 above sea level (meter a.s.l.), 14.5 m high and 109 m long, 3.5 m top width. The upstream slope was 10% and the downstream slope varies from 75% to 55% (Petaccia *et al.*, 2016).

- The Ortiglieto reservoir's watershed area is 141 km^2, reservoir surface area of 13 km^2, maximum water elevation is 323 m a.s.l, and normal water elevation is 322 a.s.l (Petaccia and Natale, 2020), (Alvi, 2015).

- The Sella Zerbino dam had no spillway or outlet.

- The foundation rock is a contact fault between serpentine schist and prasinite. The sub vertical milonite layer, located between the two geological formations, constitutes a clear weakness point.

7.2.2. Failure presentation

Description of failure:

On 13 August 1935, following a long dry period, an exceptionally severe rainfall storm hit the Orba catchment of the Sella Zerbino dam. The flood inflow entering the reservoir resulted in overflow with a water level 2 m above the dam crest. The overflow from the reservoir removed the soil on the foundation and eroded the bedrock.

Analysis

The factors contributing to the failure can be summarized as follows:

- The very heavy storm producing 366 mm of rain in 9 hours, and more than 30% of the average annual rainfall within 24 hours, is estimated to have been a 1000-year storm.
- The Shella Zerbino dam was designed and constructed quickly, without any geologic investigations.
- The dam had no spillway or erosion protection and was therefore subjected to undirected and uncontrolled overtopping.
- Conditions of foundation:
    + The foundation rock was inadequate due to extensive joints, faults, shear zones, and slaty cleavage, which resulted in high erodibility and instability. This contributed to scour at the foundation under the plunging of the water overtopping the dam.
    - The bedrock is highly fractured and inadequate to bear the stresses induced by the weight of the Sella Zerbino dam.
- Components at risk are Reservoir, gravity dam, and foundation.
- Time factor is manifested in the duration of the rainstorm, time for increasing of the water level, and erosion process of bedrock.

Failure of the Shella Zerbino dam results from a combination of factors and interactions chronologically. The first interaction is the flood inflow from the rainstorm flowing into the reservoir. The flood inflow combined with the gravity dam conditions without spillway, causing an increase of the water level until overtopping the gravity dam. The subsequent interaction occurred between the overflow and the foundation, which relates to the power stream of the flow and erosion strength of the bedrock leading to erosion of the foundation.

7.2.3. Instantiation of the failure knowledge model

The dam system operates without spillway and bottom outlets, it includes components that are the reservoir, gravity dam, foundation, and abutment. It is described in two levels: system and component level.

The external factor: Heavy rain.

The failure process is described with 4 time points: from the time point T0 to the time point T3 (Figure A-7.39):

- Time point T0: Before the heavy rain, the dam system was in a normal state; the reservoir water level was 0.5 m, the foundation was stable.
- Time point T1: On August 13, 1935, heavy rain occurred
- Time point T2: Reservoir overtopped, water overflows the dam and runs down the foundation.
- Timepoint T3: The foundation eroded.

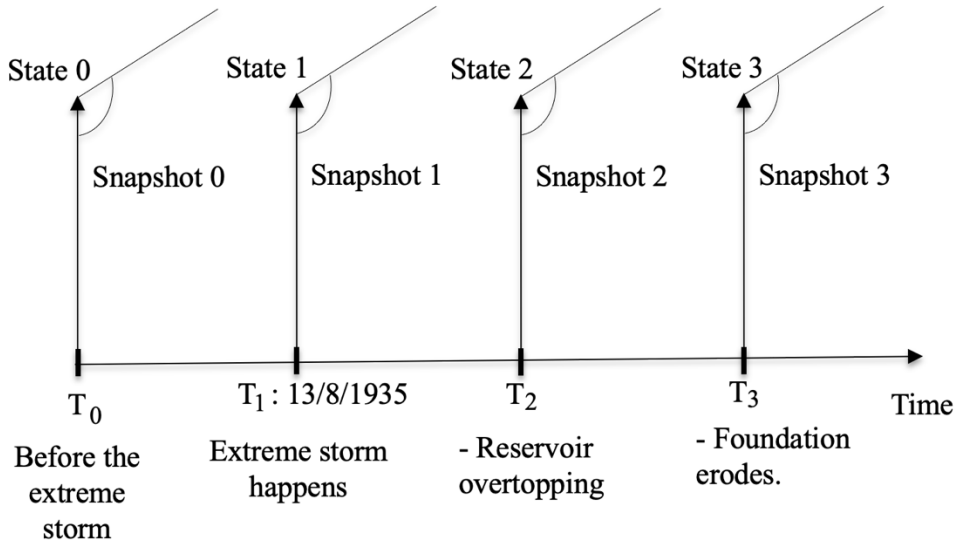


Figure A-7.39. Timepoints of the Sella Zerbino failure process

Steps to instantiate:

1. Identifying the dam system

2. Identifying the external factors

3. Identifying impacts of the external factors at T2

Performance of the reservoir at T2.

4. Interactions and performance of the foundation at T3

7.2.3.1. Identifying the dam system at T0

Identification of the Sella Zerbino dam system is performed similarly to the Koyna dam system since they have the same dam type. Figure 5.80 shows a rule graph to identify the structure of the gravity dam system. The rule can be expressed as **if** *Gravity_dam* is a component of *Dam_system*, then the main components of a gravity dam system will be created; *Dam_system* is described with its function and performance. A gravity dam system's main components include reservoir, gravity dam, foundation, abutment, spillway, and bottom outlet.

The rule graph describes the dam system with typical components. However, the real system has no spillway and bottom outlet; therefore, these components will be removed in the resulting graph.

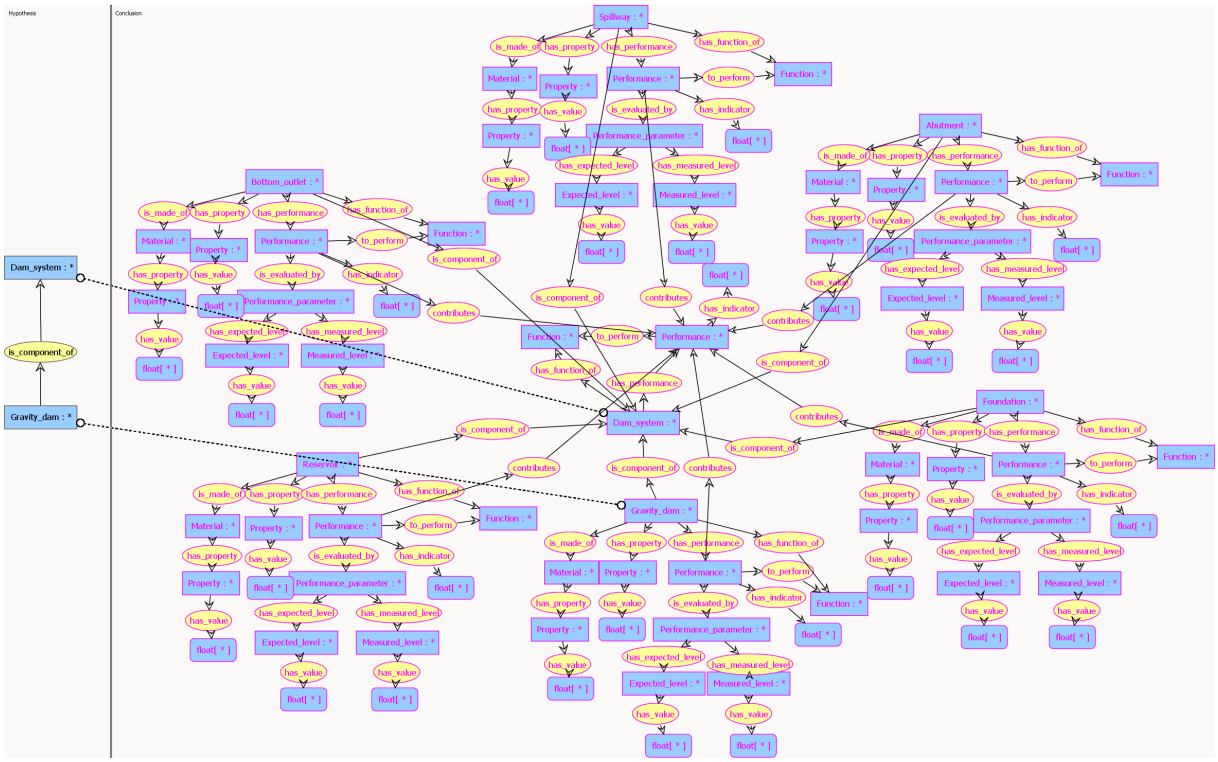
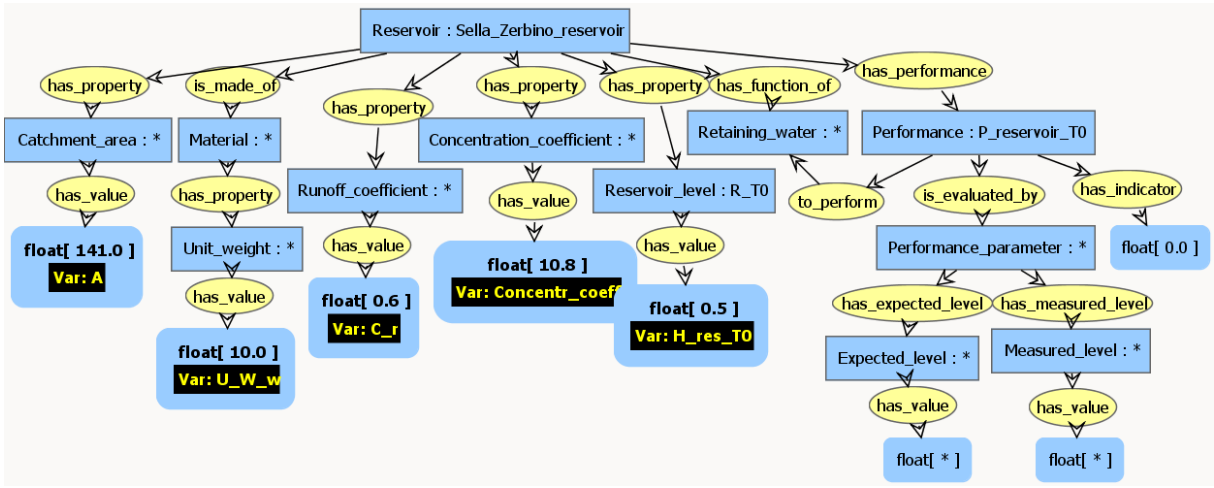


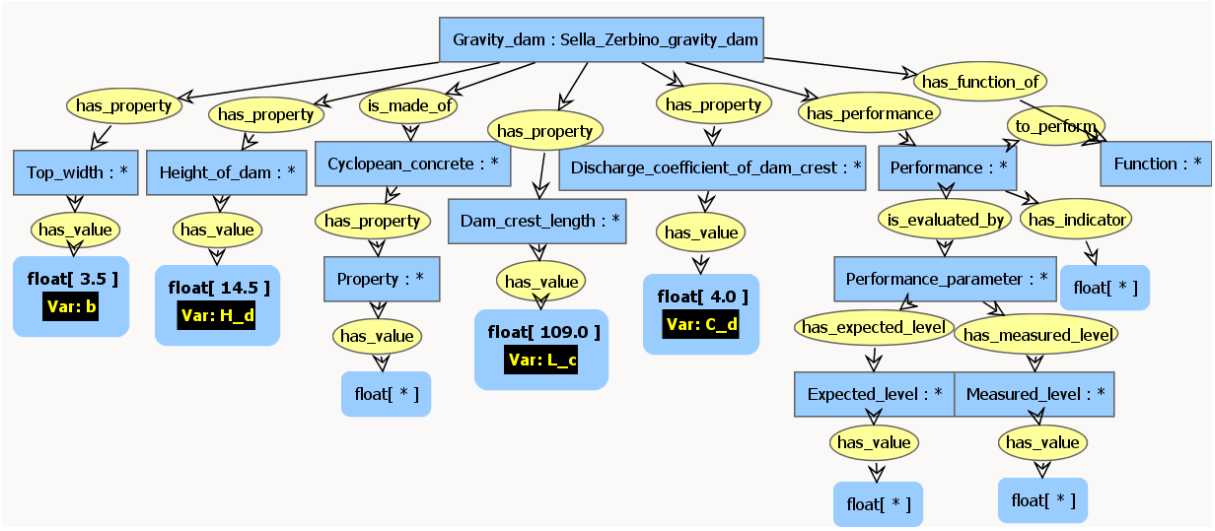
Figure A-7.40. Rule to identify the dam system

After identifying the structure of the system, all concepts are filled with information to formalize the failure. At T0, the components such as the reservoir, dam, foundation, and system are filled with necessary information as follow:



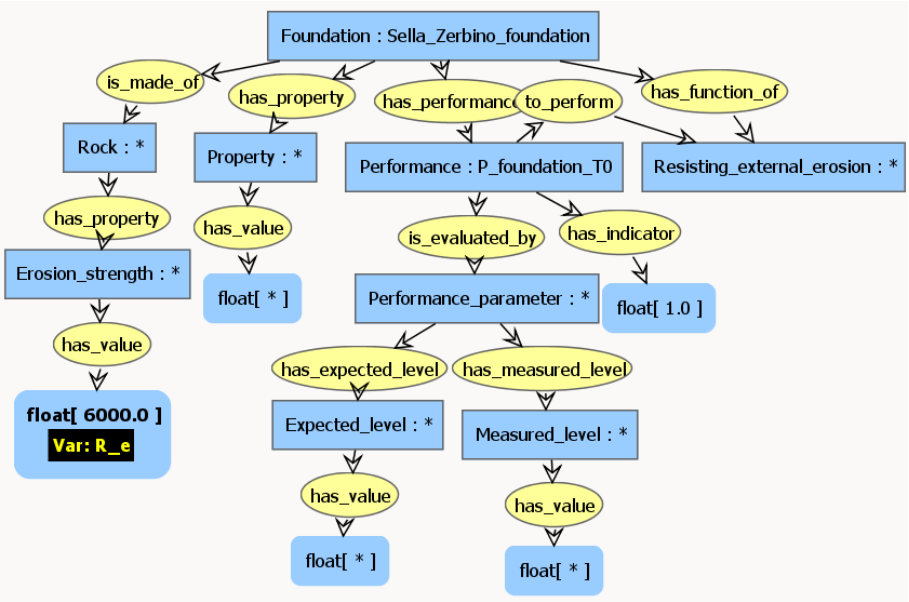
Fiugre A-7.41. Resulting graph of the reservoir

Figure A-7.41 illustrates the resulting graph of the reservoir. It is represented by an individual concept type *Reservoir: Sella_Zerbino_reservoir*. The reservoir is described with its relevant properties which are *Catchment_area*, *Runoff coefficient*, *Concentration coefficient*, *Reservoir_level*. The property of the material is *Unit weight*, which has a value of *10*. The function considered is *Retaining_water*, and the performance to perform it at T0 is *Performance: P_reservoir_T0*. The value of the indicator is assumed as 1, i.e., satisfied.



Fiugre A-7.42. Resulting graph of Sella Zerbino gravity dam

Figure A-7.42 shows a description of the Sella Zerbino dam. The dam is made of *Cyclopean concrete,* and described with properties which are *Top_width*, *Height of dam*, , *Dam_crest_length*, *Discharge coefficient of dam crest*. The properties are represented by the variables and their values.



Fiugre A-7.43. Resulting graph of Sella Zerbino foundation

Figure A-7.43 shows a description of the Sella Zerbino foundation. It is made of *Rock*, with the relevant property is *Erosion strength*. The function under consideration is *Resisting external erosion*. The performance to perform this function at T0 is *Performance: P_foundation-T0*, which is assumed as satisfied, i.e., the value of the indicator is *1*.

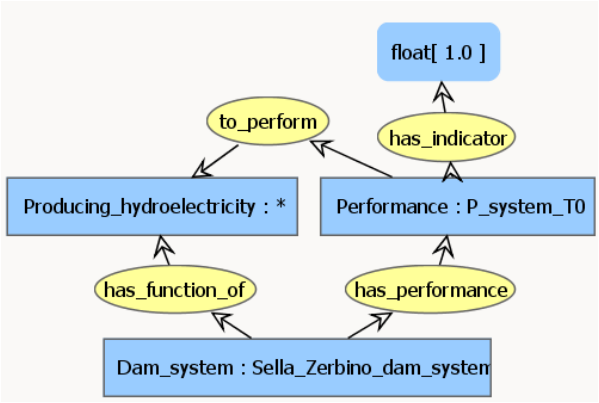


Figure A-7.44. Resulting graph of Sella Zerbino dam system

Figure A-7.44 shows the resulting graph of the Sella Zerbino dam system. The function considered is *Producing_hydroelectricity*; the performance to perform it at T0 is *P_system_T0*. The value of the indicator is assumed as *1*, which means that the system is satisfied.

7.2.3.2. Identifying the external factor

There is one external factor: Rain (Figure A-7.45).

The time point for rain is named T1: 13/8/1935.

Rain has two properties *Intensity* and *Duration*, with their values 0.336 and 7.5 respectively, are represented by variables *Int* for *Intensity* and *Dt* for *Duration*.

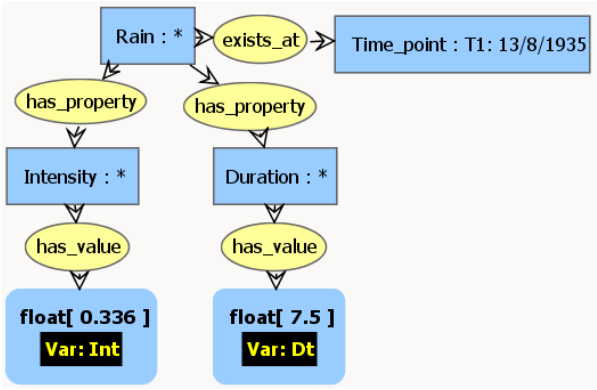


Figure A-7.45. External factor of the Sella Zerbino dam system

7.2.3.3. Identifying impacts of the external factors at T2

Surface runoff

Surface runoff is water from rain, snowmelt, or other sources that flows over a catchment area. The amount of water harvested from the catchment area is equal the amount of water that flows into the reservoir and has the height ΔH.

$$\Delta H = \text{rainfall} * K * C$$

where,

$$\text{Rainfall} = \text{duration} * \text{intensity (m)}$$

ΔH: amount of water flows ito the reservoir (m).

K: runoff coefficient, is the proportion of rainfall which flows along the ground as surface runoff. It depends amongst other factors on the degree of slope, soil type, vegetation cover, antecedent soil moisture, rainfall intensity and duration. The coefficient ranges usually between 0.1 and 0.5.

C: Catchment-Reservoir area ratio

Rule to calculate the runoff flow as follow:

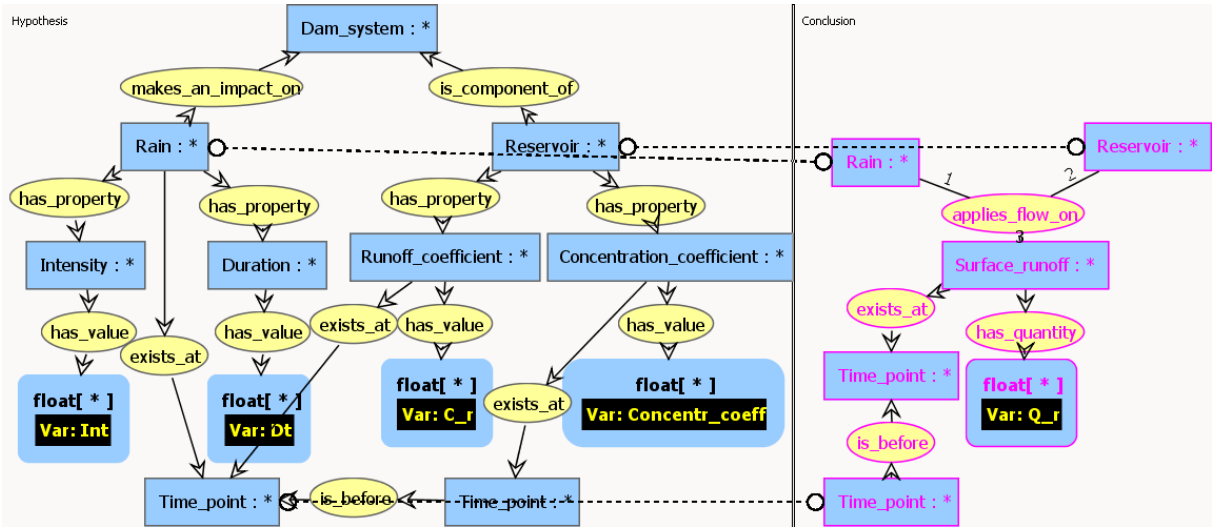


Figure A-7.46. Rule calculating surface runoff

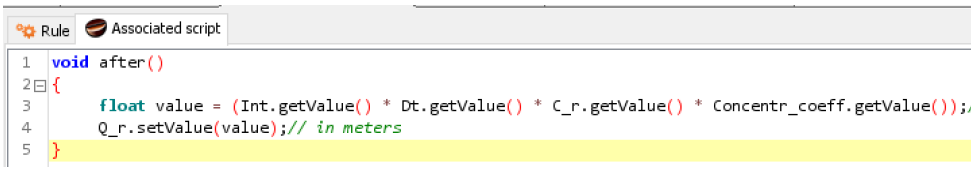


Figure A-7.47. Script calculating surface runoff

Figure A-7.46 shows a rule graph calculating the surface runoff. The rule can be explained as **if** *Rain* makes an impact on the *Dam system*, and *Reservoir* is a component of the *Dam_system*, then *Rain* applies *Surface_runoff* flow into the reservoir. The rain has two properties: *Intensity* and *Duration*. The reservoir has two properties those are *Runoff_coefficient* and *Concentration_conefficient.* The surface runoff exists at a time point after the time point of the rain. Figure A-7.47 shows the associated script.

New reservoir level

When the runoff flows into the reservoir, the water level will be increased. A new level of the reservoir after the surface runoff flows into, given by the equation :

$$H_{res_T2} = \Delta H + H_{res_T0}$$

where, H_{res_T2} : New reservoir level (m)

ΔH : amount of runoff (m)

H_{res_T0} : is the initial level of the reservoir (m)

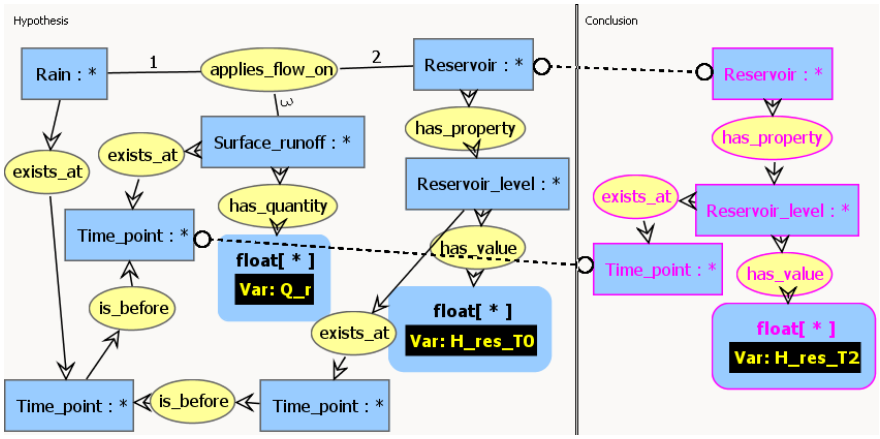


Figure A-7.48. Rule calculating new level of the reservoir

Rule | Associated script

```
1  void after()
2  {
3      float value1 = Q_r.getValue() + H_res_T0.getValue();
4
5      H_res_T2.setValue(value1);// reservoir level after fi
6  }
```

Figure A-7.49. Script calculating new level of the reservoir

Figure A-7.48 shows a rule graph calculating the new water level of the reservoir after the runoff flows into the reservoir. The rule says that **if** *Rain* applies *Surface_runoff* on *Reservoir*, and *Reservoir* has *Reservoir level* with the value is represented by a variable *H_res_T0,* **then** *Reservoir* has *Reservoir level* with a value presented by the variable *H_res_T2*. The surface runoff has a quantity presented by a variable *Q_r*. The time point of the new level is the time point of the runoff flow. Figure A-7.49 shows the associated script.

The resulting reservoir level is:

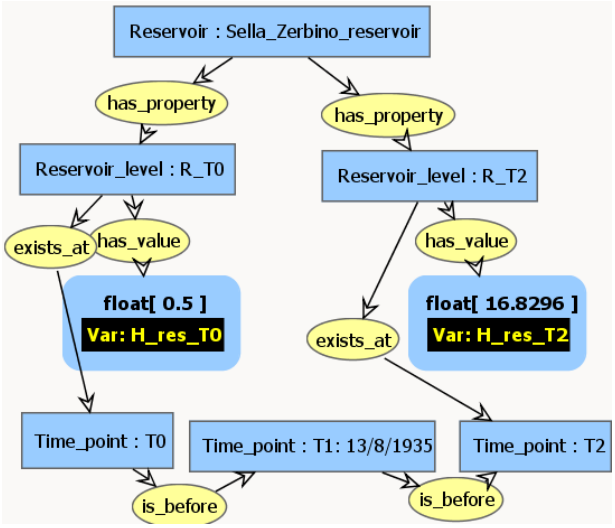


Figure A-7.50. Two levels of Sella Zerbino reservoir at different time points

Figure A-7.50 shows a change of the reservoir from the time point T0 to the time point T2. The water level increases from a height of 0.5 m to a new height that is 16.8296 m.

7.2.3.4. Performance of the reservoir at T2

When the water level changes over time, the performance of the reservoir will be considered. The performance is evaluated based on the freeboard, a distance from the water surface to the top of the dam.

Freeboard = Height of dam - Water level

Firstly, the real distance of the freeboard is calculated:

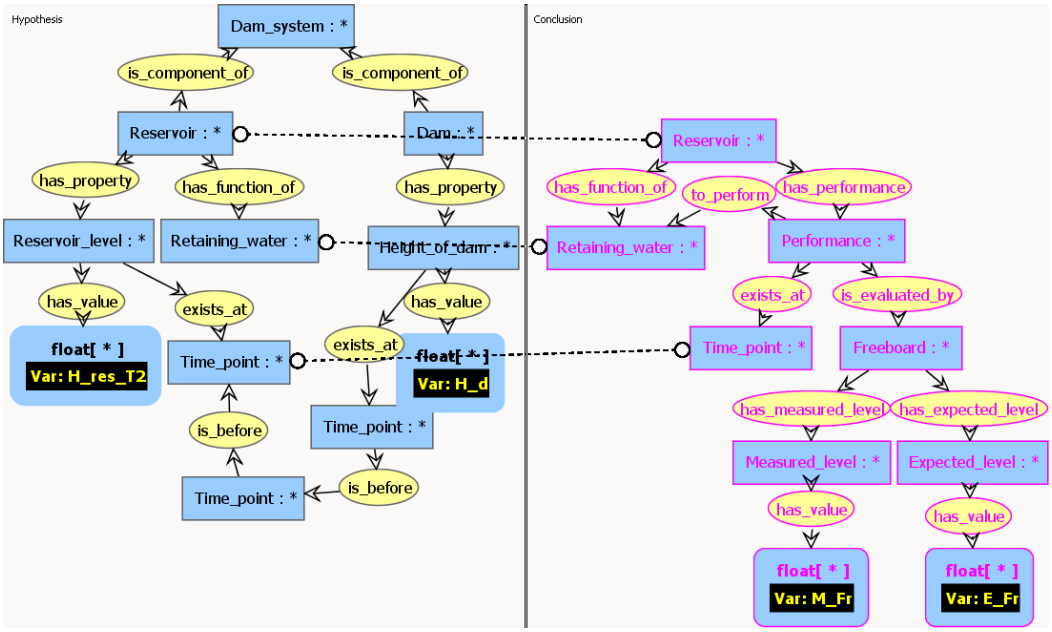


Figure A-7.51. Measured level of freeboard

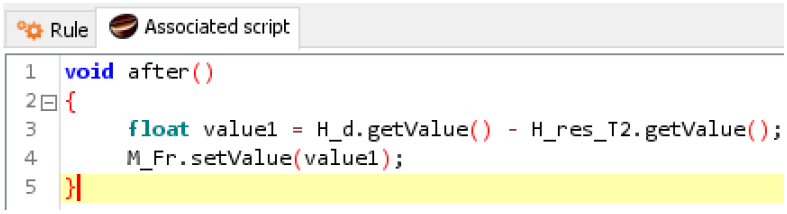


Figure A-7.52. Script calculating freeboard measured level of reservoir

Figure A-7.51 shows a rule calculating the measured level of freeboard when water level increases. The rule says that **if** *Reservoir* and *Dam* are components of *Dam_system*, *Reservoir* is at the new level, *Dam* has a *Height of dam* which is represented by variable *H_d*, **then** *Reservoir* has a new *Performance* which is evaluated by *Freeboard.* Two levels of the freeboard: *Measured level* and *Expected level* with their values are presented by variables *M_Fr* and *E_Fr*. A coref relation connects the concepts *Retaining_water* in the Hypothesis graph and the Conclusion graph. Fugure A-7.52 shows the associated script.

After identifying the real distance of freeboard, it will be compared with the expected level to determine the indicator of the reservoir performance.

Limit condition for freeboard:

If Freeboard < 0: water level exceeds the height of the dam, the reservoir overflow.

Freeboard > 0: no overflow takes place.

Rule to identify the reservoir performance as follow:

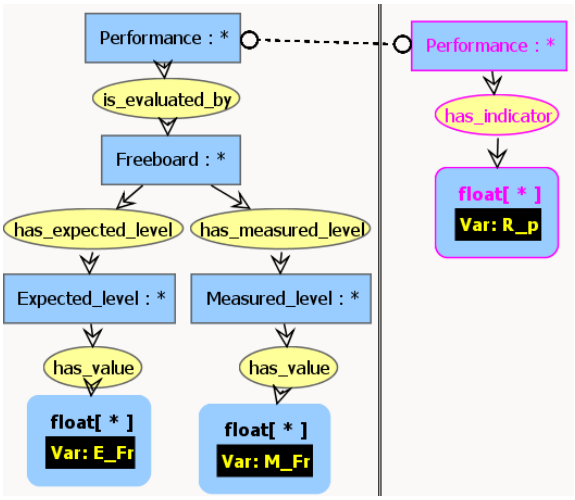


Figure A-7.53. Rule identifying performance of reservoir

Rule | Associated script

```
1  void after()
2  {
3      if (M_Fr.getValue() < E_Fr.getValue()) {
4          R_p.setValue(0);
5      }
6      else {
7          R_p.setValue(1);
8      }
9  }
```

Figure A-7.54. Script calculating performance of reservoir

Figure A-7.53 shows a rule identifying performance of the reservoir. The rule can be explained as **if** *Performance* is evaluated by *Freeboard*, and *Freeboard* has *Measured_level* and *Expected level* with variables *E_Fr* and *M_Fr* respectively, **then** *Performance* has an indicator represented by the variable *R_p*. Fugure A-7.54 shows the associated script.

Resulting performance of reservoir

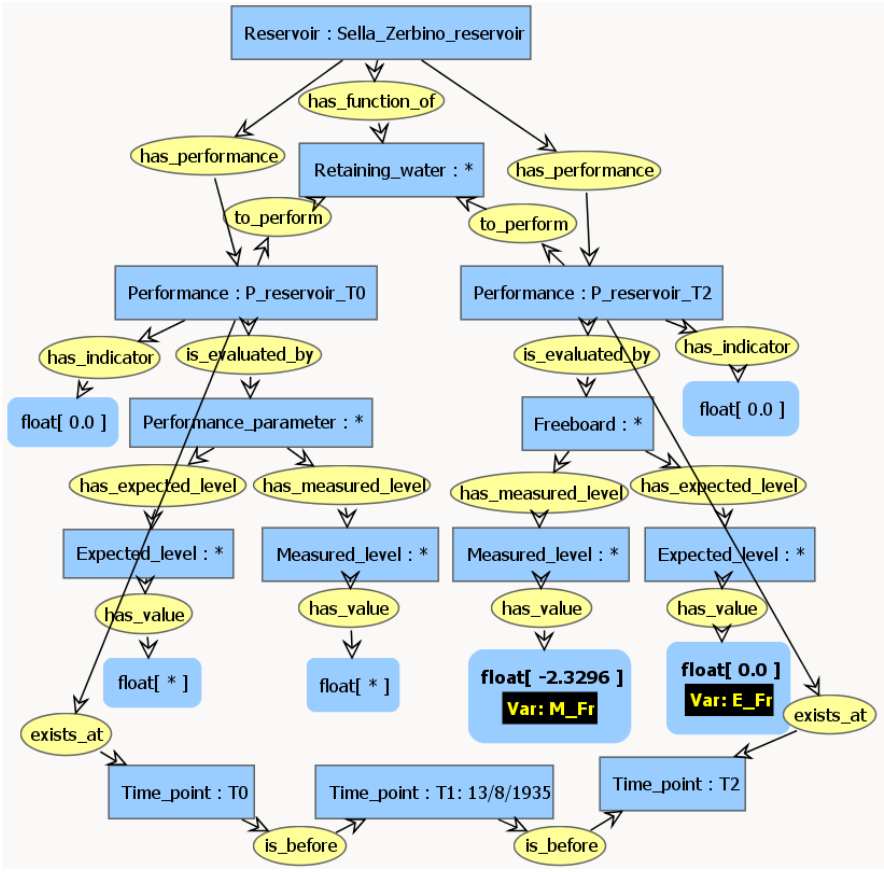


Figure A-7.55. Two performances of reservoir at two different time points

Figure A-7.55 illustrates the performances of the reservoir over time. It shows two performances at two different time points: T0 and T2. At T0, the value of the performance indicator is assumed as 0, i.e., not satisfied. At T2, the value of measured level < 0, thus *Performance: P_reservoir_T2* has a value of 0, which means that the reservoir overflow.

7.2.3.5. Interactions and performance of the foundation at T3

Overflow

When the reservoir overflow, water will be discharged over the entire length of the dam crest. This flow is an interaction between the reservoir and the dam. The discharge over the dam crest is given by the formula:

$$Q = C.L.H^{3/2}$$

Where,

Q = the discharge

C = the discharge coefficient for the dam crest

L = the length of the dam crest

H = the overtopping head

Rule calculating the overflow as follow:

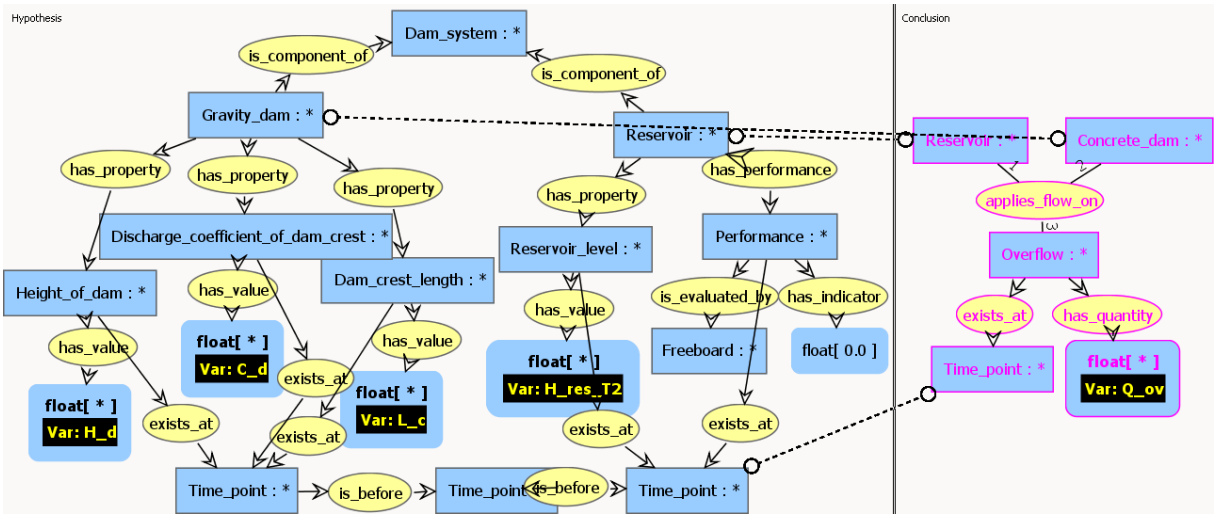


Figure A-7.56. Rule calculating overflow of reservoir

Rule | Associated script

```
1  void after()
2  {
3      float value1 = H_res_T2.getValue() - H_d.getValue();
4      float value2 = C_d.getValue() * L_c.getValue() * Math.pow(value1,1.5);
5
6      Q_ov.setValue(value2);
7  }
```

Figure A-7.57. Script calculating overflow of reservoir

Figure A-7.56 shows a rule calculating the overflow of the reservoir. The rule can be expressed as **if** *Gravity_dam* and *Reservoir* are components of *Dam_system*, and *Reservoir* has a *Reservoir_level* has *Performance* with the value of the indicator is *0,* **then** *Reservoir* applies *Overflow* on *Concrete_dam*. *Gravity_dam* is described with *Height_of_dam*, *Discharge_coefficient_of_dam_crest*, and *Dam_crest_length*. The reservoir is described

with *Reservoir level*. The time point of the overflow is the time point of the new water level. Figure A-7.57 shows the associated script.

Potential for erosion of the rock foundation due to overtopping flow

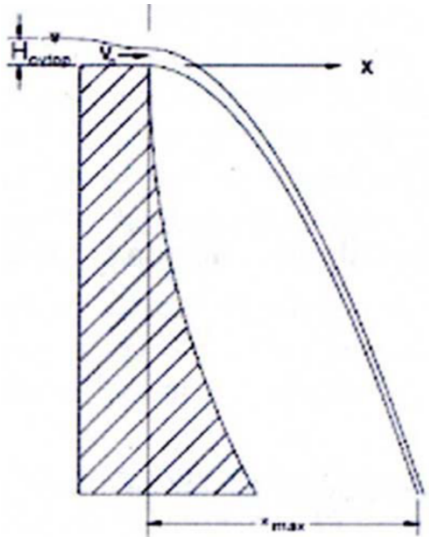


Figure A-7.58. Free jets overtopping a dam (FEMA, 2014)

The potential for rock erosion due to overtopping flows can be evaluated using the stream power-erodibility index method. The erodibilit y index (and its possible variability) represents how erodible the foundation material is. The stream power represents the erosive power of the overtopping flows. It is the rate at which energy is applied after the jet has travelled through a vertical distance, Z, to a location where the overtopping flows impacts on the foundation (FEMA, 2014).

$$P_{jet} = \gamma QZ$$

where:

P_{jet} = the total stream power of the jet

γ = the unit weight of water

Q = the total discharge

The stream power per unit area, t_j, is determined by dividing the total stream power by the base of the jet at the point of impact. If the jet has not broken up, the area should be based on the inner core thickness:

$$t_j = t_i \left(\frac{V_i}{V_j}\right)$$

Where:

t_j = the jet thickness at the point of impact

t_i = the initial brink depth

t_i is computed by the relationship:

$$d_c = \left(\frac{q^2}{g}\right)^{1/3}$$

where:

q = the discharge per unit of crest length

g = the acceleration due to gravity

V_i = initial velocity of the jet

$$V_j = (V_i^2 + 2gZ)^{1/2}$$

Where: Z = the elevation drop from reservoir level to the point impacted.

The stream power per unit area or stream power density of the jet is:

$$p_{jet} = \frac{\gamma Q Z}{t_j}$$

Rule to calculate stream power density of over jet flow is given as follow:

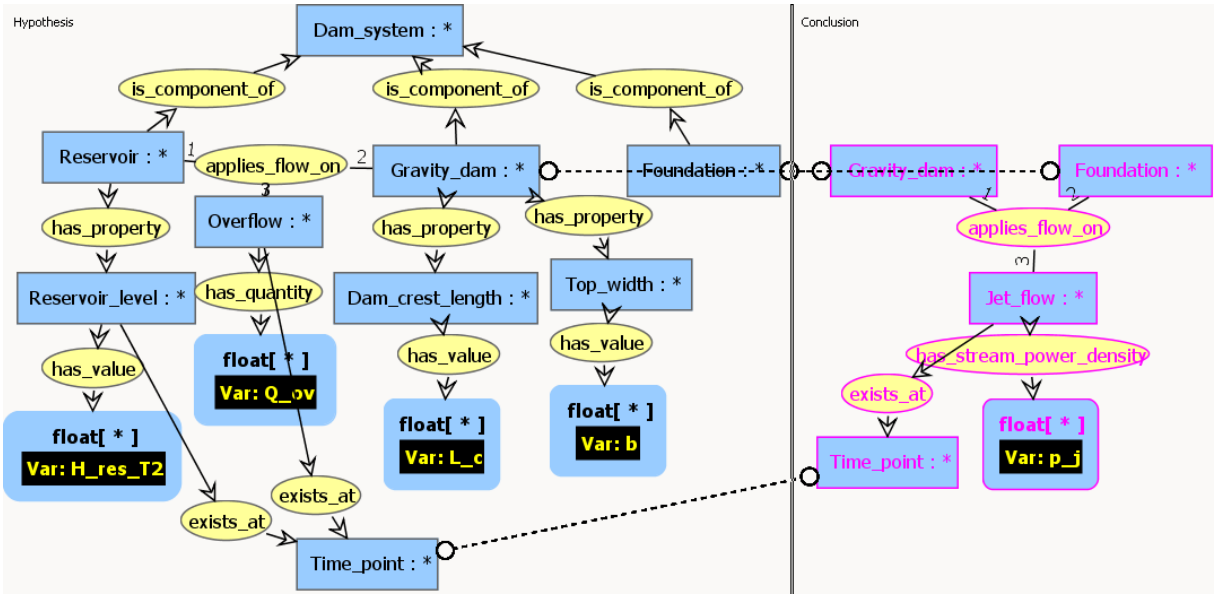


Figure A-7.59. Stream power density of jet flow

Rule | Associated script

```
1  void after()
2  {
3      float P_jet =  10 * Q_ov.getValue() * H_res_T2.getValue(); // P_jet = t
4
5      float q = Q_ov.getValue() / L_c.getValue();  // q = discharge per unit
6      float qq = q * q;// value3 = q * q
7      float t_i = Math.pow((qq / 9.8),1/3.0); // critical flow depth = t_i
8
9      float V_i = Q_ov.getValue() / (t_i * b.getValue()); // value5 = initial
10     float V_j = Math.sqrt((Math.pow(V_i,2)) + (2*9.8*H_res_T2.getValue()));
11
12     float t_j = t_i * V_i/V_j; // t_j = the jet thickness at the point of in
13
14     float value = P_jet / t_j; //  the stream power density of the jet
15
16     p_j.setValue(value);
17 }
```

Figure A-7.60. Script calculating stream power density of jet flow

Figure A-7.59 illustrates a calculation of the power stream density of the over jet flow. The rule says that **if** *Reservoir*, *Gravity_dam*, and *Foundation* are components of *Dam_system*, and *Reservoir* applies *Overflow* on *Gravity_dam*, **then** *Gravity_dam* applies *Jet_flow* on *Foundation*. The reservoir is described with *Reservoir_level* at the time point T2, *Gravity_dam* is described with *Dam_crest_length* and *Top_width*. The overflow is quantified with the variable *Q_ov*. The jet_flow is has stream power density which is represented by variable *p_j*. The time point of the jet flow is the time point of the overflow. Figure A-7.60 shows the associated script.

Performance of the rock foundation

Under the impact of the over jet flow, the rock foundation may be eroded. The performance of the foundation to resist external erosion will be evaluated by the Factor of safety against external erosion due to jet flow (F.S.E). The measured level of this factor is computed by the comparison between the stream power density of the over jet flow and erosion strength of the bedrock.

$$\text{Factor of safety against external erosion (F.S.E)} = \frac{Erosion\ strength}{Stream\ power\ density}$$

If F.S.E > 1: no failure

F.S.E < 1: erosion takes place

The measured level of the factor of safety against erosion due to jet flow:

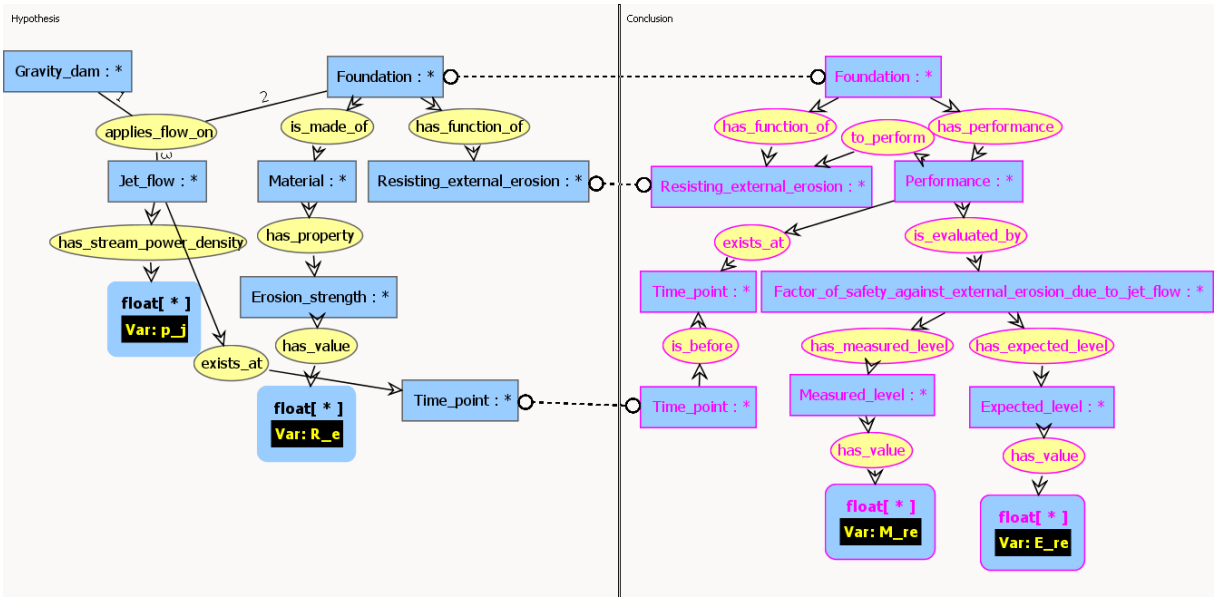


Figure A-7.61. Rule calculating measured level of factor of safety against external erosion due to jet flow

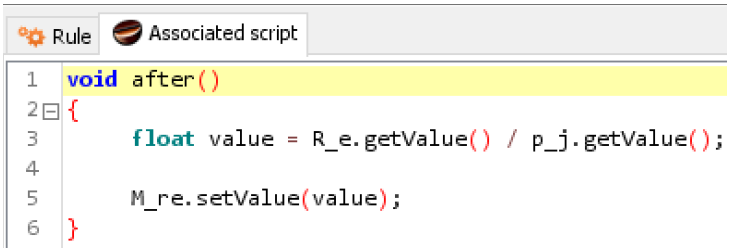


Figure A-7.62. Script calculating measured level of factor of safety against external erosion due to jet flow

Figure A-7.61 shows a rule calculating the measured level of factor of safety against external erosion of bedrock. The rule can be explained as **if** *Gravity_dam* applies *Jet_flow* on *Foundation*, then *Foundation* has a new *Performance* which is evaluated by *Factor of safety against external erosion due to jet flow*. The jet flow has stream power density, which is represented by the variable *p_j*. *Foundation* is made of *Material* that has *Erosion_strength* represented by the variable *R_e*. F.S.E has two levels: *Measured level* and *Expected level*. The time point of the erosion will be evaluated after the time point of the jet flow. There is a coref relation in the rule graph, which connects two concepts *Resisting_external_erosion*. Figure A-7.62 shows the associated script.

After calculating the measured level of F.S.E, the performance indicator will be identified based on the values of measured level and expected level of F.S.E.

Rule to calculate the performance indicator of the bedrock:

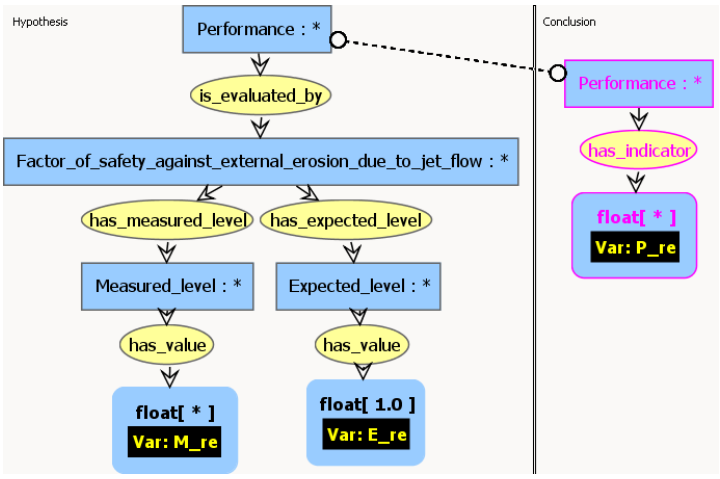


Figure A-7.63. Performance of foundation

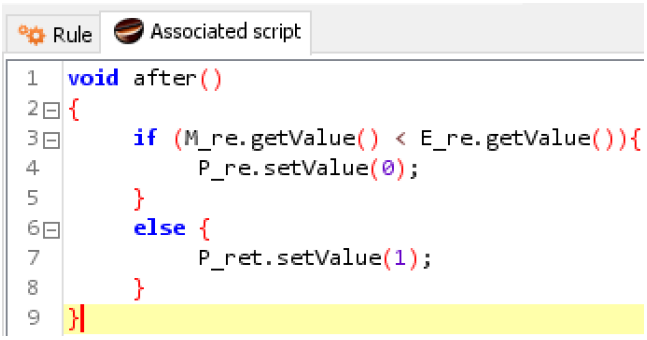


Figure A-7.64. Script calculating performance of foundation

Figure A-7.63 illustrates a rule identifying the performance indicator of the foundation to resist external erosion. The rule says that **if** *Performance* is evaluated by *Factor of safety against external erosion due to jet flow*, , **then** *Performance* has an indicator represented by the variable *P_re*. F.S.E has *Measured_level* and *Expected_level* defined by the variables *M_re* and *E_re*, respectively. Figure A-7.64 shows the associated script.

The resulting graph describing the new performance of the foundation:

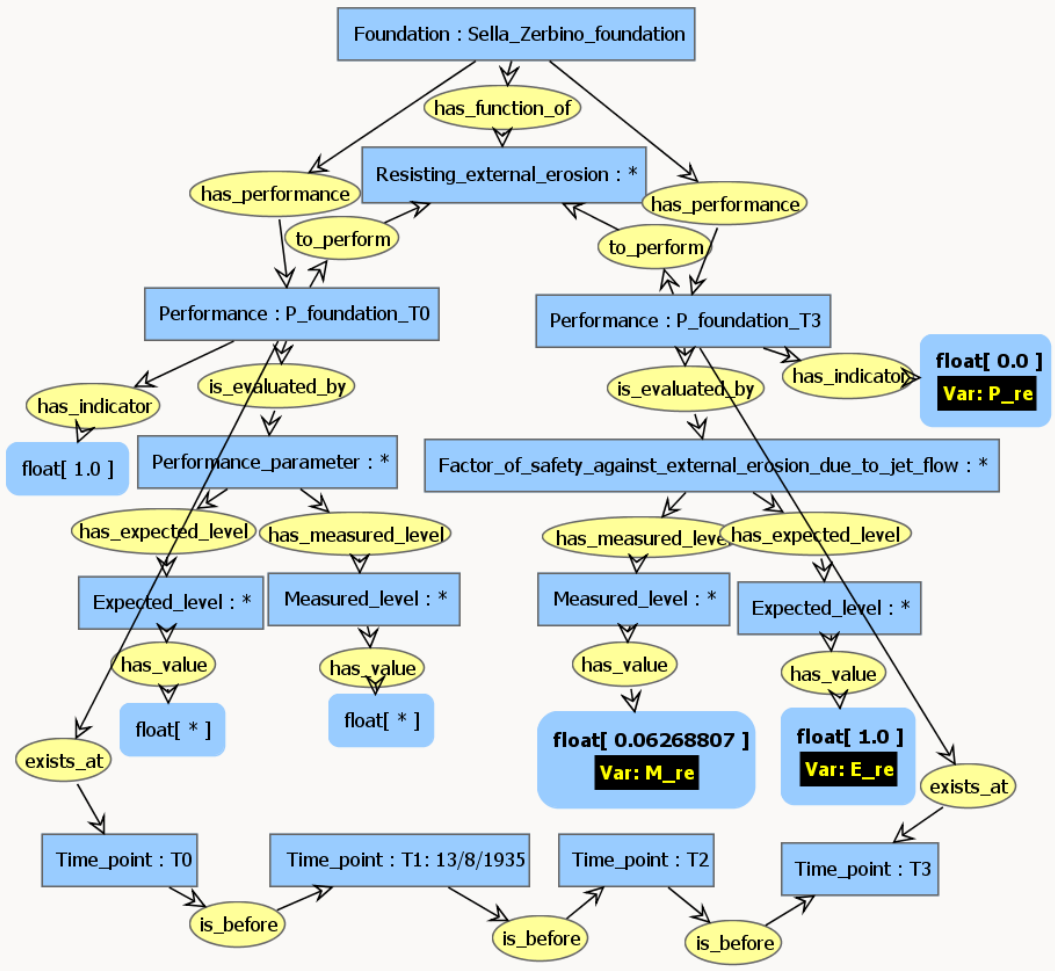


Figure A-7.65. Two performances of Sella Zerbino foundation at two different time points

Figure A-7.65 shows a change in the performance of the foundation over time. Two performances perform the function of *Resisting_external_erosion* at two different time points. The initial time is at T0; the performance is assumed as satisfied; the indicator's value is 1. The second time is at T3; the performance is not satisfied; the indicator's value is 0.

7.2.3.6. Performance of the dam system at T3

The performance of the foundation will contribute to the performance of the dam system. Rule to identify the performance of the system as follow:

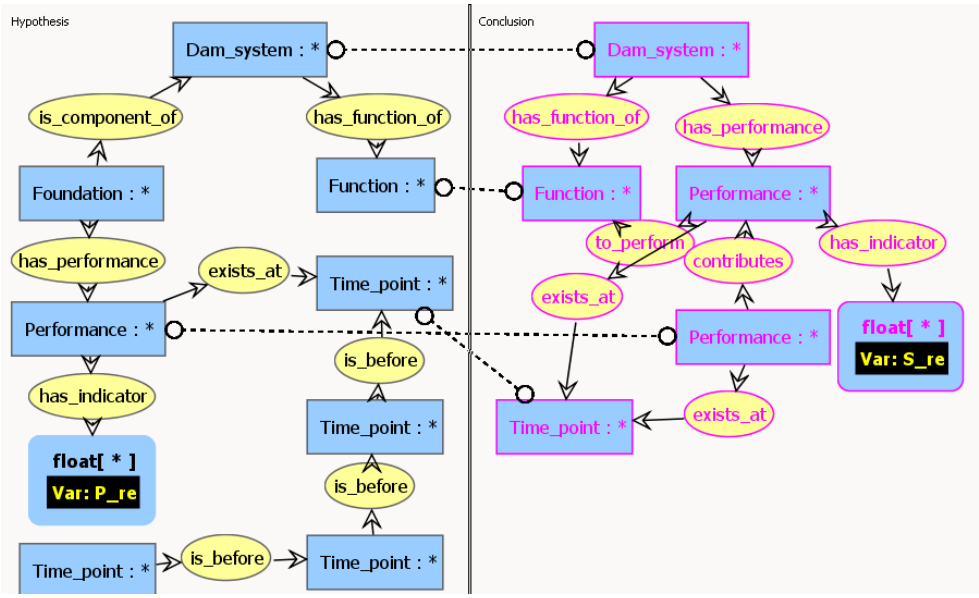


Figure A-7.66. Rule identifying performance of dam system

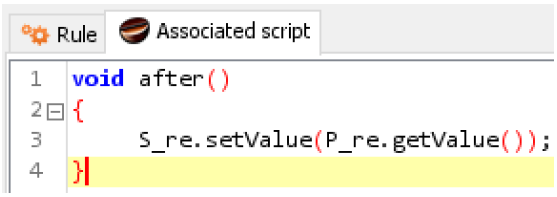


Figure A-7.67. Script identifying performance of dam system

Figure A-7.66 shows a rule to identify the performance of the dam system. The rule says that **if** *Foundation* is component of *Dam_system*, and *Foundation* has *Performance* that has an indicator represented by the variable *P_re*, **then** *Dam_system* has a new *Performance* contributed by *Performance* of *Foundation*. The time point of the system performance is the time point of the foundation performance. There is a coref relation connecting two *Function* concepts in the rule graph. Figure A-7.67 shows the associated script.

Resulting graph of performances of dam system:

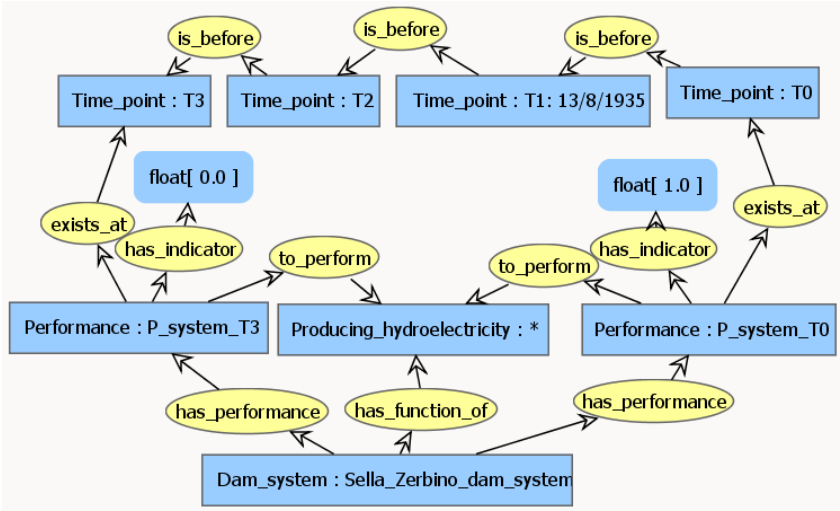


Figure A-7.68. Performances of system at two different time points

Figure A-7.68 shows the resulting graph of the performances of the system. The first performance is described by an individual concept, *Performance: P_system_T0*, which is assumed as satisfied; the value of the indicator is 1. Another performance is *Performance: P_system_T3*, which exists at T3; the indicator has a value of *0*, which means that it fails at T3. This graph presents a change in the foundation performance, from satisfied at T0 to not satisfied at T3.

7.2.4. Failure process

Failure process of the Sella Zerbino dam system is described in four snapshots in four time points, from the time point T0 to the time point T3.

- Snapshot at the time point T0 as follow:

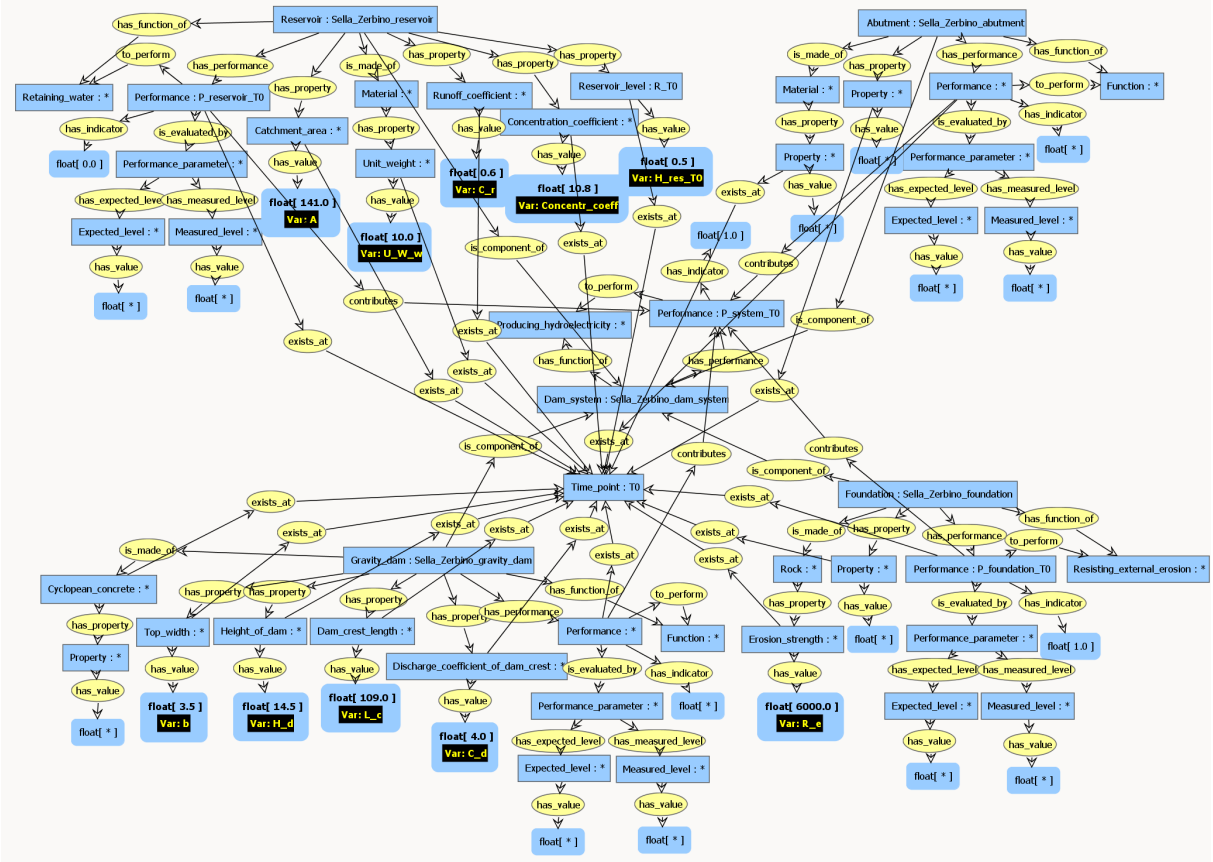


Figure A-7.69. Snapshot of the Sella Zerbino dam failure at T0

Figure A-7.69 shows the snapshot at T0, the time before the heavy rain, of the Sella Zerbino dam system failure. This snapshot describes the state of the system at the time point T0. At T0, the system's structure includes Sella Zerbino reservoir, Sella Zerbino gravity dam, Sella Zerbino foundation, and Sella Zerbino abutment. The system lacks a spillway component and bottom outlet component. The concepts that can change their values over time are connected with the concept *Time_point: T0* to identify their values and states at T0. At T0, the system experiences a long dry period. The water level is 0.5 m. The retaining water performance of the reservoir is assumed as not satisfied, i.e., the indicator has a value of 0. The function of the foundation is to resist external erosion. At T0, the foundation's

performance to resist external erosion is assumed as satisfied, i.e., the performance indicator values have values of 1. The function of the system is producing hydroelectricity. The system performance is assumed as satisfied at T0.

- Snapshot at the time point T1 as follow:

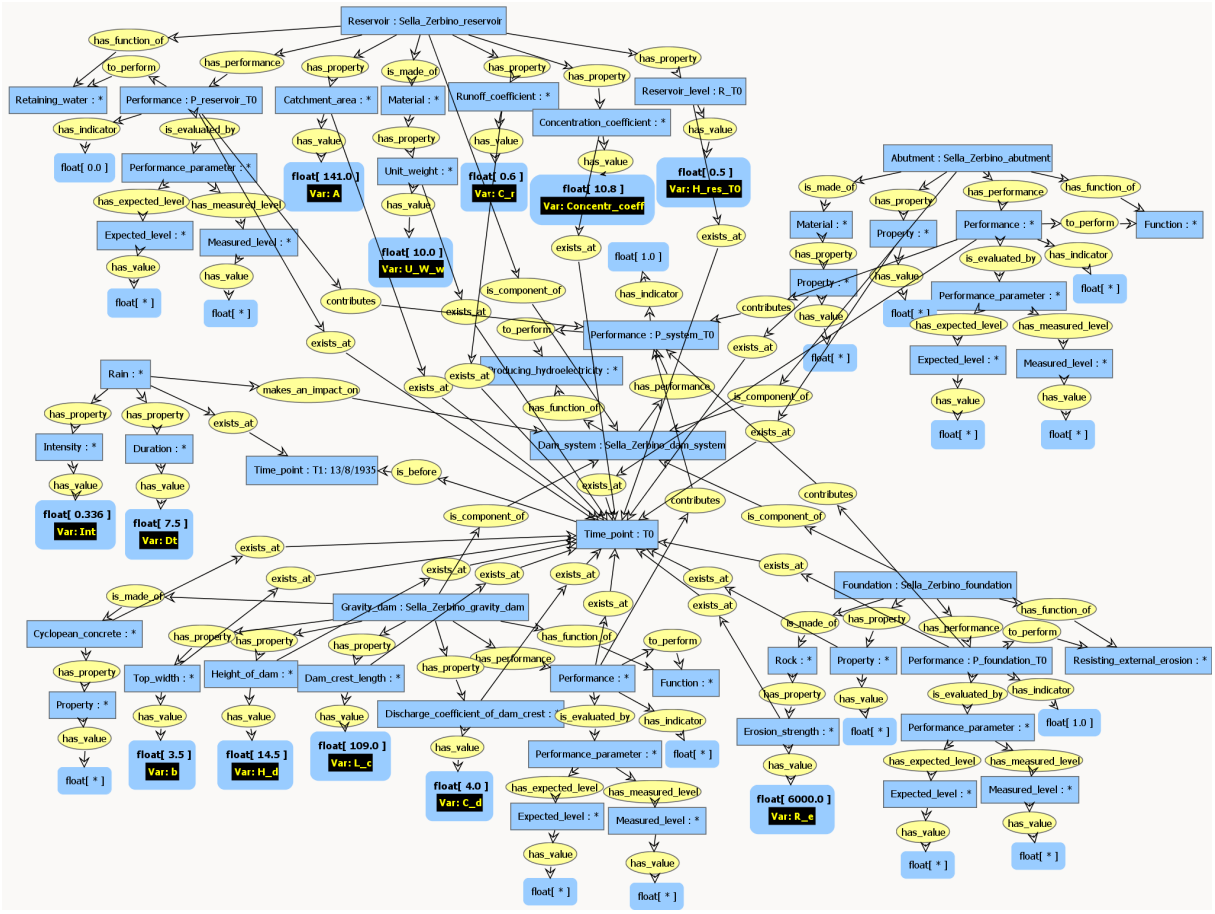


Figure A-7.70. Snapshot of the Sella Zerbino dam failure at T1

Figure A-7.70 shows the snapshot of the Sella Zerbino dam failure at T1. Based on the system's conditions at the time point T0, the snapshot at T1 is described with the addition of an external factor, which is heavy rain. The impact of the heavy rain on the system is described by the relation *makes_an_impact_on*. The concept *Rain* is connected with *Time_point: T1: 13/8/1935*. There is a relation *is_before* connecting the time point T0 and the time point T1.

- Snapshot at the time point T2 as follow:

Following the time point T1, a snapshot at the time T2 (Figure A-7.71) is described with impacts of the heavy rain on the system. The first impact is a runoff flow that the heavy rain interacts with the reservoir. This impact is described by the concept of *Surface_runoff* that exists at T2. Subsequently, due to the runoff, the reservoir increases to a new level *Reservoir_level: R_T2* with the value of 16.8 m. This value exceeds the dam's height, thus leading to an interaction *Overflow* between the reservoir and the dam. The overflow is

continued with an interaction, described by the concept *Jet_flow*, between the gravity dam and the foundation at T2. The performance of the reservoir is not satisfied.

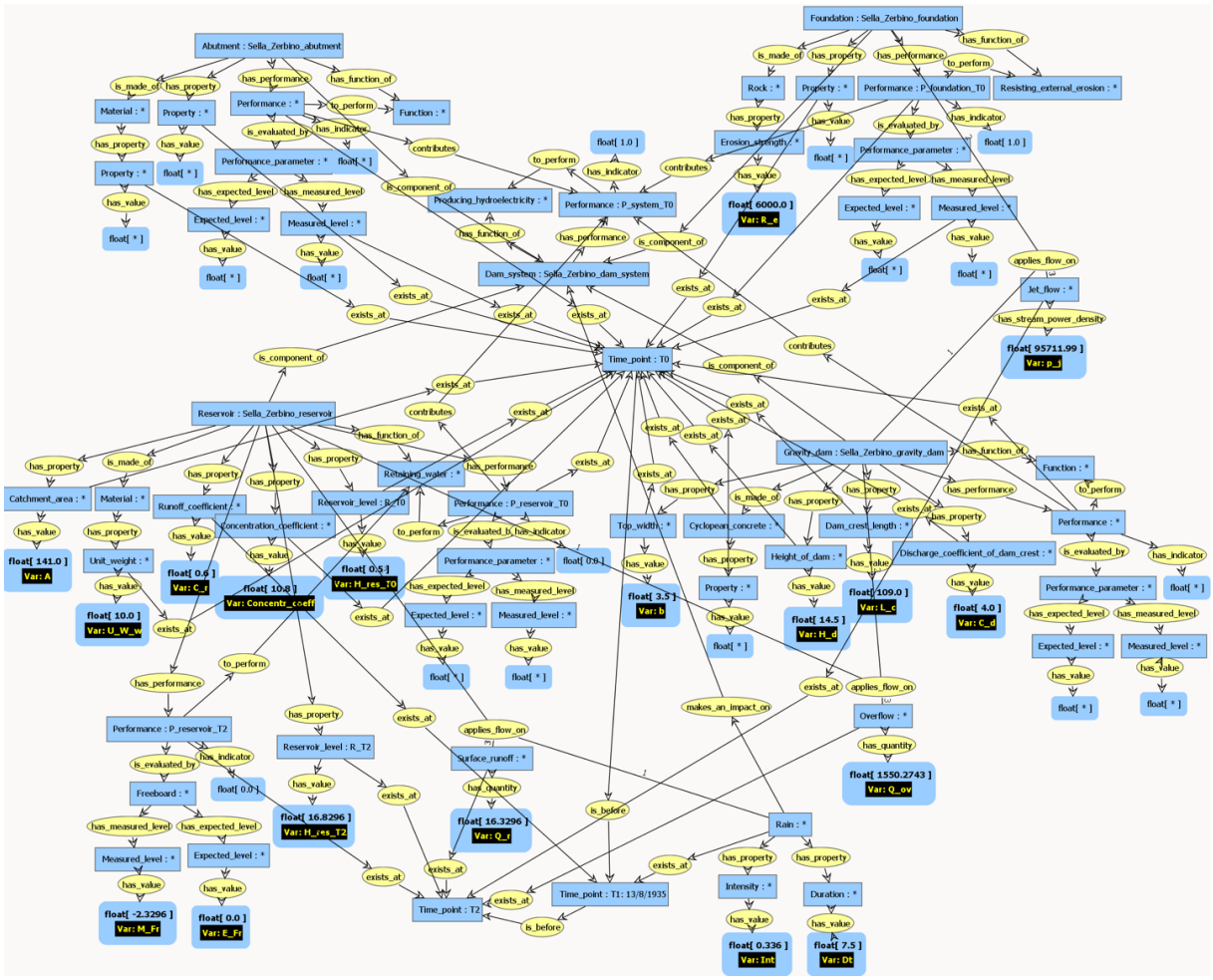


Figure A-7.71. Snapshot of the Sella Zerbino dam failure at T2

- Snapshot at the time point T3 as follow:

Following the interactions in the previous time, the snapshot at the time point T3 (Figure A-7.72) describes these interactions' consequences. Under the impact of the jet flow from the gravity dam, the foundation's performance is evaluated by considering the factor of safety against external erosion. At the time point T3, the performance indicator has a value of 0, which means that the foundation is eroded. This failure leads to the failure of the system at T3.

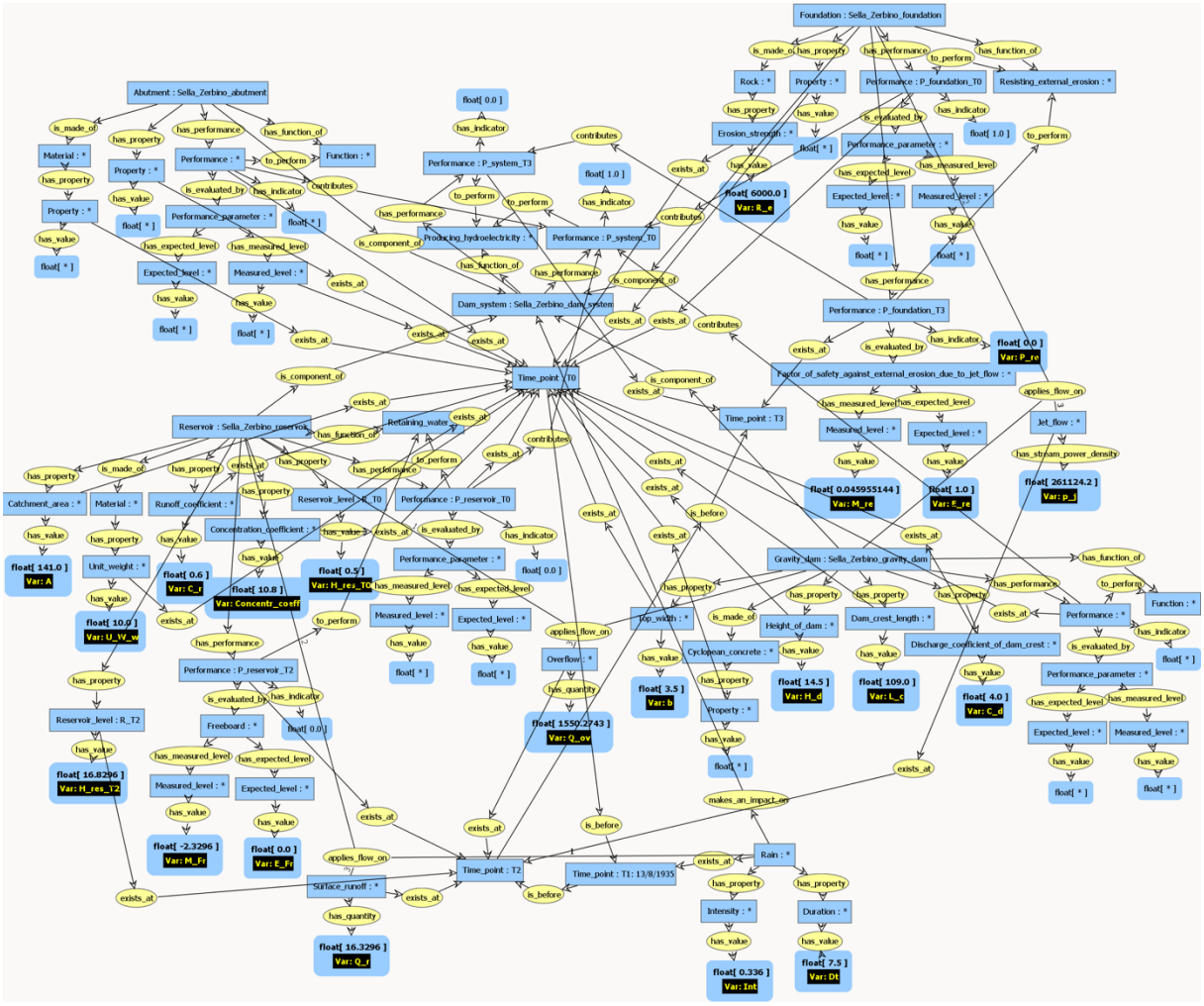


Figure A-7.72. Snapshot of the Sella Zerbino dam failure at T3

In conclusion, the four snapshots describe the Sella Zerbino dam system's failure process over time, from the time point T0 to the time point T3. The snapshot at T0 described the state of the system before the impact of the external factor. Following this, the snapshot at T1 shows the appearance of heavy rain. The interactions between the heavy rain and the system and between the components are described in the snapshot at T2. Finally, the snapshot at T3 presents the consequence of all impacts.

7.3. Case study 3 application - Tous dam system failure

7.3.1. Context of failure

General information

- Location: Valencia, Spain

- Failure: External erosion of dam

- Fatalities: 20–25 (Serra-Llobet, Tàbara and Sauri, 2013)

- Year of construction: 1958 – 1978

- Year of failure: October 20, 1982

- Function of dam system: Controlling flood

External factor

Extreme storm

Duration: 24 days

Intensity: 0.55 m/day

Description of site, structure and materials

Tous Dam (1970s-1982) was a flood control structure located in Valencia, Spain. This is one of the areas in the Western Mediterranean that is most prone to potentially catastrophic flash flood events due to its orography and the existence of Gota Fría phenomena. Tous dam was a zoned rockfill dam, composed largely of fragmented rock. It was 98.5 m high with a 400 m crest length. The dam was generally divided into three parts with very diverse characteristics: the central clay core, the drainage layers around the core, and finally, the rock-fill body that surrounds the other two zones (Figure A-7.73).

Because of a series of problems in the foundation, the abutments were made of concrete.

The spillway was designed for a maximum flow of 6968 m^3/s, controlled by three radial gates of 15 m (De Wrachien and Mambretti, 2009).

The bottom outlet had a capacity of 250 m^3/s.

The reservoir had a capacity of $120x10^6$ m^3 (Alcrudo and Mulet, 2007). Water elevation at normal operation was 84 m. The Tous dam catchment corresponds to 17.820 km^2.

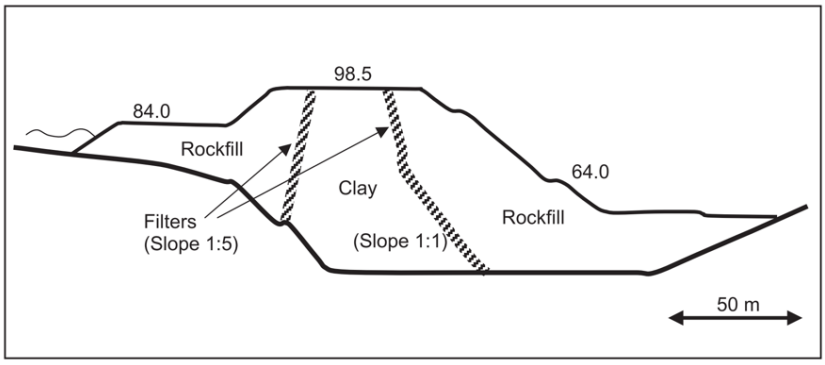


Figure A-7.73. Tous Dam cross section. Vertical and horizontal scales are equal. (Alcrudo and Mulet, 2007)

7.3.2. Failure presentation

Description of failure

On 19 - 20 October 1982, an extreme storm fell over the catchment of the Tous dam system. Due to the weather conditions, electrical power supply was out of order, making the opening of Tous dam spillway gates and bottom outlet gate impossible. The reservoir was

quickly filled up and surpassed the dam crest, causing erosion of the dam's downstream slope. (Figure A-7.74)

Figure A-7.74. Tous dam system after failure (Alcrudo and Mulet, 2006)

Analysis of failure

The factors contributing to the failure can be summarized as follows:

- Extreme storm which registered as the greatest storm of the twentieth century in the region. The rainfall intensity surpasses 500 mm in a zone where never had been registered rainfalls higher than 100 mm. Total rainfall over the catchment exceeds largely the capacity of Tous reservoir.
- During the storm, the electrical power supply was interrupted, making it impossible the opening of Tous dam spillway gates and bottom outlet gate.
- The rock-fill material is not capable of resisting external erosion.
- Components at risk are Reservoir, Zoned embankment dam, Spillway, Bottom outlet.
- Time factors are the duration of the storm, time for the erosion process.

The failure of the Tous dam system in October 1982 was a combination of many factors and interactions. The first interaction is the inflow created by the extreme storm that fell into the reservoir. As the water level increases due to the inflow, subsequent interactions between the reservoir and spillway gates and bottom outlet gate made the water level continue rising and soon exceed the dam crest. When the overflow running down the downstream face, the combination between hydraulic stress of the flow and erosion strength of rock material caused the external erosion of the downstream shell.

7.3.3. Instantiation of the failure knowledge model

Tous dam system failure is associated with the operation of spillway gates and bottom outlet gate and damage of the dam's downstream shell. Therefore, the dam system is described in three levels: system level, component level, and subcomponent level.

The external factor: extreme storm

The function considered of the reservoir is retaining water.

The function considered of the gates is controlling discharge.

The function considered of spillway and bottom outlet is controlling flood.

The function considered of the downstream shell and the dam is resisting external erosion.

The failure process is described with 4 time points: from the time point T0 to the time point T3 (Figure A-7.75):

- Time point T0: Before the extreme storm, the system works normally; the reservoir is at the height of 80 m. The reservoir performance is assumed as satisfied.

- Time point T1: on October 9, 1982 - The extreme storm happens.

- Time point T2: Water level increase. Spillway gates and Bottom outlet gate are not opened. The reservoir overtopping. The reservoir performance of the reservoir is not satisfied.

- Time point T3: Erosion of the downstream shell and the zoned dam. Failure of the dam system.

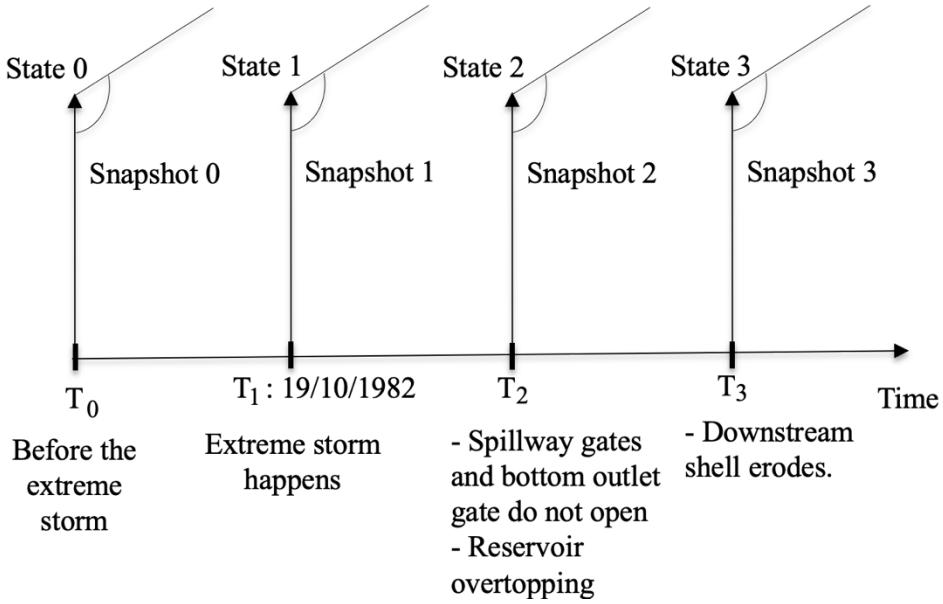


Figure A-7.75. Timepoints of the failure process

Steps to instantiate:

1. Identifying the dam system at T0

2. Identifying the external factors at T1

3. Impact of the external factor at T2

4. Interaction within the dam system at T2

5. Performance of the spillway gate at T2

6. Performance of the spillway at T2

7. Performance of the bottom outlet gate at T2

8. Performance of the bottom outlet at T2

9. Interaction and performance of the reservoir at T2

10. Interaction and performance of the downstream at T2

11. Performance of the zoned embankment dam at T3

12. Performance of the dam system at T3

7.3.3.1. Identifying the dam system at T0

Figure A-7.76 shows a rule graph to identify the structure of a zoned embankment dam system. The rule can be expressed as **if** *Zoned_embankment_dam* is a component of *Dam_system*, **then** the main components of a zoned embankment dam system will be created, those are *Reservoir, Zoned_embankment_dam*, *Foundation*, *Spillway*, and *Bottom_outlet*. *Dam_system* is described with its function and performance.

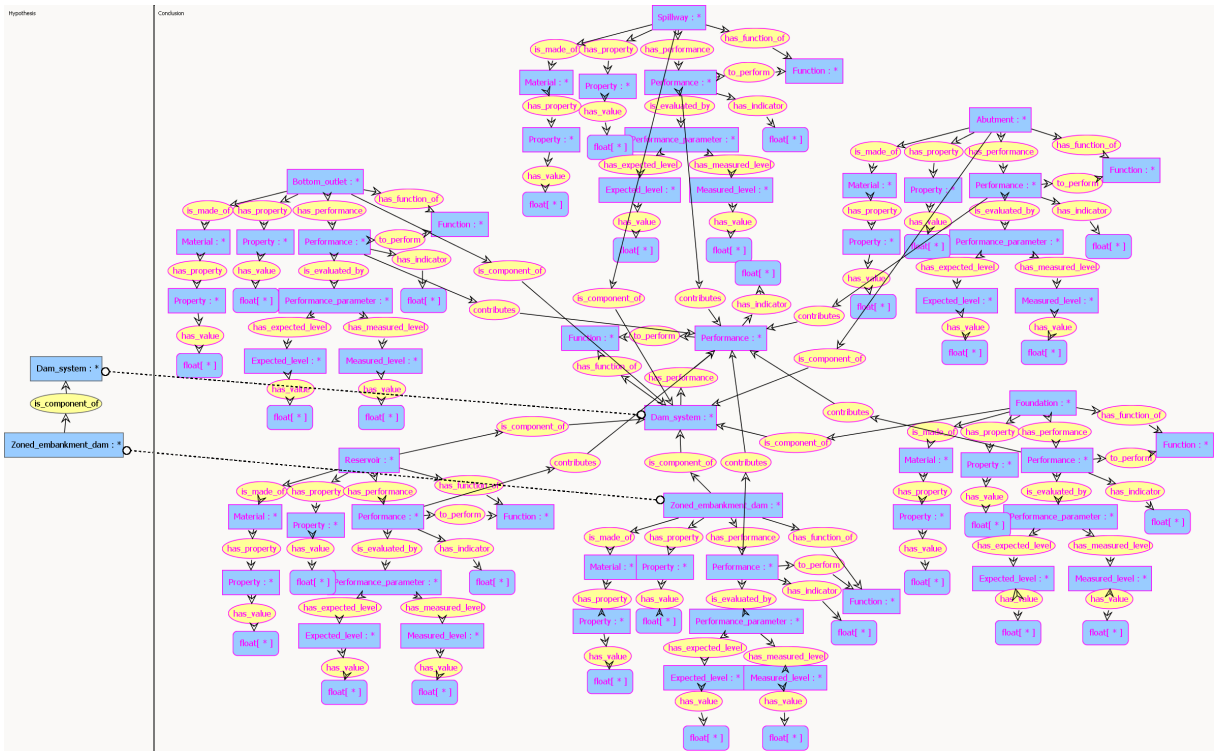


Figure A-7.76. Rule identifying zoned embankment dam system

After identifying the main components of the system, each component will be described at the lower level.

Rule to identify a zoned embanment dam as follow:

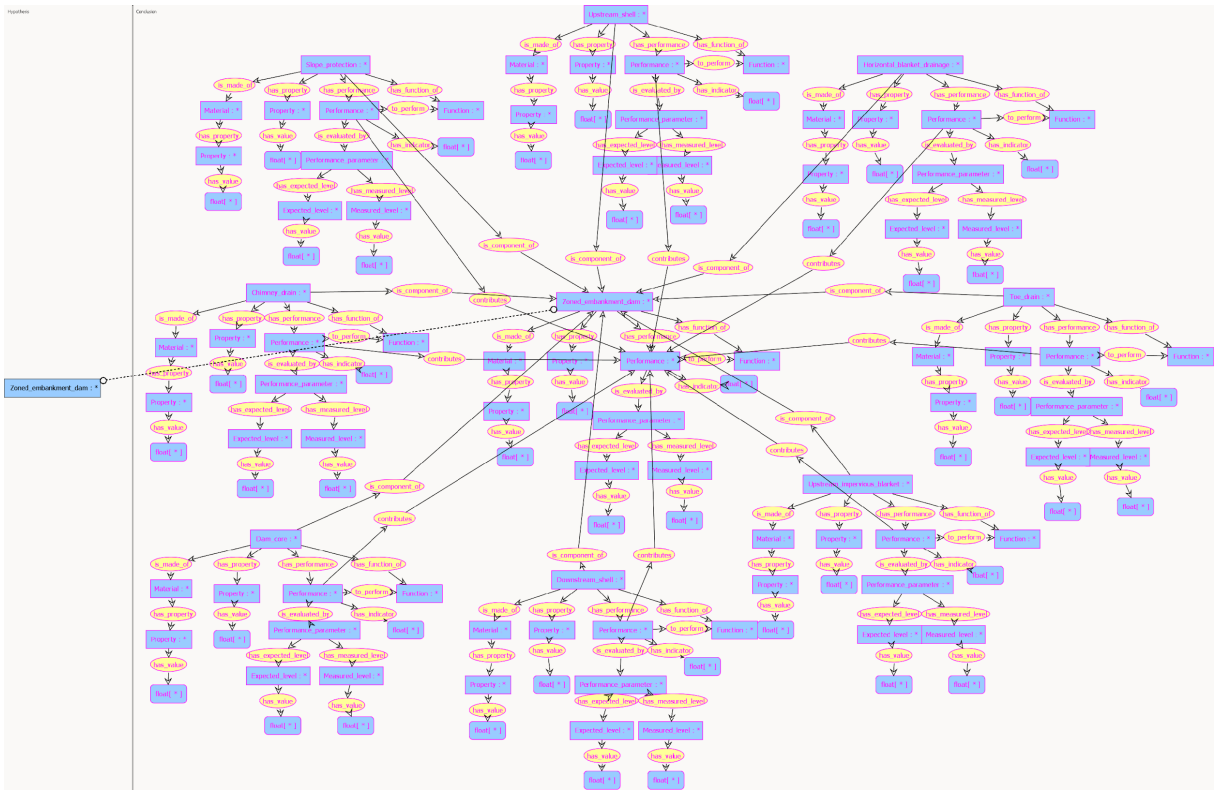


Figure A-7.77. Rule to identify zoned embankment dam

Figure ***A-7.77*** shows a rule identifying the zoned embankment dam. The dam is described with its typical component: dam core, downstream shell, upstream shell, toe drain, horizontal blanket drainage, slope protections, upstream impervious blanket, and chimney drain. All components are described by their property, material, material property, performance, function, performance parameter. The lower-components connect to the zoned embankment dam by the relation *is_component_of*. Performances of the components connect to the performance of the dam by the relation *contributes*.

Rule to identify a spillway as follow:

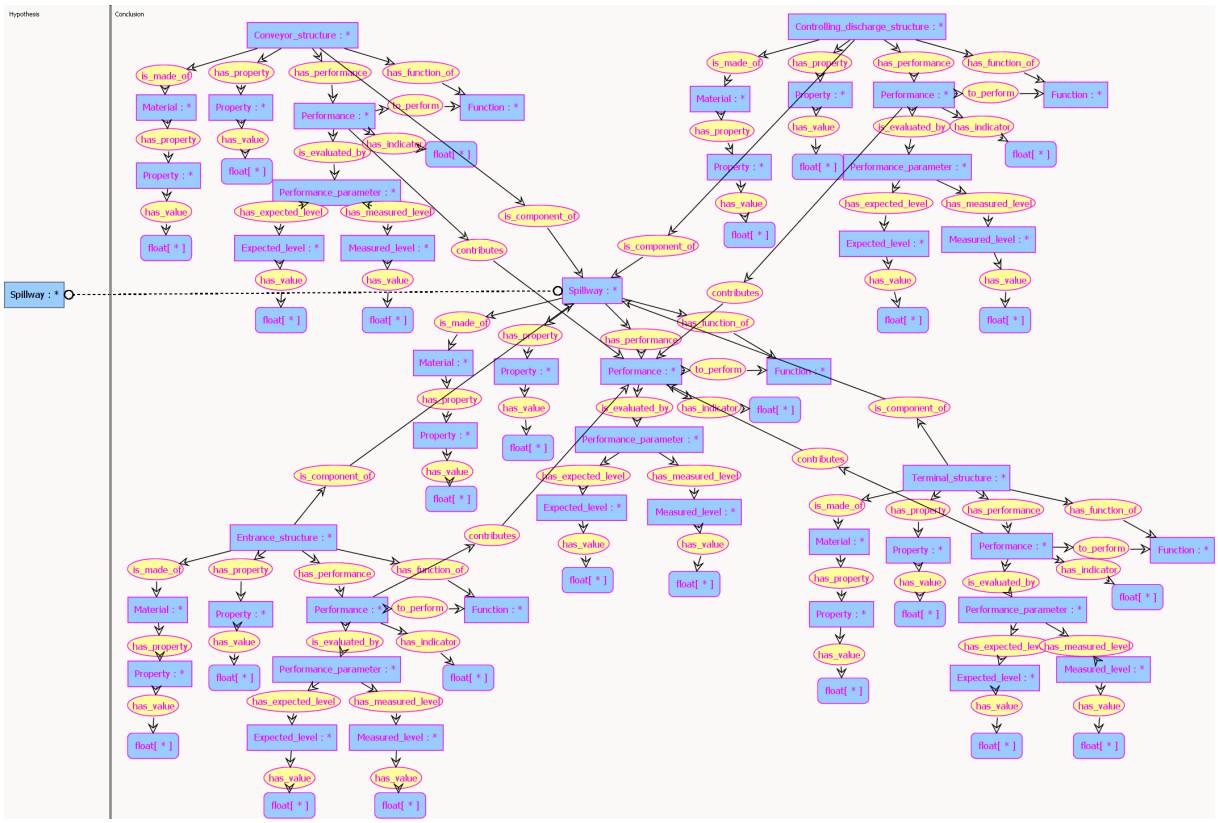


Figure A-7.78. Rule to identify spillway

Figure A-7.78 shows a rule graph identifying spillway. The rule graph says that **if** there is *Spillway*, **then** *Spillway* has components of *Entrance structure*, *Controlling discharge structure*, *Conveyor structure*, *Terminal structure*. All components are described by their property, mateiral, material property, performance, function, performance parameter. The components connect to the spillway by the relation *is_component_of*. Performances of the components connect to the perfomance of the spillway by the relation *contributes.*

Rule to identify a bottom outlet:

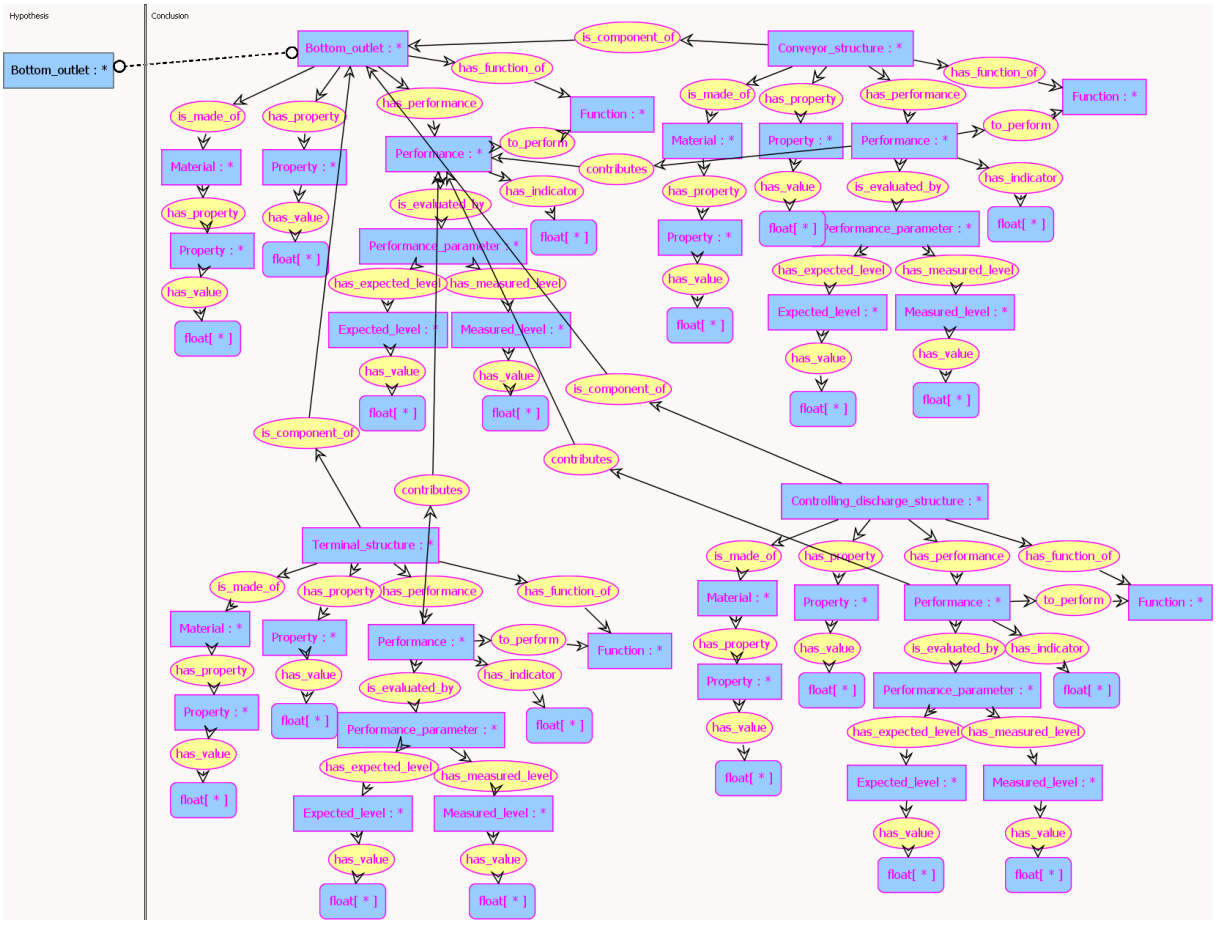


Figure A-7.79. Rule to identify bottom outlet

Figure A-7.79 shows a rule graph to identify a bottom outlet. The rule graph can be expressed as **if** there is a *Bottom-outlet*, **then** *Bottom-outlet* has components of *Controlling-discharge-structure*, *Convoyer_structure*, *Terminal_structure*. All components are described by their property, material, material property, performance, function, and performance parameter. The components connect to the bottom outlet by the relation *is_component_of*. Performances of the components connect to the performance of the bottom outlet by the relation *contributes*.

After applying the rules above, all concepts are filled with the necessary information to formalize the failure. The components that are not available in reality will be removed. For example, for the Tous spillway, which rests on the dam, the spillway had no entrance structure. Therefore, the entrance structure is removed in the fact graph. At T0, the components relating to failure are described as follow:

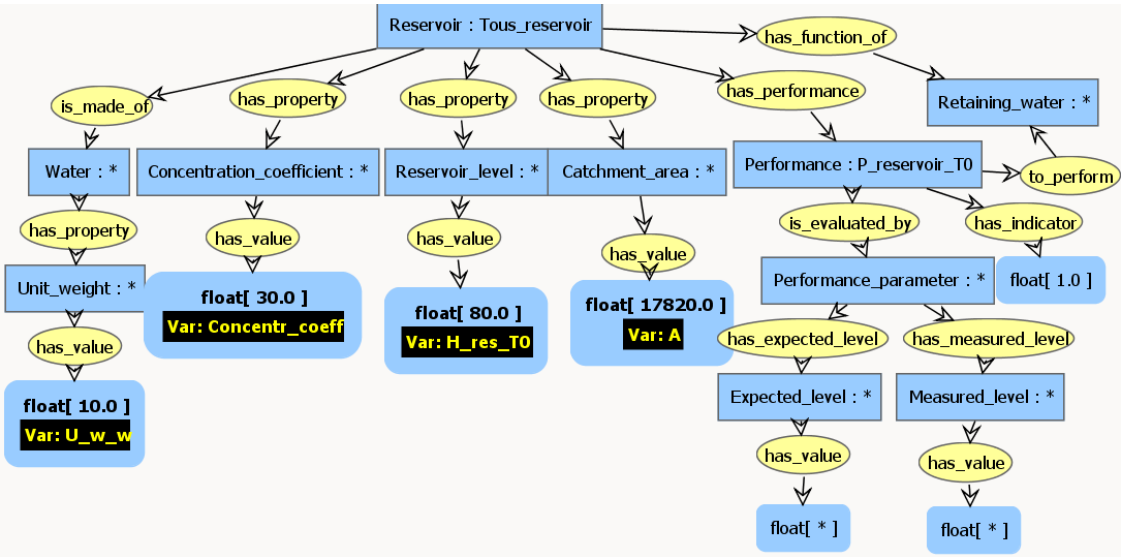


Figure A-7.80. Tous reservoir component at T0

Figure A-7.80 shows the Tous reservoir component. It is made of *Water* that has *Unit weight* represented by the variable *U_w_w*. The reservoir is described with the properties as *Concentration coefficient*, *Reservoir level*, *Catchment area*. Performance of the reservoir at T0 is *Performance: P_reservoir_T0*, assumed as satisfied, i.e., the performance indicator's value is *1*. The function of the reservoir is *Retaining water*.

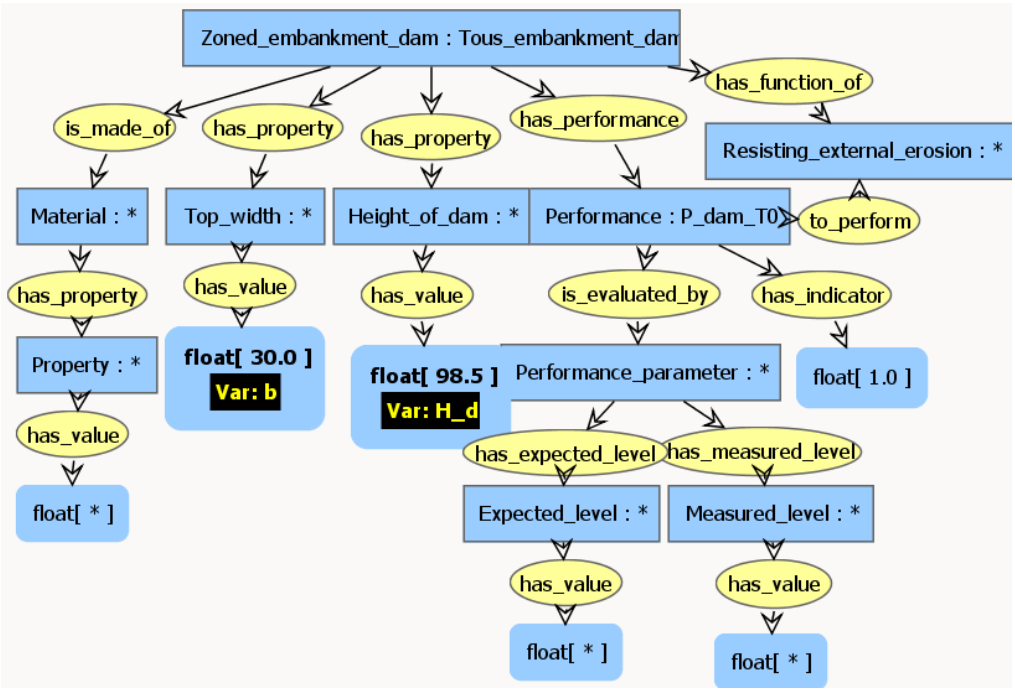


Figure A-7.81. Tous zoned-embankment dam at T0

Figure A-7.81 describes the Tous zoned embankment dam at T0. The dam is described with *Top width*, *Height of dam*, *Performance: P_dam_T0*, the function of *Resisting external erosion*. The performance is assumed as satisfied, i.e., the indicator has a value of *1*.

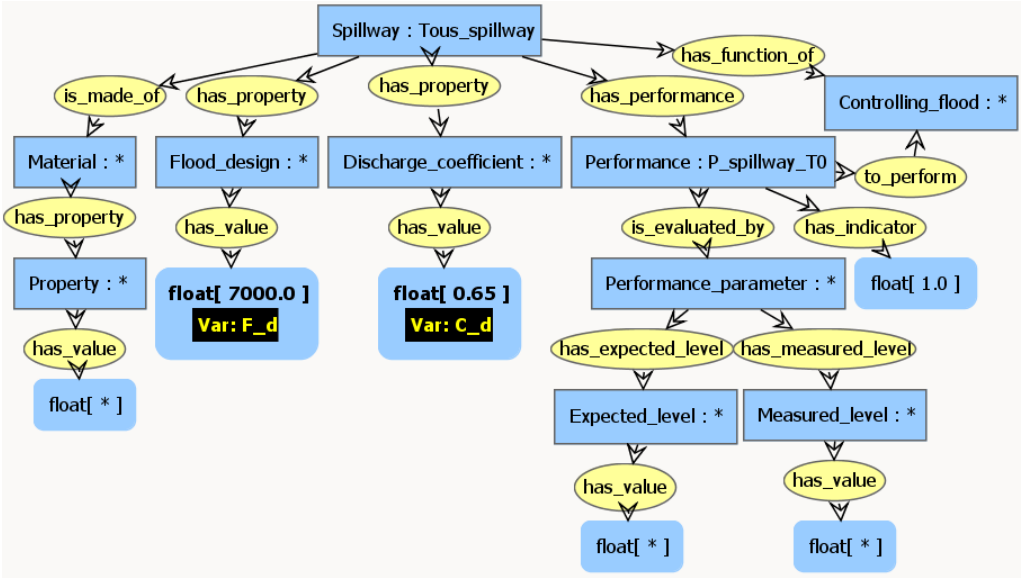


Figure A-7.82. Tous spillway component at T0

Figure A-7.82 describes the Tous spillway at T0. The spillway is described with *Flood design* with a value of *7000* assigned to variable *F_d*, *Discharge coefficient* with a value of *0.65* assigned to variable *C_d*. The performance is *Performance: P_spillway_T0* that is assumed as satisfied, i.e., the indicator has the value of *1*. The function of the spillway is *Controlling_flood*.

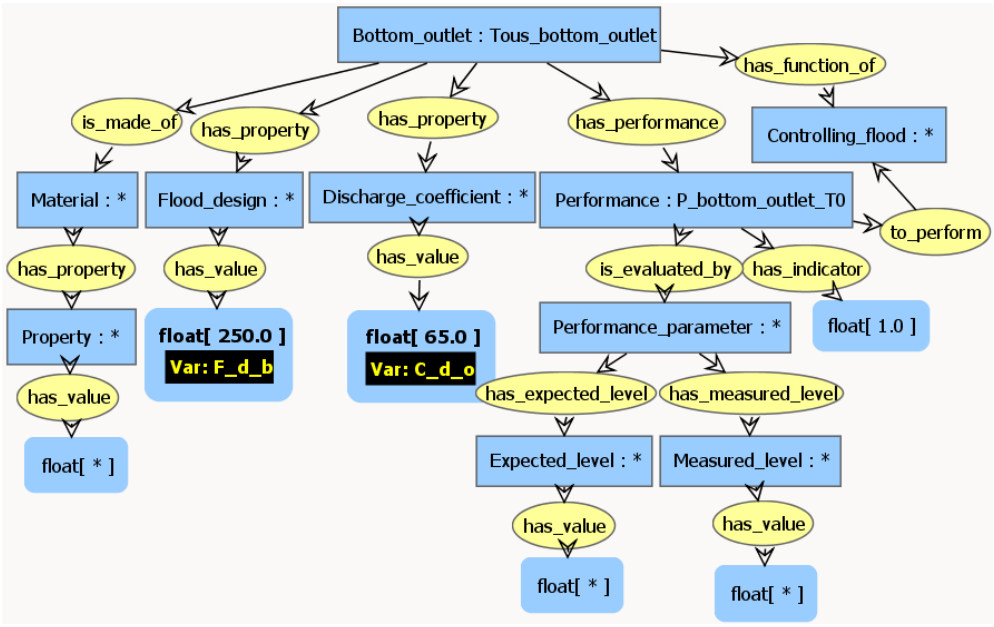


Figure A-7.83. Tous bottom outlet at T0

Figure A-7.83 shows the Tous bottom outlet component at T0. The component is described with its relevant properties: *Flood design* with a value of *250* assigned to the variable *F_d_b*, *Discharge coefficient* with a value of *65* assigned to the variable *C-d_o*. The performance is *Performance: P_bottom_outlet_T0* that is assumed as satisfied, i.e., the value of the indicator is *1*. The function of the bottom outlet is *Controlling_flood*.

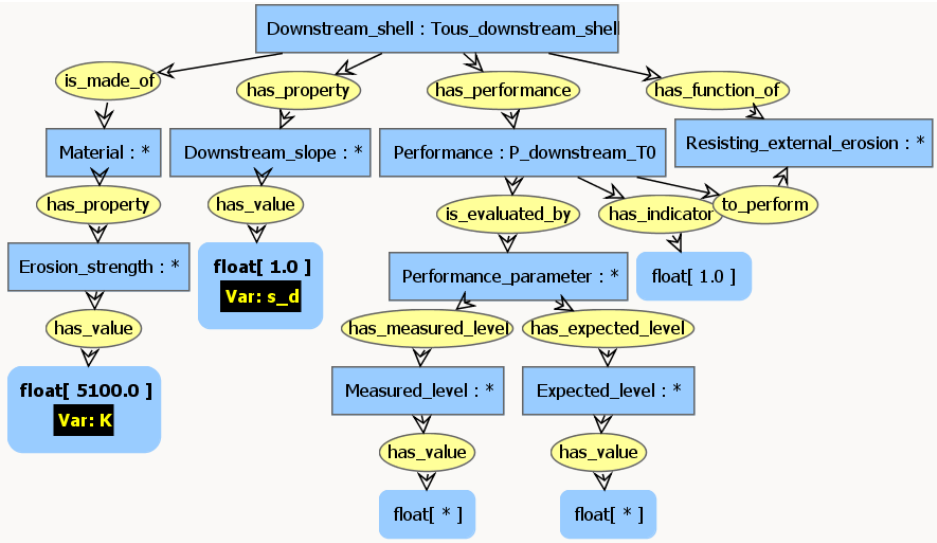


Figure A-7.84. Downstream shell at T0

Figure A-7.84 shows the downstream shell component at T0. The component is described with its material that has *Erosion_strength* with a value of *5100* assigned to the variable *K*, Downstream slope with a value of *1* assigned to the variable *s_d*. The performance is *Performance: P_downstream_T0* that is assumed as satisfied, i.e., the value of the indicator is *1*. The function of the downstream shell is *Resisting external erosion*.

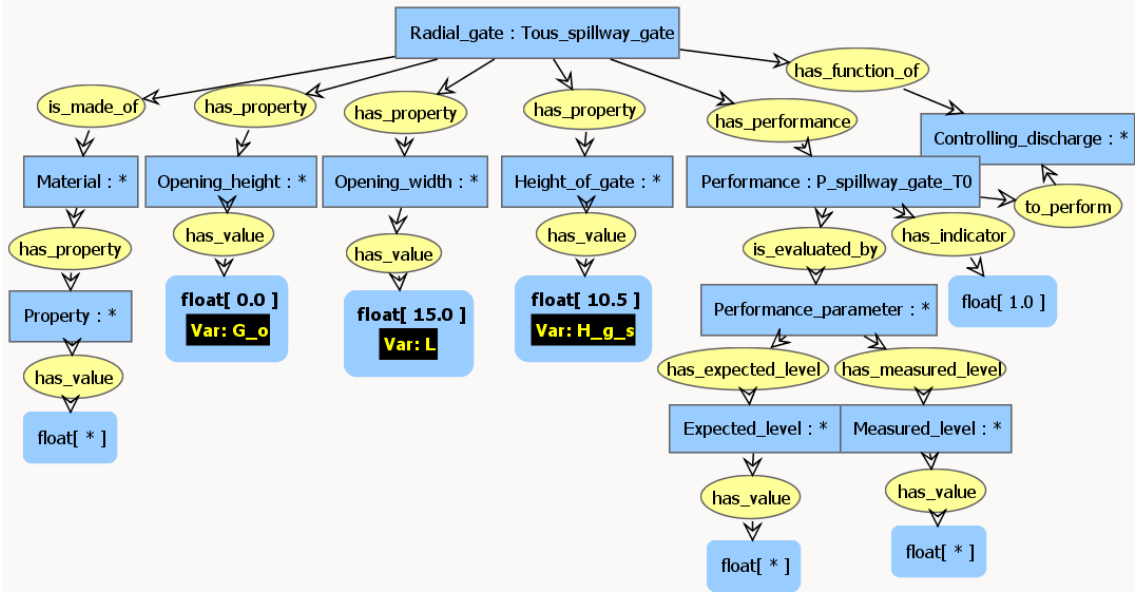


Figure A-7.85. Radial gate of spillway at T0

Figure A-7.85 shows the Tous spillway gate component at T0. The component is described by its relevant properties: *Opening_height* with a value of *0* assigned to the variable *G_o*, *Opening width* with a value of *15* assigned to the variable *L*, *Height of gate* with a value of *10.5* assigned to the variable *H_g_s*. The performance is *Performance: P_spillway_gate_T0* that is assumed as satisfied, i.e., the value of the indicator is *1*. The function of the downstream shell is *Controlling_discharge.*

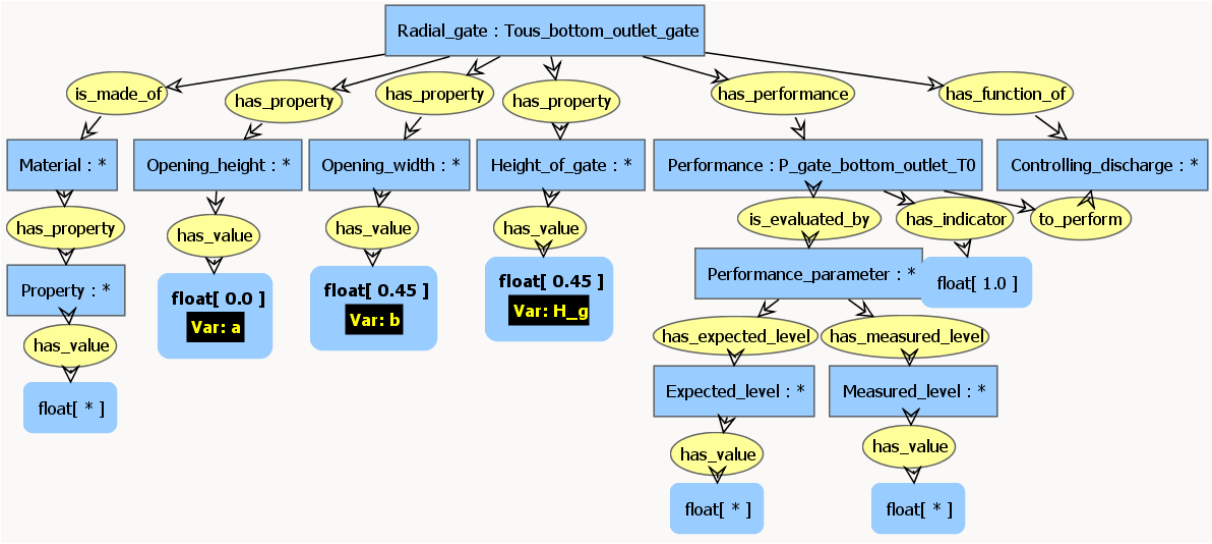


Figure A-7.86. Radial gate of bottom outlet component at T0

Figure A-7.86 shows the bottom outlet gate component at T0. The component is described by its relevant properties: *Opening_height* with a value of *0* assigned to the variable *G_o*, *Opening width* with a value of *15* assigned to the variable *L*, *Height of gate* with a value of *10.5* assigned to the variable *H_g_s*. The performance is *Performance: P_gate_bottom_outlet_T0* that is assumed as satisfied, i.e., the value of the indicator is *1*. The function of the downstream shell is *Controlling_discharge.*

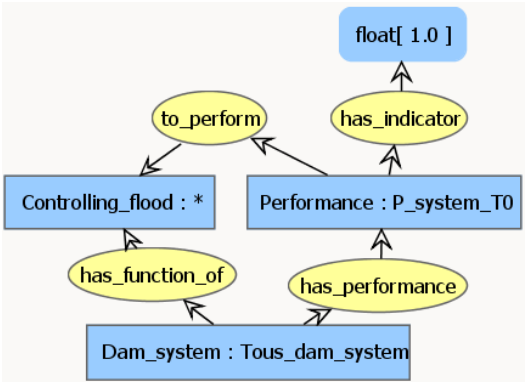


Figure A-7.87. Tous dam system at T0

Figure A-7.87 describes the Tous dam system. The system is described with the function *Controlling flood*, the performance *Performance: P_system_T0*. The performance indicator has a value of *1*, which means that the system is assumed as satisfied at T0.

7.3.3.2. Identifying the external factors at T1

There is one external factor: Rain (Figure A-7.88).

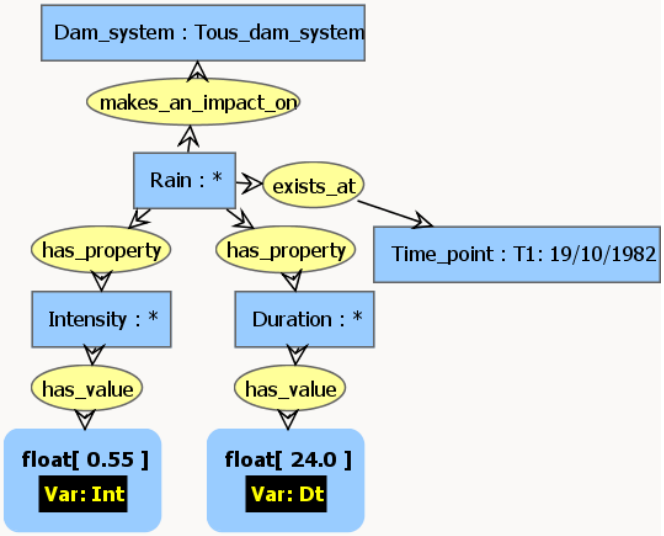


Figure A-7.88. External factor at T1

Figure A-7.88 shows a graph describing external factor that is heavy rain. The heavy rain is described with two properties, *Duration* and *Intensity.* The property *Duration* is defined by the variable *Dt*, which is assigned to a value of 24 hours. The property *Intensity* is identified by the variable *Int*, which is assigned to a value of 500 mm/hour. The time point of the external factor is set at T1: 19/10/1982, which is when the heavy rain occurs.

7.3.3.3. Impact of the external factor at T2

Computing surface runoff

Surface runoff is water from rain, snowmelt, or other sources that flows over a catchment area. The amount of water harvested from the catchment area is equal the amount of water that flows into the reservoir and has the height ΔH.

$$\Delta H = \text{rainfall} * K * C$$

where,

ΔH: amount of water flows ito the reservoir (m)

K: runoff coefficient, is the proportion of rainfall which flows along the ground as surface runoff,

C: Catchment-Reservoir area ratio

$$\text{Rainfall} = \text{duration} * \text{intensity (m)}$$

Rule calculating the runoff as follow:

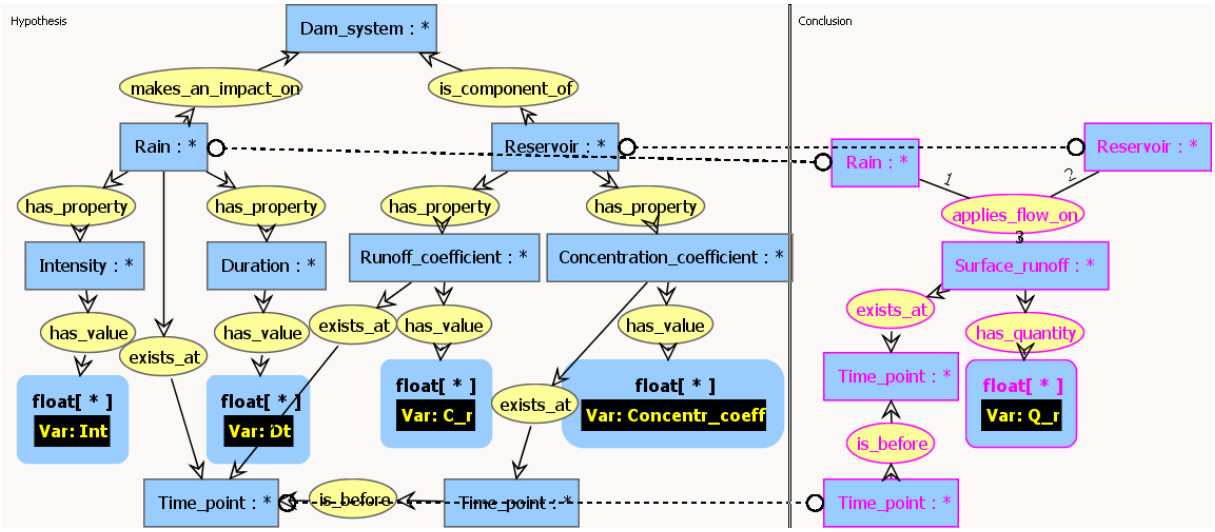


Figure A-7.89. Rule to compute runoff

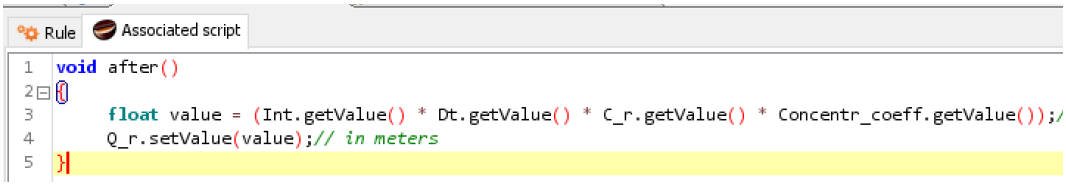


Figure A-7.90. Script to compute runoff

Figure A-7.89 shows a rule calculating the runoff. The rule says that **if** *Rain* makes an impacts on *Dam system*, and *Reservoir* is a component of *Dam_system*, **then** *Rain* will applies the *Surface runoff* on *Reservoir*. *Rain* has *Intensity* defined by the variable *Int*, and *Duration* defined by the variable *Dt*. *Reservoir* has *Runoff coefficient* defined by the variable *C_r*, and *Concentration coefficient* and defined by the variable *Concentr_coeff*. *Runoff coefficient* property of the reservoir exist at T1, because it depends on the intensity of the rain. The concentration coefficient of the reservoir exists at T0. Surface runoff exists at a time after the time point of rain. Figure A-7.90 shows the associated script.

The resulting graph is:

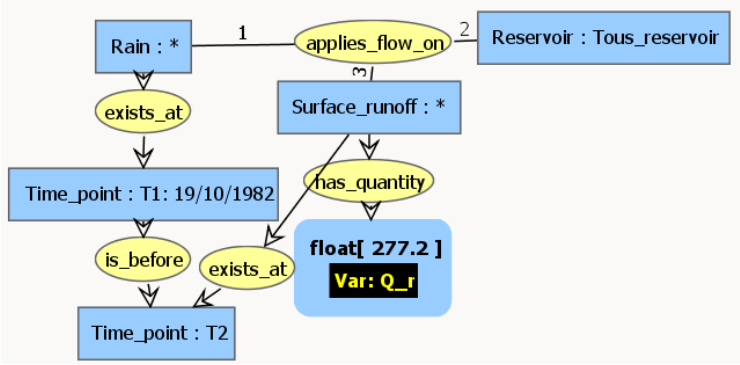


Figure A-7.91. Quantity of the surface runoff

Figure A-7.91 shows that at the time point T2, the heavy rain applies the runoff flow into the reservoir, the quantify is 277 m high.

Computing new reservoir level

Due to the runoff flow, the reservoir will increase to a new level. This level equals the total of the old level plus the runoff flow.

Rule and script to compute the new reservoir level:

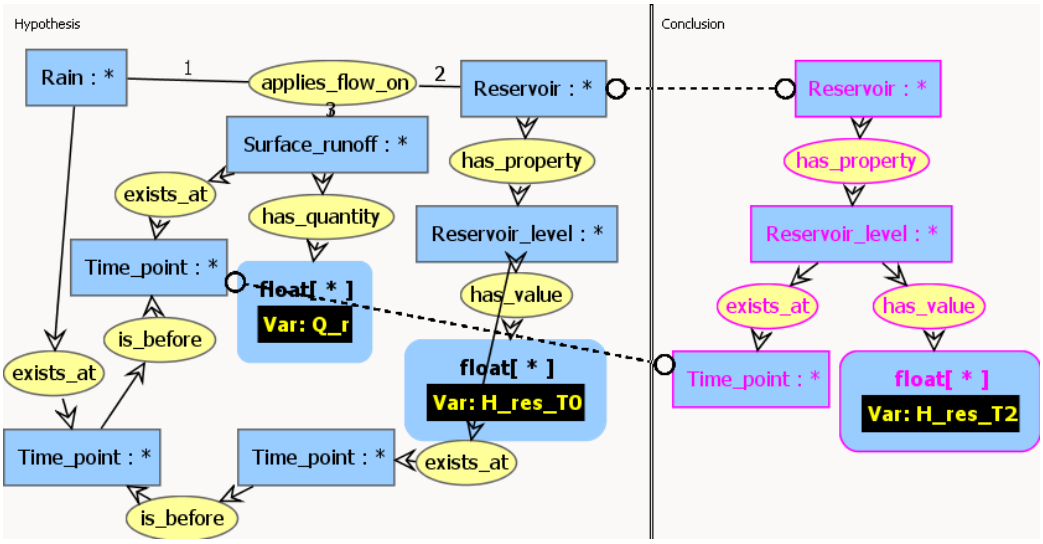


Figure A-7.92. Rule to compute new reservoir level

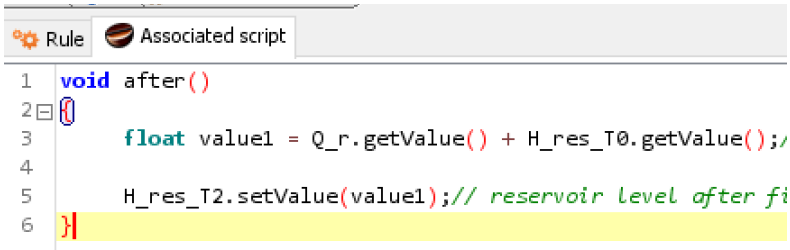


Figure A-7.93. Script to compute new reservoir level

Figure A-7.92 shows a rule calculating a new reservoir level due to the runoff. The graph can be intepreted as **if** *Rain* applies the *Surface runoff* on *Reservoir*, **then** *Reservoir* will have a new *Reservoir level*. The *Reservoir level* in the hypothesis graph is defined by the variable *H_res_T0*, while *Reservoir level* in the conclusion graph is described by the variable *H_res_T2*. The new reservoir level exists at the time point of *Surface runoff*. Figure A-7.93 shows the associated script.

The resulting graph is:

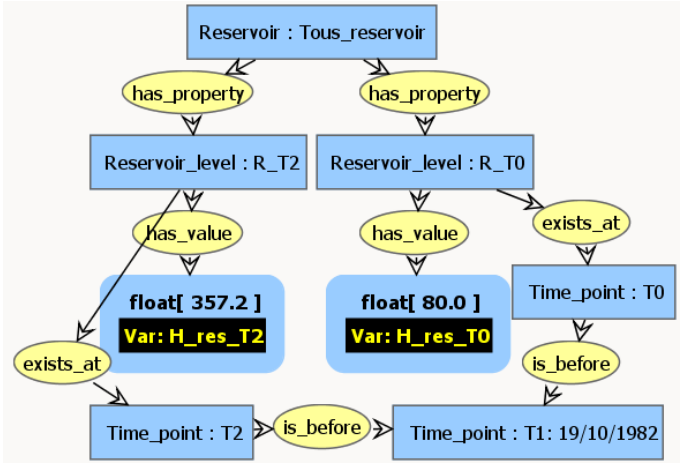


Figure A-7.94. Changing of reservoir level over time

Figure A-7.94 shows a change of reservoir level from T0 to T2. At the time of T0, the reservoir level is 80 m high. At the time T2, the new level is 357 m high, and this result is suitable with the data that total rainfall volume over the catchment reached almost 600 x 10^6 m^3, largely exceeding the capacity of Tous reservoir (120 x 10^6 m^3) (Alcrudo and Mulet, 2007).

Computing peak inflow

Peak inflow is compute to consider performance of spillway, bottom outlet, and reservoir. Based on the consistent with data (Alcrudo and Mulet, 2007), the Inglis empirical formula (Punima *et al.*, 2009) is applied to compute flood discharge:

$$Q = 123\ A^{1/2}$$

where : Q = flood discharge

A: catchment area

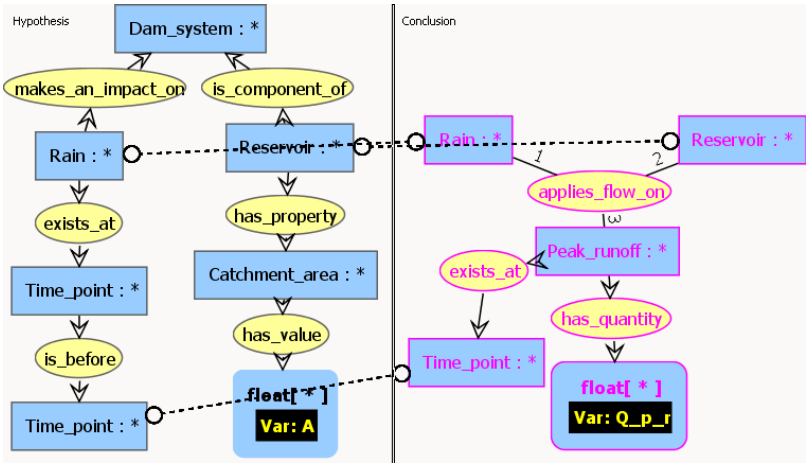


Figure A-7.95. Rule to compute peak inflow

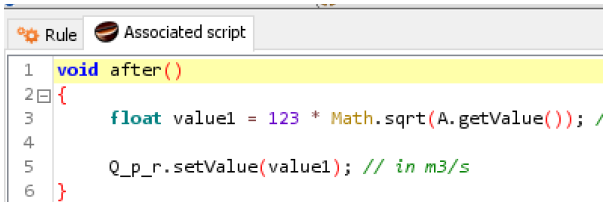


Figure A-7.96. Script to compute peak inflow

Figure A-7.95 shows a rule computing a peak flow. The rule says that **if** *Rain* makes an impact on *Dam_system*, and *Reservoir* is a component of *Dam_system*, **then** *Rain* applies *Peak runoff* on *Reservoir*. *Reservoir* has a property that is *Catchment_area* defined by the variable *A*. *Peak runoff* has a quantity defined by the variable *Q_p_r*. Figure A-7.96 shows the associated script.

The resulting graph is:

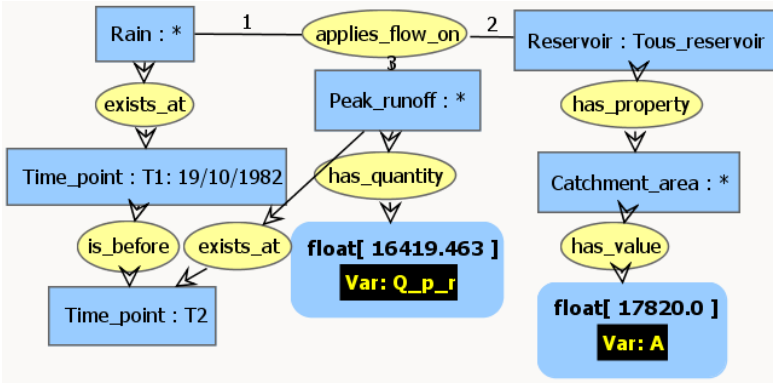


Figure A-7.97. Peak runoff flow result

Figure A-7.97 shows that after a period of rainfall, *i.e.,* from the time point T1 to the time point T2, rain applies a peak-runoff having a quantity of 16419 m^3/s into the reservoir.

7.3.3.4. Interaction within the dam system at T2

When the reservoir level increases, water will be discharged through the spillway gate and the bottom outlet gate.

Computing discharge flow of spillway with radial gate:

The discharge for gated crest at partial gate opening is similar to flow through a low head orifice and may be computed from the following equation (USBR, 2014), (Hussain, Hussain and Ahmad, 2014), (Sharma, 2017), (Figure A-7.98):

$$Q = C_d \, L \, G_o \sqrt{2gH_c}$$

where:

Q is the total discharge (m^3/s)

L is the net length of crest, excluding thickness of piers

H_c is the head over the center line of orifice and equal to $H - G_o/2$, where H is the head over the spillway crest.

C_d is the coefficient of discharge (initial suggested value includes: 0.6 for vertical wall or wheel-mounted gate and 0.65 for radial gate).

G_o is gate opening (m)

g is the acceleration due to gravity (m/s^2)

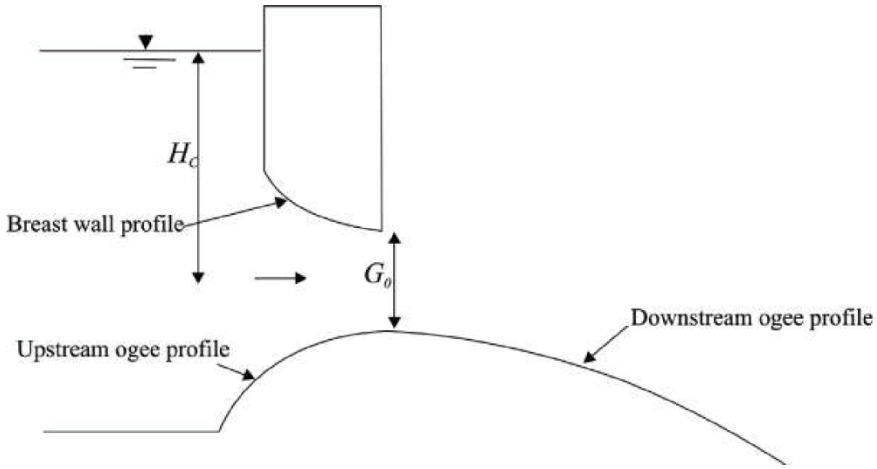


Figure A-7.98. Definition sketch of orifice type (Hussain, Hussain and Ahmad, 2014)

Rule and script to compute the discharge flow through controlled spillway:

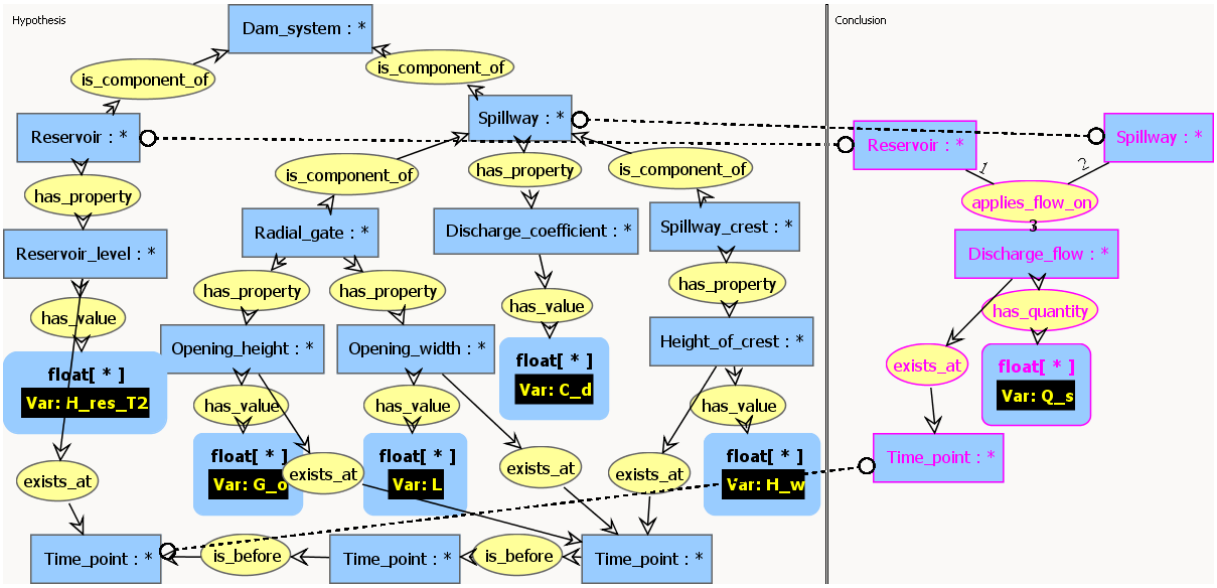


Figure A-7.99. Rule calculating discharge flow through spillway

Rule | Associated script

```
1
2  void after()
3  {
4      float value1 = C_d.getValue() * L.getValue() * G_o.getValue();
5      float value2 = H_res_T2.getValue() - H_w.getValue() - G_o.getValue()/2;
6      float value3 = Math.sqrt(2 * 9.8 * value2);
7      float value4 = value1 * value3;
8      Q_s.setValue(value4);
9  }
```

Figure A-7.100. Script calculating discharge flow through spillway

Figure A-7.99 shows a rule calculating the discharge flow through a spillway. The rule can be expressed as **if** *Reservoir* and *Spillway* are components of *Dam_system*, **then** *Reservoir* applies *Discharge_flow* on *Spillway*. *Reservoir* has *Reservoir level* at T2, which is defined by the variable *H_res_T2*. *Spillway* has *Discharge coefficient* defined by the variable *C_d*. *Radial_gate* and *Spillway_crest* are components of *Spillway*. *Radial gate* has properties *Opening height* and *Opening width* which defined by the variables *G_o* and *L*, respectively. *Spillway crest* has *Height_of_crest* represented by the variable *H_w*. The discharge flow exists at the time point T2. Figure A-8.100 shows the associated script.

The resulting graph is:

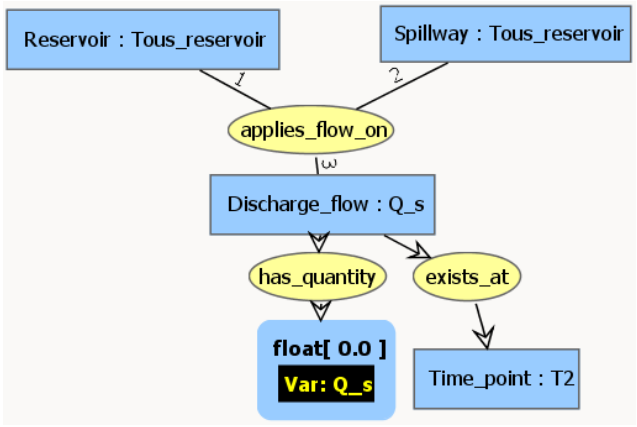


Figure A-7.101. Discharge flow through spillway

Figure A-7.101 shows that at the time point T2, the discharge flow has a value of 0 due to the radial gate can not open.

Computing discharge flow of bottom outlet with radial gate:

The discharge passing through the dam outlet can be calculated using the equation: (Garg, 2005)

$$Q = C_d \cdot A \sqrt{2gH}$$

where,

Q = Discharge flow (m^3/s)

A = Area of outlet conduit (m^2)

H = Differential head causing flow, *i.e.,* the difference of u/s and d/s water levels (m)

C_d = Coefficient of discharge, whose value depends upon various factors such as the type of gate and trash rack provided, conduit friction, transitions etc.,.

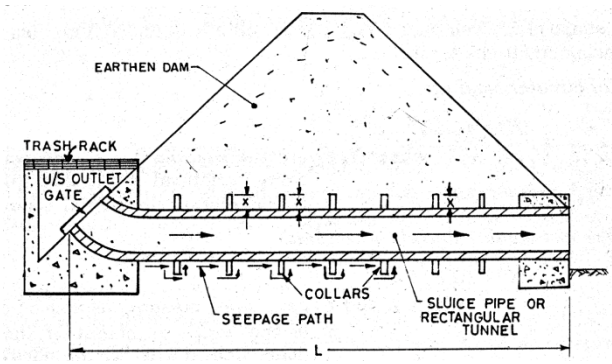


Figure A-7.102. Typical outlet arrangement through embankment dam (Garg, 2005)

Rule and script:

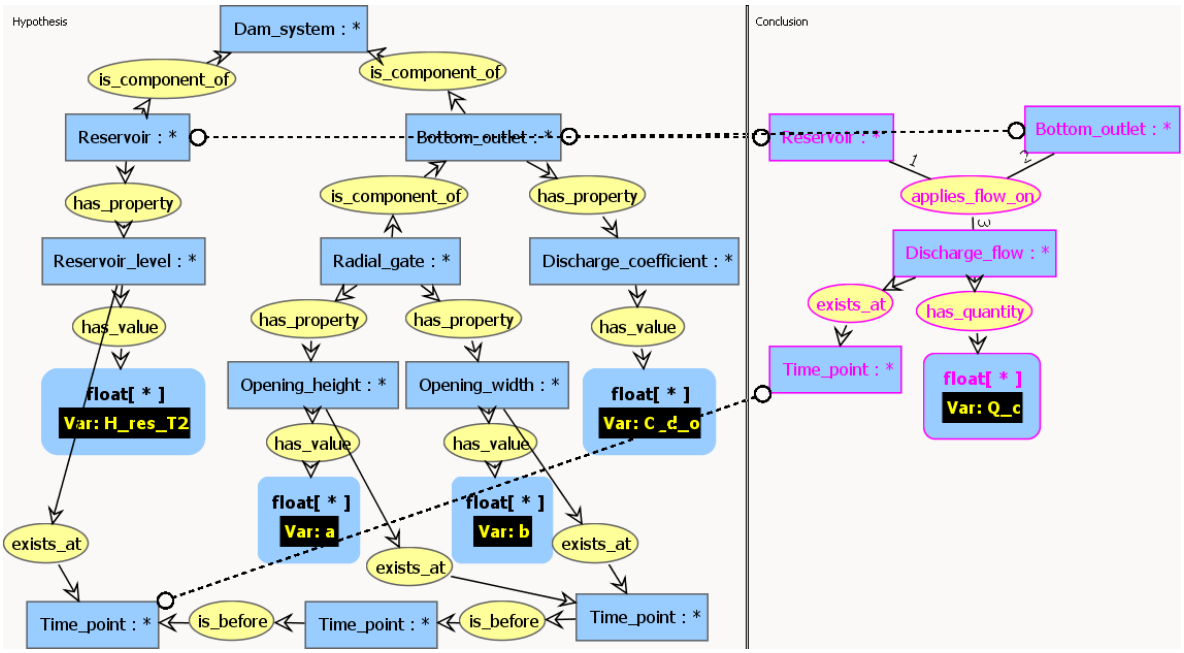


Figure A-7.103. Rule to calcualte discharge flow through bottom outlet

Rule | Associated script

```
1
2  void after()
3  {
4      float value1 = C_d_o.getValue() * a.getValue() * b.getValue();
5      float value2 = Math.sqrt(2 * 9.8 * H_res_T2.getValue());
6      float value3 = value1 * value2;
7      Q_c.setValue(value3);
8  }
```

Figure A-7.104. Script to calcualte discharge flow through bottom outlet

Figure A-7.103 shows a rule calculating the discharge flow through a bottom outlet. The rule can be expressed as **if** *Reservoir* and *Bottom outlet* are components of *Dam_system*, **then** *Reservoir* applies *Discharge_flow* on *Bottom outlet*. *Reservoir* has *Reservoir level* at T2, which is defined by the variable *H_res_T2*. *Bottom outlet* has *Discharge coefficient* defined by the variable *C_d_o*. *Radial_gate* is a component of Bottom outlet and has properties *Opening height* and *Opening width* which defined by the variables *a* and *b*,

respectively. The discharge flow exists at the time point T2. Figure A-7.104 shows the associated script.

The resulting graphs is:

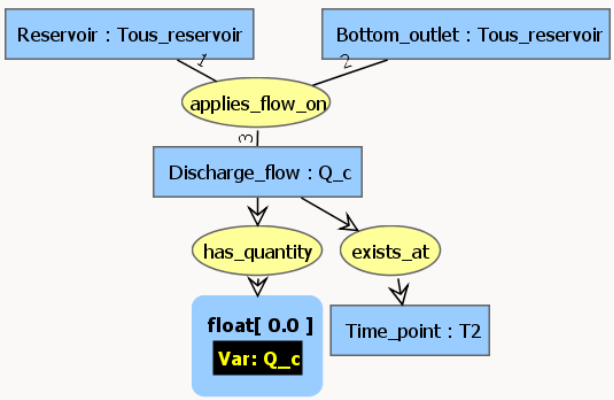


Figure A-7.105. Discharge flow through bottom outlet

The figure A-7.105 shows that at T2, the discharge flow through the bottom outlet has a quantity of 0, caused by the malfunction of the bottom outlet gate.

7.3.3.5. Performance of the spillway gate at T2

The radial gate's performance is evaluated by the opening capacity, i.e., the difference between the measured opening height and the expected opening height (height of gate). If this distance is equal to the gate's height, i.e., the gate does not open, then the performance of the gate is not satisfied.

Opening capacity = Opening height - Height of gate

Opening capacity < 0: not satisfied

Opening capacity = 0: satisfied

Rule to identify the measured level of the opening capacity as follow:

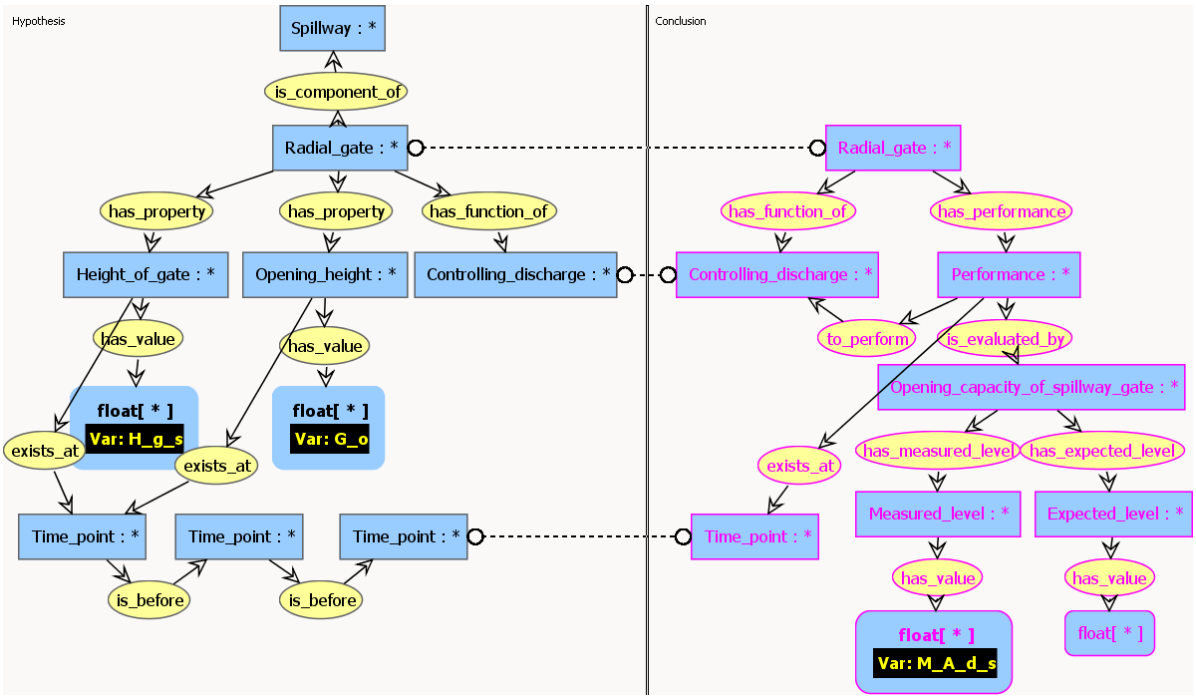


Figure A-7.106. Rule calculating measured level of the spillway gate

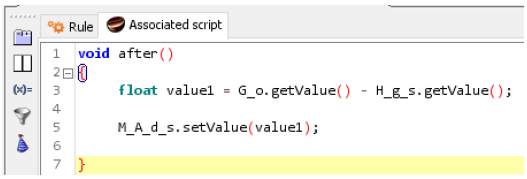


Figure A-7.107. Script calculating measured level of the spillway gate

Figure A-7.106 shows a rule calculating the measured level of the opening capacity of the spillway gate. The rule graph says that **if** *Radial_gate* has *Height_of_gate* and *Opening_height*, **then** *Radial gate* has a new *Performance* is evaluated by *Opening capacity of spillway gate*. *Opening capacity of spillway gate* has *Measured level* and *Expected level*. There is a coref relation connecting two concepts *Controlling_discharge* in the rule. The new performance exists at T2. Figure A-7.107 shows the associated script.

After calculating, the measured level of the opening capacity will be compared with the expected level to identify the performance indicator of the spillway gate.

- Computing performance of spillway gate:

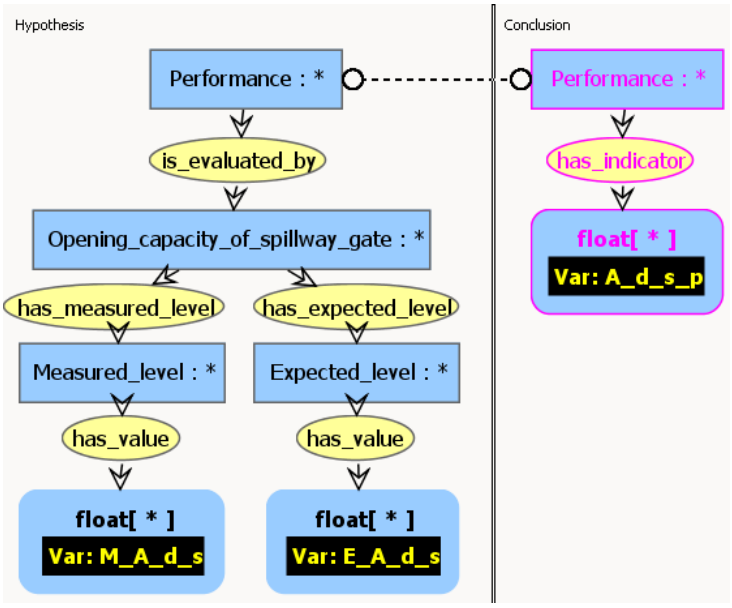


Figure A-7.108. Rule to estimate performance of spillway gate

Rule | Associated script

```
1  void after()
2  {
3      if (M_A_d.getValue() < E_A_d.getValue())  {
4         A_d_p.setValue(0);
5      }
6      else {
7           A_d_p.setValue(1);
8      }
9  }
```

Figure A-7.109. Script to estimate performance of spillway gate

Figure A-7.108 shows a rule estimating the performance indicator of the spillway gate. The rule says that **if** *Performance* is evaluated by *Opening capacity of spillway gate*, **then** *Performance* has a new indicator defined by the variable *A_d_s_p*. *Opening capacity of spillway gate* has *Measured level* and *Expected level* defined by the variables *M_A_d_s* and *E_A_d_s*, respectively. Figure A-7.109 shows the associated script.

The resulting graph is:

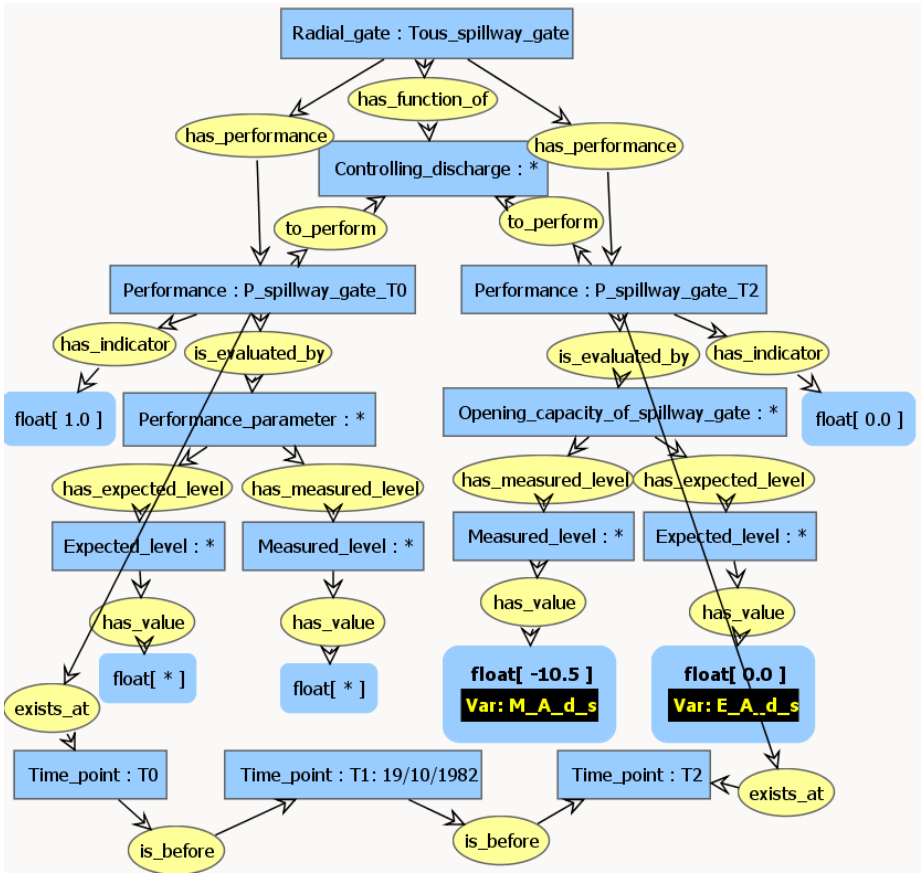


Figure A-7.110. Performances of spillway at two times

Figure A-7.110 shows a change in performance of the Tous spillway gate from the time point T0 to the time point T2. At the time point T0, *Performance: P_spillway_gate_T0* is assumed as satsified, i.e., the value of the performance indicator has a value o *1*. At the time point T2, *Performace: P_spillway_gate_T2* is evaluated by *Opening capacity of spillway gate*, which has a value of *0,* i.e., not satisfied.

7.3.3.6. Performance of the spillway at T2

The discharge performance of the spillway is evaluated by discharge capacity, which is calculated by flood design and discharge flow to the spillway.

Discharge capacity = Flood design - Discharge flow

If Discharge capacity > 0: satisfied

Discharge capacity < 0: not satisfied

Measured level of performance parameter of spillway:

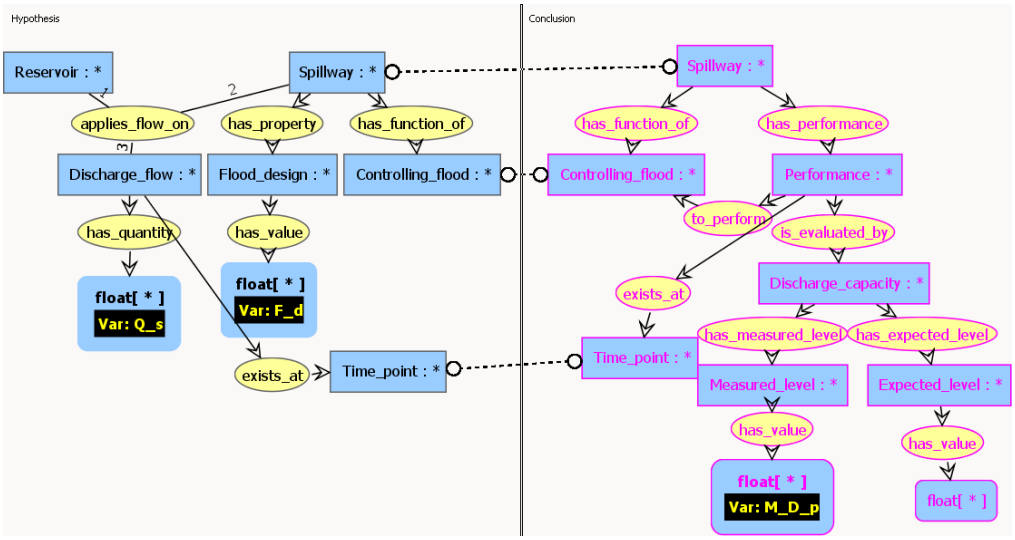


Figure A-7.111. Rule to calculate the measured level of the discharge capacity of the spillway

Rule | Associated script

```
1  void after()
2  {
3      float value1 = F_d.getValue() - Q_s.getValue();
4
5      M_D_p.setValue(value1);
6
7  }
```

Figure A-7.112. Script to calculate the measured level of the discharge capacity of the spillway

Figure A-7.111 shows a rule calculating the measured level of the discharge capacity of the spillway. The rule can be expressed as **if** *Reservoir* applies *Discharge flow* on *Spillway*, **then** *Spillway* has a new *Performance* evaluated by *Discharge capacity*. *Spillway* has *Flood designed* defined by the variable *F_d*. *Discharge flow* has a quantity defined by the variable *Q_s*. *Discharge capacity* has *Measured level* and *Expected level*. There is a coref relation between two concepts *Controlling_flood* in the rule. The time point of the performance is the time point of *Discharge_flow*. Figure A-7.112 shows the associated script.

Computing performance of spillway:

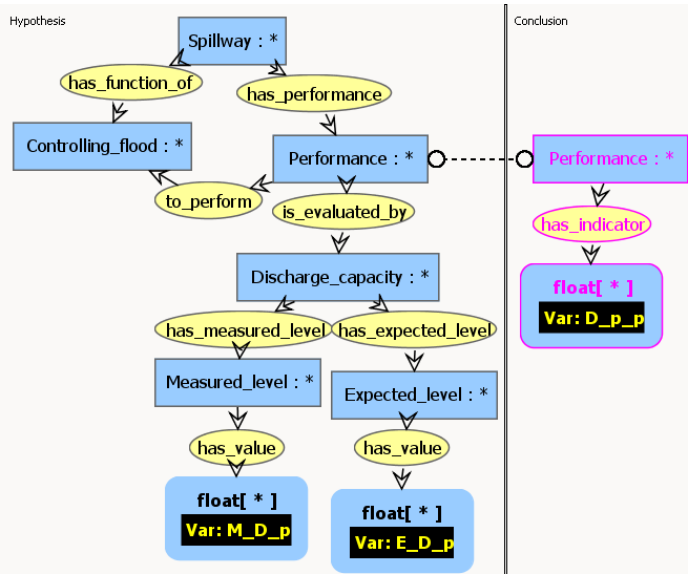


Figure A-7.113. Rule to calculate the performance of spillway

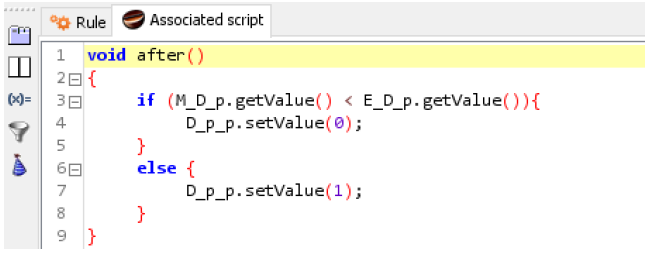


Figure A-7.114. Script to calculate the performance of spillway

Figure A-7.113 shows a rule calculating the performance of the spillway. The rule says that **if** *Spillway* has a *Performance* evaluated by *Discharge capacity*, and *Discharge capacity* has *Measured level* and *Expected level* defined by the variables *M_D_p* and *E_D_p* respectively, **then** *Performance* has an indicator defined by the variable *D_p_p*. Figure A-7.114 shows the associated script.

The resulting graph of spillway performance as follows:

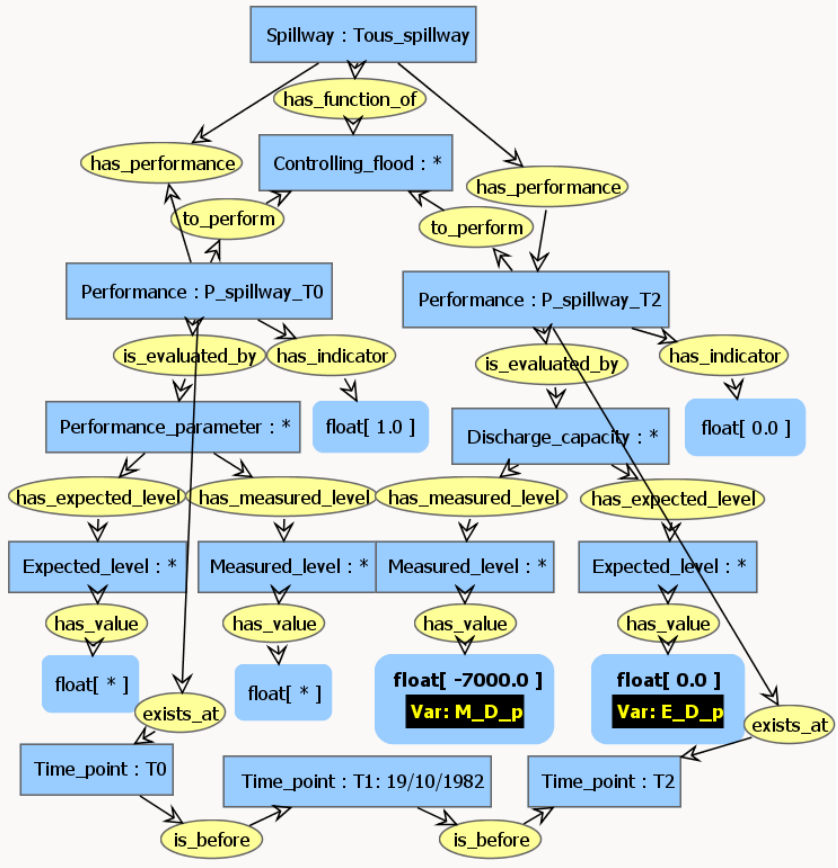


Figure A-7.115. The performance of spillway

Figure A-7.115 shows a change in the spillway performance over time. At the initial time, T0, the performance to control flood of the spillway is assumed as satisfied, i.e., the indicator has a value of 1. At the time point T2, the performance indicator has a value of 0, i.e., not satisfied.

7.3.3.7. Performance of the bottom outlet gate at T2

The controlling discharge performance of conduit gate is consider by the parameter of opening capacity.

Opening capacity = Height of gate - Opening height

If Opening capacity = 0: satisfied

Opening capacity > 0: not satisfied

- Determination of measured level of the radial gate of bottom outlet:

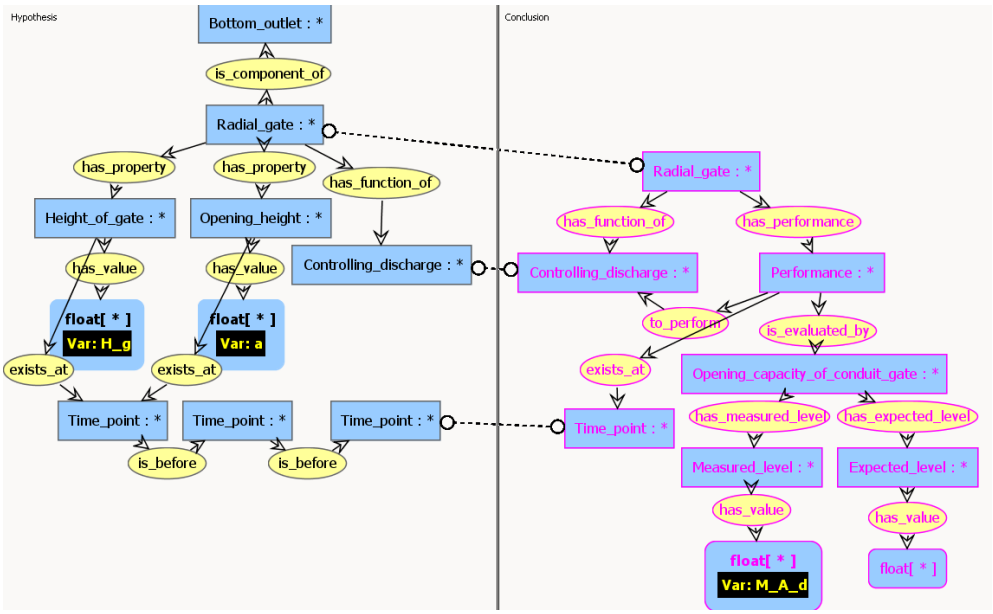


Figure A-7.116. Rule to calculate the measured level of opening capacity of conduit gate

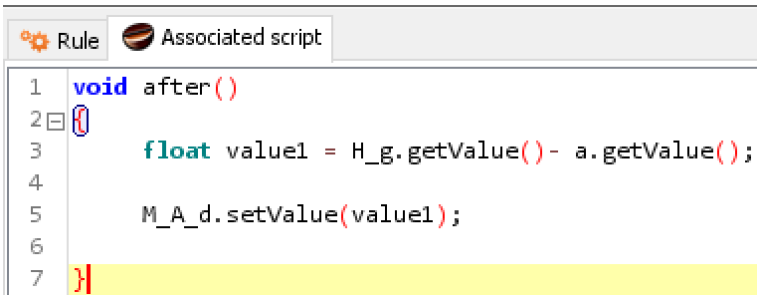


Figure A-7.117. Script to calculate the measured level of opening capacity of conduit gate

Figure A-7.116 shows a rule computing performance of the bottom outlet gate. The rule says that **if** *Radial gate* is a component of *Bottom outlet*, *and Radial gate* has *Height of gate* and *Opening height*, those are defined by the two variables *H_g* and *a* respectively, **then** *Radial gate* has a new *Performance* evaluated by *Opening capacity of conduit gate*. *Opening capacity of conduit gate* has *Measured level* and *Expected level*. There is a coref relation between two concepts *Controlling_discharge* in the rule. The time point of the performance is at T2. Figure A-7.117 shows the associated script.

- Computing performance of bottom outlet gate:

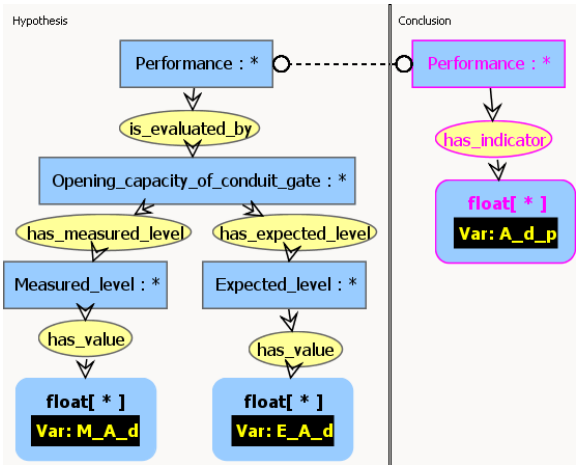


Figure A-7.118. Rule to compute of the performance of bottom outlet gate

Rule | Associated script

```
1  void after()
2  {
3      if (M_A_d.getValue() < E_A_d.getValue())  {
4         A_d_p.setValue(0);
5      }
6      else {
7           A_d_p.setValue(1);
8      }
9  }
```

Figure A-7.119. Script to compute the performance of bottom outlet gate

Figure A-7.118 shows a rule estimating the performance indicator of the bottom outlet gate. The rule says that **if** *Performance* is evaluated by *Opening capacity of conduit gate*, **then** *Performance* has a new indicator defined by the variable *A_d_p*. *Opening capacity of conduit gate* has *Measured level* and *Expected level* defined by the variables *M_A_d* and *E_A_d*, respectively. Figure A-7.119 shows the associated script.

- Resulting gaph is:

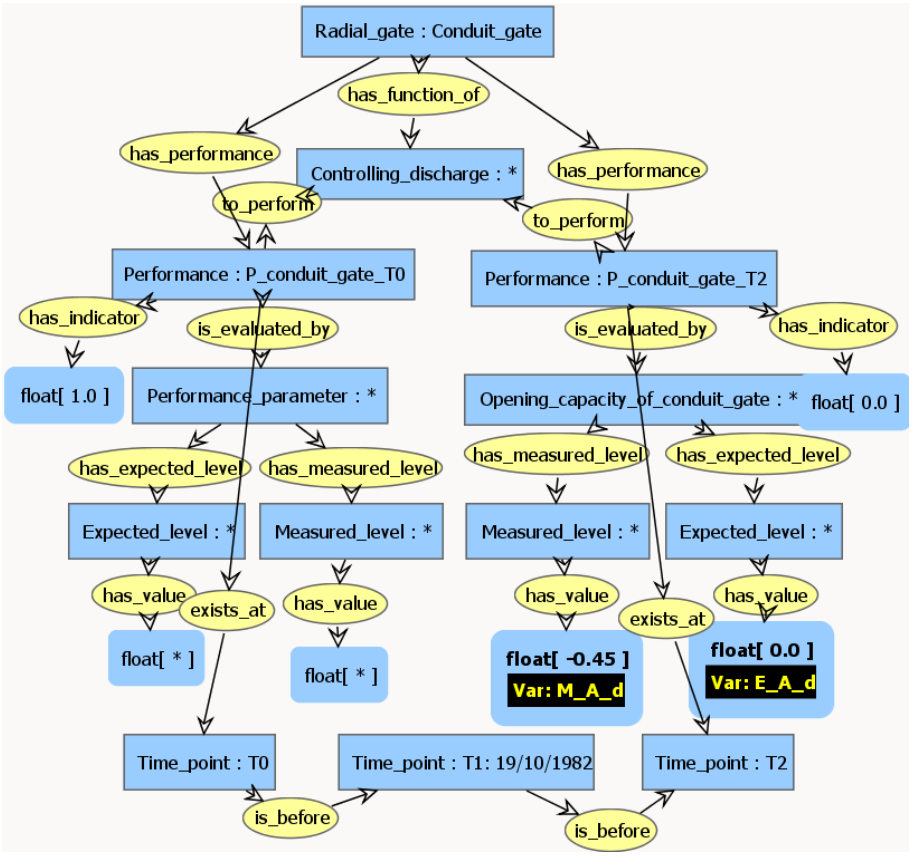


Figure A-7.120. Peformance of bottom outlet gate

Figure A-7.120 shows a change in performances of the bottom outlet gate. At the initial time T0, performance is described by the individual concept *P_conduit_gate_T0* assumed as satisfied, i.e., the performance indicator has a value of *1*. At T2, *Performance: P_conduit_T2* evaluated by *Opening capacity of conduite gate* has a value of *0*, i.e., not satisfied.

7.3.3.8. Performance of the bottom outlet at T2

The discharge performance of the spillway is evaluated by discharge capacity, which is calculated by flood design and discharge flow to the bottom outlet.

Discharge capacity = Flood design - Discharge flow

If Discharge capacity > 0: satisfied

Discharge capacity < 0: not satisfied

Measured level of performance parameter of bottom outlet:

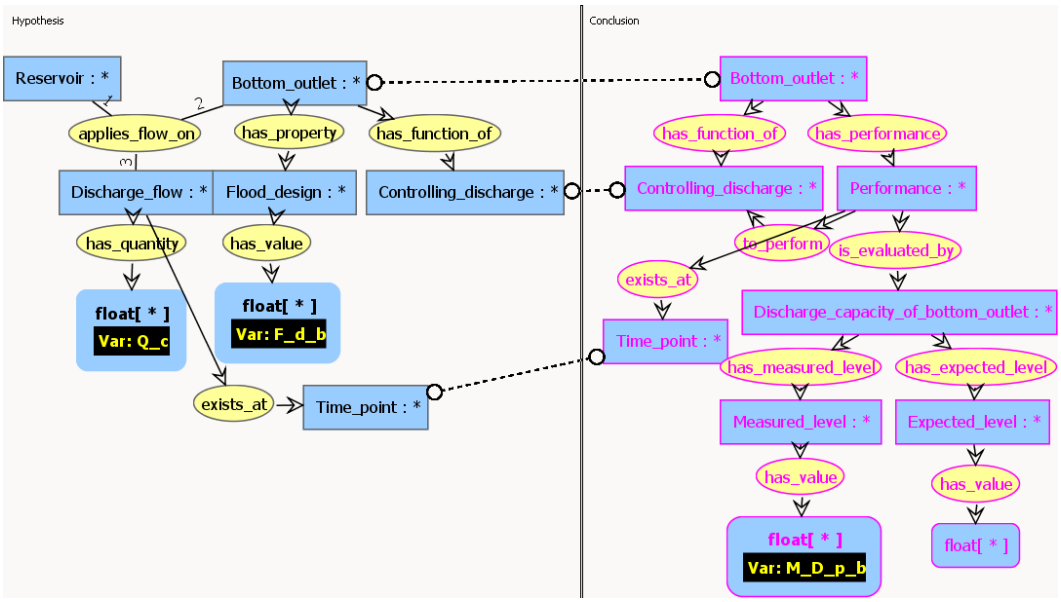


Figure A-7.121. Rule to compute measured discharge capacity of bottom outlet

Rule | Associated script

```
1  void after()
2  {
3      float value1 = F_d_b.getValue() - Q_c.getValue();
4
5      M_D_p_b.setValue(value1);
6
7  }
```

Figure A-7.122. Script to compute measured discharge capacity of bottom outlet

Figure A-7.121 shows a rule calculating the measured discharge capacity of the bottom outlet. The rule can be expressed as **if** *Reservoir* applies *Discharge flow* on *Bottom outlet*, **then** *Bottom outlet* has a new *Performance* evaluated by *Discharge capacity*. *Bottom outlet* has *Flood designed* defined by the variable *F_d_b*. *Discharge flow* has a quantity defined by the variable *Q_c*. *Discharge capacity* has *Measured level* and *Expected level*. There is a coref relation between two concepts *Controlling_flood* in the rule. The time point of the performance is the time point of *Discharge_flow*. Figure A-7.122 shows the associated script.

Performance of bottom outlet

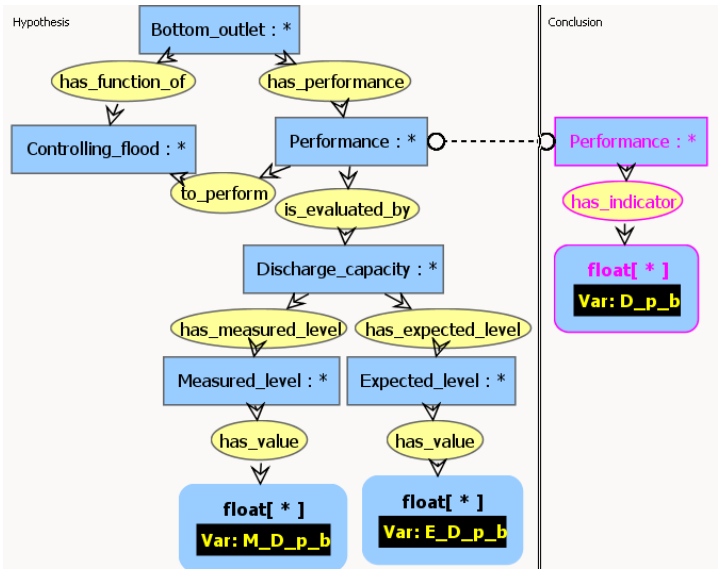


Figure A-7.123. Rule to compute discharge capacity of bottom outlet

Rule | Associated script

```
1  void after()
2  {
3       if (M_D_p_b.getValue() < E_D_p_b.getValue()){
4            D_p_b.setValue(0);
5       }
6       else {
7            D_p_b.setValue(1);
8       }
9  }
```

Figure A-7.124. Script to compute discharge capacity of bottom outlet

Figure A-7.123 shows a rule calculating the performance of the bottom outlet. The rule says that **if** *Bottom outlet* has a *Performance* evaluated by *Discharge capacity*, and *Discharge capacity* has *Measured level* and *Expected level* defined by the variables *M_D_p_b* and *E_D_p_b* respectively, **then** *Performance* has an indicator defined by the variable *D_p_b*. Figure A-7.124 shows the associated script.

Resulting graph is:

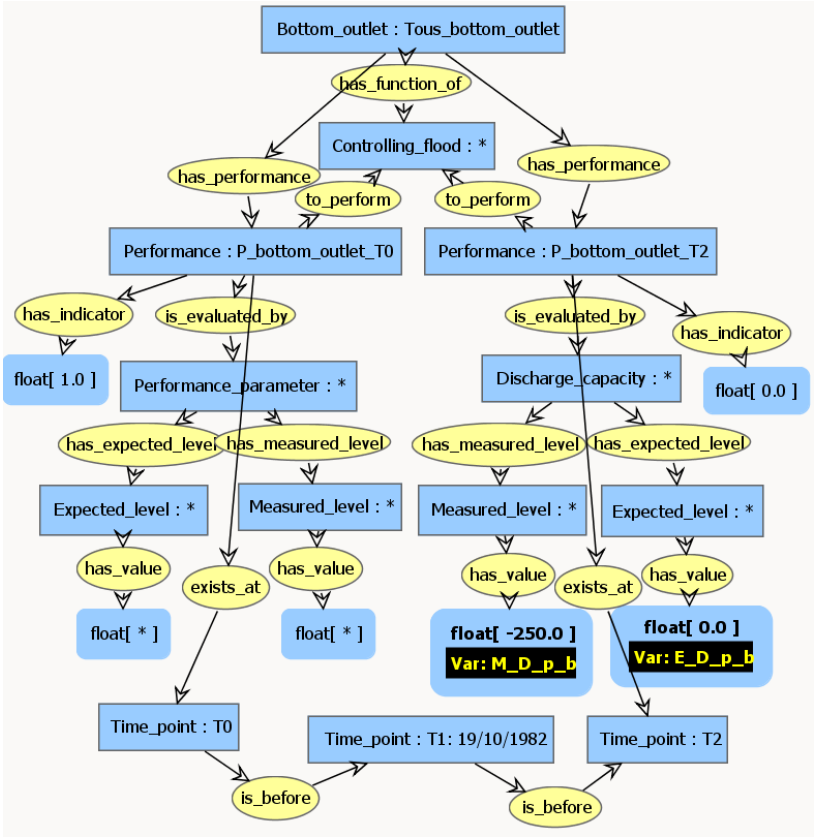


Figure A-7.125 Discharge performance of bottom outlet

Figure A-7.125 shows a change in the bottom outlet performance over time. At the initial time, T0, the performance to control flood of the bottom outlet is assumed as satisfied, i.e., the indicator has a value of 1. At the time point T2, the performance indicator has a value of 0, i.e., not satisfied.

7.3.3.9. Interaction and performance of the reservoir at T2

When the water level increases while the spillway and bottom outlet do not work, the reservoir performance to retain water will be considered.

The reservoir performance is evaluated by two parameters: freeboard and flood retention.

- Freeboard: the vertical distance between the top of the dam and the reservoir level

- Flood retention: the amount of water in the reservoir being equal to the change in storage due to the difference between the inflow and outflow rate in an interval time. The flood retention parameter shows us the capacity to retain water during floods.

If the water level exceeds while the retention capacity is positive, the reservoir will fail to retain water.

(1) Freeboard parameter

$$\text{Freeboard} = \text{Height of dam} - \text{Water level}$$

If freeboard > 0: water level is lower than the dam crest (safety)

If freeboard < 0: water level exceedes the crest of dam

(2) Flood retention

Flood retention is evaluated by the relation between inflow, inflow, is given by the equation:

$$P - O = R$$

i.e.: Inflow - Outflow = Retention (all in m^3/s)

If P > O, R is positive, the reservoir level increases (the reservoir is being filled);

if P < O, R is negative, the reservoir level decreases (the reservoir is being emptied).

Rule to estimate the measured level of freeboard:

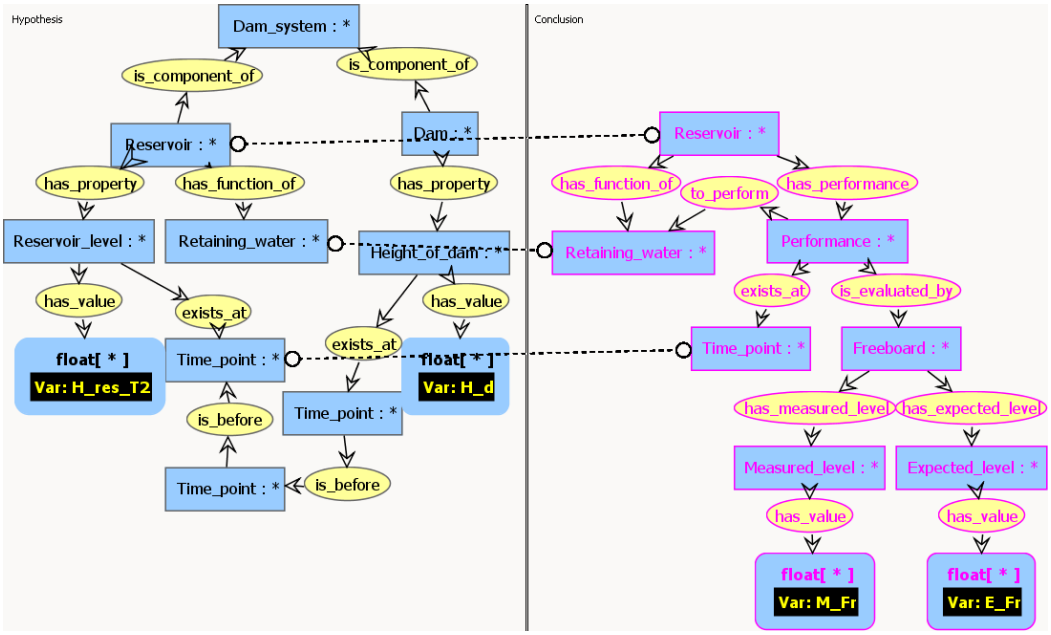


Figure A-7.126. Rule to calculate the measured freeboard

Rule | Associated script

```
1  void after()
2  {
3      float value1 = H_d.getValue() - H_res_T2.getValue();
4      M_Fr.setValue(value1);
5  }
```

Figure A-7.127. Script to calculate the measured freeboard

Figure A-7.126 shows a rule calculating the measured freeboard of the reservoir. The rule says that **if** *Reservoir* and *Dam* are components of *Dam_system*, **then** *Reservoir* has a new *Performance* evaluated by *Freeboard*. *Reservoir* has *Reservoir level* defined by the variable *H_res_T2* and has function *Retaining_water*. *Dam* has *Height of dam* defined by the variable *H_d*. *Freeboard* has *Measured level* and *Expected level*. The time point of the performance is the time point of *Reservoir level*. Figure A-7.127 exposes the associated script.

Rule to estimate the measured flood retention:

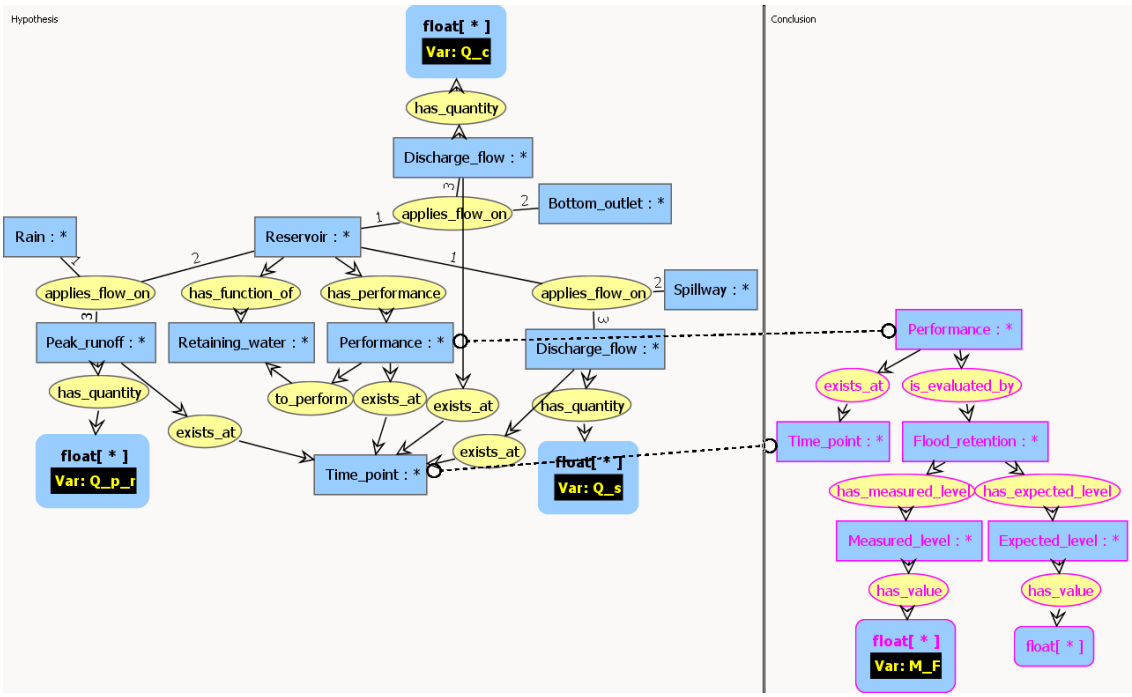


Figure A-7.128. Rule to compute the measured flood retention

Rule | Associated script

```
1  void after()
2  {
3      float value1 = Q_p_r.getValue() - Q_c.getValue() - Q_s.getValue();
4      M_F.setValue(value1);
5  }
```

Figure A-7.129. Script to compute the measured flood retention

Figure A-7.128 shows a rule estimating the measured flood retention of the reservoir. The rule can be expressed as **if** *Rain* applies *Peak_runoff* on *Reservoir*, *Reservoir* applies *Discharge flow* on *Spillway* and *Bottom outlet*, *Reservoir* has *Performance* to perform *Retaining_water*, **then** *Performance* is evaluated by *Flood_retention* that has *Measured level* and *Expected level*. Figure A-7.129 shows the associated script.

The reservoir performance voir is evaluate based on two parameters: Flood retention and Freeboard as follow:

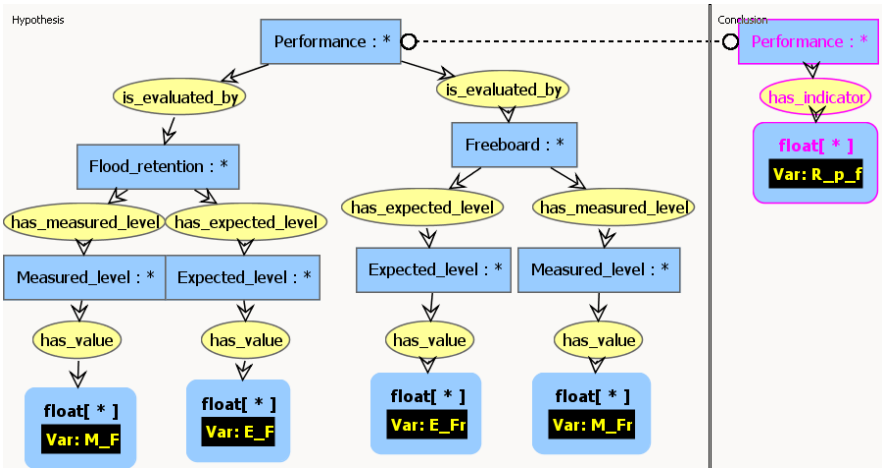


Figure A-7.130. Rule to evaluate performance of reservoir during flood

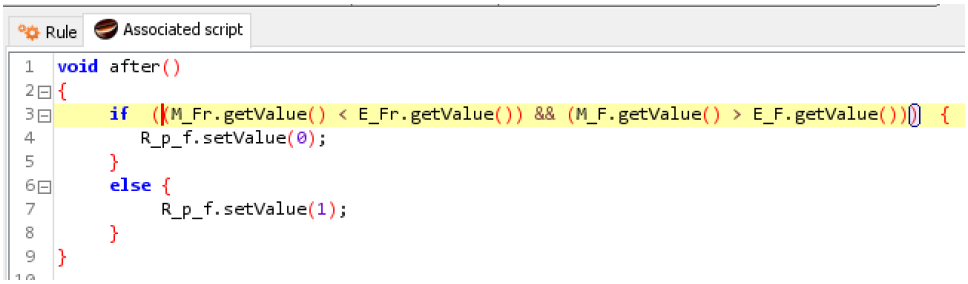


Figure A-7.131. Script to evaluate performance of reservoir during flood

Figure A-7.130 shows a rule estimating performance of the reservoir during flood. The rule says that **if** *Performance* is evaluated by *Freeboard* and *Flood retention*, **then** *Reservoir* has an indicator defined by the variable *R_p_f*. *Freeboard* has *Measured level* and *Expected level* defined by the variables *M_Fr* and *E_Fr*, respectively. *Flood retention* has *Measured level* and *Expected level* defined by the variables *M_F* and *E_F*, respectively. Figure A-7.131 shows the associated script.

The resulting graph is:

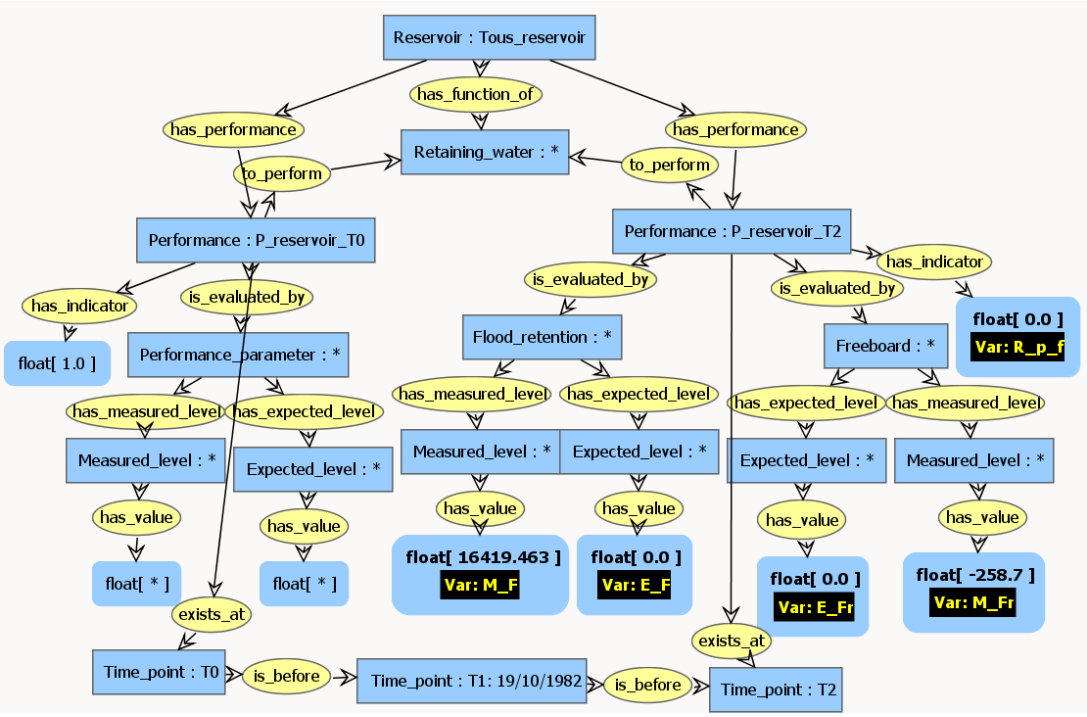


Figure A-7.132. Performance of reservoir during flood

Figure A-7.132 shows a change in performance of the Tous reservoir from the time point T0 to the time point T2. At the time point T0, *Performance: P_reservoir_T0* is assumed as satisfied, i.e., the value of the performance indicator has a value o *1*. At the time point T2, *Performace: P_reservoir_T2* is evaluated by *Flood retention* and *Freeboard*, which has a value of *0,* i.e., not satisfied.

So, at T2, the Tous reservoir is overtopping due to a combination of the heavy rain and the malfunctions of the spillway and the bottom outlet.

7.3.3.10. Interaction and performance of the downstream at T2

Overflow

When the reservoir overtops, the overflow from the reservoir interacts with the downstream face. The overflow is calculated as follow:

$$\text{Overflow} = \text{Inflow} - \text{Outflow}$$

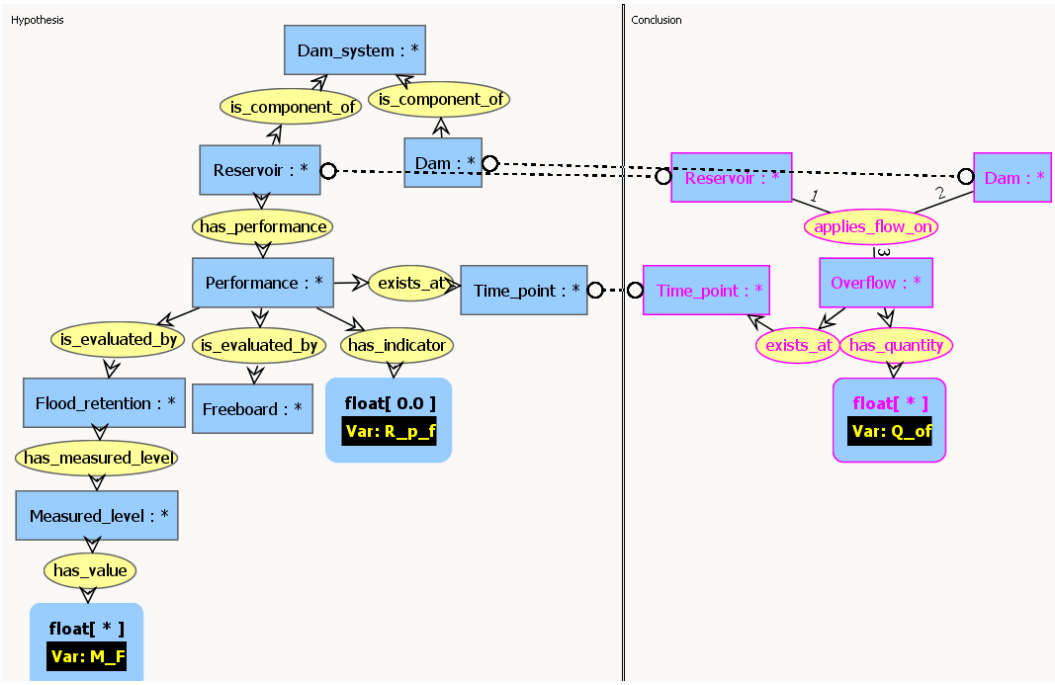


Figure A-7.133. Rule calculating overflow of reservoir during flood

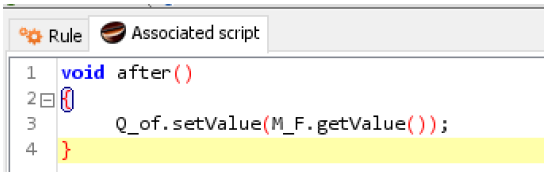


Figure A-7.134. Script calculating overflow of reservoir during flood

Figure A-7.133 shows a rule calculating the overflow of a reservoir. The rule says that **if** *Reservoir* and *Dam* are components of *Dam_system*, *Reservoir* has *Performance* evaluated by *Freeboard* and *Flood retention*, and the performance indicator has a value of 0, **then** *Reservoir* applies *Overflow* on *Dam*. The *Overflow* has a quantity defined by the variable *Q_of*.

Stream power

Once the dams have been overtopped by floods, severe erosion has often been observed to begin where sheet flow on the slope meets an obstacle, such as a structure, a large tree, or the groin, as indicated in Figure A-7.135. erosion occurs when the hydraulic attack produced from the flow is greater than the resisting physical properties of the soil or rock.

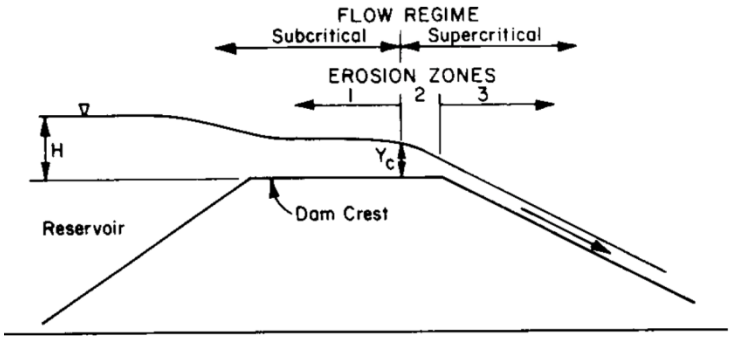


Figure A-7.135. Downstream slope locations for embankment overtopping (L.Wahl, 1998)

The stream power-erodibility index method can be used to estimate the likelihood of initiating rock erosion. The erodibility index (and its possible variability) represents how erodible the foundation material is. This index was correlated empirically to the erosive power of flowing water, or the energy rate of change, termed "stream power". The stream power represents the erosive power of the overtopping flows. Stream power is the rate of energy dissipation of flow per unit of surface area. For flow down a slope, the rate of energy dissipation per unit of surface area (P) is a function of the flow depth, flow velocity, and the energy slope (USBR, 2018):

$$P=\gamma V_t h S$$

where,

γ = unit weight of water,

V_t = flow velocity,

h = water depth, and

S = hydraulic energy grade line slope

The analysis of erosion stability is performed at the location where the value of energy dissipation is the highest. Under overtopping flow conditions, the flow intensity is highest at the dam toe. The energy slope is assumed to be approximately equal to the bed slope, and flow depths are taken to be equal to the normal depth computed for steady-state flow conditions.

The depth of flow for the frequency flood discharges can be determined from Q = VA, where Q is the discharge, V is the average flow velocity and A is the area of flow.

A simplified approach that neglects friction losses can be used to calculate an upper bound for the velocity. This can be determined by the equation (USBR, 2019):

$$V_t = [2g(H+h)]^{1/2}$$

where,

H is the reservoir head, and

h is the change in elevation from the crest to a point in downstream

Given Q and V, the area of the flow can be determined and then the depth of flow determined by dividing the flow area by the crest width.

Rule and script to calculate the average velocity of the overflow:

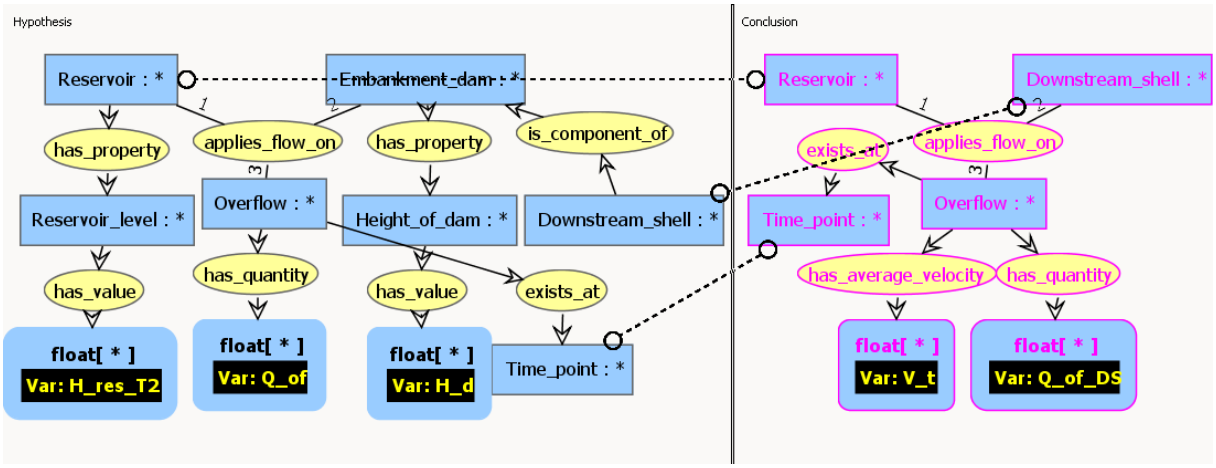


Figure A-7.136. Rule calculating average velocity of the overflow

Rule | Associated script

```
1  void after()
2  {
3      float value1 =  Math.sqrt(2 * 9.8 * (H_res_T2.getValue() + H_d.getValue()));
4      V_t.setValue(value1);
5      Q_of_DS.setValue(Q_of.getValue());
6  }
```

Figure A-7.137. Script calculating average velocity of the overflow

Figure A-7.136 shows a rule graph calculating the average velocity of the overflow. The rule says that **if** *Reservoir* applies *Overflow* on *Embankment_dam*, and *Downstream shell* is a component of *Embankment dam*, **then** *Reservoir* applies *Overflow* on *Downstream shell*. *Reservoir* has *Reservoir level* defined by the variable *H_res_T2*. *Embankment dam* has *Height of dam* defined by the variable *H_d*. The *Overflow* in the hypothesis graph has a quantity defined by the variable *Q_of*. The *Overflow* in the conclusion graph has average velocity and quantity defined by the variables *V_t* and *Q_of_DS*, respectively. Figure A-7.137 shows the associated script.

Rule and script to calculate the depth flow:

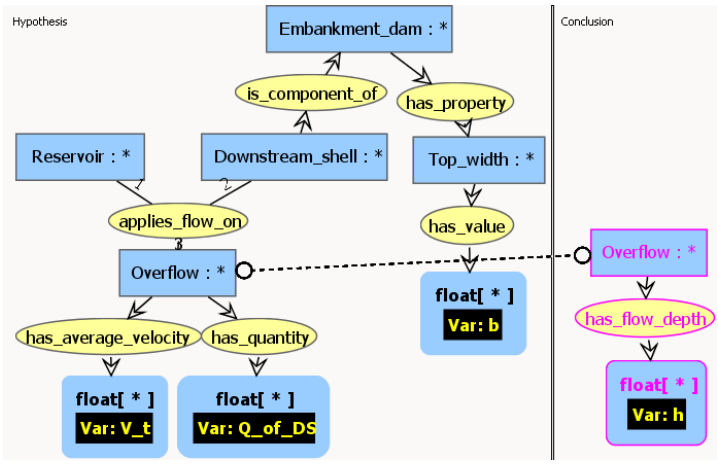


Figure A-7.138. Rule calculating depth flow of overflow

Rule Associated script

```
1  void after()
2  {
3       float value1 =  Q_of_DS.getValue() / (V_t.getValue() * b.getValue());
4
5       h.setValue(value1);
6  }
```

Figure A-7.139. Script calculating depth flow of overflow

Figure A-7.138 shows a rule calculating the depth flow of the overflow. The rule says that **if** *Reservoir* applies *Overflow* on *Downstream shell* with average velocity and quantity defined by the variables *V_t* and *Q_of_DS*, respectively, *Embankment dam* has *Top_width* defined by the variable *b*, **then** *Overflow* has depth flow represented by the variable *h*. Figure A-7.139 shows the associated script.

Rule calculating the stream-power as follow:

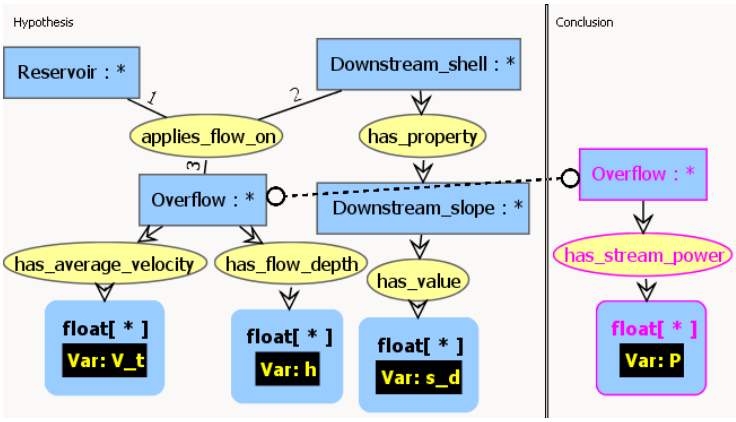


Figure A-7.140. Rule calculating stream power of overflow

Rule Associated script

```
1  void after()
2  {
3       float value1 =  10 * V_t.getValue() * h.getValue() * s_d.getValue();
4
5       P.setValue(value1);
6  }
```

Figure A-7.141. Script calculating stream power of overflow

Figure A-7.140 shows a rule calculating the stream power of the overflow. The rule can be expressed as **if** *Reservoir* applies *Overflow* on *Downstream shell*, *Downstream shell* has *Downstream slope* represented by the variable *s_d*, **then** *Overflow* has stream power defined by the variable *P*. Figure A-7.141 shows the associated script.

The resulting graph of overflow is:

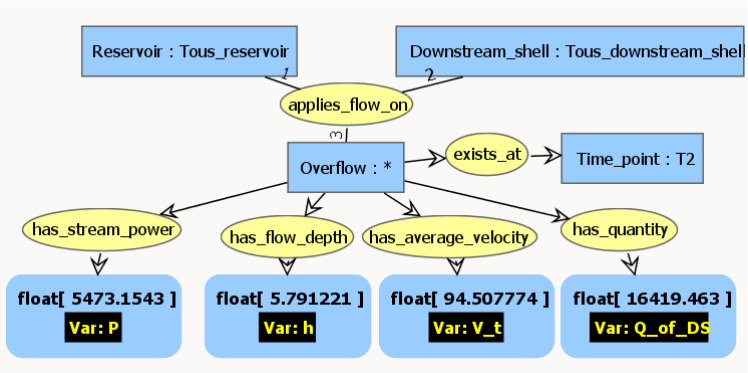


Figure A-7.142. Resulting graph of the overflow

Figure A-7.142 shows the overflow described with stream power, flow depth, average velocity, and quantity. All properties are defined by their variables and values. The flow is at T2.

Performance of the downstream to resist external erosion:

Downstream performance to resit external erosion is evaluated by factor of safety against external erosion.

Factor of safety against external erosion (F.S.Es) = $\frac{Erosion\ strength}{Stream\ power}$

If F.S.Es > 1: satisfied

F.S.Es < 1: downstream shell is eroded.

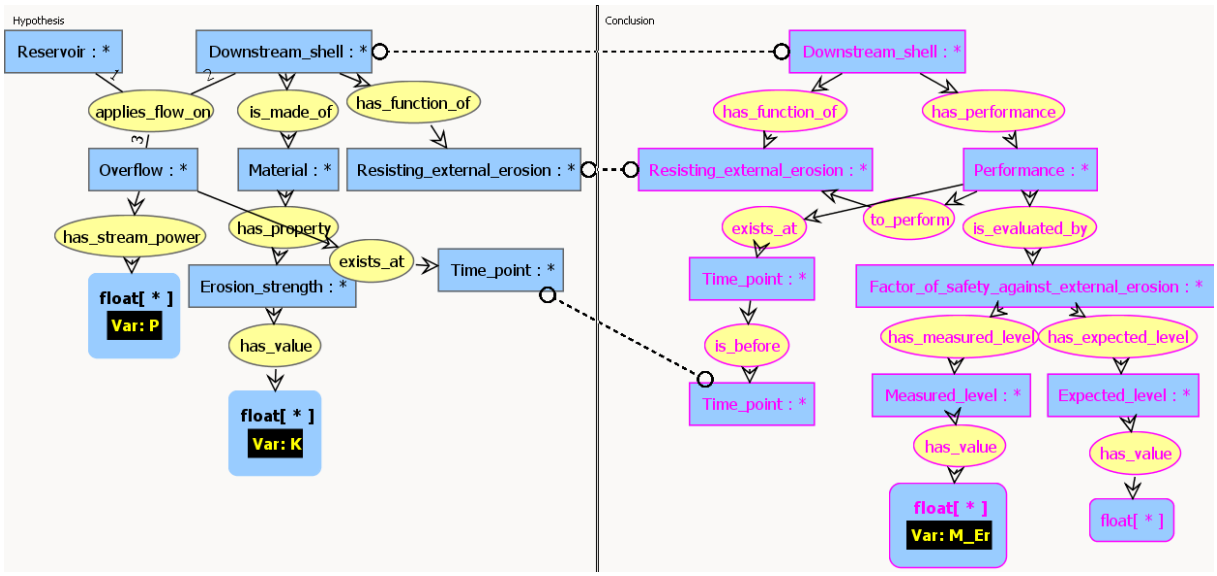


Figure A-7.143. Rule calculating measured F.S.Es

Rule | Associated script

```
1  void after()
2  {
3      float value1 = K.getValue() / P.getValue();
4      M_Er.setValue(value1);
5  }
```

Figure A-7.144. Script calculating measured F.S.Es

Figure A-7.143 shows a rule calculating the measured level of the factor of safety against external erosion. The rule says that **if** *Reservoir* applies *Overflow* on *Downstream shell*, and *Downstream shell* is made of *Material* with *Erosion strength* defined by the variable *K*, **then** *Downstream shell* has a new *Performance* evaluated by *Factor of safety against external erosion*. *F.S.Es* has *Measured lev*el and *Expected level*. The time point of performance is after the time of the overflow. Figure A-7.144 shows the associated script.

Performance of the downstream to resist external erosion:

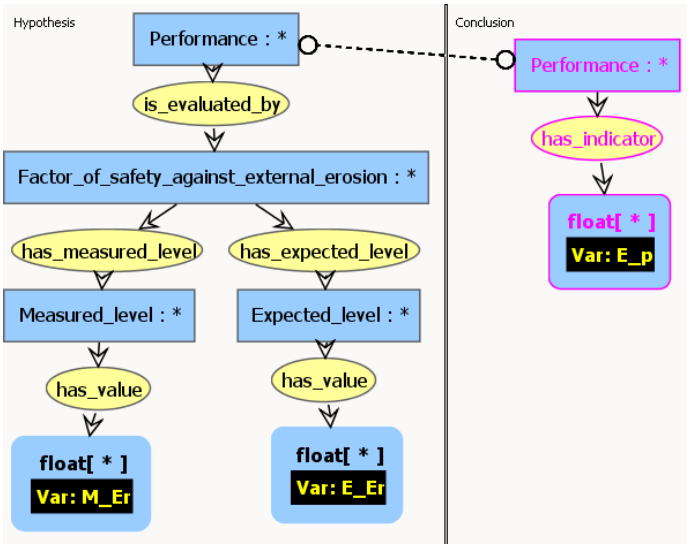


Figure A-7.145. Rule estimating performance resisting external erosion

Rule | Associated script

```
1  void after()
2  {
3      if (M_Er.getValue() < E_Er.getValue())  {
4
5          E_p.setValue(0);
6      }
7      else {
8          E_p.setValue(1);
9      }
10 }
```

Figure A-7.146. Script estimating performance resisting external erosion

Figure A-7.145 shows a rule graph identifying the performance resisting external erosion of the downstream shell. The rule says that **if** *Performance* is evaluated by *Factor of safety against external erosion* with *Measured level* and *Expected level*, **then** *Performance* has an indicator defined by the variable *E_p*. Figure A-7.146 shows the associated script.

The resulting graph is:

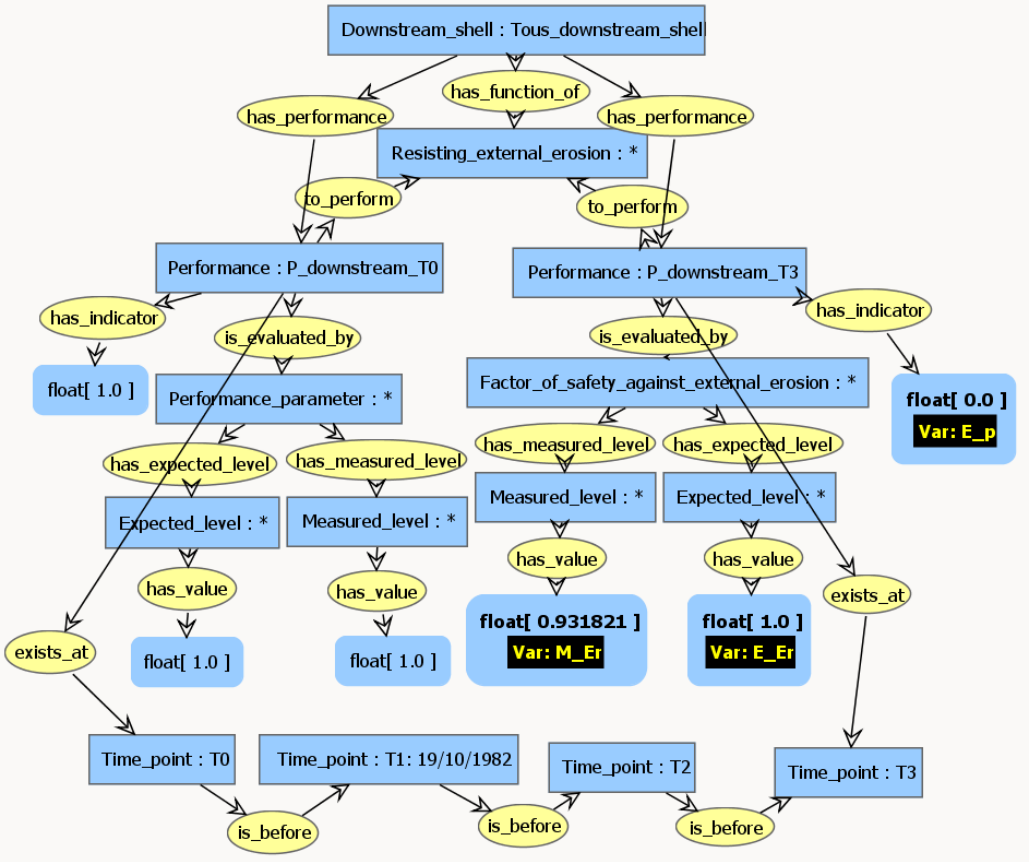


Figure A-7.147. Performances of Downstream shell

Figure A-7.147 illustrates the performances of the downstream shell over time. At the initial time, T0, the performance is assumed as satisfied, i.e., the indicator has a value of *1*. At the time point T3, the performance has the indicator with a value of *0*, i.e., the downstream is eroded.

7.3.3.11. Performance of the zoned embankment dam at T3

The performance of the zoned embankment dam is contributed by the performance of the downstream shell. Rule to identify the performance of the dam as follow:

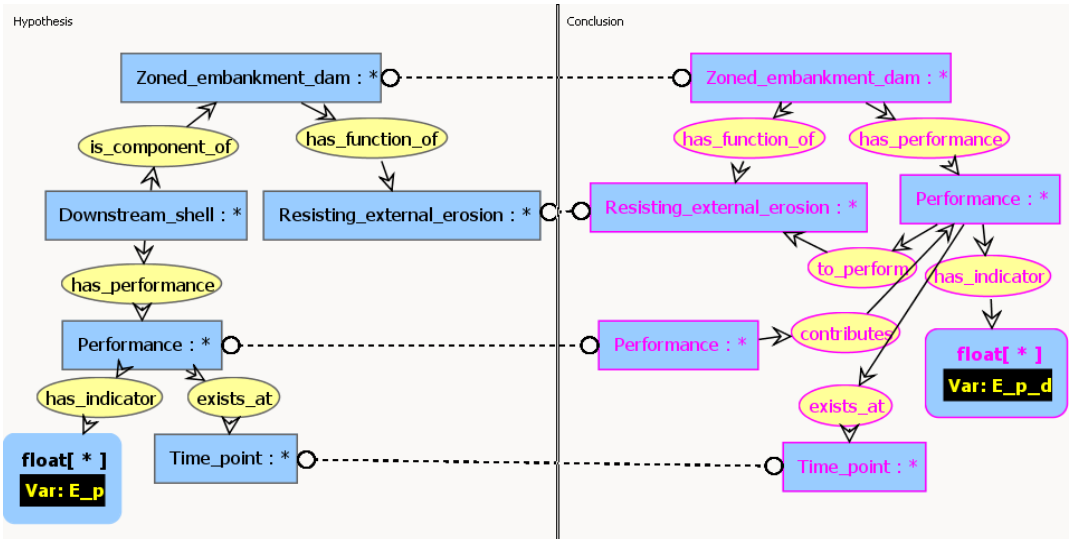


Figure A-7.148. Rule identifying performance of zoned embankment dam

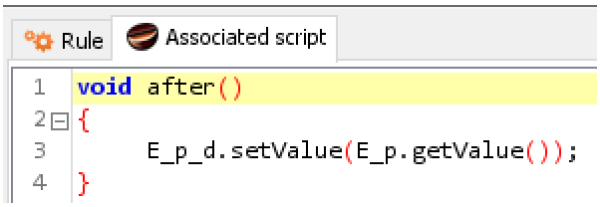


Figure A-7.149. Script identifying performance of zoned embankment dam

Figure A-7.148 shows a rule identifying the performance of the zoned embankment dam based on the performance of the downstream shell. The rule can be expressed as **if** *Downstream shell* is a component of *Zoned embankment dam*, and *Downstream shell* has *Performance* defined by the variable *E_p*, **then** *Zoned embankment dam* has a new *Performance* contributed by *Performance* of *the Downstream shell*. The performance indicator of the dam is defined by the variable *E_p_d*. There is a coref relation between two concepts *Resisting external erosion*. The time point of the dam performance is the time point of the downstream performance. Figure A-7.149 shows the associated script.

The resulting graph is:

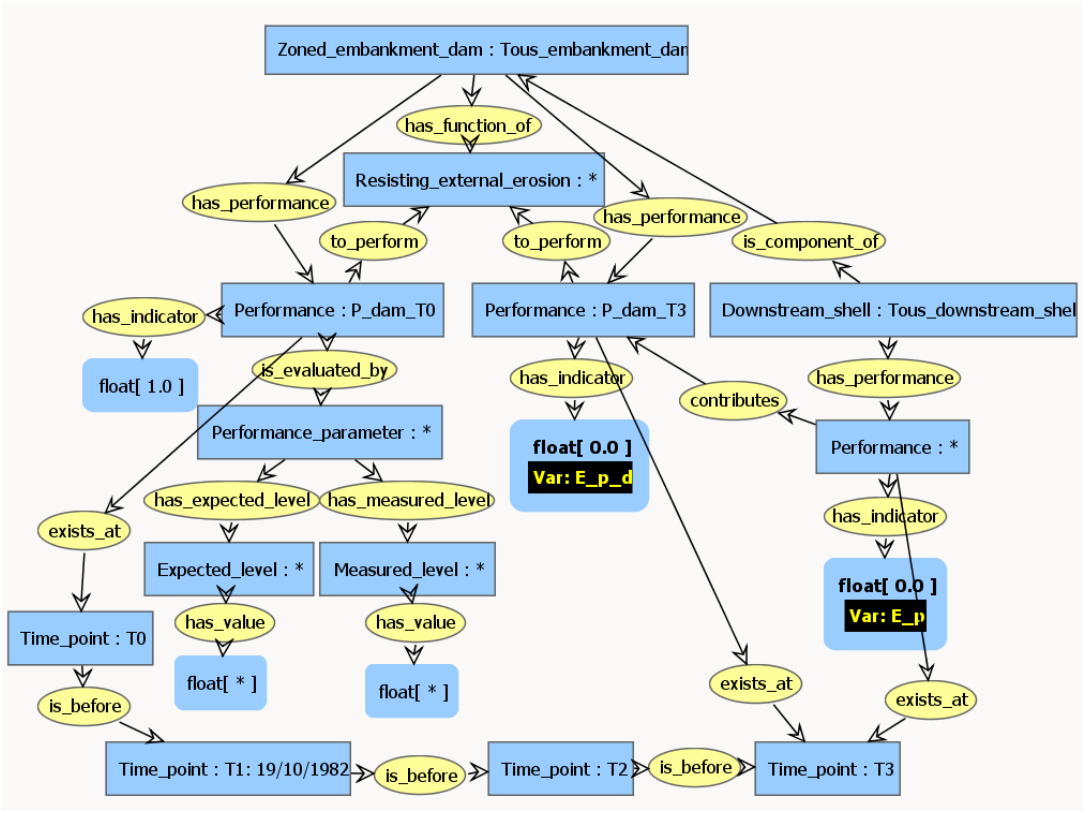


Figure A-7.150. Performances of Tous dam at different time points and relation with the downstream performance

Figure A-7.150 illustrates the performances of the dam over time. At the initial time, T0, the dam has *Performace: P_dam_T0* is assumed as satisfied, i.e., the indicator has a value of *1*. At the time point T3, the dam has *Performance: P_dam_T3* with the indicator has a value of *0*, which means that the performance is not satisfied. The relation *contributes*

connects the *Performance* of *Tous_downstream shell* with the performance *P_dam_T3* of the dam.

7.3.3.12. Performance of the dam system at T3

Performance of the Tous dam system is contributed by the performance of Tous zoned embankment dam. Rule to identify performance of the system as follow:

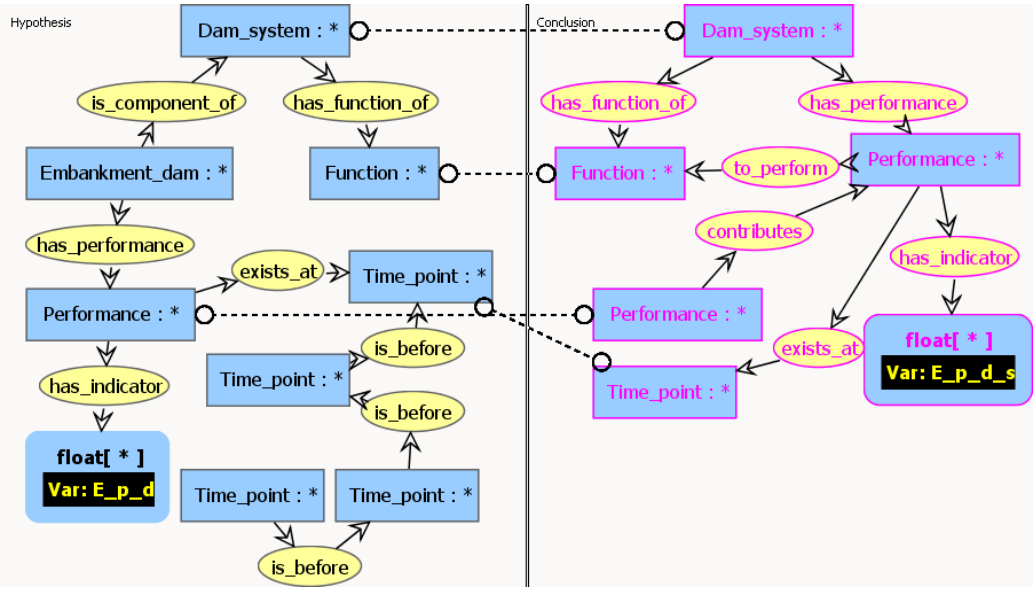


Figure A-7.151. Rule identifying performance of dam system

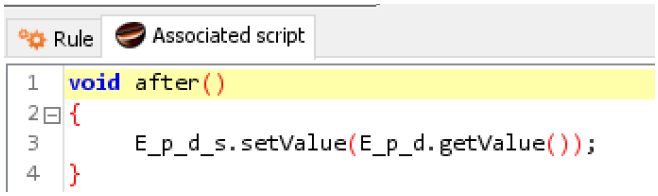


Figure A-7.152. Script identifying performance of system

Figure A-7.151 shows a rule identifying the performance of a dam system. The rule says that **if** *Embankment dam* is a component of *Dam_system*, and *Embankment dam* has a *Performance* with the indicator defined by the variable *E_p_d*, *Dam system* has a *Function*, **then** *Dam system* has a new *Performance* to perform its *Function*, the *Performance* of the system is contributed by the *Performance* of the dam. The time point of the system performance is the time point of the dam performance. There is a coref relation between two concepts *Function* in the rule. Figure A-7.152 exposes the associated script.

The resulting graph is:

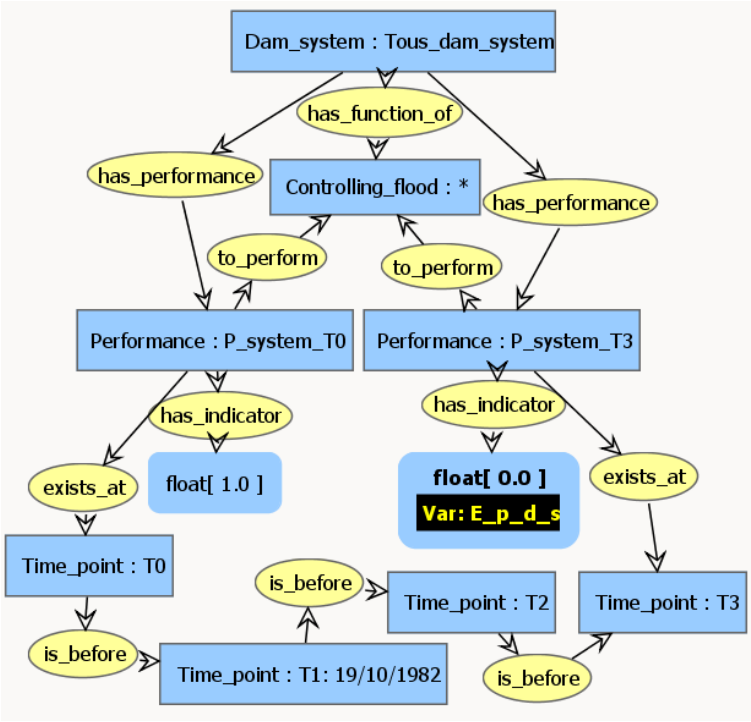


Figure A-7.153. Resulting graph of system performance

Figure A-7.153 illustrate the performances of the system through T0 and T3. At the T0, the system performance is assumed as satisfied, i.e., the indicator has a value of 1. At the time T3, the performance has an indicator with 0, which means that the Tous dam system is not satisfied to control flood.

7.3.4. Failure process

The failure process of the Tous dam system is described in six snapshots with six time points, from the time point T0 to the time point T5.

- Snapshot at the time point T0 as follow:

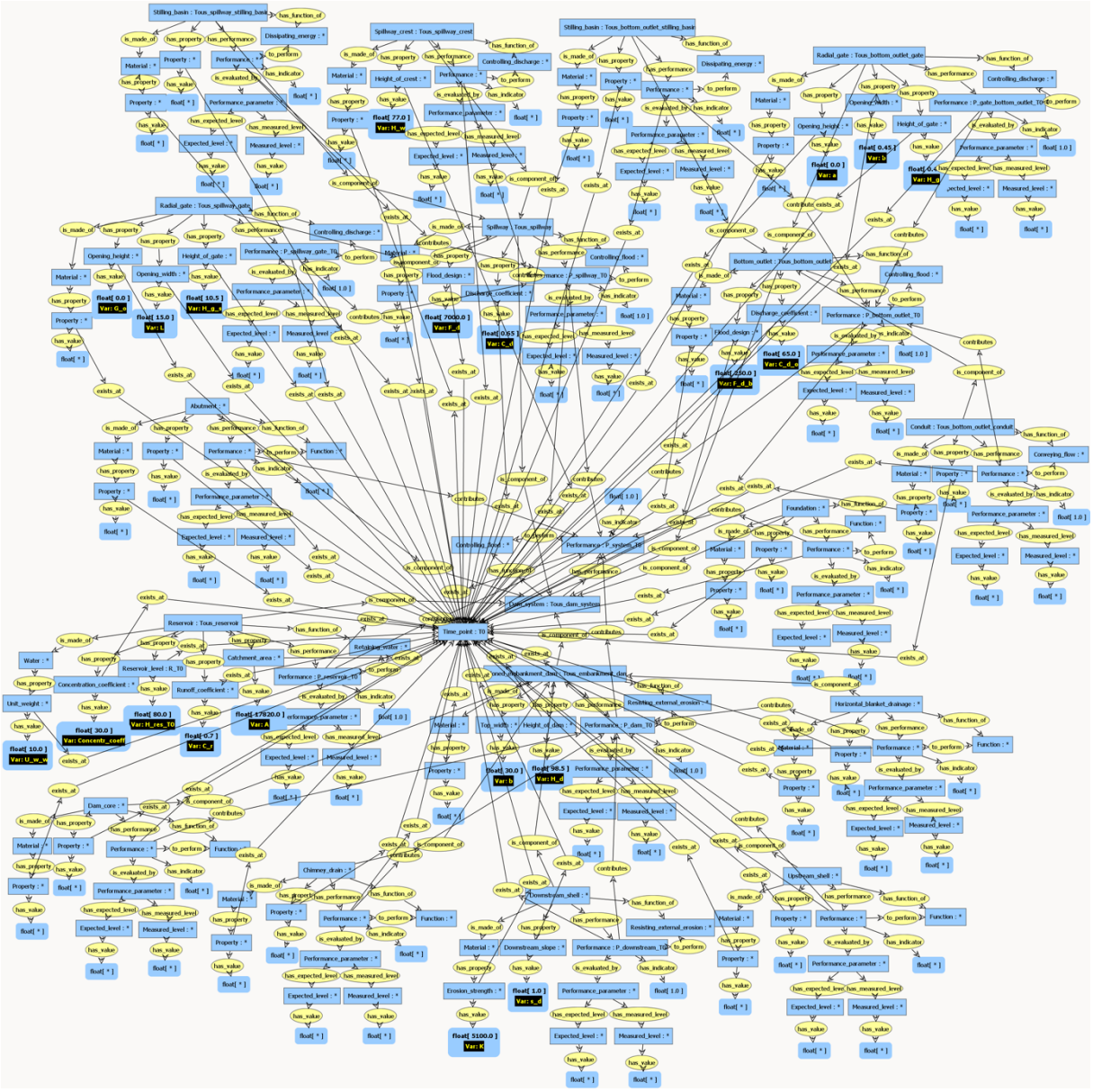


Figure A-7.154. Snapshot of the Tous dam system failure at T0

Figure A-7.154 shows the snapshot at T0, the time before the rainstorm, of the Tous dam system failure. This snapshot describes the state of the system at the time point T0. At T0, the system's structure includes a reservoir, zoned embankment dam, foundation, spillway, bottom outlet, abutment, components of the zoned dam including dam core, downstream shell, upstream shell, chimney drain, horizontal blanket drainage, components of bottom outlet including conduit, radial gate, stilling basin, components of spillway including spillway crest, radial gate, spillway stilling basin. All components are described with constituted material, properties, function, and performance at T0. The concepts that can change their values over time are connected with the concept Time_point: T0 to identify their values and states at T0. At T0, the system operates normally, and the water level is 80 m. The retaining water performance of the reservoir is assumed as satisfied, i.e., the performance indicator has a value of 1. The functions of the dam and downstream shell are to resist external erosion. The performances to perform these functions are assumed as

satisfied, i.e., the performance indicator has a value of 1. Spillway and bottom outlet have a function of controlling flood, with the performances to perform this function are satisfied. Radial gates also have a satisfactory performance to perform the function of controlling discharge. The function of the system is to control floods. The system performance is assumed as satisfied at T0.

- Snapshot at the time point T1 as follow:

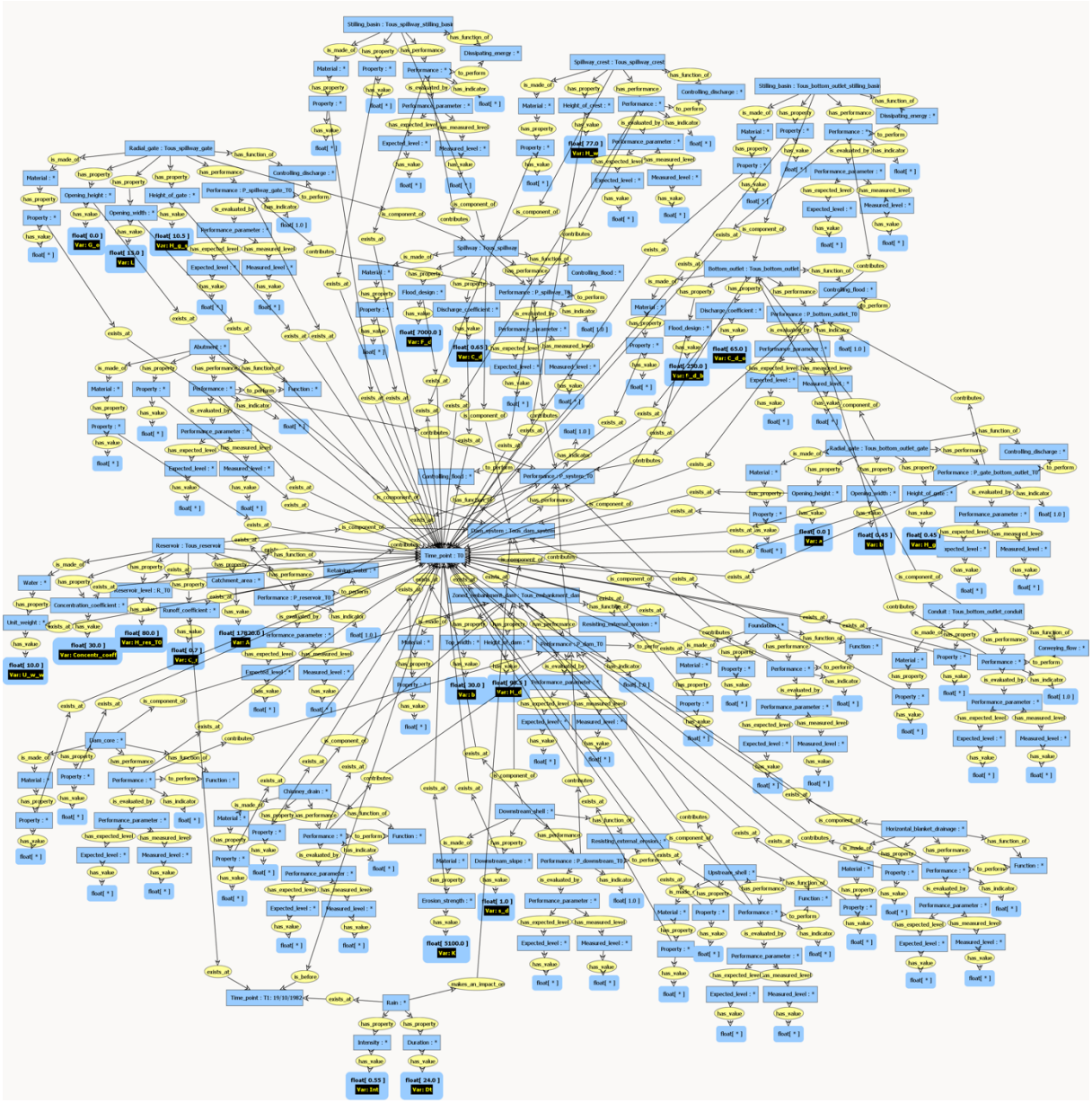


Figure A-7.155. Snapshot of the Tous dam system failure at T1

Figure A-7.155 shows the snapshot of the Tous dam failure at T1. Based on the system's conditions at the time point T0, the snapshot at T1 is described with the addition of an external factor, which is heavy rain. The impact of the heavy rain on the system is described by the relation *makes_an_impact_on*. The concept *Rain* is connected with *Time_point: T1: 19/10/1982.* There is a relation *is_before* connecting the time point T0 and the time point T1

- Snapshot at the time point T2 as follow:

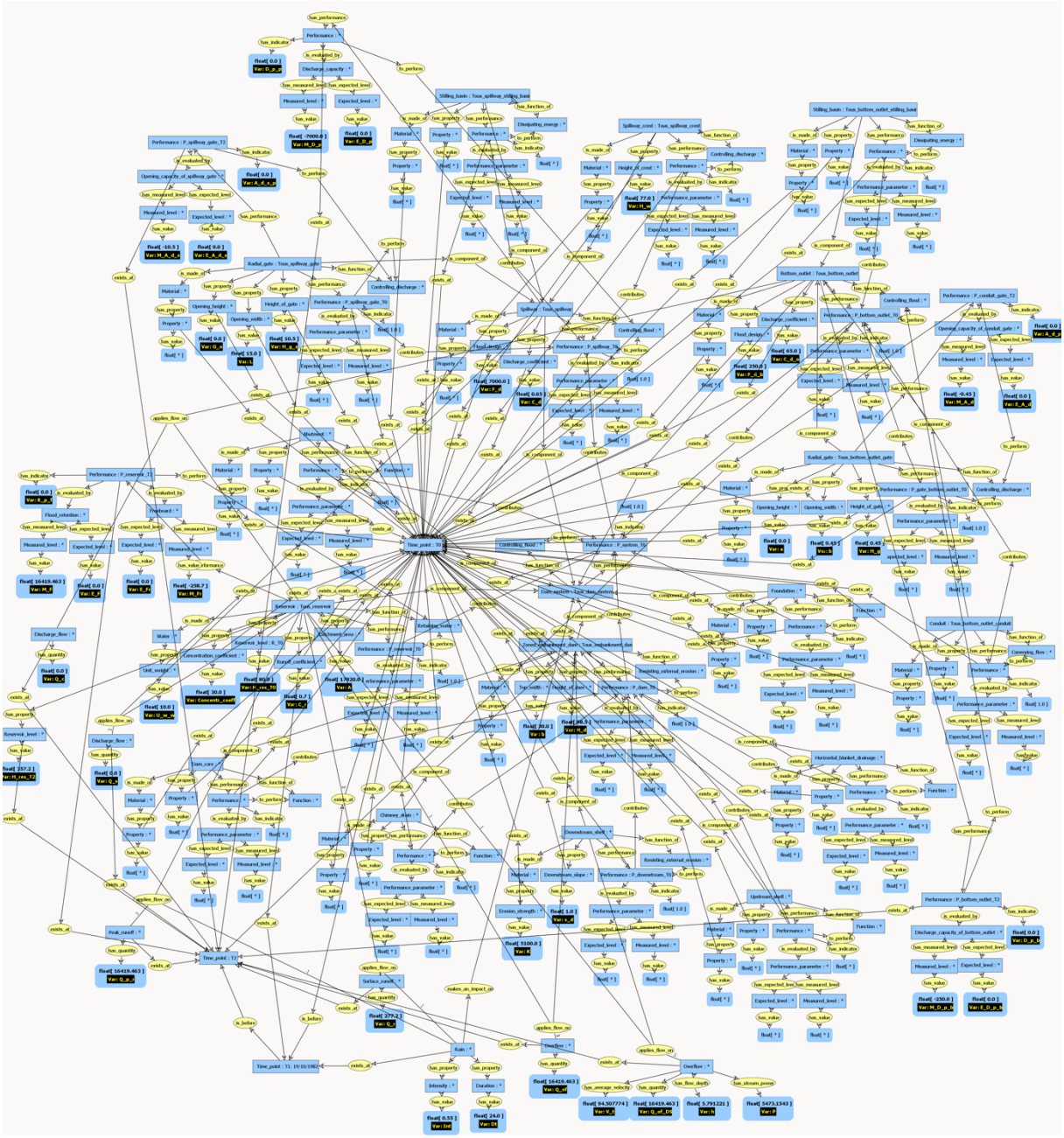


Figure A-7.156. Snapshot of the Tous dam system failure at T2

Following the time point T1, a snapshot at the time T2 (Figure A-7.156) describes the impacts of the heavy rain and interactions within the system. The impact of heavy rain on the system is described by *Surface_runoff* that *Rain* applies on *Reservoir*. In turn, this flow increases the water level, which induces a new *Reservoir level* at T2. As the reservoir rose, subsequent interactions between the reservoir and spillway, and bottom outlet are performed. These are described by the concept *Discharge flow* that the reservoir applies on the spillway and bottom outlet. Due to the radial gates can not open, the spillway and bottom outlet's performances to control flood are not satisfied. This leads to an interaction between the reservoir and the downstream shell described by the concept *Overflow*. The performance of the reservoir is not satisfied at T2.

- Snapshot at the time point T3 as follow:

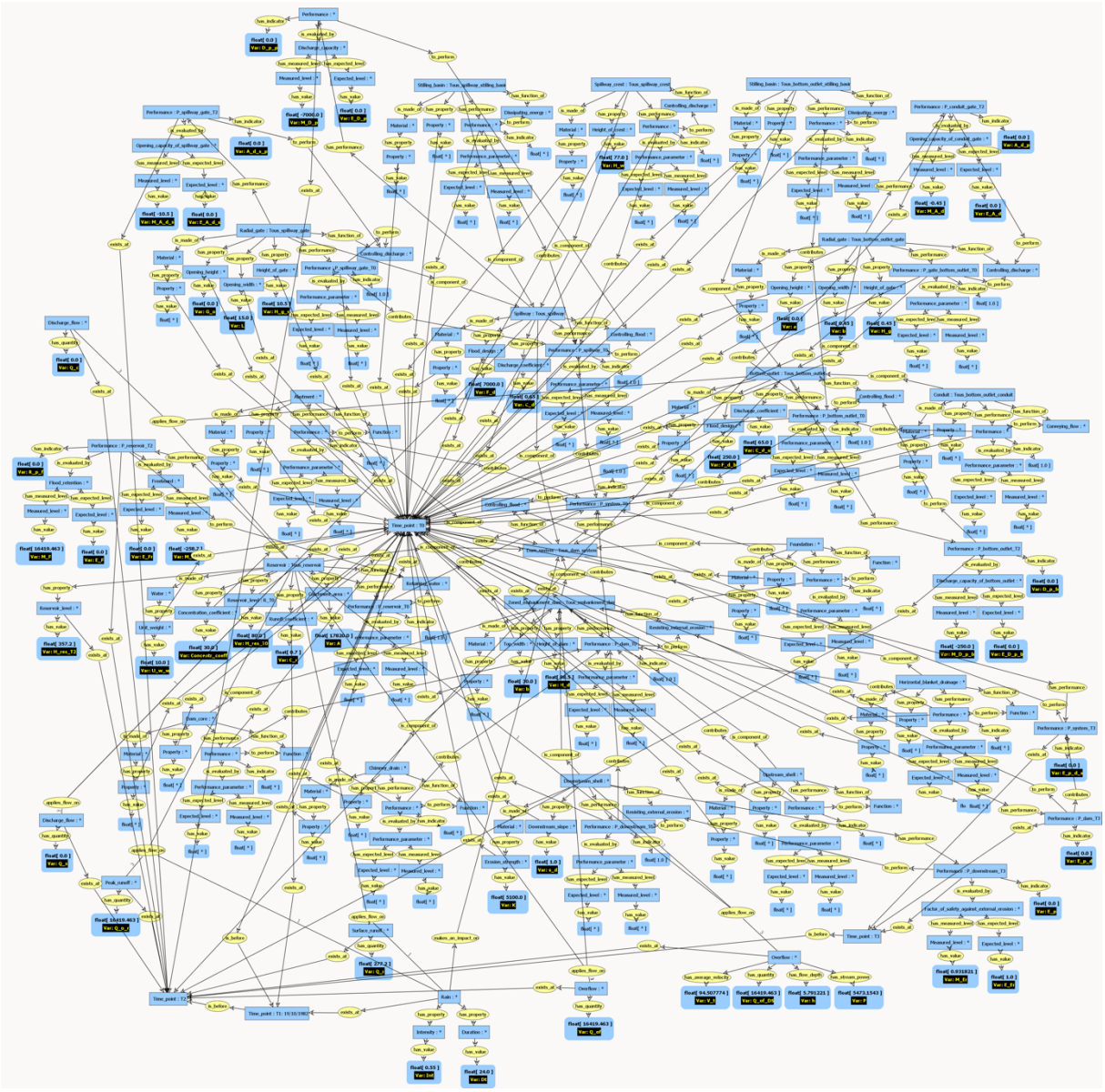


Figure A-7.157. Snapshot of the Tous dam system failure at T3

Following the overflow in T2, the snapshot in T3 (Figure A-7.157) describes the effect of this flow on the downstream shell. The performance of the downstream is evaluated by *Factor of safety against external erosion*. At the time point T3, the performance indicator has a value of 0, which means that the downstream is eroded. This failure leads to the failure of the zoned embankment dam and the system's failure at T3.

In conclusion, the four snapshots provided an overview of the Tous Dam system's failure process over time. The first snapshot, the snapshot at T0, depicts the system's state before the impact of external factors. After that, the second snapshot shows the participation of heavy rain. The third snapshot describes the interactions that occur between the heavy rain and the dam system and the interactions within the system. Each interaction that takes place is the result of a combination of various factors: properties of the components, properties of

materials, and the properties of the interactive flows. Finally, the snapshot at T3 shows the failure of the components and the system.

7.4. Case study 4 application – Sparmos dam system failure

7.4.1. Context of failure

General information

- Location: Paleohore, Greece
- Failure: Breach of dam
- Fatalities: 0
- Year of failure: March 27, 2016
- Year of construction: late 1980s
- Function of dam system: Irrigation

External factor

First filling activity

Intensity: 300 mm/day

Duration: 46 days

Description of site, structure and materials

- Sparmos dam is a homogeneous structure with a maximum height (crest to downstream toe) of 15.8m. The dam without any obvious filters or drains.

- The Sparmos dam is built on gneiss bedrock and is constructed by weathered gneiss excavated locally. The material was classified as SC according to USCS having on average gravel 13.9%, sand 60.6% and fines 25.5%. The coefficient of permeability was measured on a sample compacted at a dry unit weight of 97% of the maximum dry unit weight and was found to be 7×10^{-5} m/s (Zekkos *et al.*, 2016).

- The reservoir is fed by a nearby stream in a controlled manner.

- An unlined spillway channel is exacavated on the right abutment.

7.4.2. Failure presentation

Description of failure

After first filling of the reservoir, leakages were developed in the embankment dam immediately. The leakages were observed for many years but left un-intervened to stop. The erosion was then accelerated in March 2016 and it took just two days to breach the embankment. It is most probably a case where contact erosion started along segregated construction layer interfaces and 27 years later developed into piping that caused the breach of the dam (Dounias and Bardanis, 2019).

Figure A-7.158. Aerial view of the Sparmos Dam failure. (Zekkos *et al.*, 2016).

Contact erosion is a form of internal erosionn which occurs where a coarse soil such as a gravel is in contact with a fine soil, and flow parallel to the contact in the coarse soil erodes the fine soil. Particles of the finer layer may be destablized by the water flow and transported through the pores of the coarser layer parallel to the interface when the Darcy velocity in the coarse soil is sufficient to erode the fine soil continuously (Cheng, Draper and An, 2014). This process causes a pipe within the embankment, and then the pressure drops around that pipe, causing the roof collapse. Those materials fill in the lower part of the pipe and enlarge it at the top. Then the roof of the new pipe is decompressed and, step by step, the pipe progresses along a practically vertical chimney towards the top of the dam until the collapse of new roof causes the breach of embakment (ICOLD, 2017).

Analysis

The factors contributing to the failure can be summarized as follows:

- The first filling activity which is a critical phase in the life for the dam. In this phase, it is common for design, construction, and/or material deficiencies of a new dam to become apparent during the first filling (ASDSO, 2020).
- The Sparmos embankment dam was very vulnerable to internal erosion because it was homogeneous (unzoned), made of erodible material without any control to stop internal erosion.
- Material was capable to develop a pipe since it could hold a “roof”, i.e., the fines content of the soil > ≥ 15% fines.
- Components at risk are Reservoir, Earthfill dam.
- Time to progress erosion, 27 years in the case of Sparmos dam, before a definite pipe formed, time to enlarge a pipie.

The Sparmos dam system's failure resulted from a combination of multiple interactions in chronological order. The first interaction was generated by associating the first filling

activity and the reservoir, which increased the water level. As the water level rose, resulting in the subsequent interaction between the seepage flow and the homogeneous dam. The combination of conditions of the dam and the seepage flow over time developed internal erosion, then forming a pipe, and eventually breach of the dam.

7.4.3. Instantiation of the failure knowledge model

Sparmos dam is a homogeneous structure without any obvious filters or drains. Therefore, the Sparmos system is described in two levels: system and component level.

The external factor: First filling activity

The function of the reservoir is retaining water.

The functions of the homogeneous dam are resisting contact erosion, resisting piping, and resisting breach.

The failure process is described with 6 time points: from the time point T0 to the time point T5 (Figure A-7.159):

- Time point T0: Before the first filling activity, the construction of the system finished, the reservoir was empty. The performance of the reservoir is assumed as not satisfied.
- Time point T1: in 1990 - The first filling activity happens.
- Time point T2: The increasing of reservoir level. The performance of the reservoir is satisfying. Water seeps through the embankment dam.
- Time point T3 - 25/3/2016: Contact erosion develops within the embankment. The dam failed to resist contact erosion.
- Time point T4 - 27/3/2016: Contact erosion progresses, and a pipe is formed. The dam failed to resist piping.
- Time point T5: The pipe develops and then breaks the embankment. Water releases a flood flow. There are two failures: breach of the dam and reservoir discharges.
- Finally, failure of the Sparmos dam system.

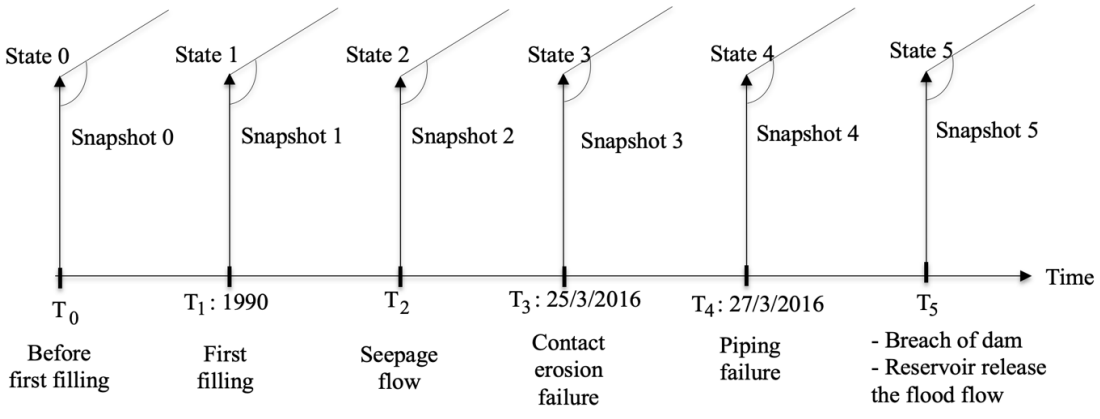


Figure A-7.159. Timepoints of the failure process

Steps to instantiate:

1. Identifying the dam system at T0

2. Identifying the external factors at T1

3. Interactions and performance of the reservoir at T2

4. Interactions and performance of the embankment dam at T3

5. New performance of the Sparmos dam at T4

6. Interactions and new performance of the Sparmos dam at T5

7. Interactions and new performance of the Sparmos reservoir at T5

8. New performance of the Sparmos dam system at T5

7.4.3.1. Identifying the dam system at T0

Figure A-7.160 shows a rule graph to identify the structure of the homogeneous dam system. The rule can be expressed as **if** *Homogeneous_embankment_dam* is a component of *Dam_system*, **then** the main components of a homogeneous dam system will be created, those are *Reservoir, Homogeneous_embankment_dam*, *Foundation*, *Spillway*, *Bottom_outlet*. *Dam_system* is described with its function and performance.

Rule to identify the homogeneous dam system.

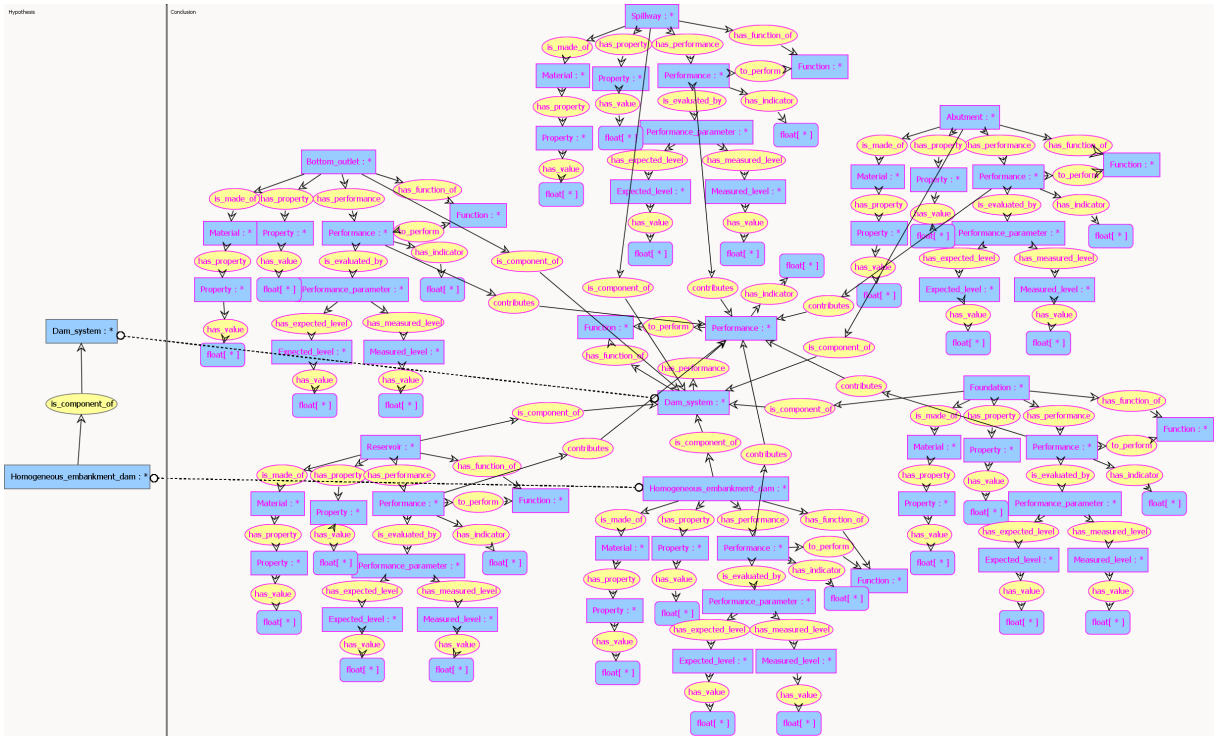
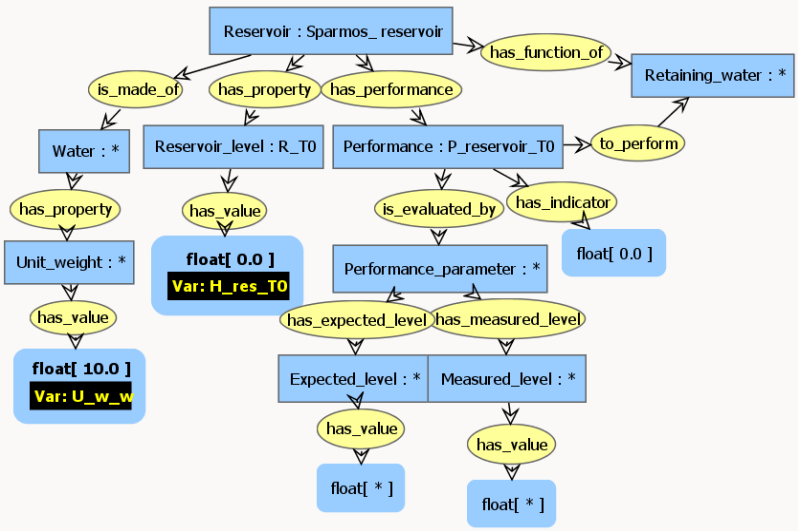


Figure A-7.160. Rule of identification of the system

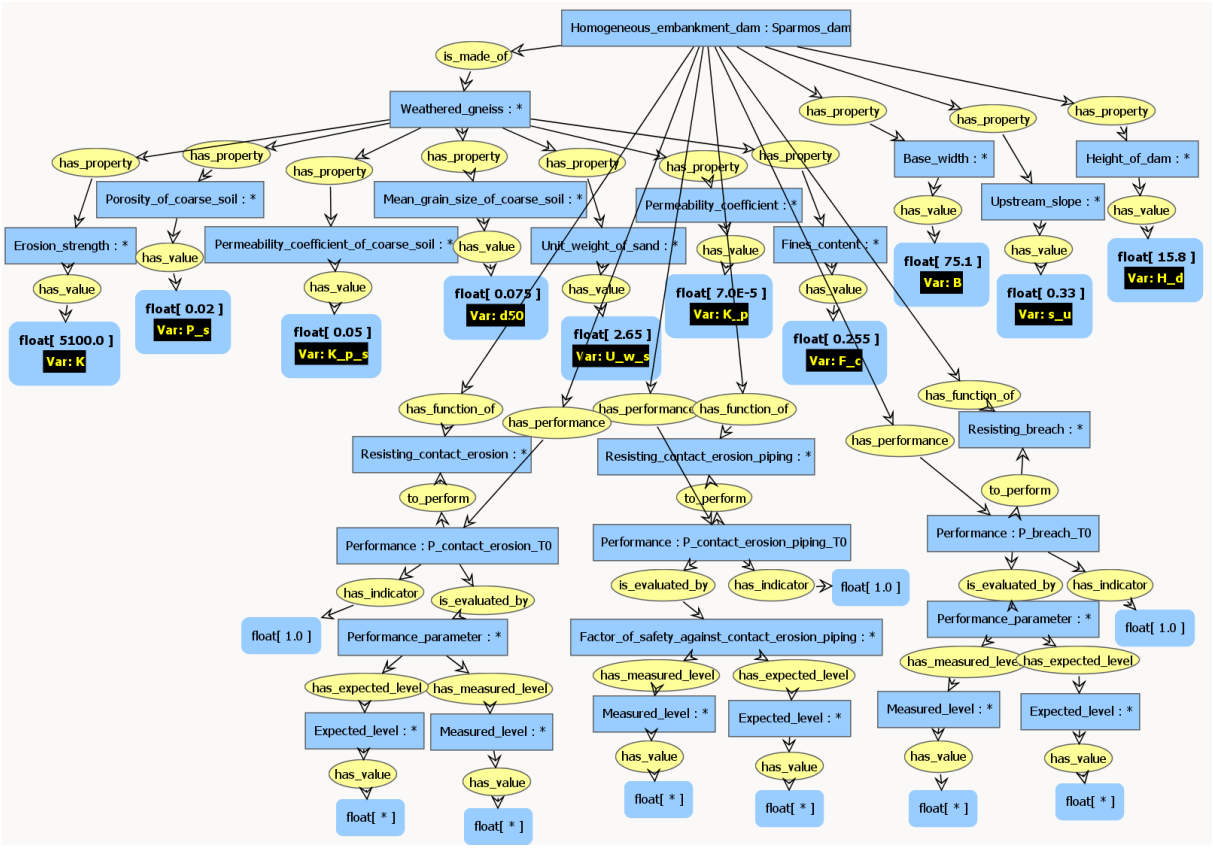
After identifying the structure of the system, all concepts are filled with information to formalize the failure. At T0, the reservoir, the dam, and the system are filled with necessary information as follow:



Fiugre A-7.161. Resulting graph of the reservoir at T0

Figure A-7.161 illustrates the resulting graph of the reservoir. It is represented by an individual concept type *Reservoir: Sparmos_reservoir*. The reservoir is described with its level *Reservoir_level: R_T0,* at T0 the value of water level is 0; the property of the material is *Unit_weight*, which has a value of *10*. The function considered is *Retaining_water*, and the performance to perform it at T0 is *Performance: P_reservoir_T0*. The value of the indicator is assumed as 0, i.e., not satisfied.

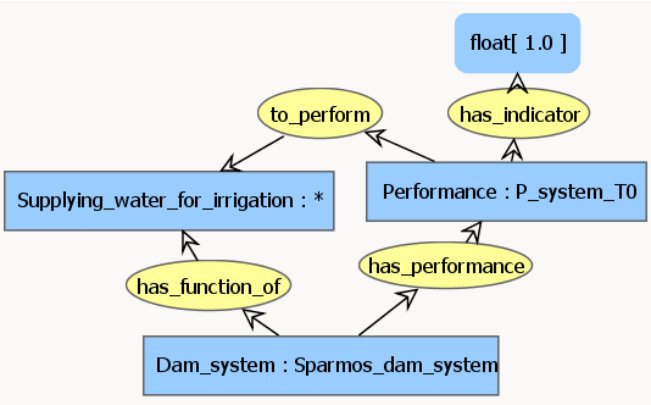
The resulting graph of the embankment dam at T0:



Fiugre A-7.162. Resulting graph of Sparmos homogeneous dam at T0

Figure A-7.162 shows a description of the Sparmos dam at T0. The dam is described with its properties, which are *Height of dam*, *Base_width, Upstream_slope;* material *Weathered_gnesiss* that has properties of *Erosion_strength*, *Porosity of coarse soil*, *Permeability coefficient of coarse soil*, *Main grain size of coarse soil*, *Unit weight of sand*, *Permeability coefficient*, *Fines content*. The properties are represented by the variables and their values. The functions considered of the dam are *Resisting contact erosion*, *Resisting contact erosion piping*, *Resisting breach*. All performances are assumed as satisfied, i.e., the indicator value is *1*.

The resulting graph of the dam system at T0:



Fiugre A-7.163. Resulting graph of Sparmos dam system at T0

Figure A-7.163 shows the resulting graph of the Sparmos dam system. The function considered is *Supplying water for irrigation*; the performance to perform it at T0 is *P_system_T0*. The value of the indicator is assumed as *1*, which means that the system is satisfied.

7.4.3.2. Identifying the external factors at T1

There is one external factor: First filling activity (Figure A-7.164).

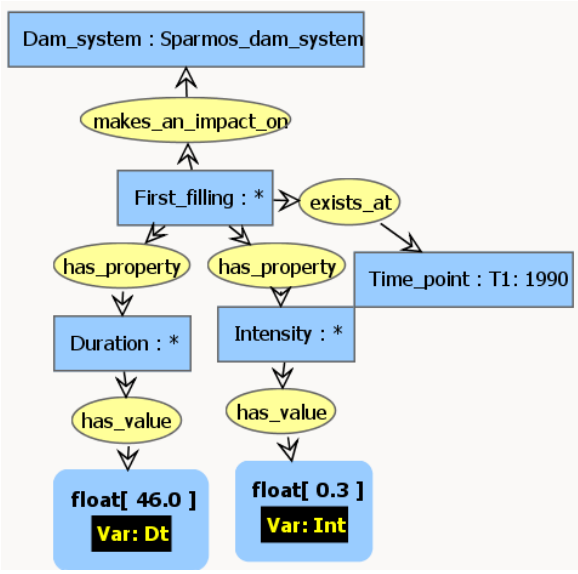


Figure A-7.164. The first filling activity

Figure A-7.164 shows a graph of the first filling activity. The activity is described with two properties, *Duration* and *Intensity*. The property *Duration* is defined by the variable *Dt*, which is assigned to a value of 46 days. The property *Intensity* is identified by the variable *Int*, which is assigned to a value of 300 mm/day. The time point of the external factor is set at T1: 1990, which is when the activity happens.

7.4.3.3. Interaction and performance of the reservoir at T2

Inflow due to the first filling activity

When the first filling activity occurs, an inflow will enter the reservoir. The quantity of the inflow will be calculated as follow:

$$\text{Inflow} = \text{Duration} * \text{Intensity}$$

Duration: the period of time during which the filling activity occurs, in days.

Intensity: is the ratio of the amount of inflow during a given period to the filling duration. It is expressed in depth units per unit time, in m/h.

Rule to calculate the inflow:

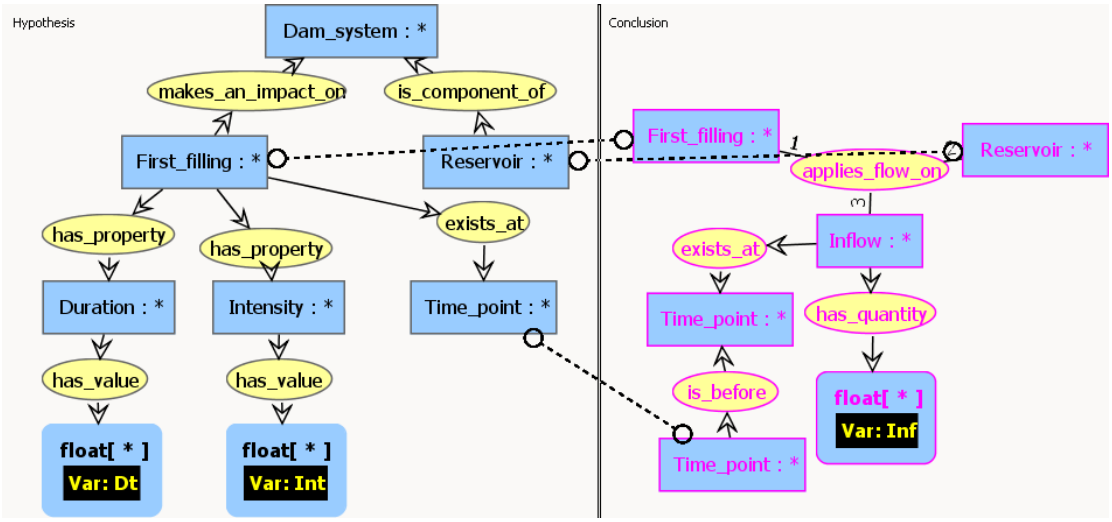


Figure A-7.156. Rule calculating the inflow into reservoir

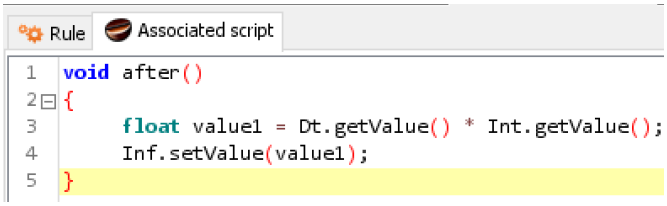


Figure A-7.166. Script calculating the inflow into reservoir

Figure A-7.165 shows a rule graph calculating the inflow into the reservoir. The rule graph says that **if** *First filling* activity makes an impact on *Dam_system*, and *Reservoir* is a component of *Dam_system*, **then** *First_filling* applies *Inflow* on *Reservoir*. *First_filling* is described with *Duration* and *Intensity*. The inflow occurs at a time point after the time point of the activity. Figure A-7.166 shows the associated script.

Rising of the reservoir level due to the inflow

When the inflow enters the reservoir, water level in the reservoir will increase a height equal to the inflow amount.

New water level = Previous level + Inflow.

Rule to calculate the new reservoir level as follow:

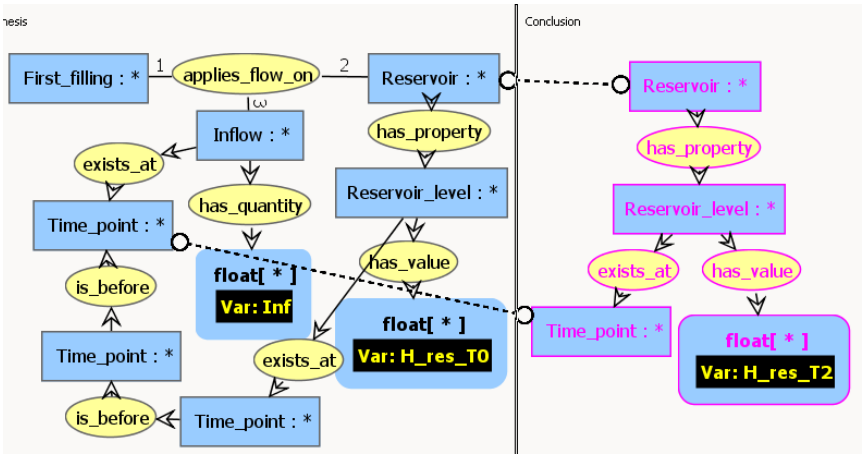


Figure A-7.167. Rule to calculate new reservoir level

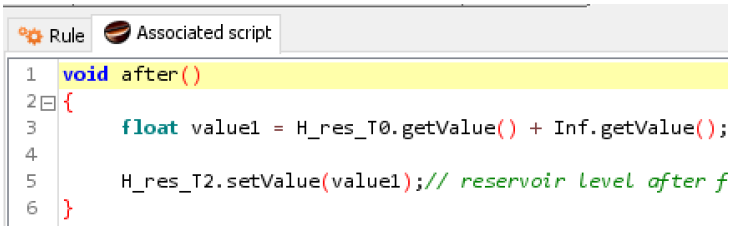


Figure A-7.168. Script to calculate the new reservoir level

Figure A-7.167 shows a rule graph calculating the new level of the reservoir. The rule graph can be interpreted in sentences as **if** the *First_filling* with its quantity applies *Inflow* on *Reservoir*, **then** *Reservoir* has a new *Reservoir_level*. *Reservoir_level* in the hypothesis graph is defined by the variable *H_res_T0*. *Reservoir_level* in the conclusion graph is identified by the variable *H_res_T2*. The time point of the new level is the time point of the inflow. Figure A-7.168 shows the associated script.

The resulting graph of the new reservoir level:

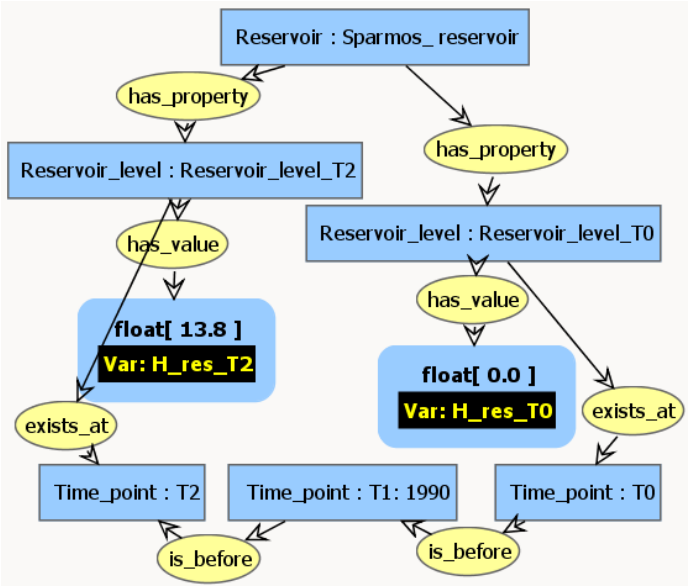


Figure A-7.169. New reservoir level

The resulting graph (Figure A-7.169) shows a new level of the reservoir. It increases from the value of 0 m at the time T0 to the valule of 13.8 m at the time T2.

When the reservoir changes its levels, performance to retaining water of the reservoir will be considered. The performance parameter is freeboard, which is the distance from the water level to the top of the dam.

Freeboard = Height of dam – Reservoir level

If Freeboard < 0: the reservoir overflow

Freeboard > 0: no overflow takes place.

Rule to calculate the measured level of freeboard as follow:

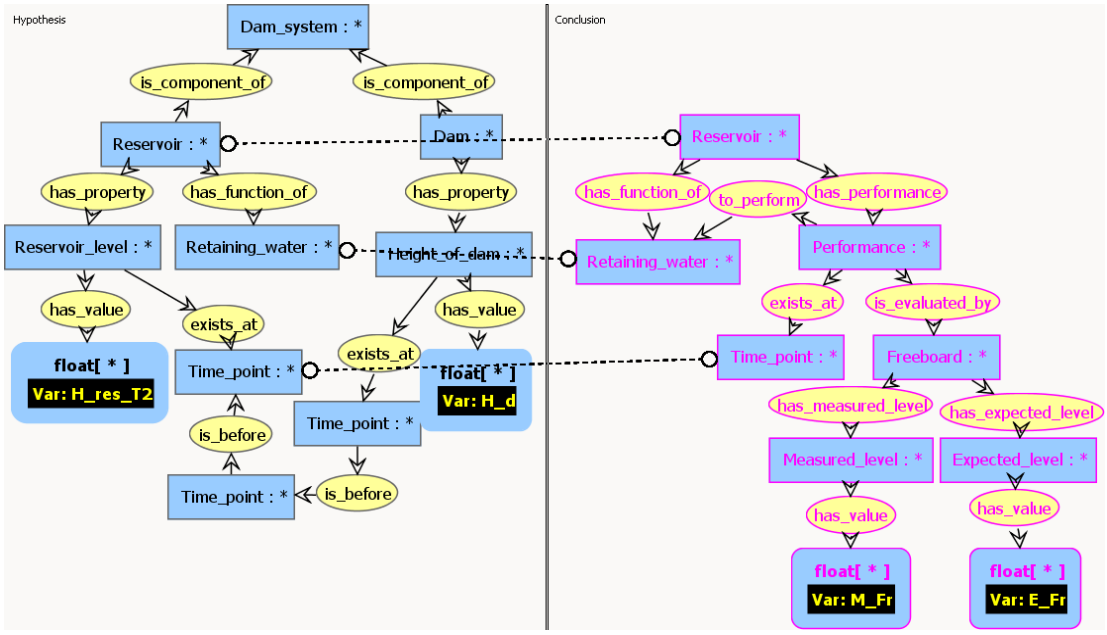


Figure A-7.170. Rule calculating measured level of freeboard at T2

Rule | Associated script

```
1  void after()
2  {
3      float value1 = H_d.getValue() - H_res_T2.getValue();
4      M_Fr.setValue(value1);
5  }
```

Figure A-7.171. Script calculating measured level of freeboard at T2

Figure A-7.170 illustrates a rule graph calculating the measured level of freeboard. The rule graph says that **if** *Reservoir* and *Dam* are components of *Dam_system*, *Reservoir* has *Reservoir_level* and a function of *Retaining_water*, **then** a new *Performance* will be created. The performance is evaluated by *Freeboard*, which has *Measured level* and *Expected level*. The time point of the new performance is the time point of the new reservoir level. Figure A-7.171 shows the associated script.

Performance of the reservoir at time point T2

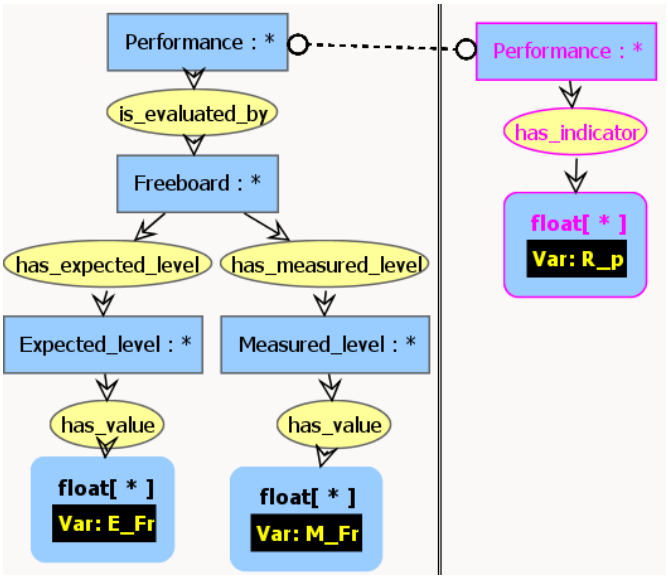


Figure A-7.172. Rule identifying performance indicator of reservoir at T2

Rule | Associated script

```
1  void after()
2  {
3      if (M_Fr.getValue() < E_Fr.getValue()) {
4          R_p.setValue(0);
5      }
6      else {
7          R_p.setValue(1);
8      }
9  }
```

Figure A-7.173. Script calculating performance indicator of reservoir at T2

Figure A-7.172 shows a rule graph calculating performance of the reservoir. The graph can be expressed as **if** *Performance* is evaluated by *Freeboard*, and *Freeboard* has *Measured level* and *Expected level*, **then** *Performance* has an indicator. Figure A-7.173 shows the associated script.

The resulting graph of the reservoir performance:

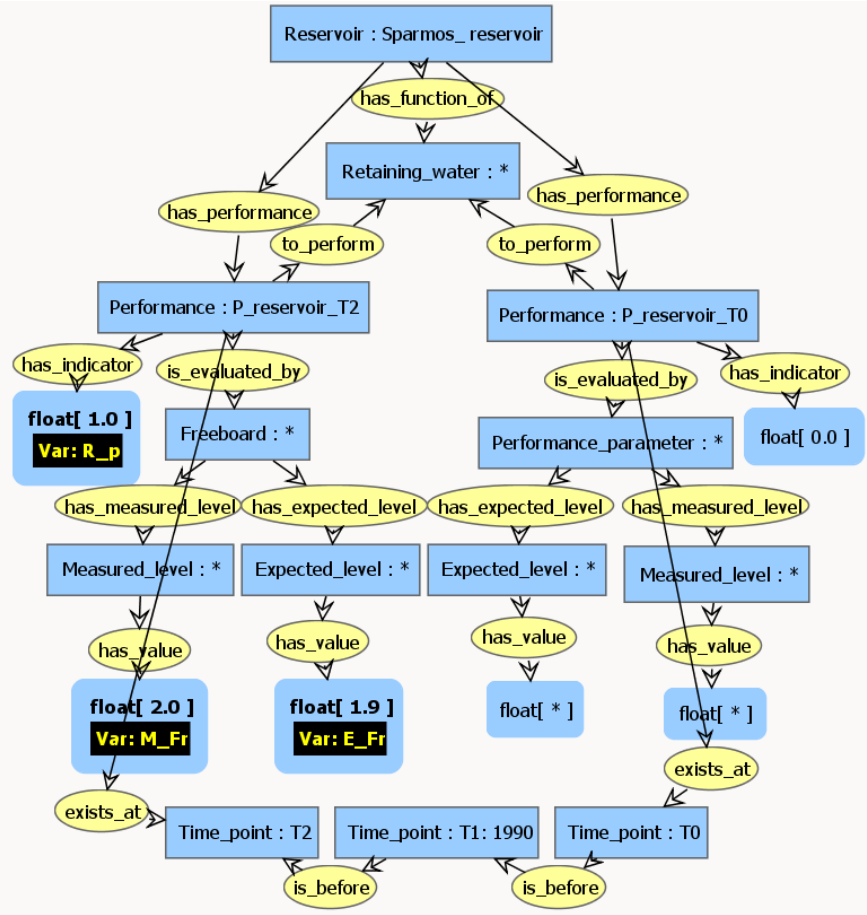


Figure A-7.174. Two performances of reservoir at two different time points

Figure A-7.174 shows the resulting graph of the reservoir performance. Two performances are presented at two different time points: T0 and T2. At the time point T0, the reservoir's performance is assumed as satisfied, i.e., the indicator has a value of *1*. At the time point T2, the performance indicator has a value of *0*; this means that the reservoir overflow.

7.4.3.4. Interactions and performance of the embankment dam at T3

Seepage flow through the embankment dam

Due to the increase of the reservoir level, water seeps through the embankment dam. The relevant equation for estimating the amount of seepage is:

$$q = KS$$

where,

q: seepage discharge per unit width of the dam

K: coefficient of permeability

S: focal distance, is the distance of the point (x,y) from the directrix (Figure A-7.175)

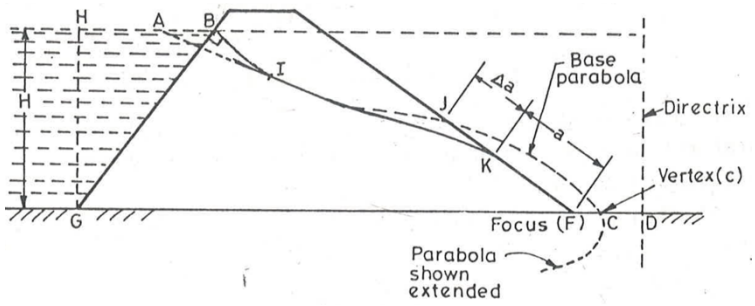


Figure A-7.175. Phreatic line (Garg, 2005)

$$S = \sqrt{x^2 + y^2} - x$$

where x,y : are the co-ordinates of any point on the parabola

Rule to estimate the amount of seepage:

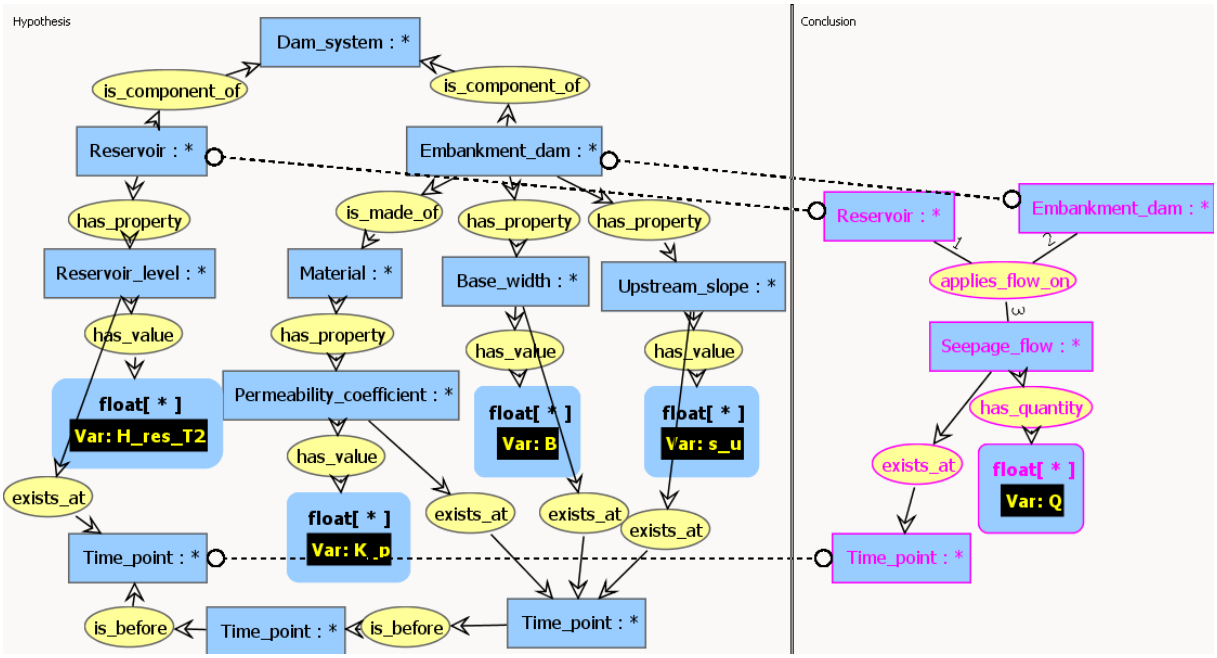


Figure A-7.176. Rule to estimate the amount of seepage

Rule | Associated script

```
1  void after()
2  {
3      float value1 = H_res_T2.getValue() * s_u.getValue(); // value1 = L
4      float value2 = B.getValue() - (0.7*value1); // value2 = x_C
5      float value3 = (Math.sqrt(Math.pow(value2,2) + Math.pow(H_res_T2.getValue(),2))) - value2;
6      float value4 = K_p.getValue() * value3;// q = m3/s
7
8      Q.setValue(value4);//
9
10     }
```

Figure A-7.177. Script to estimate the seepage flow through embankment dam

Figure A-7.176 shows a rule graph to estimate the seepage flow through the embankment dam. The rule says that **if** *Reservoir* and *Embankment dam* are components of *Dam_system*, *Reservoir* is described with *Reservoir level*, *Embankment dam* is described with *Permeability coefficient* of material, *Base width,* and *Upstream slope*, **then** *Reservoir* applies

Seepage flow on *Embankment dam*. The time point of the seepage flow is the time of *Reservoir level*. Figure A-7.177 shows the associated script.

Contact erosion

Contact erosion occurs when particles of the finer layer may be destablized by the water flow and transported through the pores of the coarser layer parallel to the interface. This phenomenon requires the flow velocity is sufficient to detach particles and to transport them. To assess the likelihood of initiation and progression of soil contact erosion, the critical velocity can be compared to the estimated Darcy velocity for the head water level under consideration. The factor of safety against contact erosion can be estimated as (USBR, 2018):

$$FS = \frac{V_c}{k_h i}$$

where,

k_h = hydraulic conductivity (horizontal) of the coarse layer; and

i = seepage gradient for the reservoir level under consideration.

V_c: critical velocity

Brauns (1985) proposed an expression for critical velocity which provides a good approximation for sand below gravel:

$$V_c = 0.65 n_F \sqrt{(G_s - 1) g d_{50}}$$

where,

n_F = porosity of the coarse soil (gravel)

G_s = specific gravity of the sand particles

g = acceleration of gravity (9.81 m/s^2); and

d50 = mean grain size of the base soil (sand)

Exceeding the limit-state condition provides an indication of the likelihood for soil contact erosion to initiate and progress.

Rule to estimate the critical velocity of the seepage flow:

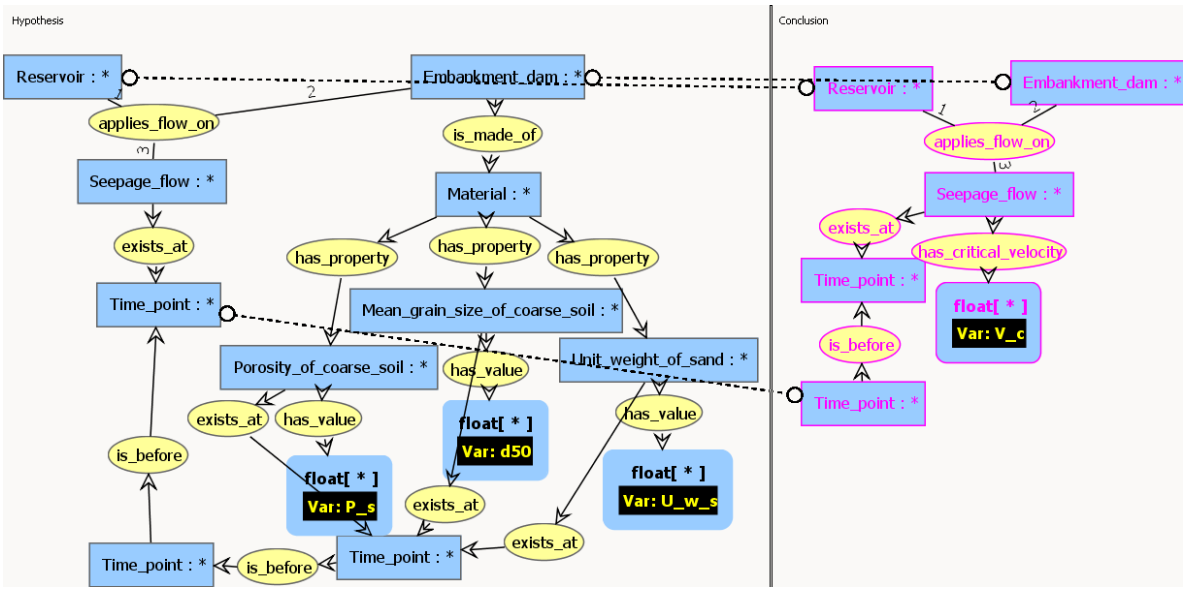


Figure A-7.178. Rule to estimate the critical velocity

Rule | Associated script

```
1
2  void after()
3  {
4      float value1 = 0.65 * P_s.getValue() * Math.pow((U_w_s.getValue() - 1) * 9.81 * d50.getValue(),2);
5
6      V_c.setValue(value1);
7  }
```

Figure A-7.179. Script to estimate the critical velocity

Figure A-7.178 shows a rule graph computing the critical velocity of the seepage flow. The rule says that **if** *Reservoir* applies *Seepage_flow* on *Embankment_dam*, and *Embankment dam* is made of *Material* with properties as *Porosity of coarse soil*, *Mean grain size of coarse soil*, *Unit_weight of sand*, **then** *Reservoir* applies *Seepage_flow* with a critical velocity on *Embankment dam*. The time point of *Seepage flow* with critical velocity is after the previous seepage flow. Figure A-7.179 shows the associated script.

Performance of the embankment dam to resist contact erosion at T3

The consideration the performance of Sparmos dam at T3 includes two steps:

- Computing the measured level of factor of safety against contact erosion

- Estimating the performance indicator at T3

Rule to compute the measured level of the safety against contact erosion:

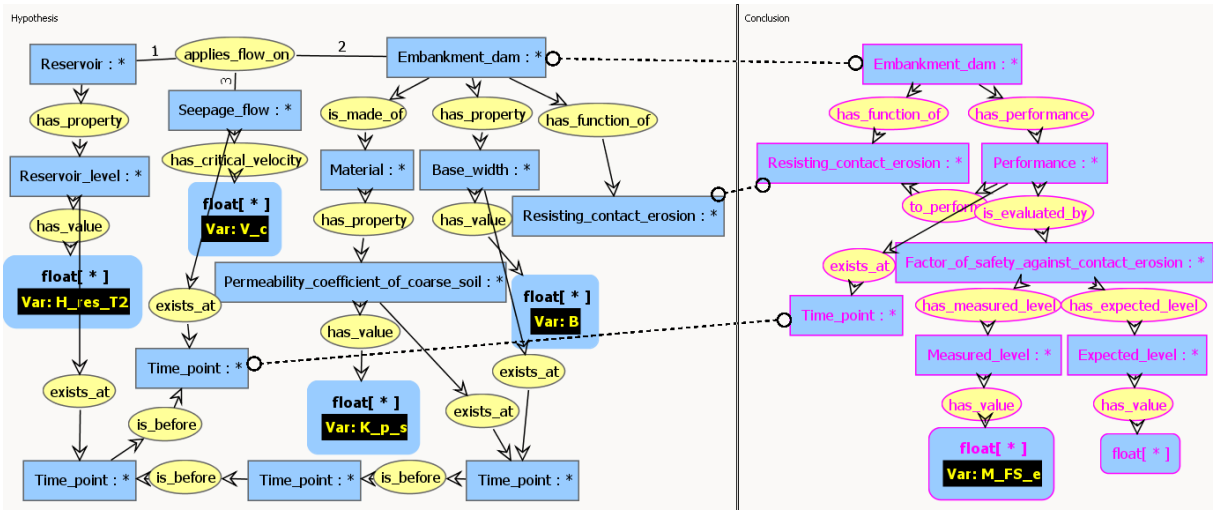


Figure A-7.180. Estimating the measured level of factor of safety against contact erosion

Rule | Associated script

```
1
2  void after()
3  {
4      float value1 = K_p_s.getValue() * H_res_T2.getValue() / B.getValue();
5      float value2 = V_c.getValue() / value1;
6
7      M_FS_e.setValue(value2);
8  }
```

Figure A-7.181. Scritp to estimate the measured level of factor of safety against contact erosion

Figure A-7.180 shows a rule graph calculating the measured level of the factor of safety against contact erosion. The rule graph says that **if** *Reservoir* applies *Seepage_flow* on *Embankment dam*, *Reservoir* is described with *Reservoir level* at *T2, Seepage_flow* has a critical velocity, *Embankment_dam* is made of *Material*, which has the property of *Permeability coefficient of coarse soil*, *Embankment_dam* has *Base_width*, **then** *Embankment_dam* has a *Performance* which is evaluated by *Factor of safety against contact erosion*. The new performance is at T3. Figure A-7.181 exposes the associated script.

To identify the performance indicator of the Sparmos dam, the value of the measured level of the factor of safety against contact erosion will be compared with the expected level of this factor. The value of the expected level is set as 1.

Rule to identify the new performance of the Sparmos dam at T3 as follow:

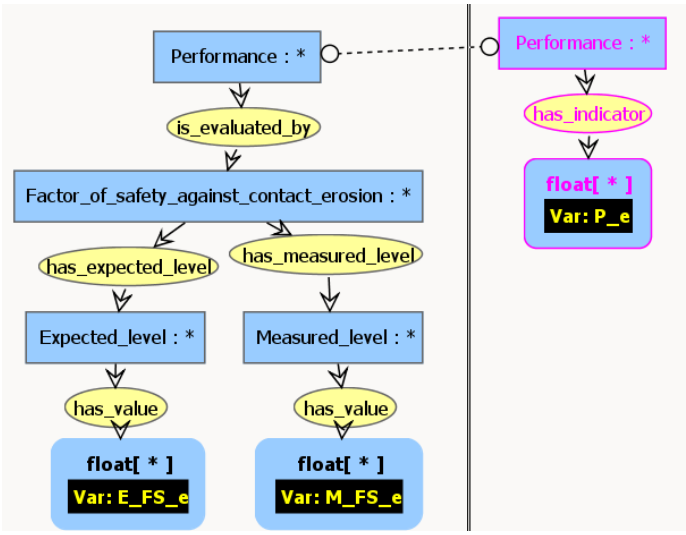


Figure A-7.182. Rule to identify the performance indicator to resist contact erosion

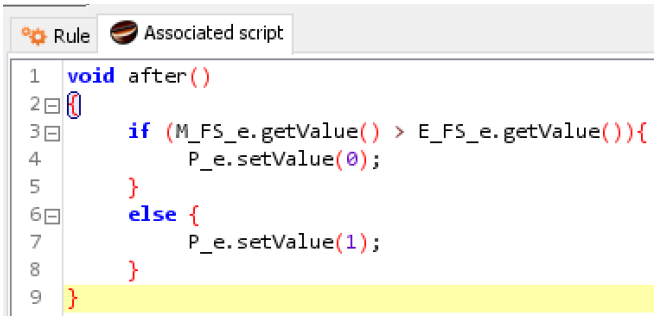


Figure A-7.183. Script to identify the performance indicator to resist contact erosion

Figure A-7.182 shows a rule graph identifying the performance indicator of the embankment dam to resist contact erosion. The rule says that **if** *Performance* is evaluated by *Factor of safety against contact erosion*, **then** *Performance* has a new indicator. The factor of safety has *Expected level* and *Measured level.* Figure A-7.183 shows the associated script.

The resulting graph of the resisting contact erosion performance:

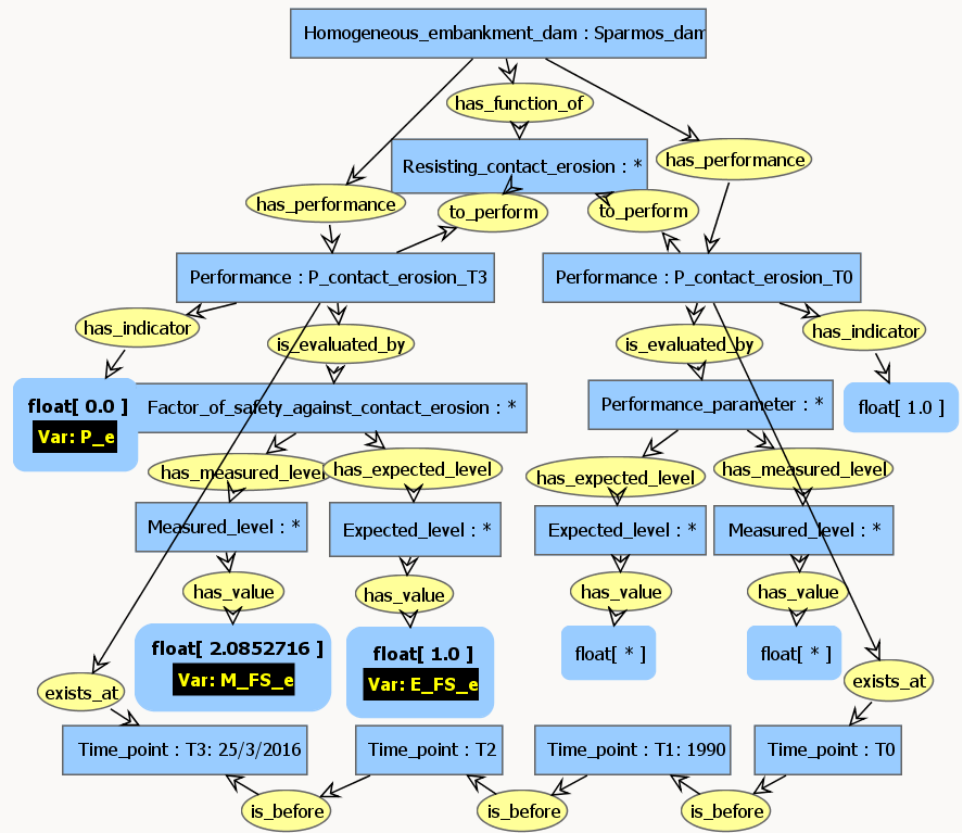


Figure A-7.184. The performances of Sparmo dam at two different time points

The resulting graph (Figure A-7.184) shows a change in the contact erosion performance of the Sparmos dam in two different time points, T0, and T3. At T0, the performance is described by an individual concept *Performance: P_contact_erosion_T0*. It is assumed as satisfied, i.e., the value of the performance indicator is *1*. At T3, *Performance: P_contact_erosion_T3* has an indicator with the value of *0,* i.e., the dam fails to resist the contact erosion. It should be noted that the duration from T0 to T3, i.e., from 1990 to 25/3/2016, is 27 years.

7.4.3.5. Interactions and performance of the embankment dam at T4

Sparmos dam is constructed mainly of earthfill and has poor internal erosion and seepage control. Therefore, contact erosion in the embakment progresses to a pipe rapidly.

The likelihood to form a pipe through the embankment depends on whether:

- The soil will “hold a roof” over a pipe
- Flow in the developing pipe will not be restricted by an upstream zone (for example a concrete face slab) or by hydraulic losses in upstream and downstream zones.

The cohesion of the embankment material allowed the development of the pipe since it could maintain a “roof’’ (Dounias and Bardanis, 2019). The most important factors that determine whether a roof can be formed and maintained are (ICOLD, 2017):

- The fines content of the soil (% passing 0.075 mm) ≥ 15% fines likely to be able to hold a roof regardless of whether the fines were non plastic or plastic.

- Whether the soil was partially saturated or saturated.

Factor of safety against piping (F.S.P) = Fine contents – 15%

F.S.P > 0: piping

F.S.P < 0: no piping take place

Rule to consider the measured level of factor of safety against piping:

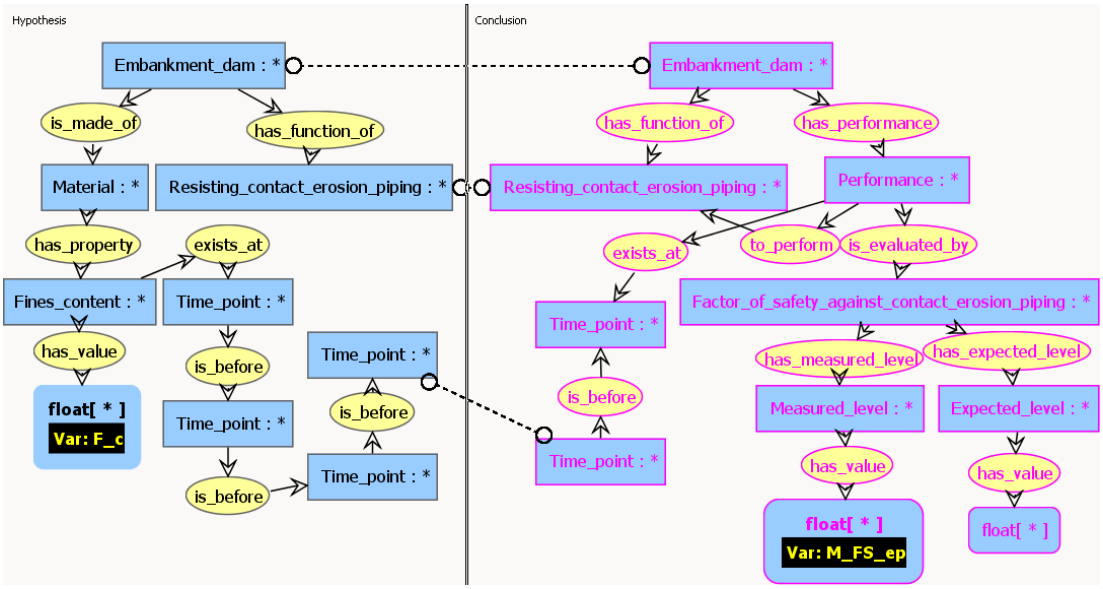


Figure A-7.185. Rule to compute measured level of factor of safety against piping

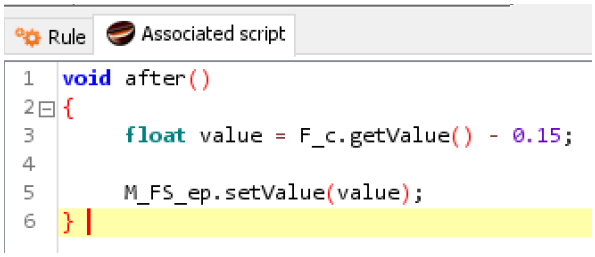


Figure A-7.186. Script to compute measured level of factor of safety against piping

Figure A-7.185 shows a rule computing the measured level of the factor of safety against contact erosion piping of the embankment dam. The rule says that **if** *Embankment_dam* is made of *Material* with *Fines_content*, which is presented by the variable *F_c*, **then** *Embankment_dam* has a new *Performance* evaluated by *Factor of safety against contact erosion piping*. The *F.S.P* has *Measured_level* and *Expected_level*. There is a coref relation connecting two concepts *Resisting_contact_erosion_piping* in the rule. The time point of the piping performance is after the time point of the contact erosion performance. Figure A-7.186 shows the associated script.

After calculating the F.S.P's measured level, the performance indicator is indicated by comparing the measured and expected values. The value of the expected level is 0.

The rule to identify the performance indicator as follow:

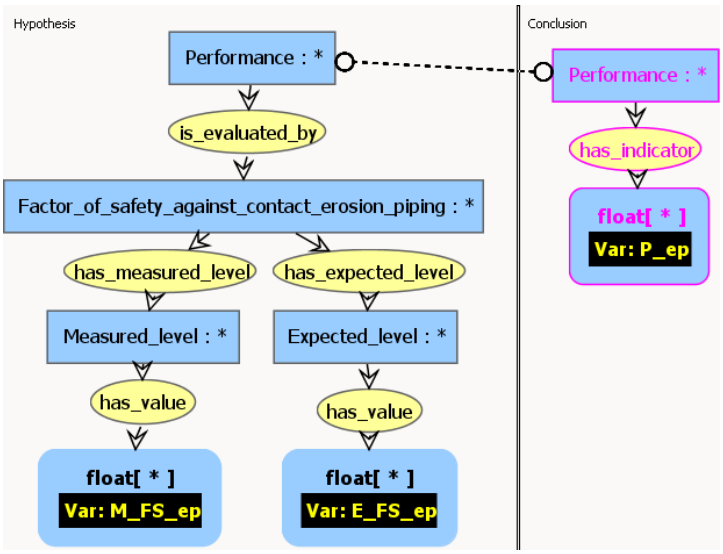


Figure A-7.187. Rule to estimate performance indicator

Rule | Associated script

```
1  void after()
2  {
3      if (M_FS_ep.getValue() > E_FS_ep.getValue()){
4          P_ep.setValue(0);
5      }
6      else {
7          P_ep.setValue(1);
8      }
9  }
```

Figure A-7.188. Script to estimate performance indicator

The rule graph (Figure A-7.187) shows the estimation of the performance indicator to resist piping. The rule says that **if** *Performance* is evaluated by *Factor of safety against contact erosion piping* that has *Measured level* and *Expected level*, **then** *Performance* has a new indicator. The measured level and expected level are determined by two variables *M_FS_ep* and *E_FS_ep*, respectively. Figure A-7.188 shows the associated script.

The resulting graph is:

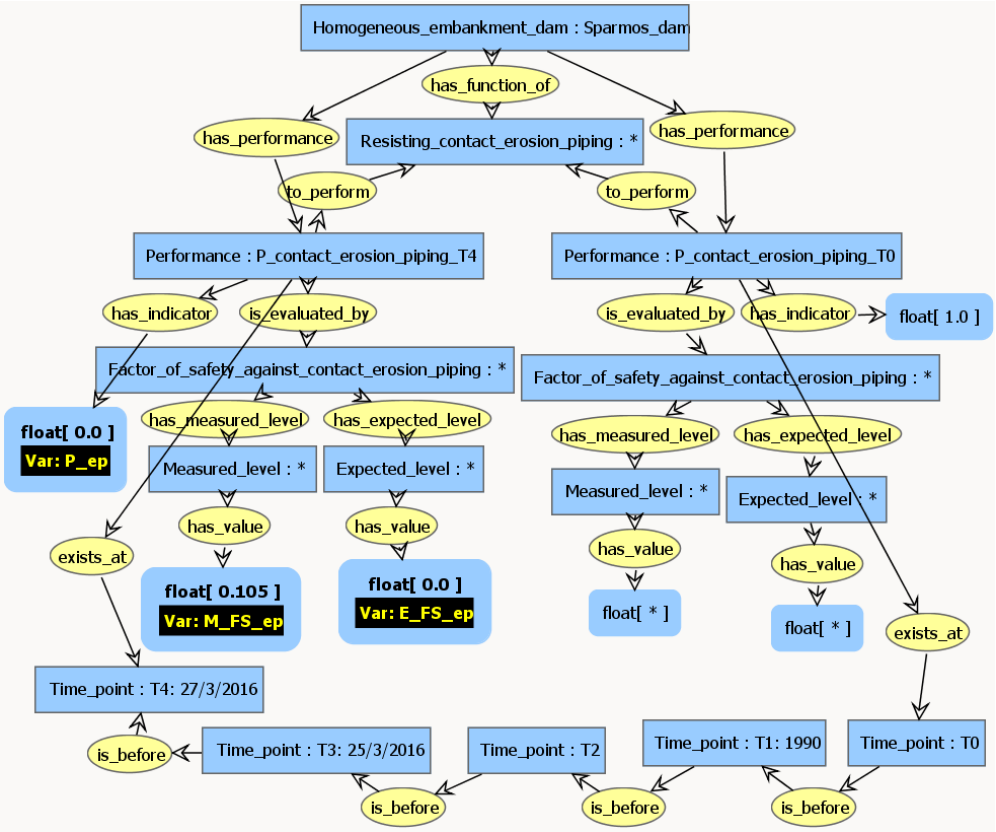


Figure A-7.189. Performances of embankment to resist piping

Figure A-7.189 shows a change in the piping performance of the embankment dam over time. Two performances perform the function of *Resisting_contact_erosion_piping* at two different time points. The initial time is at T0; the performance is assumed as satisfied; the indicator's value is 1. The second time is at T4: 27/3/2016; the performance is not satisfied; the indicator's value is 0.

7.4.3.6. Interactions and performance of the embankment dam at T5

Breach of dam occurs when the hydraulic shear stress in the pipe over the erosion resistance of the soil. To estimate the hydraulic shear stresses in cylinders, the following equation can be used to estimate the hydraulic shear stress on the surface of a cylindrical pipe. The assumptions are (ICOLD, 2017):

- Linear head loss from upstream to downstream

- Zero pressure head at the downstream eand

- Driving force = frictional resistance.

$$\tau = \rho_w \frac{gH_f d}{4L}$$

where,

τ: Hydraulic shear stress in N/m^2

ρ_w: Density of water in kg/m^3

g: Acceleration due to gravity = 9.8 m/s^2

H_f: Head loss in pipe in meters

d: Diameter of the pipe in meters

L: Length of pipe in meters

Rule to calculate the hydraulic shear stress on the surface of the pipe:

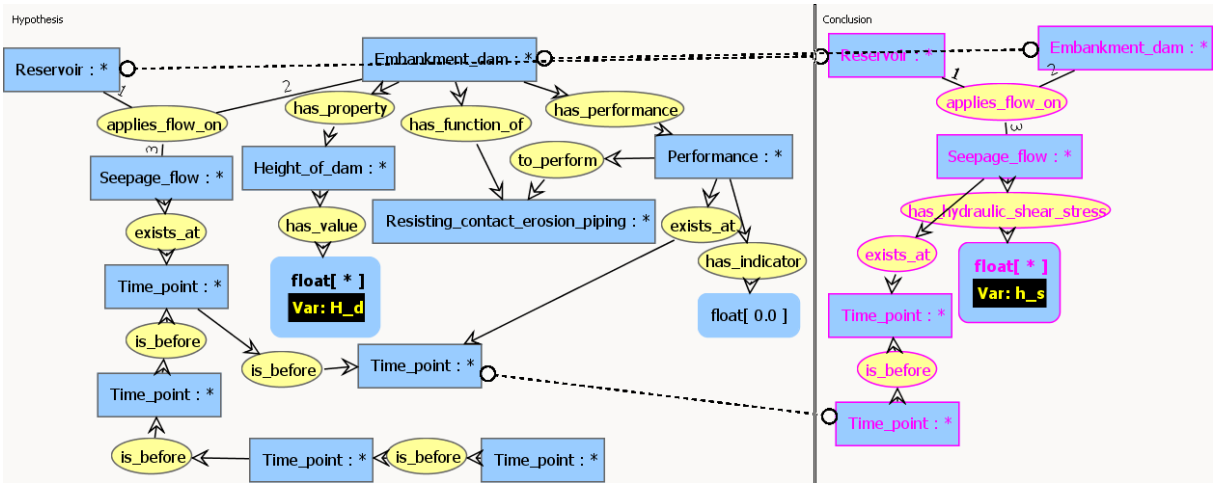


Figure A-7.190. Rule calculating hydraulic shear stress

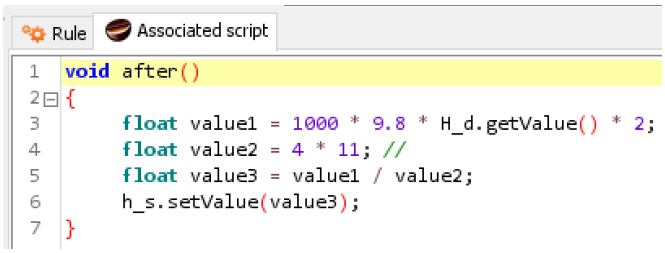


Figure A-7.191. Script calculating hydraulic shear stress

Figure A-7.190 shows a rule graph calculating the hydraulic shear stress in the pipe. The rule says that **if** *Reservoir* applies *Seepage_flow* on *Embankment dam*, **then** *Reservoir* applies *Seepage_flow* with hydraulic shear stress on *Embankment_dam*. The conditions of embankment dam are *Embankment_dam* has *Height of dam* determined by the variable *H_d*, and *Performance* to resist contact erosion piping has the value of performance indicator is *0*, means that piping developed within the dam. The seepage flow has hydraulic shear stress, which is identified by the variable *h_s*. Figure A-7.191 shows the associated script.

Performance of the embankment to resist breaching is evaluated by Factor of safety against breaching:

Factor of safety against breaching (F.S.B) = $\frac{Hydraulic\ shear\ stress}{Erosion\ strength}$

If F.S.B > 1 : dam breaks

F.S.B < 1 : no breach occurs

Rule calculating the measured level of the F.S.B as follow:

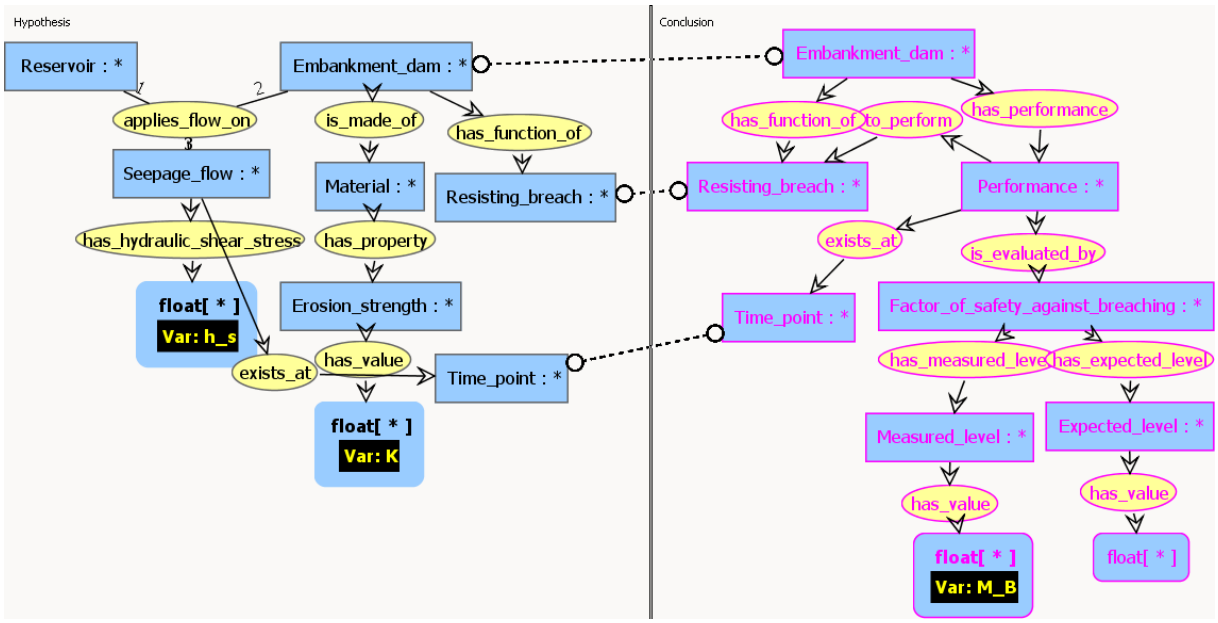


Figure A-7.192. Rule to estimate the measured level of F.S.B

Rule | Associated script

```
1  void after()
2  {
3      float value1 = h_s.getValue() / K.getValue();
4      M_B.setValue(value1);
5  }
```

Figure A-7.193. Script estimating the measured level of F.S.B

Figure A-7.192 shows a rule calculating the measured level of the factor of safety against breaching of the embankment dam. The rule says that **if** *Reservoir* applies *Seepage flow* with hydraulic shear stress determined by the variable *h_s*, and *Embankment_dam* is made of *Material* with *Erosion_strength* identified by the variable *K*, then *Embankment_dam* has a new *Performance* which is evaluated by *Factor of safety against breaching*. The F.S.B is evaluated by *Measured level* and *Expected level*. The time point of the performance is the time point of the seepage flow with hydraulic shear stress. There is a coref relation between two concepts *Resisting_breach* in the rule. Figure A-7.193 shows the associated script.

New performance of Sparmos dam to resist breaching:

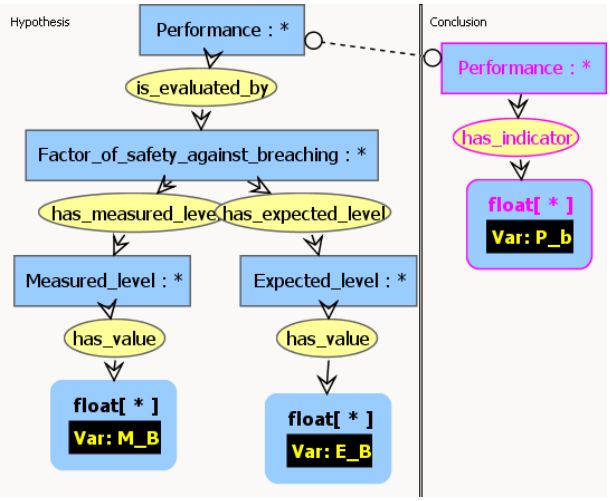


Figure A-7.194. Rule to estimate performance indicator

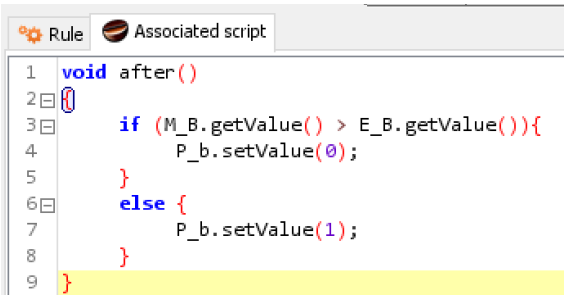


Figure A-7.195. Script to estimate performance indicator

Figure A-7.194 shows a rule estimating the performance indicator to resist breach of embankment dam. The rule says that **if** *Performance* is evaluated by *Factor of safety against breaching*, then *Performance* has a new indicator determined by the variable *P_b*. Figure A-7.195 shows the associated script.

Resulting graph of new performance is:

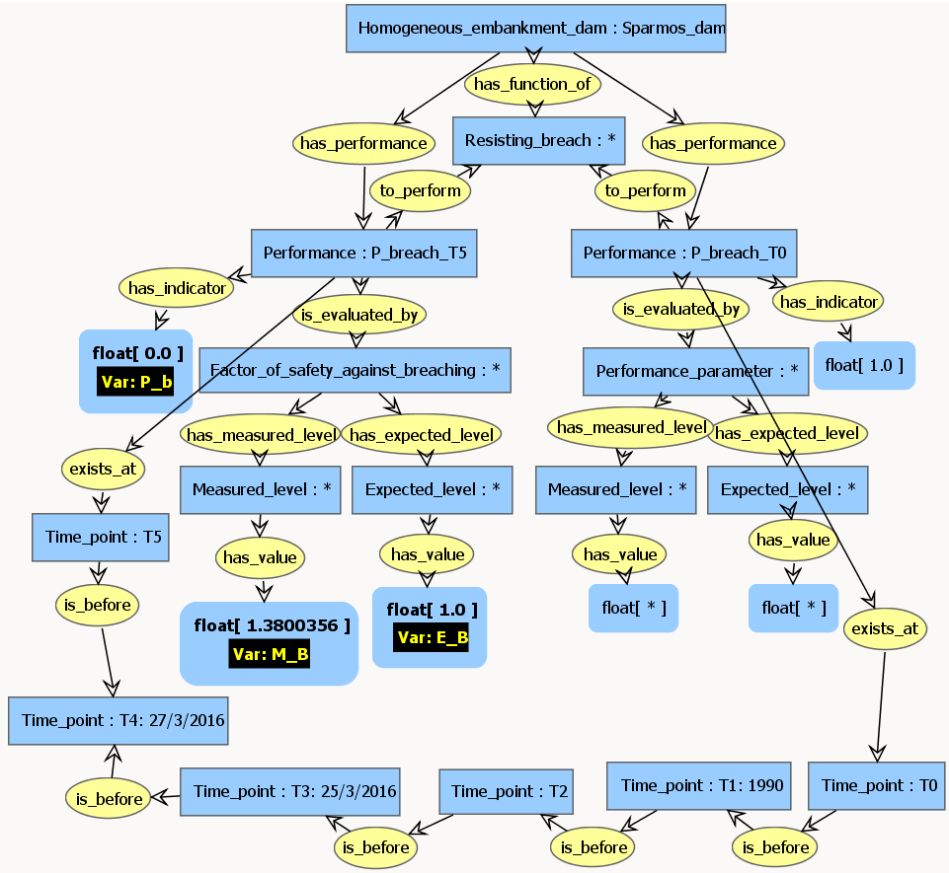


Figure A-7.196. The new and old performances of Sparmos dam

Figure A-7.197 shows a change in the performances of Sparmos dam over time. At the initial time, T0, the performance to resist breaching has a value of the indicator is 1, i.e., satisfied. After 27 years, the value of the performance indicator is 0, i.e., not satsified. The dam breaks at the time point T5.

7.4.3.7. Interactions and new performance of the reservoir at T5

Once the Sparmos dam breaks, the reservoir releases an outflow through the breach. The peak outflow can be estimated by the following equation (Hood *et al.*, 2019):

$$Q_p = 13.4 * H_d^{1.89}$$

where H_d: height of dam

Rule to estimate the outflow:

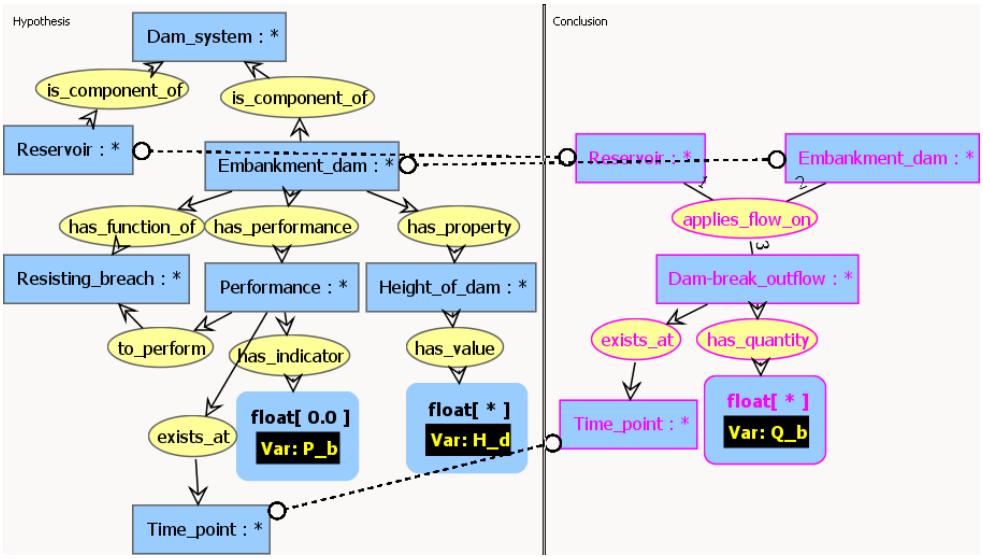


Figure A-7.197. Rule to calculate the dam-break outflow

Rule | Associated script

```
1  void after()
2  {
3       float value =  13.4 * Math.pow(H_d.getValue(),1.89);
4
5       Q_b.setValue(value);
6  }
```

Figure A-7.198. Script to calculate the peak outflow

Figure A-7.197 shows a rule calculating the outflow from reservoir. The rule says that **if** *Reservoir* and *Embankment_dam* are components of *Dam_system*, **then** *Reservoir* applies *Dam-break outflow* on *Embankment_dam*. The dam has *Height_of_dam*, and *Performance* to perform *Resisting_breach* has a value of *0,* i.e., the dam breaks. The time point of the outflow is the time point of the breach of the dam. Figure A-7.198 shows the associated script.

The outflow from the reservoir will induce a change in the retention capacity of the reservoir. The retention capacity is evaluated by the Dam-break outflow rentention parameter.

Dam-break outflow retention = Inflow – Outflow = Peak inflow – Peak outflow

For the case of a dam breach, inflow has a value of 0.

If Dam-break outflow retention > 0: satisfied

Dam-break outflow retention < 0: not satisfied

Rule to calculate the measured level of the dam-break outflow retention:

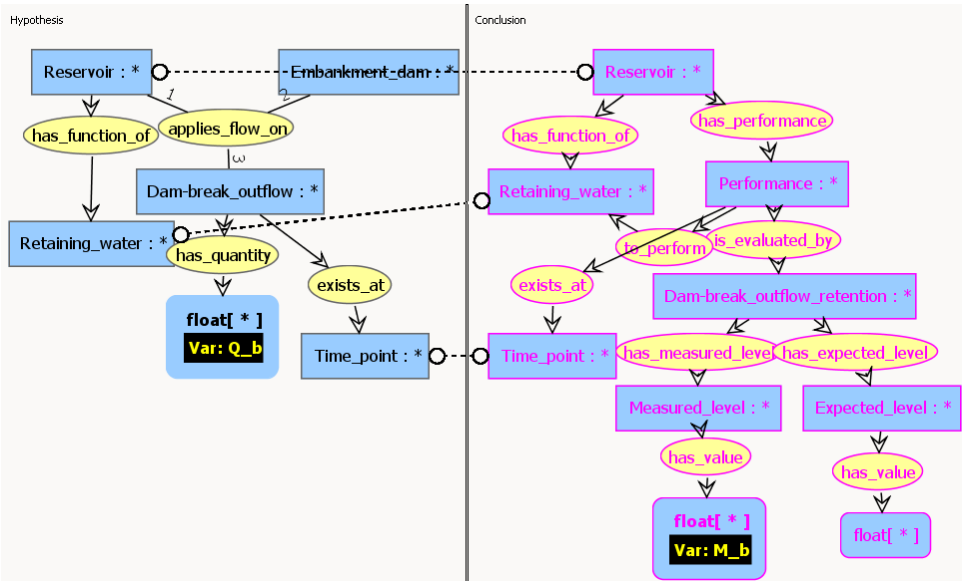


Figure A-7.199. Rule of measurred level of dam-break outflow retention

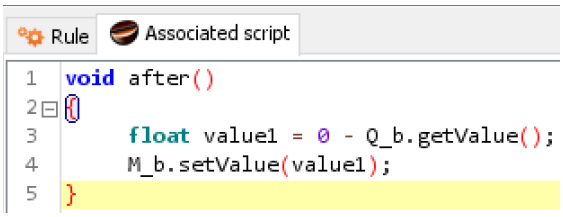


Figure A-7.200. Script of measured level of dam-break outflow retention

Figure A-7.199 shows a rule calculating the measured level of the dam-break outflow retention. The rule says that **if** *Reservoir* applies *Dam-break outflow* on *Embankment dam*, **then** *Reservoir* has a new *Performance* evaluated by *Dam-break outflow retention* which has *Measured level* and *Expected level*. A coref relation connects the concepts *Retaining_water* in the rule. The time point of the performance is the time point of the outflow. Figure A-7.200 shows the associated script.

New performance of the Sparmos reservoir at T5:

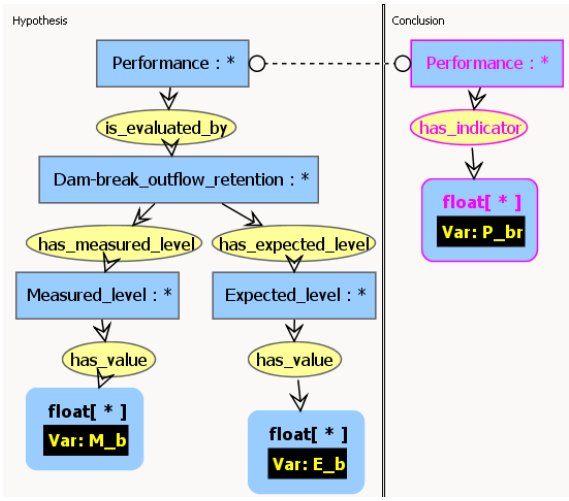


Figure A-7.201. Rule estimating the performance indicator

Rule | Associated script

```
1  void after()
2  {
3      if (M_b.getValue() < E_b.getValue()) {
4          P_br.setValue(0);
5      }
6      else {
7          P_br.setValue(1);
8      }
9  }
```

Figure A-7.202. Script estimating the performance indicator

Figure A-7.201 shows a rule estimating the performance indicator resist breach of the dam. The rule says that **if** *Performance* is evaluated by *Dam-break outflow retention*, that has *Measured level* and *Expected level* presented by the two variables *M_b* and *E_b* respectively, **then** *Performance* has a new indicator presented by the variable *P_br*. Figure A-7.202 shows the associated script.

The resulting graph of the reservoir performance is described as follow:

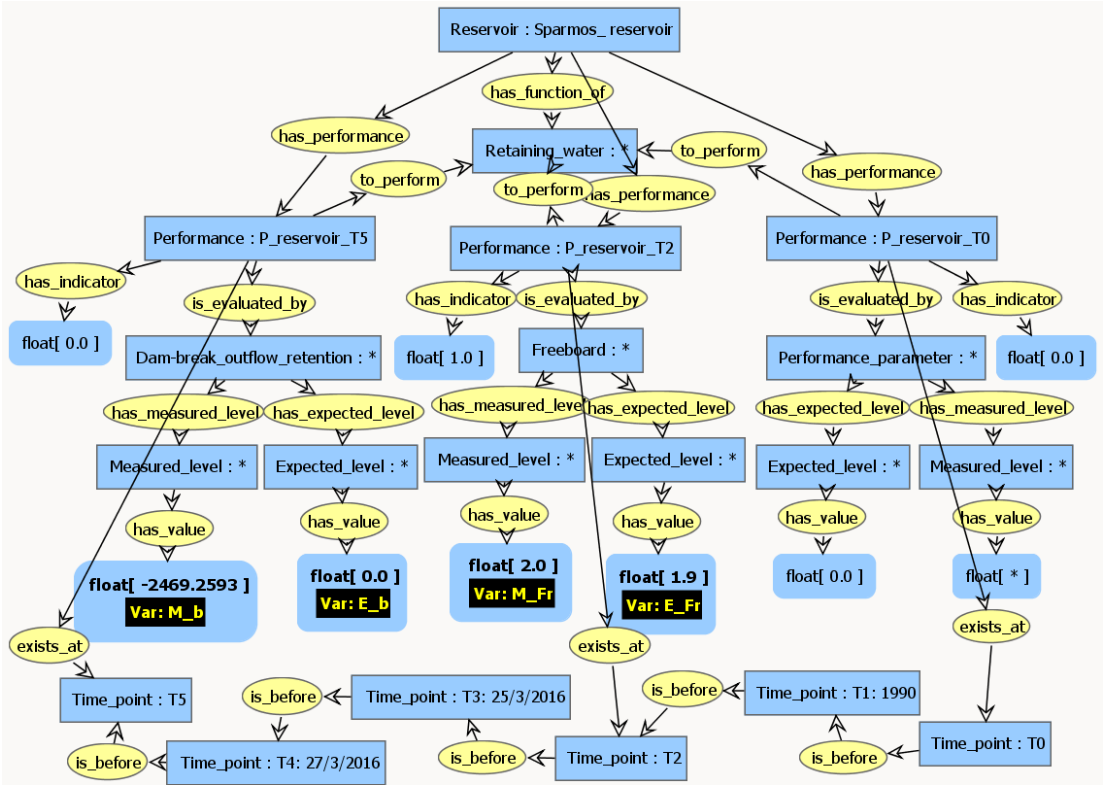


Figure A-7.203. Performances of the Sparmos reservoir over time

Figure A-7.203 shows the new performance of Sparmos reservoir at the time point T5. The measured level value of dam-break outflow retention (i.e., -2469) is smaller than the expected level value (i.e., 0). It results in a performance indicator value of 0. This means that the reservoir fails.

The graph also shows the changes in the performance of the reservoir over time. At T0, the performance is assumed as not satisfied, i.e., the indicator has a value of 0. At the time

T2, reservoir level increases, the performance indicator has a value of 1, i.e., satisfied. At the time T5, the performance indicator returns to 0.

7.4.3.8. Performance of the dam system at T5

The performance of a dam system is contributed by the performance of all components. In the Sparmos dam system, the reservoir's failure is the lastest failure; thus, system performance is considered based on reservoir performance.

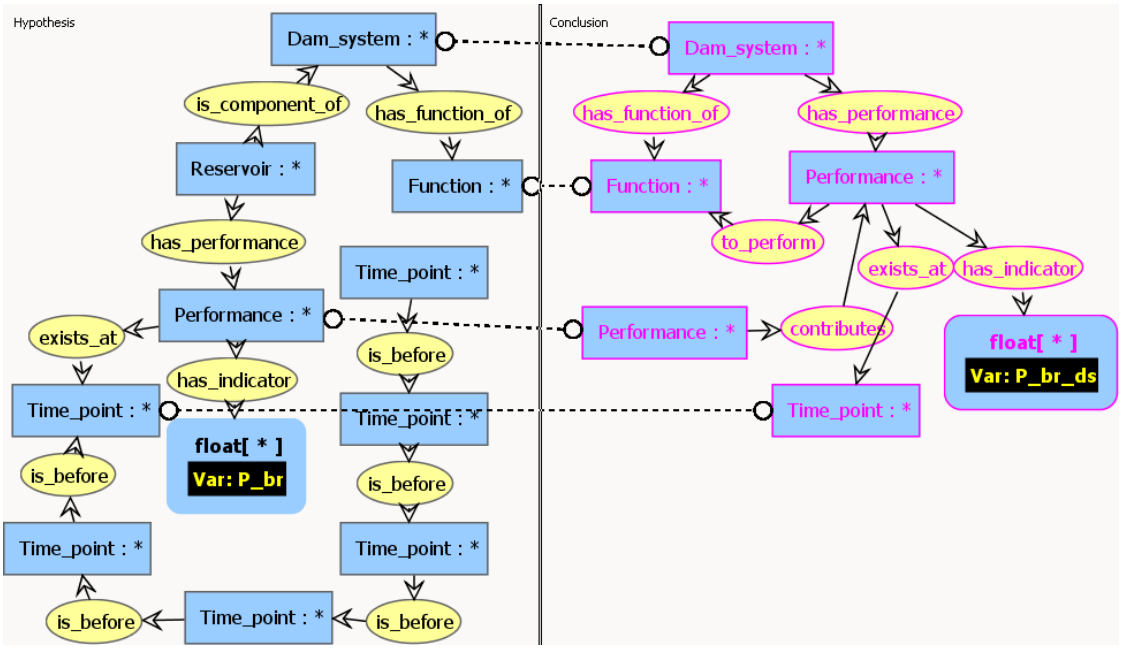


Figure A-7.204. Rule estimating performance of dam system

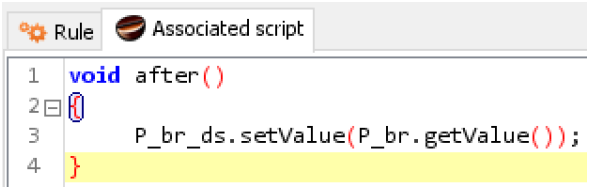


Figure A-7.205. Script estimating performance of dam system

Figure A-7.204 shows a rule graph estimating the performance of the dam system. The rule graph says that **if** *Reservoir* is a component of *Dam_system*, and *Reservoir* has *Performance* presented by the variable *P_br*, **then** *Dam_system* has a new *Performance* contributed by the performance of *Reservoir*. The new performance indicator is presented by the variable *P_br_ds*. The coref relation connects two concepts *Function* in the rule. The time point of the system's performance is set at the time point of the reservoir's performance. Figure A-7.205 shows the associated script.

The resulting graph is:

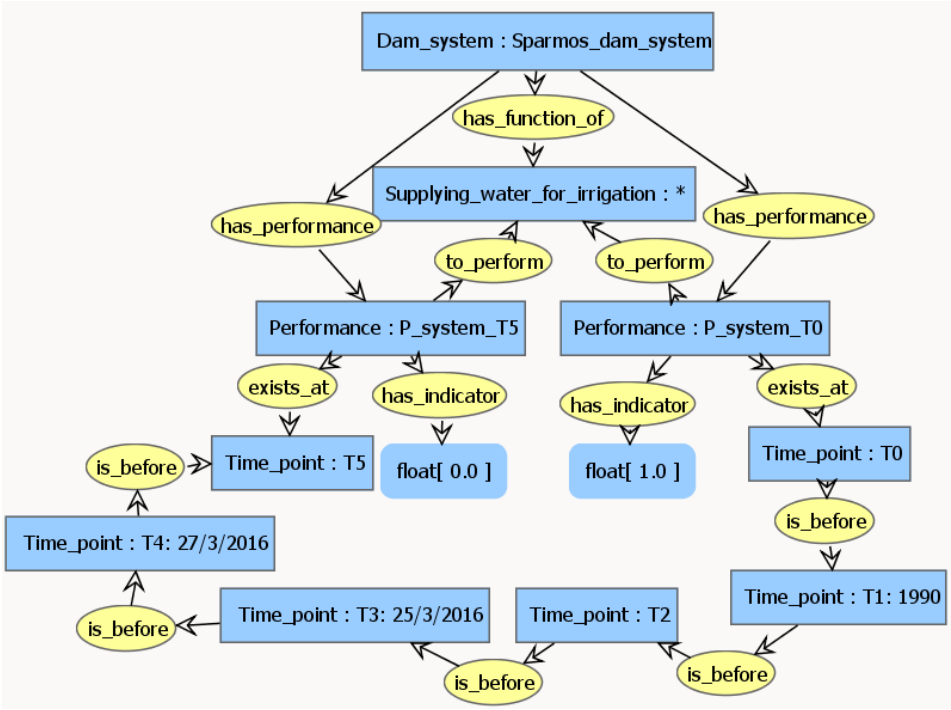


Figure A-7.206. The performances of the Sparmos dam system

Figure A-7.206 shows a change in the performance of the Sparmos dam system over time. At the initial time, T0, the performance is assumed as satisfied, i.e., the indicator has a value of 1. At T5, the performance indicator has a value of 0, i.e., the system fails.

7.4.4. Failure process

Failure process of the Sparmos dam system is described in six snapshots with six time points, from the time point T0 to the time point T5.

- Snapshot at the time point T0 as follow:

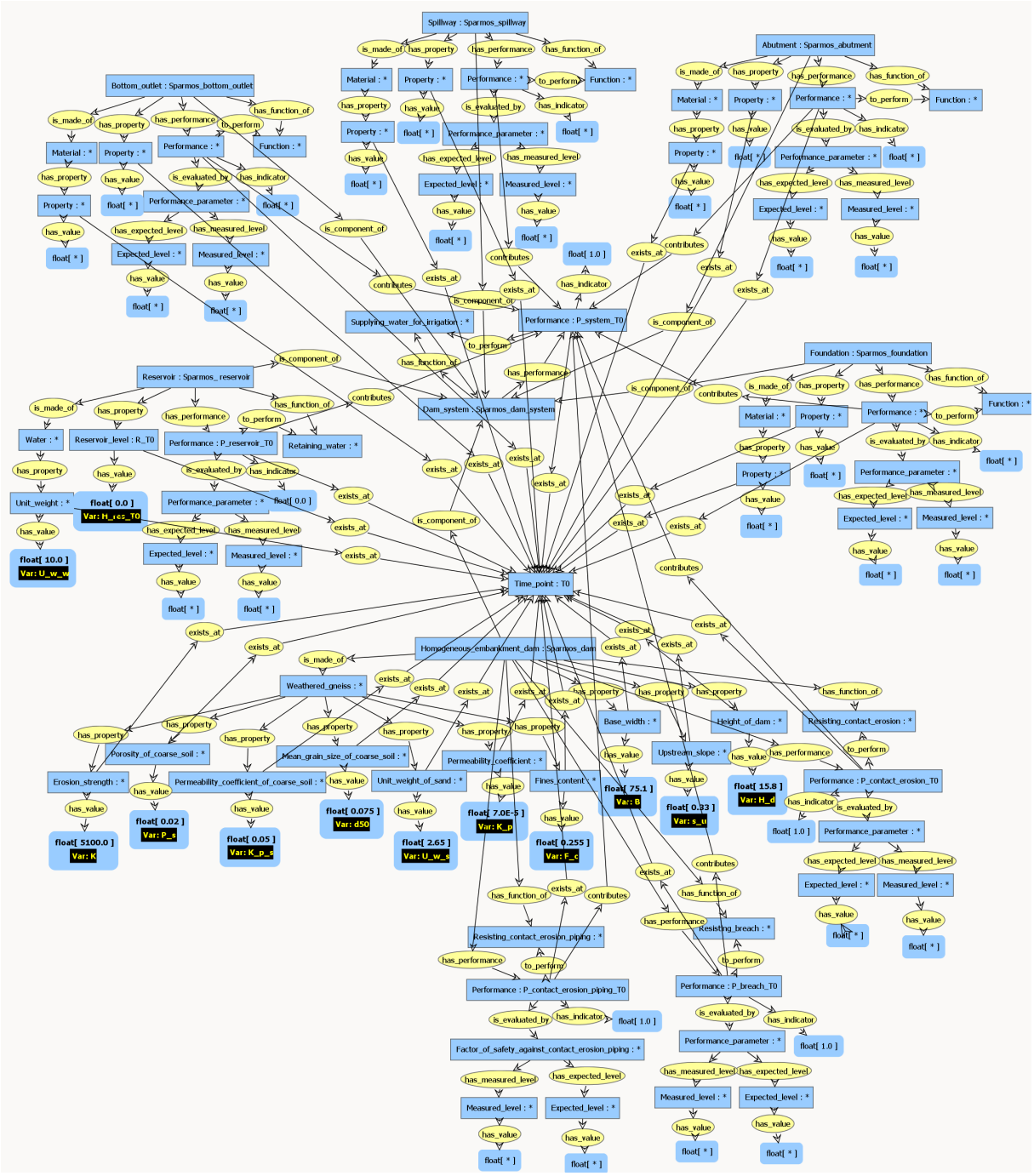


Figure A-7.207. Snapshot of the Sparmos dam system failure at T0

Figure A-7.207 shows the snapshot at T0, the time before the first filling activity, of the Sparmos dam system failure. This snapshot describes the state of the system at the time point T0. At T0, the system's structure includes reservoir, homogeneous embankment dam, foundation, spillway, bottom outlet, and abutment. The concepts that can change their values over time are connected with the concept *Time_point: T0* to identify their values and states at T0. At T0, the system just finishes construction, the water level is 0 m. The retaining water performance of the reservoir is assumed as not satisfied, i.e., the indicator has a value of 0. The functions of the dam are to resist contact erosion, to resist contact erosion piping, and to resist breach. At T0, the dam's performances to perform these function are assumed as

satisfied, i.e., the performance indicators have values of 1. The function of the system is supplying wter for irrigation. The system performance is assumed as satisfied at T0.

- Snapshot at the time point T1 as follow:

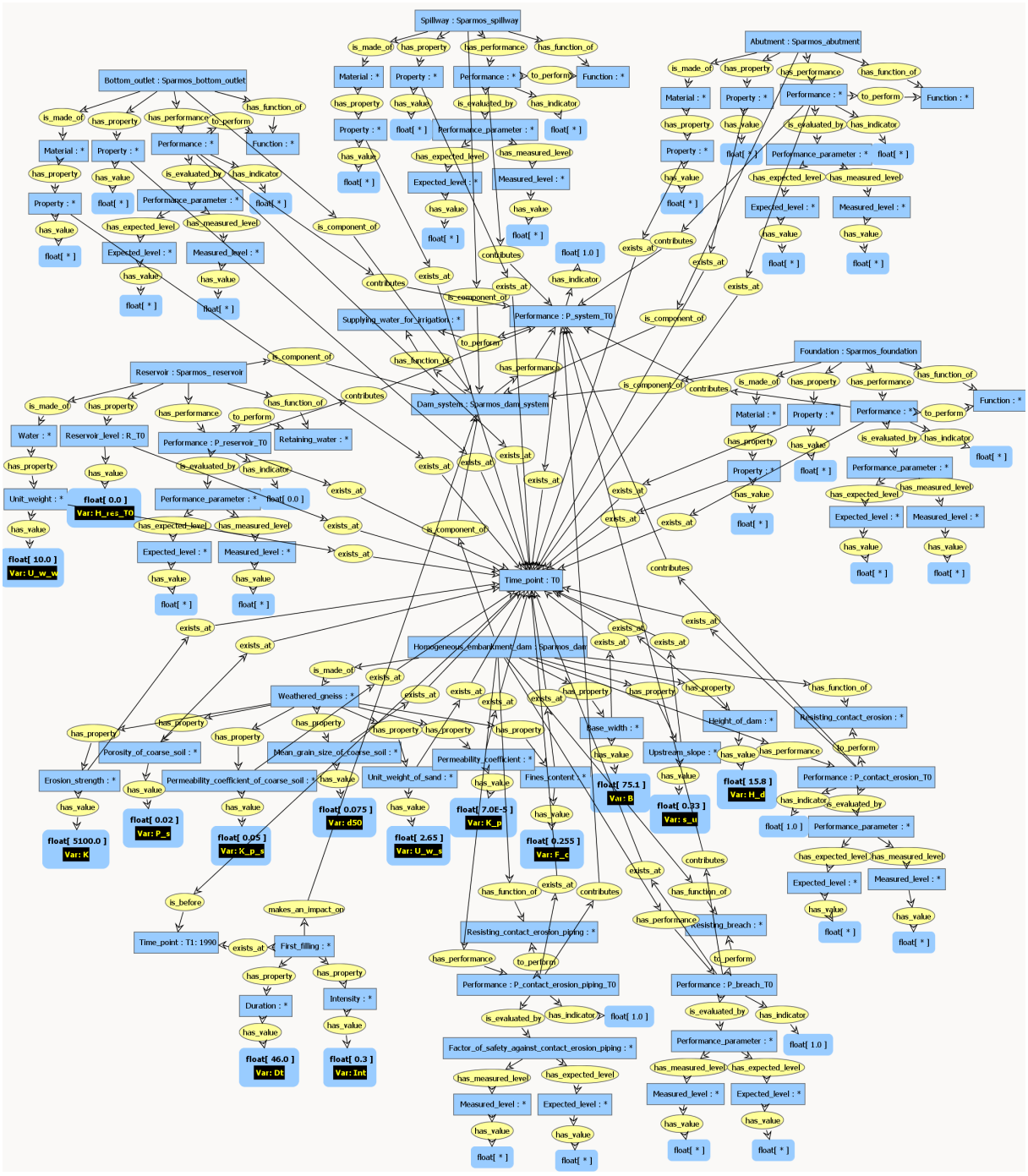


Figure A-7.208. Snapshot of the Sparmos dam system failure at T1

Figure A-7.208 shows the snapshot of the Sparmos dam failure at T1. Based on the system's conditions at the time point T0, the snapshot at T1 is described with the addition of an external factor, which is first filling activity. The impact of the activity on the system is described by the relation *makes_an_impact_on*. The concept *First_filling* is connected with

Time_point: T1: 1990. There is a relation *is_before* connecting the time point T0 and the time point T1.

- Snapshot at the time point T2 as follow:

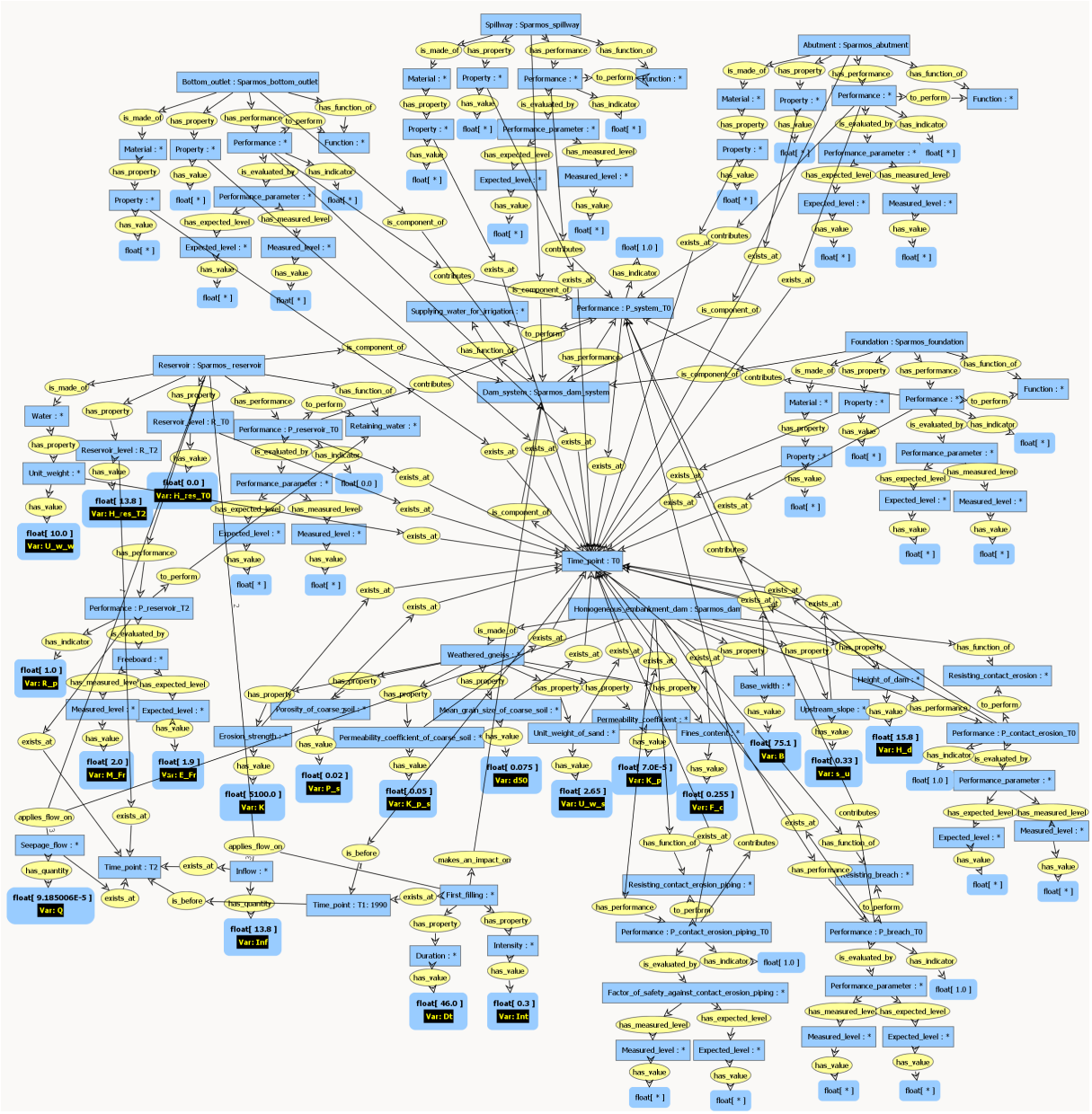


Figure A-7.209. Snapshot of the Sparmos dam system failure at T2

Following the time point T1, a snapshot at the time T2 (Figure A-7.209) is described with impacts of the first filling activity on the system. The first impact is an inflow that the activity interacts with the reservoir. This impact is described by the concept *Inflow* that exists at T2. Subsequently, due to the inflow, the reservoir increases to a new level *Reservoir_level: R_T2* with the value of 13.8 m. In turn, this effect induces another interaction between the reservoir and the embankment dam, that is *Seepage_flow* that exists at T2. The performance of the reservoir is satisfied at T2.

- Snapshot at the time point T3 as follow:

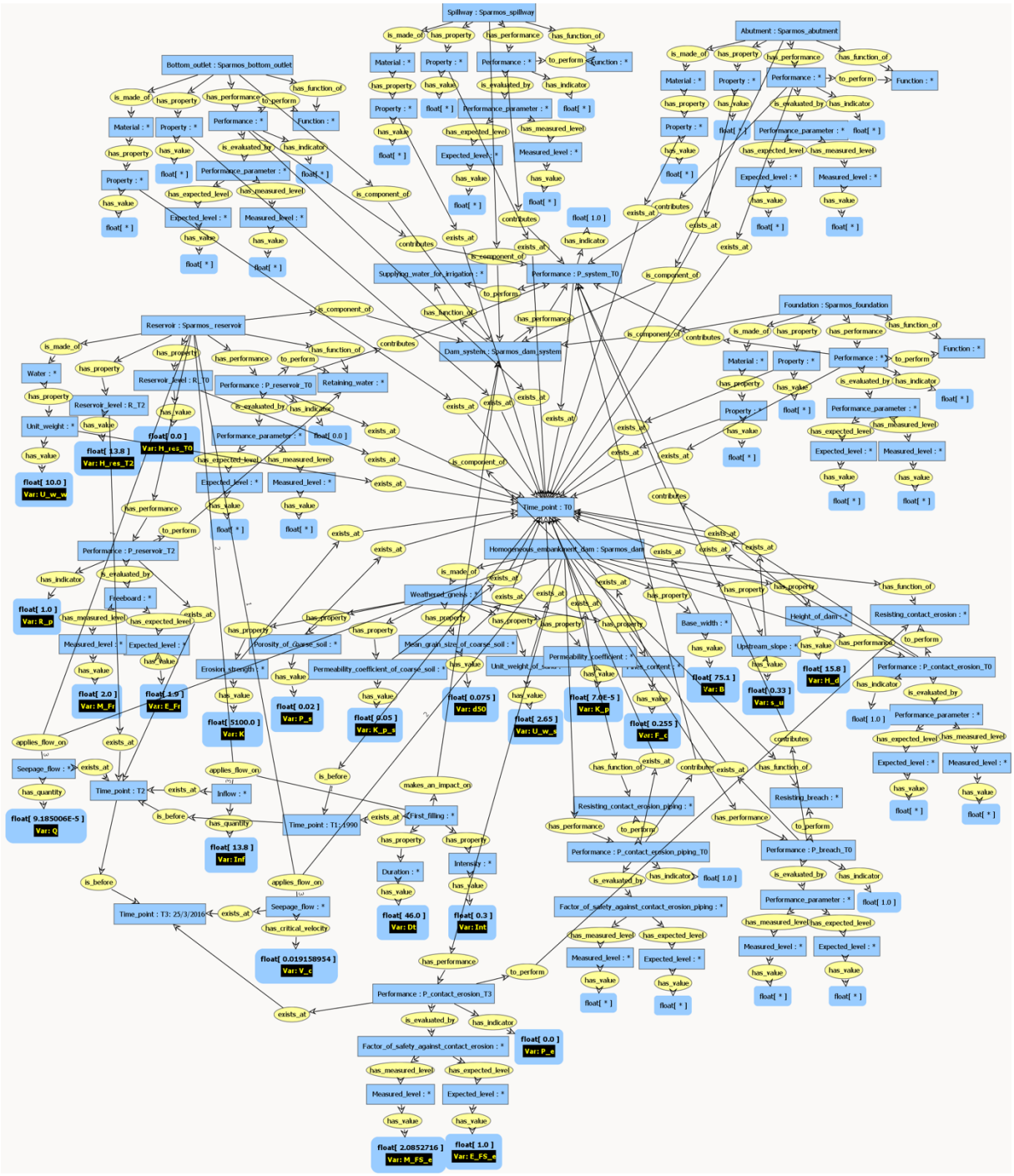


Figure A-7.210. Snapshot of the Sparmos dam system failure at T3

Sequent the impacts of the first filling activity on the reservoir and the embankment dam, the snapshot at the time point T3 (Figure A-7.210) describes the progression of the seepage flow at T3, 25/3/2016, means that after 27 years. A new interaction is created; that is, the seepage flow with a critical velocity that has a value of 0.02 m/s. Under the impact of this seepage flow, the dam has a new performance, *P_contact_erosion_T3*. This performance has an indicator with a value of *0*, which means that the dam fails to resist contact erosion at T3. There is a relation *is_before* connecting the time point T2 and the time point T3.

- Snapshot at the time point T4 as follow:

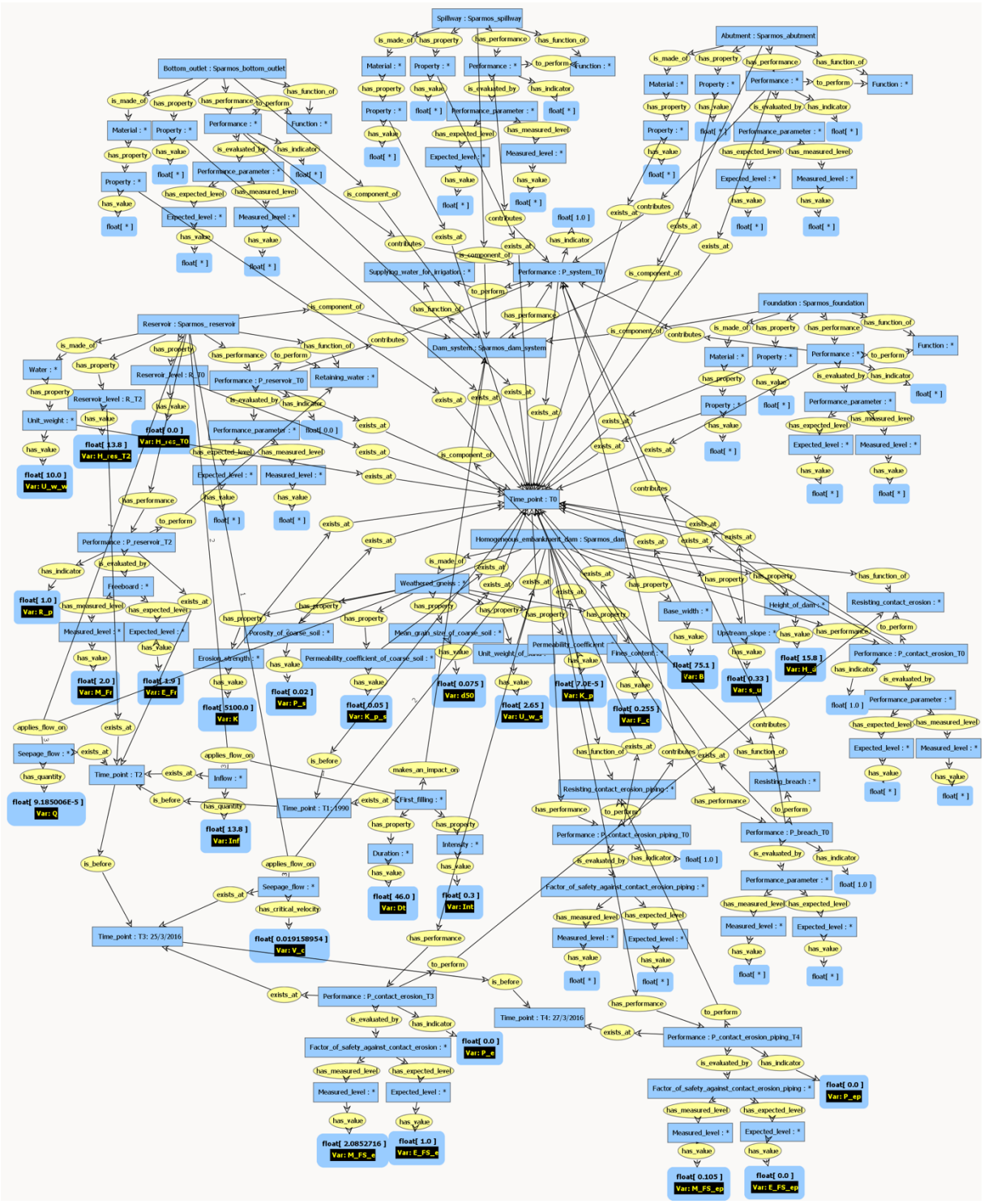


Figure A-7.211. Snapshot of the Sparmos dam system failure at T4

Figure A-7.211 shows the snapshot of the failure at T4. This snapshot describes the progression of contact erosion to form a pipe in the embankment dam. Based on the conditions of the system at T3, those are property of dam material that is fines content of the soil ≥ 15% and the contact erosion failure of the dam, a pipe is developed within the dam. The performance to perform the function of resisting contact erosion has an indicator with a value of 0, which means that the dam fails to resist piping at T4. The time point T4 is

27/3/2016, just 2 days after the erosion failure of the dam. This shows the rapid progress of the failure.

- Snapshot at the time point T5 as follow:

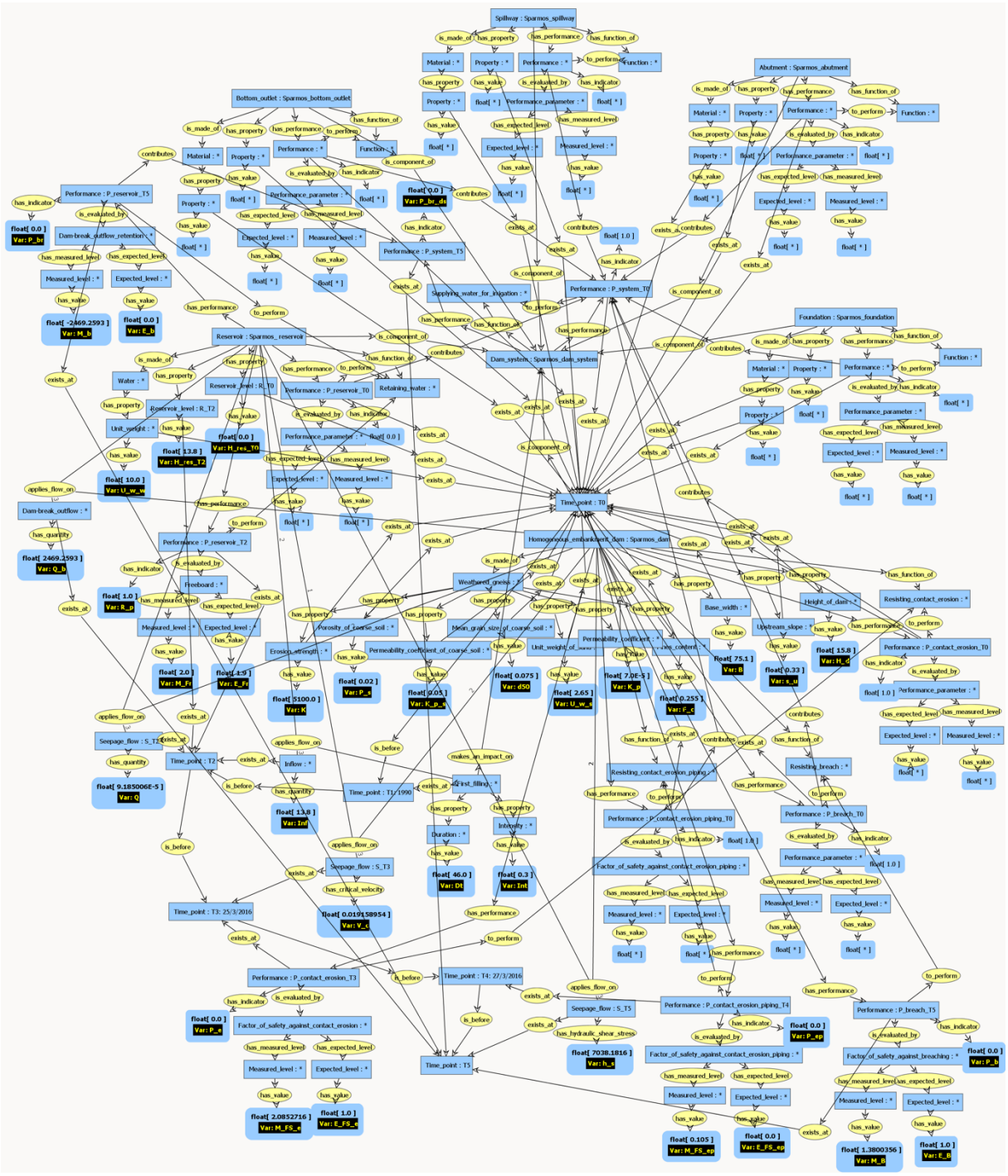


Figure A-7.212. Snapshot of the Sparmos dam system failure at T5

Figure A-7.212 shows the snapshot of the failure at T5. This snapshot describes the progression of piping to breach the embankment dam and failure of the reservoir. At the time point T5, the available state of the system is erosion and piping within the dam. With the development of piping, the hydraulic shear stress in the pipe over the erosion resistance of

the soil and breach of dam occurs. The performance of the dam to resist breach is evaluated by *Factor of safety against breach*. The performance indicator has a value of 0, which means that the dam fails to resist the breach. Due to this breach, there is a flow *Dam-break_outflow* of the reservoir releasing through the breach, leading to the reservoir's failure. The reservoir performance is evaluated by *Dam-break_outflow_retention* and has an indicator with a value of *0*, i.e., the reservoir fails to retain water. The time point T5 is just after the time point T4, two hours showing the rapid progress of piping.

In conclusion, the six snapshots provided an overview of the Sparmos dam system's failure process over time. It should be noted that this process took place for 27 years, from the completion of construction to the dam's breach. The first snapshot, the snapshot at T0, depicts the system's state before the impact of external factors. At this time, the new dam is completed and the reservoir is empty. Subsequently, the second snapshot shows the appearance of the first filling activity. The third snapshot describes the interactions that occur between the filling activity and the reservoir. The seepage flow that appears within the embankment dam. After 27 years, the fourth snapshot describes the progress of the seepage flow that erodes the dam. In the next snapshot, the development of a pipe in the dam is presented. And finally, the sixth snapshot shows the breach of the dam and the empty of the reservoir due to this breach.

7.5. Using theo failure knowledge model

7.5.1. Similarity request

Request for *Embankment dam system – First filling activity – Internal erosion*

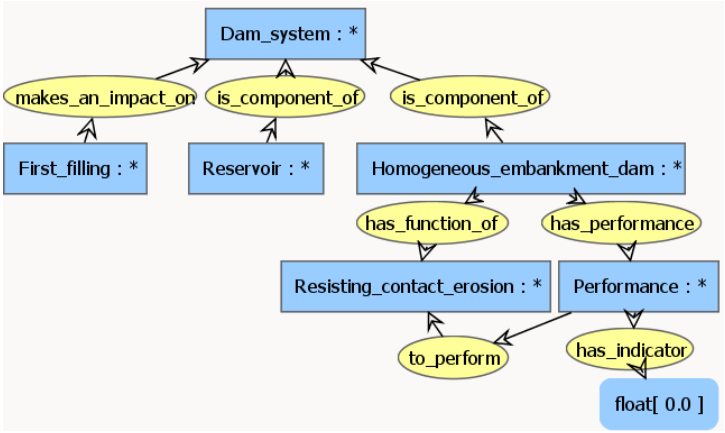


Figure A-7.213. Graph request for *Embankment dam – First filling – Internal erosion*

Figure A-7.213 shows a request graph applied to an embankment dam system subjected to a first filling activity, that has an internal erosion. The system has components at risk, which are *Embankment dam* and *Reservoir*. The failure is identified by the function *Resisting contact erosion* that the performance needs to perform. The dam's state is identified by the performance indicator that has a value of *0*, which means that not satisfied.

Figure A-7.214 shows an answer to the query above. Elements answering the query are elements in the fact graph that are highlighted in green. For this case, they identify the erosion failure at the time point T3 of the Sparmos dam failure process.

Information collected from the fact graph identifies the conditions contributing to the erosion. It is a combination of the critical velocity of the seepage flow in the dam, permeability coefficient of soil, the base width of the dam, and reservoir level.

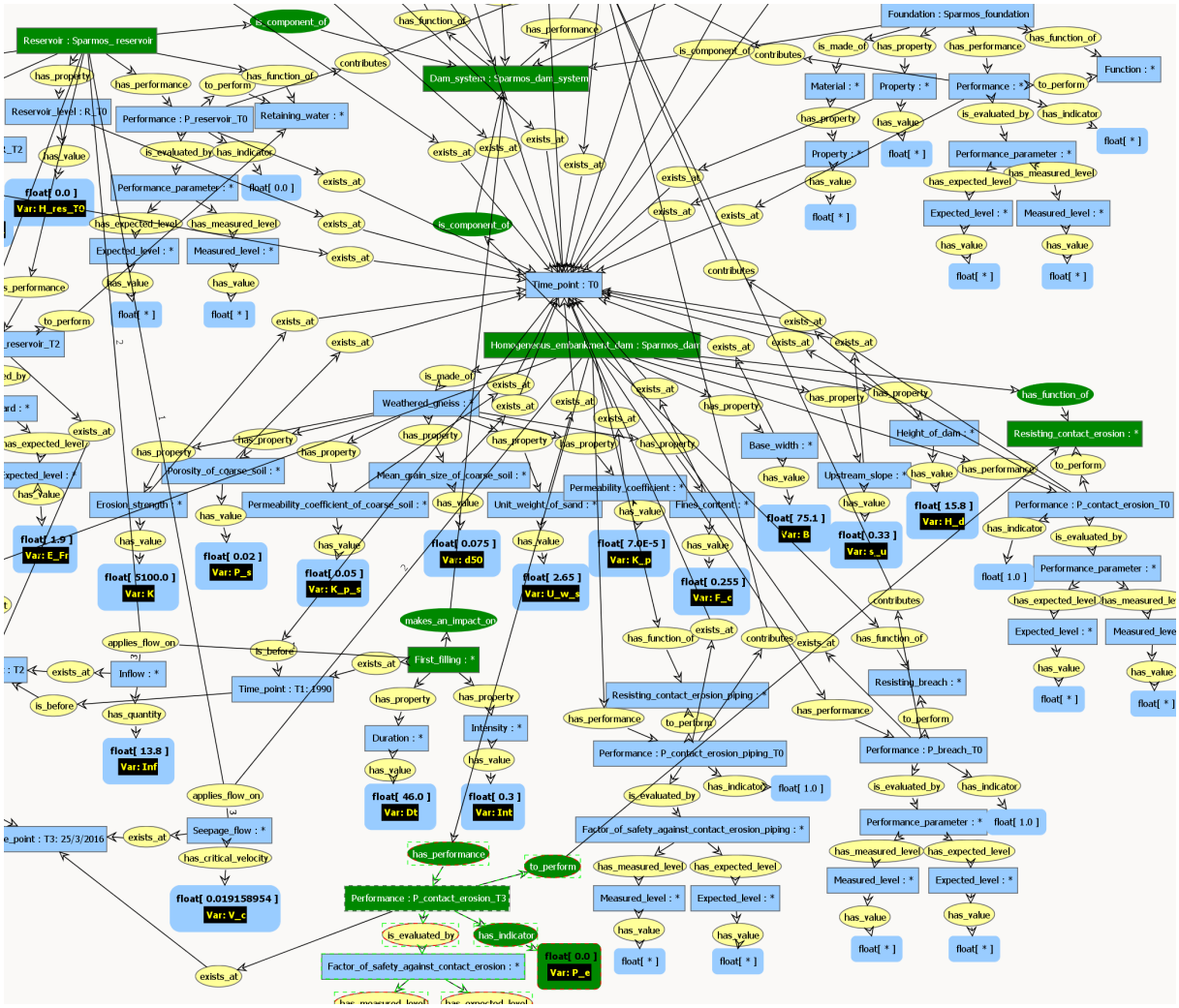


Figure A-7.214. An answer to the query for *Embankment dam – First filling – Contact erosion*

Request for *Zoned embankment dam system – Heavy rain – External erosion*

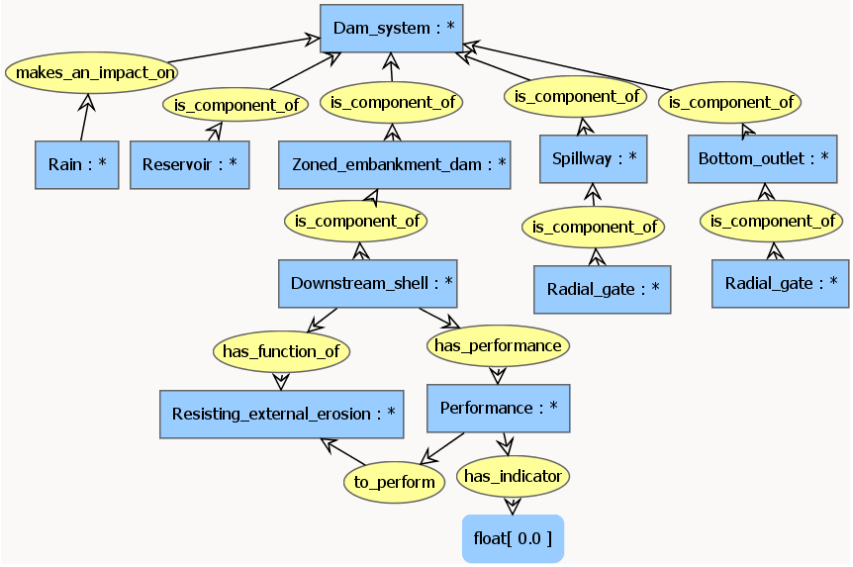


Figure A-7.215. Graph request for *Downstream shell – Heavy rain – External erosion*

The next query is constructed based on the Tous failure instance. Figure A-7.215 shows a request graph that identifies a downstream shell subjected to heavy rain and fails to resist external erosion. The failure of the downstream relates to components, which are zoned embankment dam, reservoir, spillway, bottom outlet, and radial gates. The failure is identified by the function *Resisting external erosion* that the performance needs to perform. The downstream's state is identified by the performance indicator with a value of *0*, which means that not satisfied.

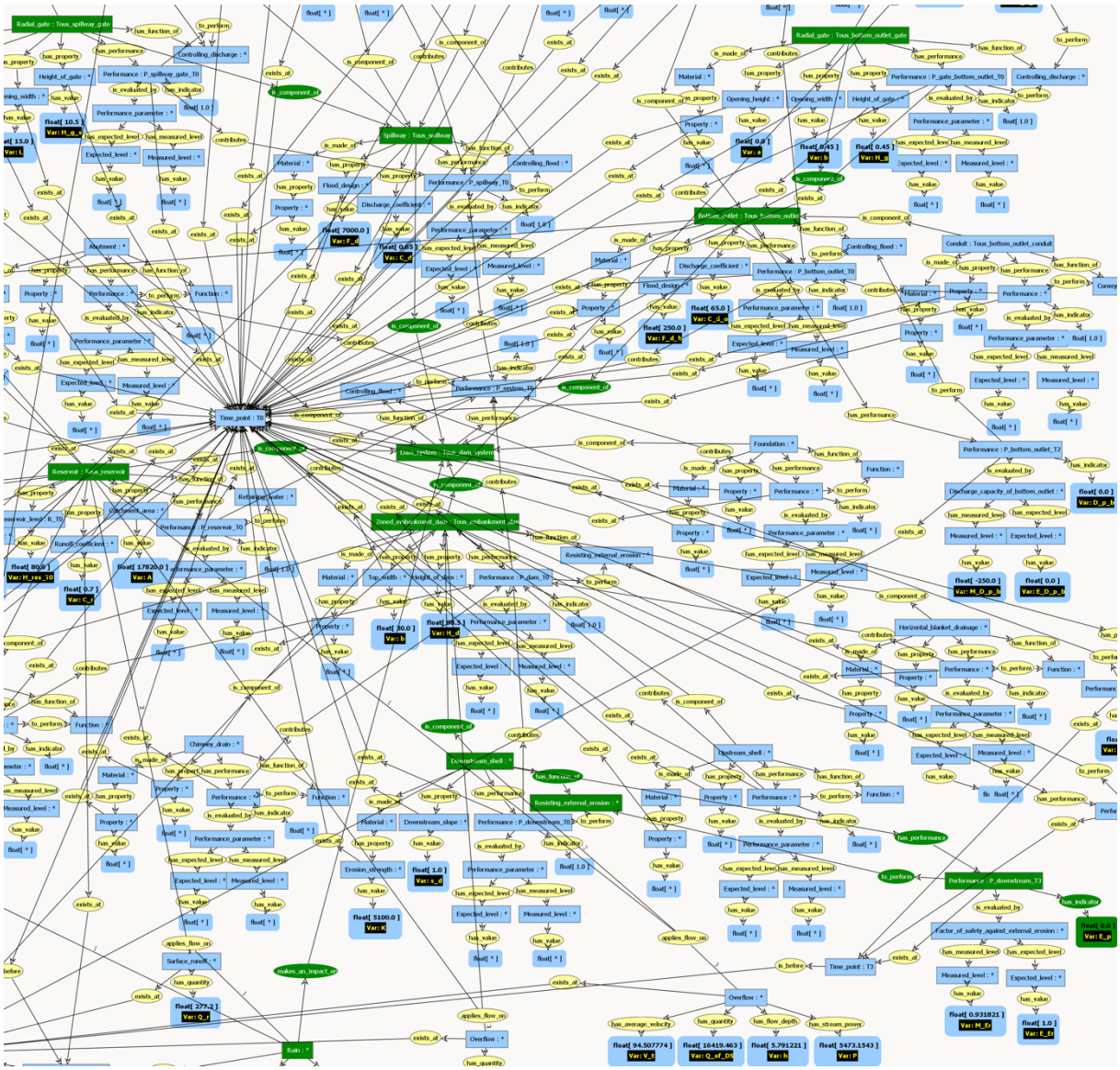


Figure A-7.216. An answer to the query for *Downstream shell – Heavy rain – External erosion*

Figure A-7.216 shows an answer to the query for the downstream shell that subjects to heavy rain. Elements answering the query are elements in the fact graph that are highlighted in green. For this case, they identify the Tous dam failure, which is the external erosion.

Information collected from the Tous failure instance identifies the conditions relating to the failure and the failure process. It shows a combination of the impact of the heavy rain, the interactions between the reservoir and the spillway and bottom outlet, and the erosion strength property of rockfill. The failure process is progressed with the reservoir's overflow, the inadequate capacity of the spillway and bottom outlet, and the external erosion of the downstream shell.

Request for *Earthfill dam system – Drawdown activity – Upstream sliding*

The next request is constructed based on the Pilarcitos failure instance. Figure A-7.217 shows a request graph applied to an embankment dam system subjected to a drawdown activity. The system has components at risk, which are *Homogeneous embankment dam* and *Reservoir.* The failure is identified by the function of *Resisting sliding of upstream shell*. The dam's state is identified by the performance indicator that has a value of *0*, which means that not satisfied.

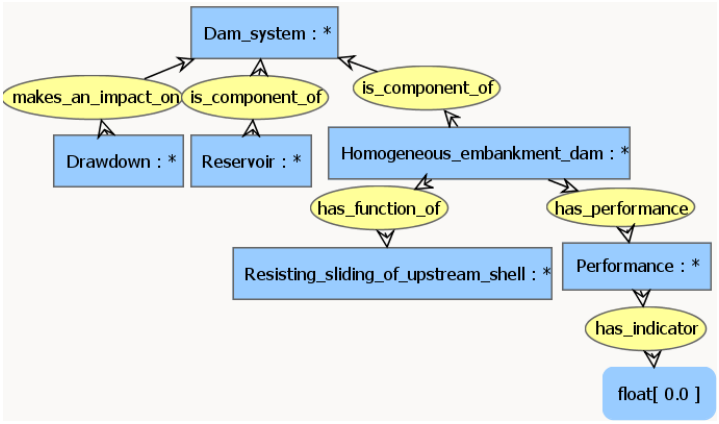


Figure A-7.217. Graph request for *Earthfill dam – Drawdown – Upstream sliding*

Figure A-7.218 shows an answer to the query. Elements answering the query are elements in the failure instance that are highlighted in green. For this case, they identify the Pilarcitos dam failure, which sliding of the upstream shell due to the drawdown activity.

Information collected from the Pilarcitos failure instance identifies the conditions relating to the failure. It shows a combination of the impact of drawdown activity, the high level of the reservoir, and the shear strength of soil result in sliding of the upstream shell.

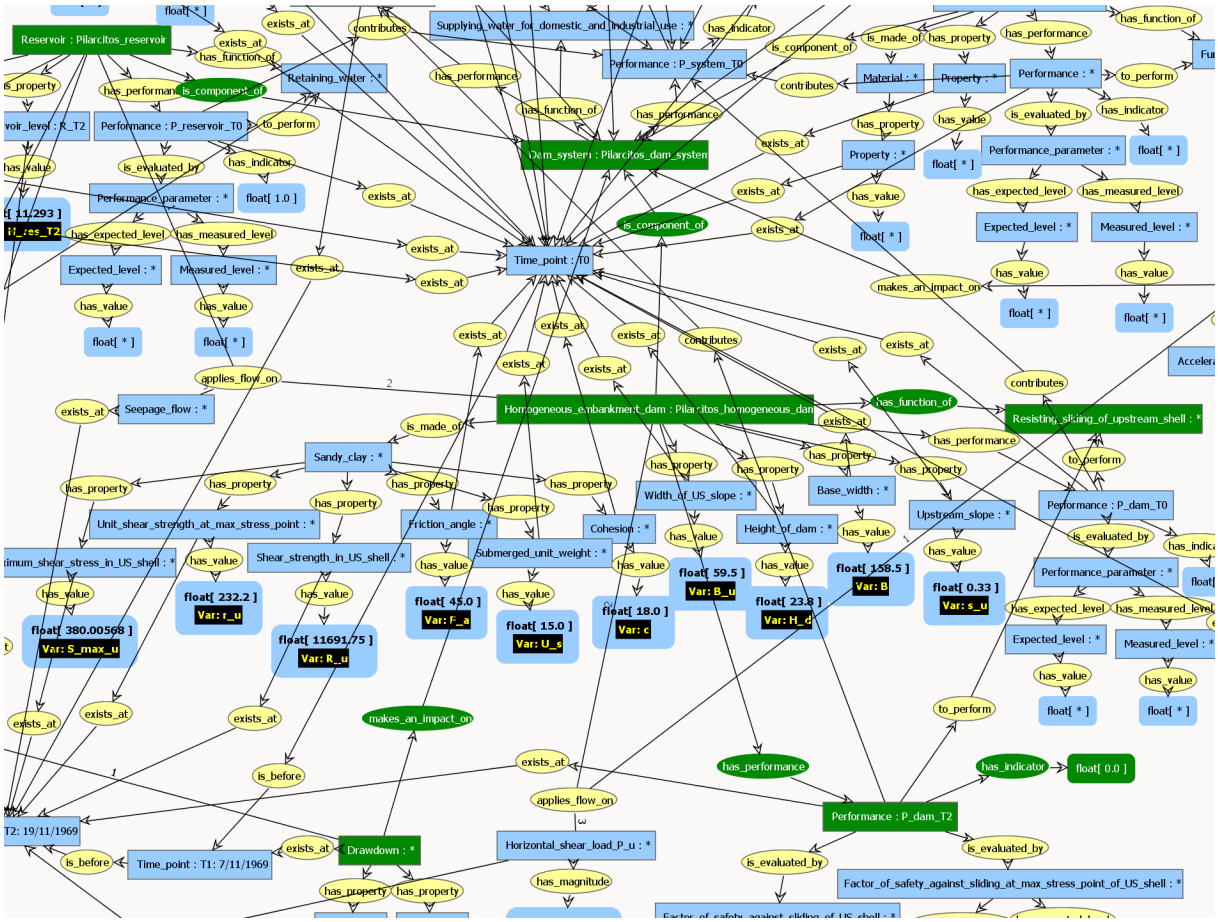


Figure A-7.218. An answer to the query for Earthfill dam – Drawdown – Upstream sliding

7.5.2. Inferring rules from facts

Rule for *Foundation - Heavy rain*

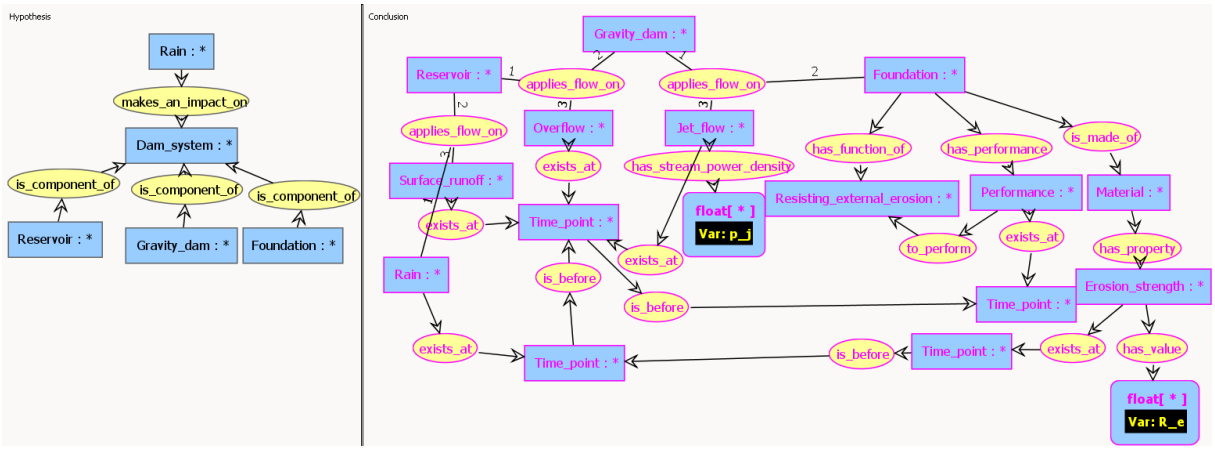


Figure A-7.219. Rule for *Foundation – Heavy rain*

Figure A-7.219 shows a rule applying for a case of a gravity dam system subjected to heavy rain. This rule is built from the Sella Zerbino dam system failure instance. The hypothesis graph includes information about the structure that is *Dam_system* has components at risk, which are *Gravity_dam*, *Reservoir* and *Foundation*, and an external

factor that is *Rain*. The conclusion graph describes the failure process and identifies the external erosion failure of the foundation. The process is started with the impact of heavy rain on the reservoir that is *Surface runoff*, which increases the water level rapidly. This interaction leads to a subsequent interaction that *Reservoir* applies on *Gravity_dam* that is *Overflow*. After that, the overflow induces the interaction *Jet_flow* between *Gravity_dam* and *Foundation*. Finally, a combination of stream power of the jet flow and erosion strength of the bedrock leads to external erosion of the foundation. The failure is identified by the performance indicator with a value of *0*.

Figure A-7.220 describes the result of applying the rule for a *Foundation – Heeavy rain* on a system with the same structure and external factors. By applying this rule, a new graph will be created, showing what can happen when a gravity dam system is subjected to heavy rain. The failure is the external erosion of the foundation.

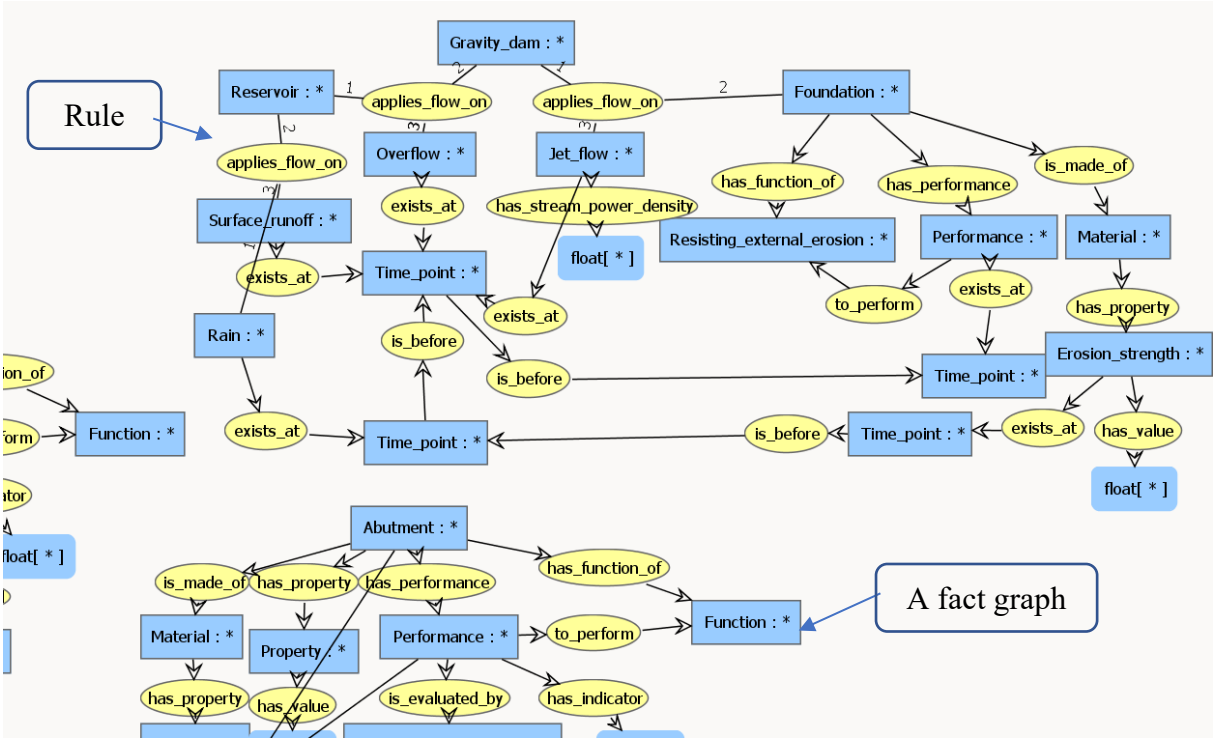


Figure A-7.220. A result of application of the rule for *Foundation – Heavy rain*

Rule for *Embankment dam – First filling*

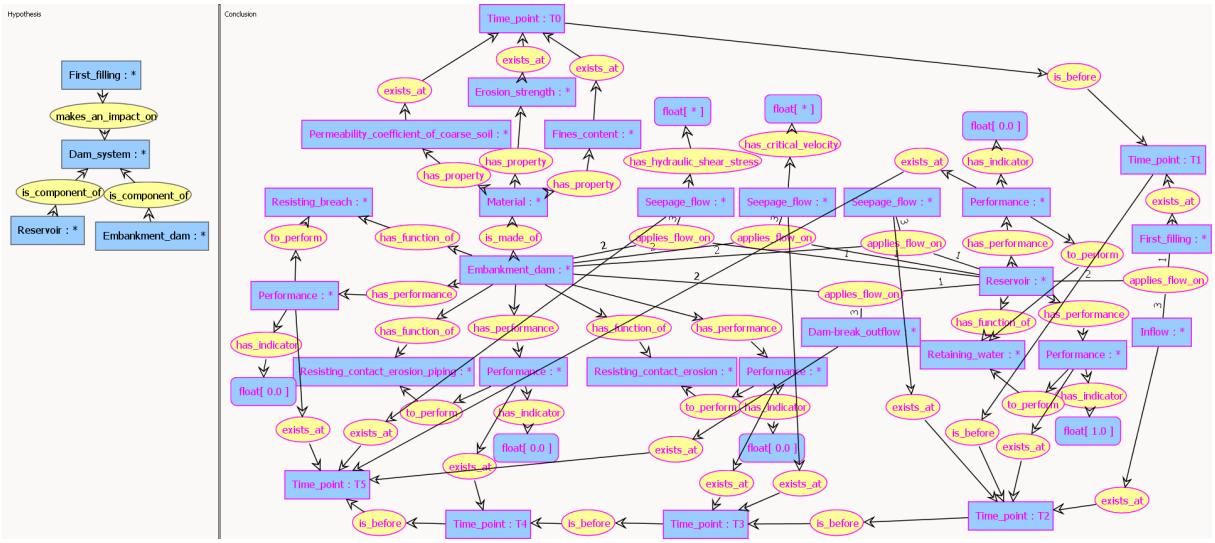


Figure A-7.221. Rule for *Embankment dam – First filling*

Figure A-7.221 shows a rule applying for a case of embankment dam system subjected to first filling activity. This rule is built from the Sparmos dam system failure instance. The hypothesis graph includes information about the structure that is *Dam_system* has components at risk, which are *Embankment_dam* and *Reservoir*, and an external factor that is *First_filling*. The conclusion graph describes the failure process and identifies a failure that is dam breach. The process is started with the impact of the first filling activity on the reservoir that is *Inflow*, which increases the water level. This interaction leads to a subsequent interaction that *Reservoir* applies on *Embankment_dam* that is *Seepage_flow*. In the next time point, this flow develops and erodes the soil, which induces the contact erosion failure of the dam. After that, the seepage progresses, leading to the piping failure of the dam. Finally, a combination of hydraulic shear stress in the pipe and erosion strength causes the dam to breach, and the reservoir discharges. The performances to perform *Resisting contact erosion*, *Resisting contact erosion piping*, *Resisting breach*, and *Retaining water* are identified by the performance indicators with a value of *0*, which means that failure.

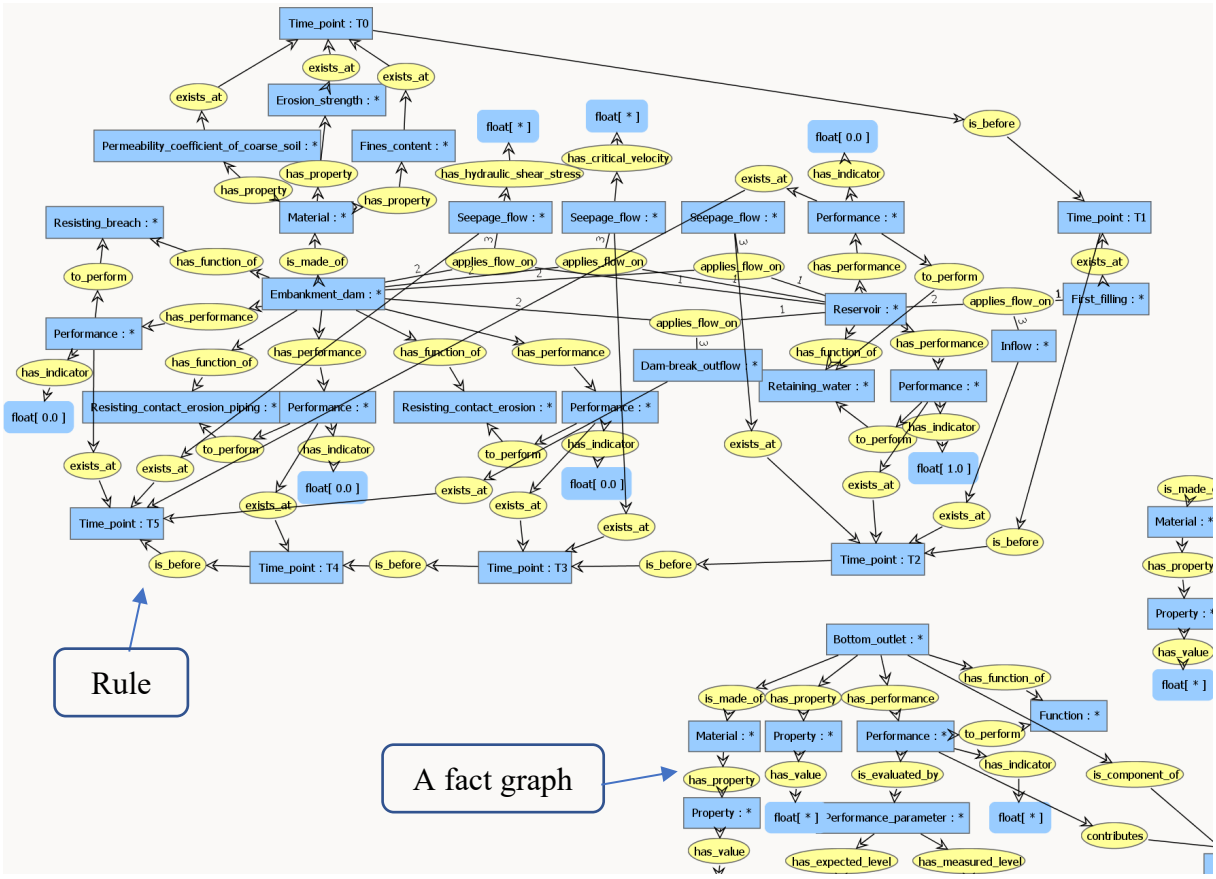


Figure A-7.222. A result of application of the rule for *Embankment dam subjected to First filling*

Figure A-7.222 describes the result of applying the rule for a *Embankment dam subjected to First filling* on a system with the same structure and external factors. By applying this rule, a new graph will be created, showing what can happen when a embankment dam system is subjected to first filling activity. The failure is the breach of the dam.

Rule for *Zoned embankment dam – Heavy rain*

Figure A-7.223 shows a rule applying for a case of a zoned embankment dam system subjected to heavy rain. This rule is built from the Tous dam system failure instance. The hypothesis graph includes information about the structure that is *Dam_system* has components at risk, which are *Zoned embankment_dam*, *Reservoir*, *Downstream shell*, *Spillway*, *Bottom outlet*, and *Radial gates*, and an external factor that is *Rain*. The conclusion graph describes the failure process and identifies external erosion of the downstream shell. The process is started with the impact of the heavy rain on the reservoir that is *Surface runoff*, which increases the water level. This interaction leads to subsequent interactions between *Reservoir* and *Radial gates*, which induce the inadequate capacities of *Spillway* and *Bottom outlet*. The performance indicators of *Radial gates*, *Spillway*, and *Bottom outlet* have a value of *0*, which means that failure. These causing an overflow that the reservoir applies on the *Downstream shell*. A combination between the power stream of the flow with erosion strength of rockfill causes external erosion of downstream shell.

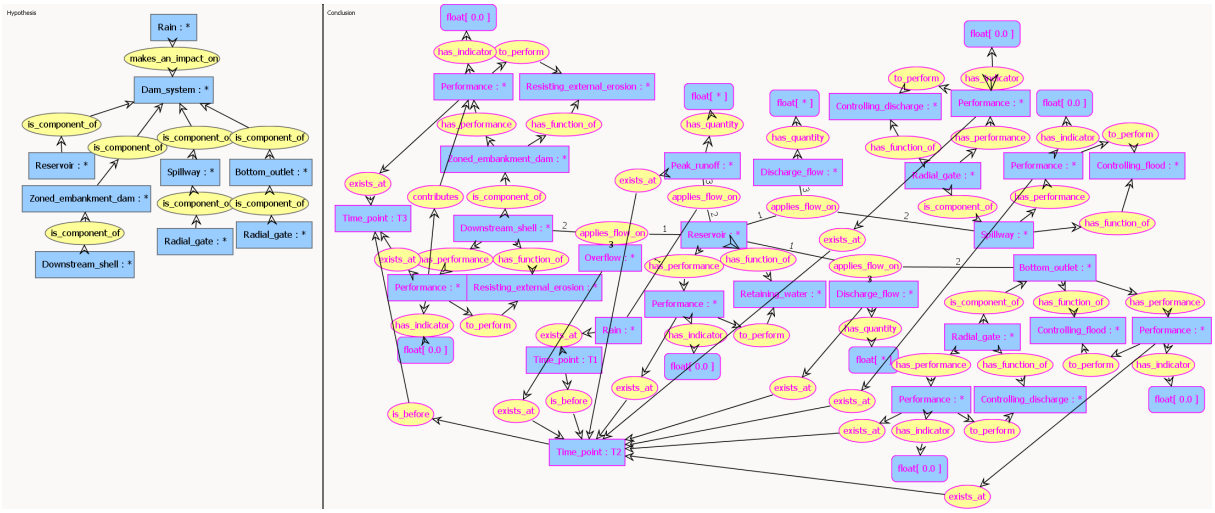


Figure A-7.223. Rule for *Zoned embankment dam – Heavy rain*

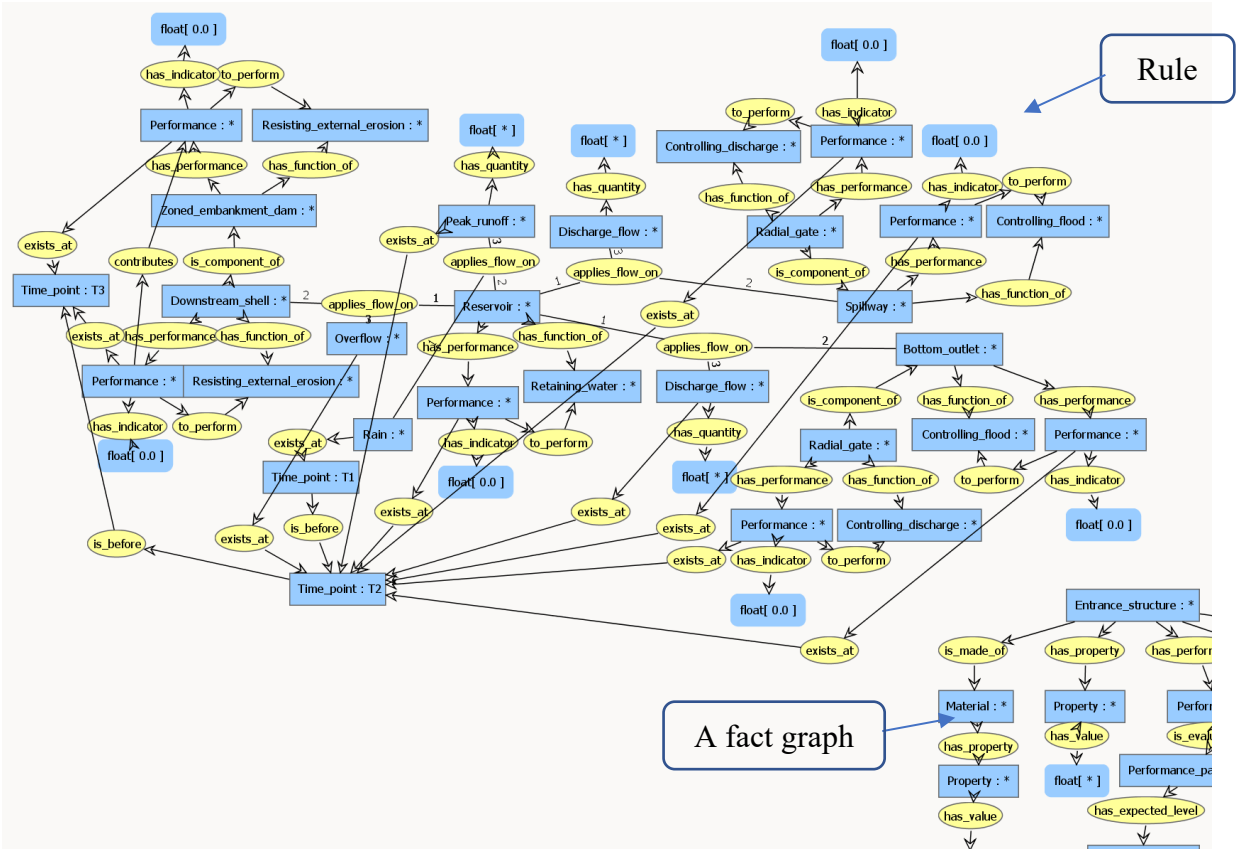


Figure A-7.224. A result of application of the rule for *Embankment dam subjected to First filling*

Figure A-7.224 describes the result of applying the rule for a *Zoned embankment dam subjected to Rain* on a system with the same structure and external factors. By applying this rule, a new graph will be created, showing what can happen when a zoned embankment dam system is subjected to heavy rain. The failure is the external erosion of the downstream shell.

References

Alcrudo, F. and Mulet, J. (2007) 'Description of the Tous Dam break case study (Spain)', *Journal of Hydraulic Research*, 45(SPEC. ISS.), pp. 45–57. doi: 10.1080/00221686.2007.9521832.

Alvi, I. A. (2015) 'Failure of Sella Zerbino Secondary Dam in Molare, Italy', pp. 1–9.

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8.1.1. Impacts of rainfall

8.1.1.1. Surface runoff

When rain falls, water is intercepted by leaves and stems of vegetation. This is usually referred to as interception storage. As the rain continues, if the soil is permeable, water percolates into the ground surface until it becomes saturated. After that, water flows laterally in the surface soil and fill depressions, generates runoff.

The term runoff is used for water that is on the "run" or in a flowing state, in contrast to the water held in depression storage and water evaporated in the atmosphere. The runoff of a catchment area in any specified period is the total quantity of water draining into a stream or into a reservoir in that period.

It is commonly assumed that the quantity (volume) of runoff is a proportion (percentage) of the rainfall depth.

$$\text{Runoff [mm]} = K \times \text{Rainfall depth [mm]}$$

$$\text{Rainfall depth} = \text{duration} * \text{intensity}$$

where, K: runoff coefficient is the proportion of rainfall that flows along the ground as surface runoff. It depends on the degree of slope, soil type, vegetation cover, antecedent soil moisture, rainfall intensity, and duration. The coefficient usually ranges between 0.1 and 0.5.

Water harvested from the catchment area is a function of the runoff amount created by the rainfall in the area. For a defined time scale, this runoff is calculated by multiplying a rainfall with a runoff coefficient.

$$\text{Water harvested} = \text{Catchment area} * \text{runoff}$$

$$= \text{Catchment area} * \text{rainfall} * K$$

This amount will equal the amount of water that flows into the reservoir and has the height ΔH

$$I = \text{Reservoir area} * \Delta H$$

These two amounts of water establish an equation :

$$\text{Catchment area} * \text{Rainfall} * K = \text{Reservoir area} * \Delta H$$

$$\frac{\boldsymbol{Catchment\ area}}{\boldsymbol{Reservoir\ area}} = \frac{\boldsymbol{\Delta H}}{\boldsymbol{Rainfall * K}}$$

where, Catchment-reservoir area ratio C is called concentration coefficient

$$\frac{Catchment\ area}{Reservoir\ area} = C \Rightarrow \Delta H = \text{Rainfall} * K * C$$

where, ΔH : the amount of water flows into the reservoir (m)

K : runoff coefficient

C: Catchment-reservoir ratio

Rule to calculate surface runoff

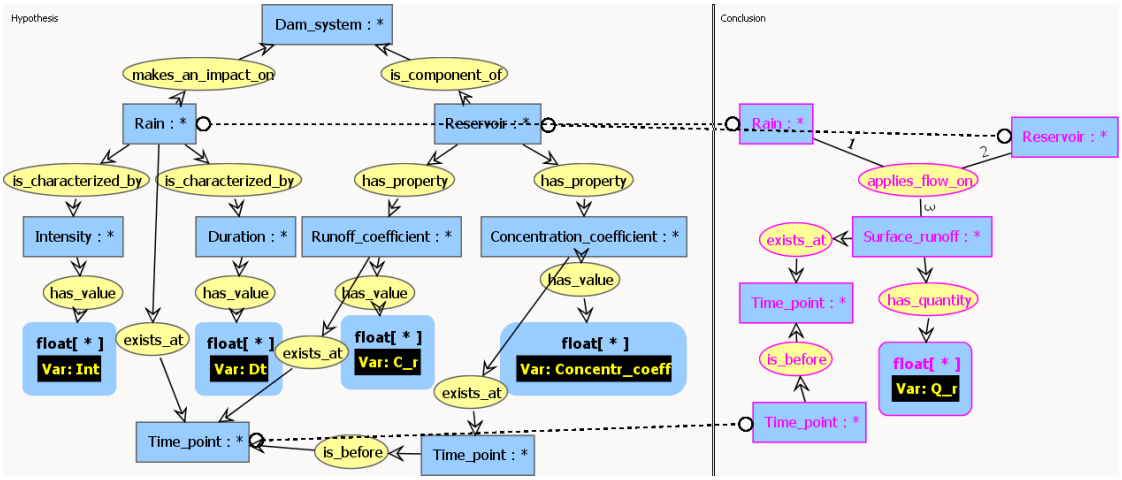


Figure A-8.1. Rule to calculate surface runoff

Figure A-8.1 illustrates the calculating of surface runoff. The runoff flow is the interaction between rain and the reservoir of the system. The rule graph can be expressed as **if** *Rain* makes an impact on *Dam system*, and *Reservoir* is a component of *Dam-system*, **then** *Rain* applies *Surface runoff* on the *Reservoir*". The surface runoff is quantified by relevant characteristics of rain, and those are intensity and duration, properties of the reservoir those are runoff coefficient and concentration coefficient. The time point of the surface runoff is after the time point of rain. Figure A-8.2 shows the associated script.

Rule | Associated script

```
1  void after()
2  {
3      float value = (Int.getValue() * Dt.getValue() * C_r.getValue() * Concentr_coeff.getValue());//
4      Q_r.setValue(value);// in meters
5  }
```

Figure A-8.2. Script to calculate surface runoff

8.1.1.2. New reservoir level

New lever of the reservoir after the surface runoff flows into, given by the equation :

$$H_{res_T1} = \Delta H + H_{res_T0}$$

where, H_{res_T1} : new reservoir level (m)

ΔH : the amount of water flows into the reservoir (m)

H_{res_T0} : is the initial level of the reservoir (m)

Rule to calculate the new reservoir level:

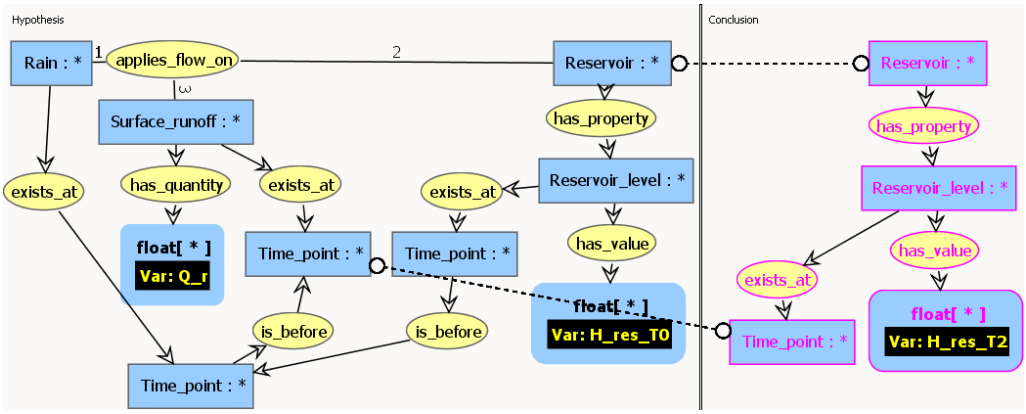


Figure A-8.3. Rule to calculate new reservoir level

Figure A-8.3 shows the computing of the new reservoir level. The new level of the reservoir is based on the quantity of surface runoff at the same time point and old reservoir level. It should be noted that the old water level is at an earlier point in time. It does not change until the time point of the new level. Figure A-8.4 illustrates the associated script.

Rule | Associated script

```
1  void after()
2  {
3      float value1 = Q_r.getValue() + H_res_T0.getValue();/
4
5      H_res_T2.setValue(value1);// reservoir level after fi
6  }
```

Figure A-8.4. Script to calculate new reservoir level

8.1.1.3. Peak runoff

Peak inflow is computed to consider the performance of the spillway, bottom outlet, and reservoir. The Inglis empirical formula (Punima *et al.*, 2009) is applied to compute flood discharge:

$$Q = 123\ A^{1/2}$$

where : Q = flood discharge

A: catchment area

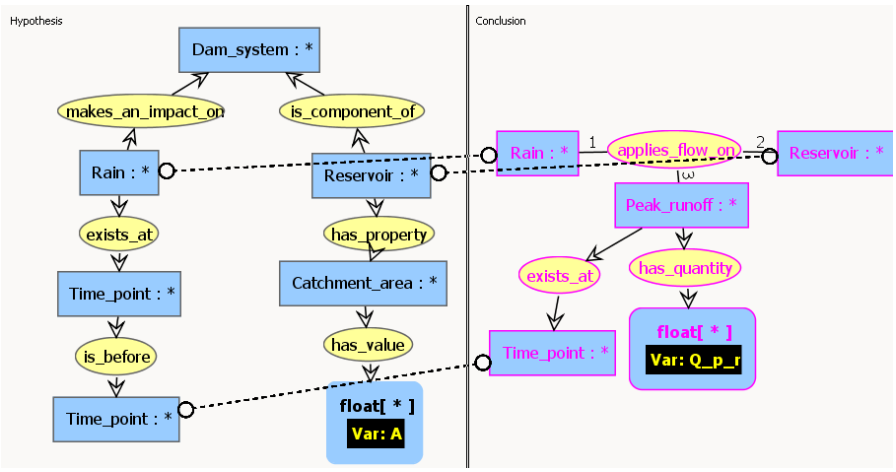


Figure A-8.5. Rule to calculate peak runoff

The rule graph in Figure A-8.5 presents the calculating of peak runoff. Its quantity is computed based on the value of the catchment area. The rule graph can be expressed as **if** *Rain* makes an impact on *Dam_system*, and *Reservoir* is a component of *Dam_system*, **then** *Rain* applies peak runoff on *Reservoir*. The time point of peak runoff is after the time point of rain. Figure A-8.6 illustrates the associated script

Rule | Associated script

```
1  void after()
2  {
3      float value1 = 123 * Math.sqrt(A.getValue());
4
5      Q_p_r.setValue(value1); // in m3/s
6  }
```

Figure A-8.6. Script to calculate peak runoff

8.1.2. Impacts of first filling

The first filling of a reservoir is a critical phase in life for the dam system. It is the first test that the dam will perform the function for which it was designed. The first filling can be defined as the increase in water level from the time construction is complete until it reaches the desired operating level (FMEA, 2014). During the initial filling of the reservoir, it is typical for design, construction, and/or material deficiencies of a new dam to become apparent during the first filling. According to (Sharma and Kumar, 2013), about two-thirds of the failures occur on the first filling.

8.1.2.1. Inflow

The quantity of inflow into the reservoir = Duration * Intensity

Duration: the period during which the filling activity occurs

Intensity: is the ratio of the amount of inflow during a given period to the filling duration. It is expressed in depth units per unit time, in m/h.

Rule to calculate the inflow:

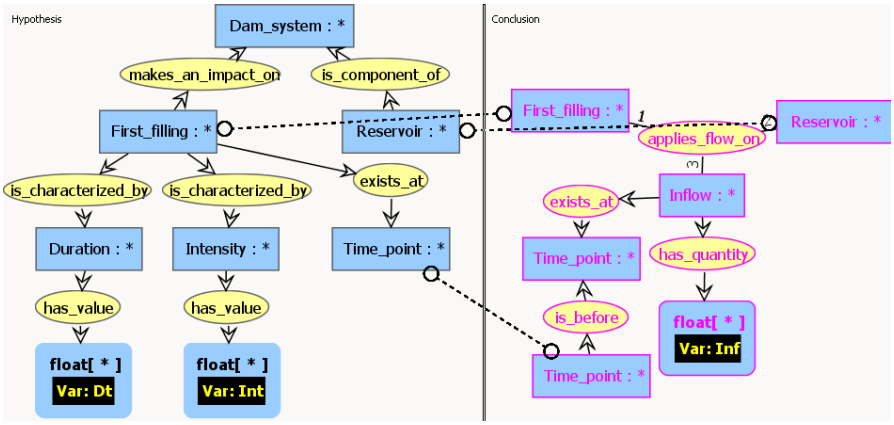


Figure A-8.7. Rule to calculate the inflow

Figure A-8.7 illustrates the interaction between a first filling activity and reservoir. The inflow is generated by inference as **if** *First_filling* makes an impact on *Dam_system*, and *Reservoir* is a component of *Dam_system*, **then** *First_filling* applies inflow on *Reservoir*. The quantity of inflow is calculated based on the duration and intensity of the first filling activity. The time point of inflow is after the time of the first filling activity. Figure A-8.8 shows the associated script.

Rule | Associated script

```
1  void after()
2  {
3      float value1 = Dt.getValue() * Int.getValue();
4      Inf.setValue(value1);
5  }
```

Figure A-8.8. Script to calculate the inflow

8.1.2.2. Increasing of reservoir level due to first filling activity

New reservoir level = Old level + Inflow

Rule to calculate the new reservoir level:

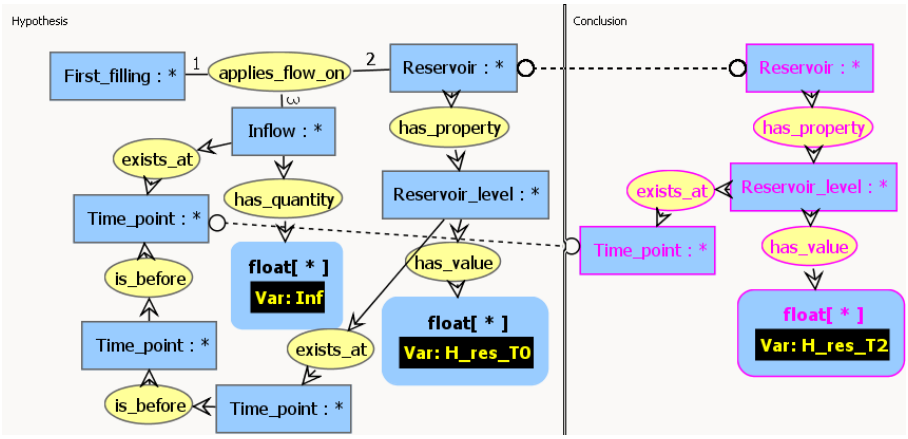


Figure A-8.9. Rule to calculate new reservoir level

The rule graph in Figure A-8.9 illustrates the appearance of a new reservoir level due to the first filling activity. The new level is computed based on the quantity of the inflow and the old level of the reservoir. The rule graph can be explained as **if** *First_filling* applies *Inflow* on *Reservoir*, **then** *Reservoir* has *Reservoir level* at *Time-point*. The time of the new level is the time of inflow. Figure A-8.10 exposes the associated script.

Rule | Associated script

```
1  void after()
2  {
3      float value1 = H_res_T0.getValue() + Inf.getValue();
4
5      H_res_T2.setValue(value1);// reservoir level after f
6  }
```

Figure A-8.10. Script to calculate new reservoir level

8.1.3. Impacts of earthquak

An earthquake introduces momentary dynamic loads generated due to the inertia of the dam and the retained body of water. It produces waves that impart accelerations to the foundation of the dam in any direction. Two accelerations, i.e., one horizontal acceleration (α_h) (upstream or downstream) and one vertical acceleration (α_v) (upward or downward), have values that are generally expressed as a percentage of the acceleration due to gravity (g), i.e. α = 0.1 g or 0.2 g, etc.

Under full reservoir conditions, the most adverse earthquake loading will then occur when a ground shock is associated with:

1. horizontal acceleration is acting upstream, and

2. vertical acceleration is acting downwards (Chen, 2014)

8.1.3.1. Vertical earthquake load (E_v) :

The vertical inertia load of the foundation due to the vertical acceleration (α_v) exerts a load into the dam, given by the equation:

$$E_v = \frac{W_c}{g}\alpha_v$$

where, E_v : Vertical earthquake load (kN)

g: Gravity acceleration = 9.81m/s^2

W_c: Self-weight load of the dam (kN)

α_v : Vertical acceleration

$$\alpha_v = k_v * g \Rightarrow E_v = \frac{W_c}{g}\ k_v\, g = W_c * k_v$$

where, k_v : is the fraction of gravity adopted for vertical acceleration, such as 0.1 or 0.2, etc.

Moment of vertical earthquake load about the toe of the dam:

$$M_{e_v} = (-)\, M_{w_c} * k_v$$

where,

M_{e_v}: Moment of vertical earthquake load about the toe of the dam

M_{w_c}: moment of self-weight load about the toe of the dam

k_v: is the fraction of gravity adopted for vertical acceleration, such as 0.1 or 0.2, etc.

Assuming that vertical earthquake load acts upward, thus the moment of this load is clockwise (-).

Rule to calculate vertical earthquake load and its moment about the toe of the dam:

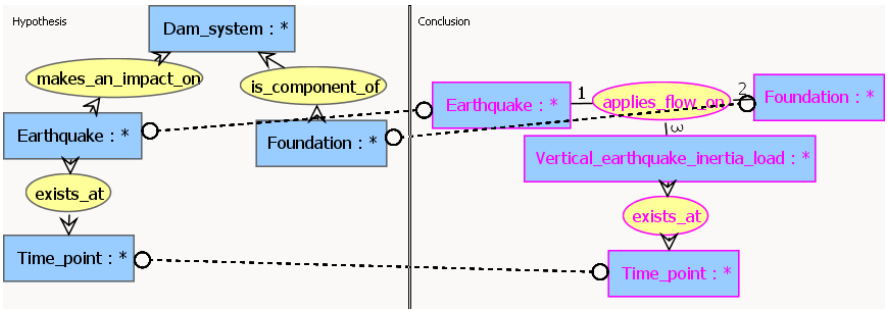


Figure A-8.11. The impact of an earthquake on the foundation

Figure A-8.11 shows a rule graph for generating the effect of an earthquake on the foundation of a dam system. The rule graph can be expressed as **if** *Earthquake* makes an impact on *Dam_system*, and *Foundation* is a component of *Dam_system*, **then** *Earthquake* applies *Vertical earthquake inertia load* on *Foundation*. The time point of the earthquake load is the time point of the earthquake.

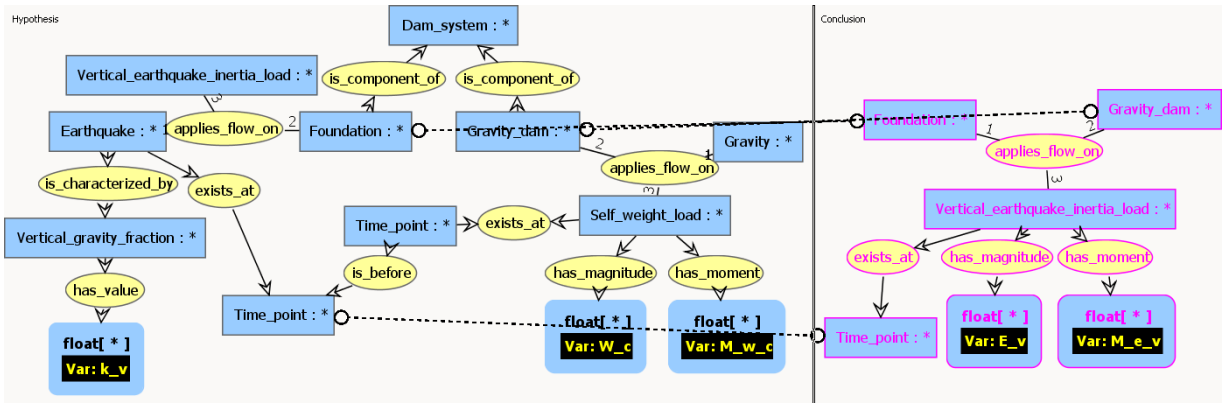


Figure A-8.12. Rule computing vertical earthquake load

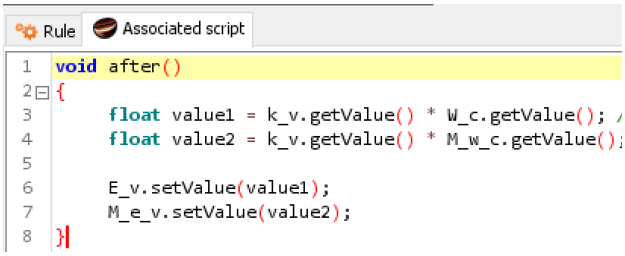


Figure A-8.13. Script to compute the vertical earthquake load

Figure *A-8.12* shows a computation of the vertical earthquake inertia load, impacting the foundation on gravity dam during an earthquake. The vertical earthquake load is computed based on the value of the vertical gravity fraction of the earthquake and the shelf-weight load of the gravity dam. The rule graph can be expressed as **if** *Earthquake* characterized by *Vertical gravity fraction* applies *Vertical earthquake inertia load* on *Foundation*, *Gravity dam* has *Self-weight load*, and *Foundation* and *Gravity dam* are components of *Dam_system*, **then** *Foundation* applies *Vertical earthquake inertia load* on *Gravity_dam*. The time point of the vertical earthquake inertia load is the time point of the earthquake. Figure A-8.13 shows the associated script.

8.1.3.2. Horizontal earthquake load

Horizontal acceleration (α_h) causes horizontal inertia load, which exerts into the dam. The direction of this load will be opposite to the acceleration imparted by the earthquake. The amount of this horizontal inertial load is equal to the product of the mass of the dam and the acceleration. This horizontal inertia load is given by the following equation:

$$E_h = \left(\frac{W_c}{g}\right) \alpha_h = \frac{W_c}{g} * k_h * g = W_c * k_h$$

where,

E_h : is horizontal earthquake load

W_c: self-weight of dam-body

k_h : is the fraction of gravity adopted for horizontal acceleration, such as 0.1 or 0.2, etc.

This load acts at the center of gravity of the dam.

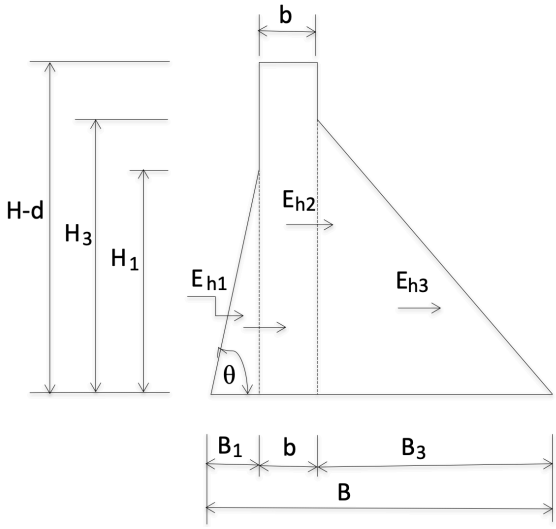


Figure A-8.14. Typical cross-section of gravity dam – Horizontal earthquake load

The horizontal inertia load may be the sum of 3 loads :

$$E_h = E_{h1} + E_{h2} + E_{h3}$$

$E_{h1} = W_1 \cdot k_h$

$E_{h2} = W_2 \cdot k_h$

$E_{h3} = W_3 \cdot k_h$

Moment of horizontal earthquake load about the toe of the dam:

$$M_{e\text{-}h} = M_{e\text{-}h1} + M_{e\text{-}h2} + M_{e\text{-}h3}$$

$M_{e\text{-}h1} = (-)\ E_{h1} \cdot \frac{H_1}{3}$

$M_{e\text{-}h2} = (-)\ E_{h2} \cdot \frac{H}{2}$

$$M_{e\text{-}h3} = (-)\, E_{h3} \,.\, \frac{H_3}{3}$$

Assuming that horizontal earthquake load acts downstream, thus the moment is clockwise (-).

Rule to calculating horizontal earthquake load and its moment about the toe of the dam is given:

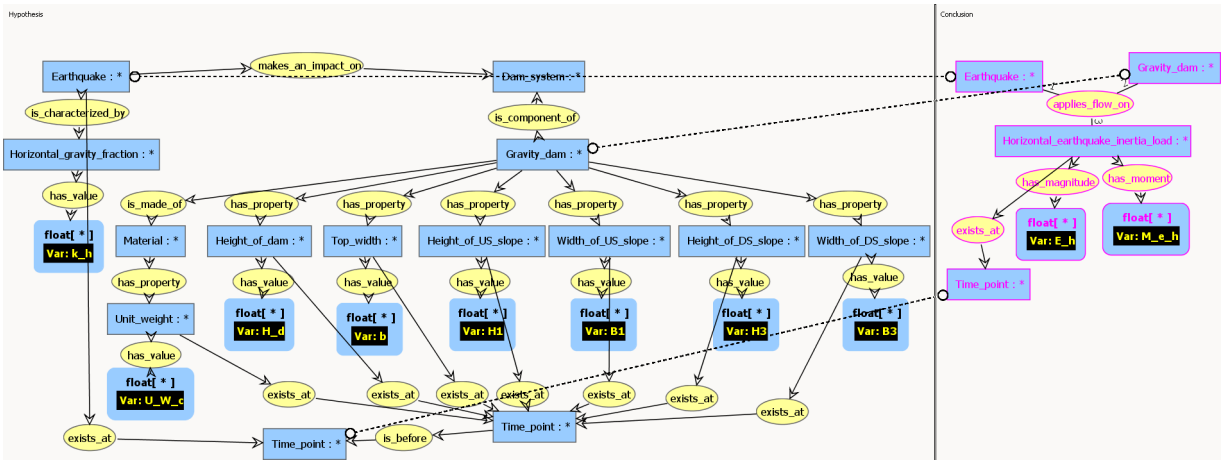


Figure A-8.15. Rule to calculate horizontal earthquake load

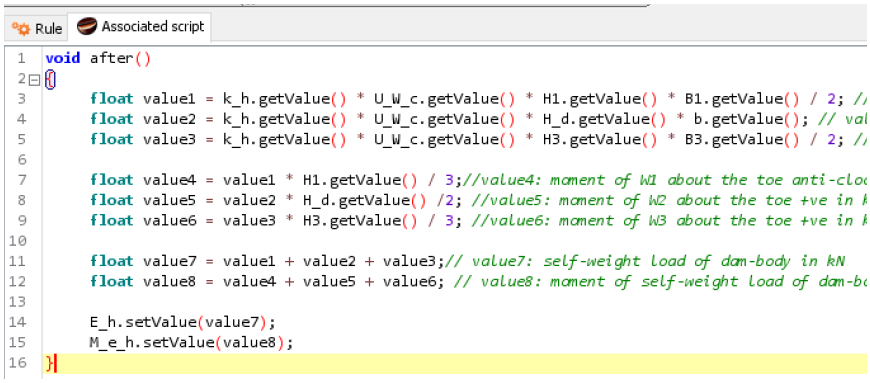


Figure A-8.16. Script to calculate horizontal earthquake load

Figure A-8.15 shows a rule graph for calculating the horizontal earthquake load of an earthquake applying to a gravity dam. The load is calculated based on the value of the horizontal gravity fraction of the earthquake, the properties of dam material, and the geometrical parameters of the gravity dam. The rule graph can be explained as **if** *Earthquake* makes an impact on *Dam_system*, and *Gravity_dam* is a component of *Dam_system*, **then** *Earthquake* applies *Horizontal earthquake inertia load* on *Gravity dam*. The time point of the resulting load is the time point of the earthquake. Figure A-8.16 exposes the associated script.

8.1.3.3. Earthquake hydrodynamic load

Horizontal acceleration acting towards the reservoir causes a momentary increase in the water pressure. The foundation and dam accelerate towards the reservoir, and the water

resists the movement owing to its inertia. The extra load exerted by this process is known as a hydrodynamic load.

According to Von-Karman, the amount of this hydrodynamic load (E_d) is given by:

$$E_d = 0.555.k_h.\ \gamma_{w.}\ H_{res}^2$$

And it acts at the height of $\frac{4H_{res}}{3\pi}$ above the base, as shown in Figure …

Where k_h is the fraction of gravity adopted for horizontal acceleration, such as 0.1, 0.2, etc.,.

γ_w: unit weight of water

Moment of earthquake hydrodynamic load about the base:

$$M_{e_d} = E_d \left(\frac{4H}{3\mu}\right) = 0.424.\ E_d.\ H_{res}$$

Rule to calculate hydrodynamic earthquake load and its moment about the toe of the dam:

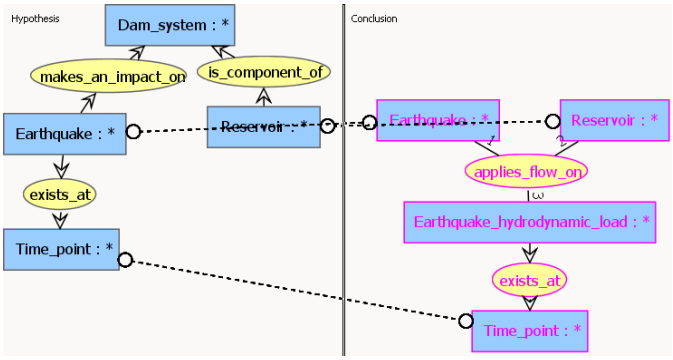


Figure A-8.17. Rule to identify earthquake hydrodynamic load

Figure A-8.17 shows the impact of an earthquake on the reservoir. The rule graph can be expressed as **if** *Earthquake* makes an impact on *Dam system*, and *Reservoir* is a component of *Dam_system*, **then** *Earthquake* applies *Earthquake hydrodynamic load* on *Reservoir*. The time point of the load is the time of the earthquake.

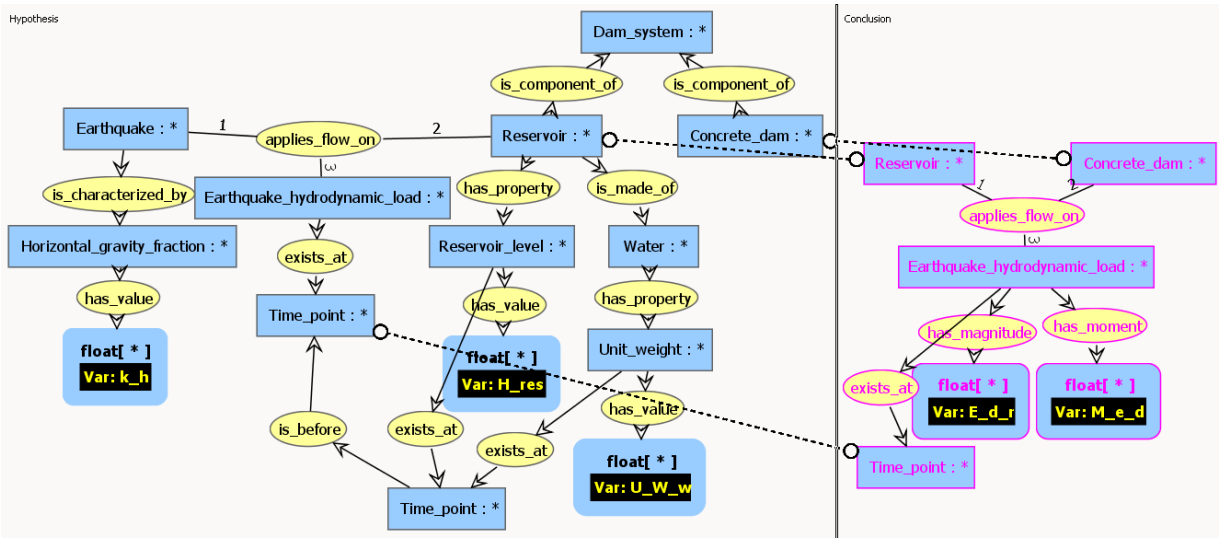


Figure A-8.18. Rule to compute the hydrodynamic load and its moment at the base

The rule graph in Figure A-8.18 calculates the hydrodynamic earthquake load of the reservoir applying to the concrete dam. The load is computed based on the value of the horizontal gravity fraction of the earthquake and the properties of the reservoir. The rule graph can be explained as **if** *Earthquake* applies *Earthquake hydrodynamic load* on *Reservoir*, and *Reservoir* and *Concrete dam* are components of *Dam_system*, **then** *Reservoir* applies *Earthquake hydrodynamic load* on *Concrete dam*. The time point of the resulting load is the time point of the earthquake. Figure A-8.19 shows the associated script.

Rule | Associated script

```
1  void after()
2  {
3      float value1 = 0.555 * k_h.getValue() * U_W_w.getValue() * Math.pow(H_res.getValue(),2.0);
4      float value2 = 0.424 * value1 * H_res.getValue();
5
6      E_d_r.setValue(value1);
7      M_e_d.setValue(value2);
8  }
```

Figure A-8.19. Script of the rule to compute the hydrodynamic load and its moment at the base

8.2. Interactions and performances of gravity dam

8.2.1. Loads and moment acting on gravity dam

8.2.1.1. Self-weight load of gravity dam:

Self-weight is attributable to gravity, and its magnitude is determined by the density of the materials that constitute the structure.

The relevant equation of self-weight load:

$$W_c = \gamma_c * A$$

where,

W_c: self-weight load of gravity dam

γ_c is the unit weight of concrete, γ_c = 23.0 - 23.5 kN/m^3

A is the cross-sectional area of the structure.

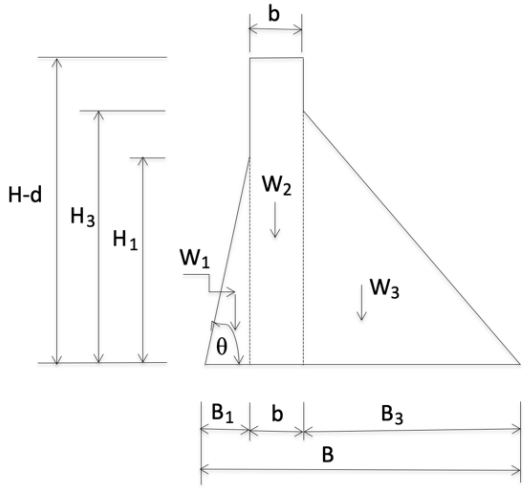


Figure A-8.20. Typical cross-section of gravity dam

Fig.A-8.20 shows a typical cross-section of gravity dam with a combination of downstream slope face and upstream slope face.

$$W_c = W1 + W2 + W3$$

$$W1 = ½ B_1 . H_1 . \gamma_c$$

$$W2 = b . H . \gamma_c$$

$$W3 = ½ B_3 . H_3 . \gamma_c$$

where,

B: Base width of dam (m);

b: Top width of dam (m);

H-d: Height of dam (m);

B_1: Width of the slope of the upstream face of the dam;

H_1: Height of the slope of the upstream face of the dam;

B_3: Width of the slope of the downstream face of the dam;

H_3: Height of the slope of the downstream face of the dam.

Moment of the self-weight load of the concrete dam about the toe of the dam is given as:

The load is considered to act through the centroid of the cross-sectional area of the dam.

Moment can be calculated by the equation:

Moment of a load = load * moment arm

where,

Moment (kNm)

Load (kN)

Moment arm (m): is the perpendicular distance between the line of action of the load and the center of moments.

Moment about the toe of the self-weight load of the dam is composed of the moment of W1, W2, and W3.

$$M_{wc} = M_{wc1} + M_{wc2} + M_{wc3}$$

Moment of W1: M_{wc1} = (+) W1 . $\left(B - \frac{2}{3}B_1\right)$

Moment of W2: M_{wc2} = (+) W2 . $\left(B_3 + \frac{b}{2}\right)$

Moment of W3: M_{wc3} = (+) W3 . $\frac{2}{3}B_3$

Rule to calculate the self-weight-load and its moment about the toe of the dam:

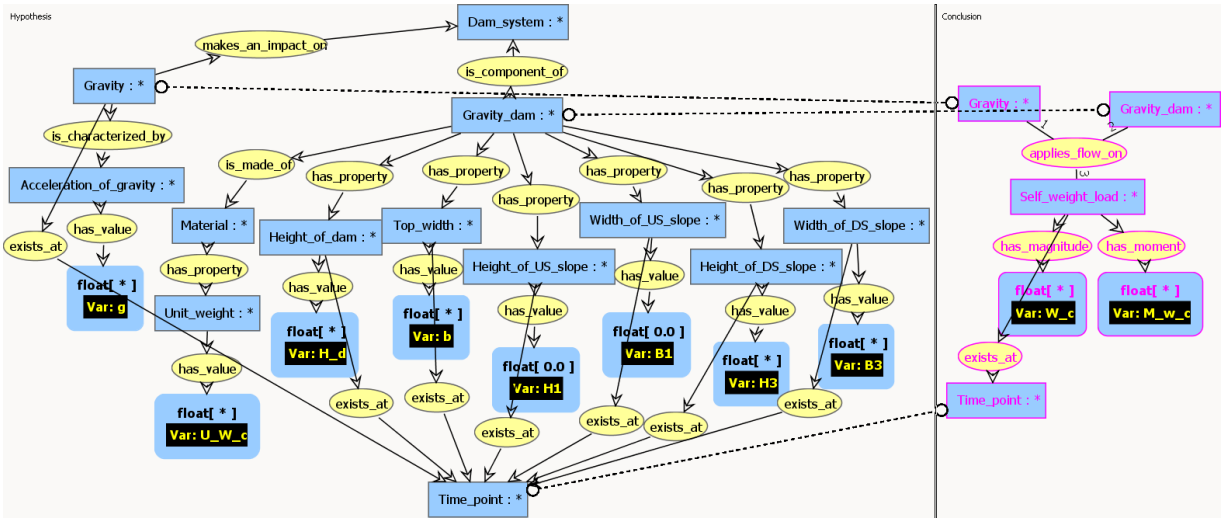


Figure A-8.21. Rule to compute self-weight load of gravity dam

Figure A-8.21 illustrates a rule graph for calculating the self-weight load of gravity dam. The load is computed based on the properties of dam material and geometrical parameters of the dam. The rule graph can be expressed as **if** *Gravity* makes an impact on *Dam_system*, and *Gravity_dam* is a component of *Dam_system*, **then** *Gravity* applies a self-weight load on *Gravity dam*. The resulting hydrodynamic load is set at the time point of the gravity dam. Figure A-8.22 shows the associated script.

Rule | Associated script

```
1  void after()
2  {
3      float value1 = U_W_c.getValue() * H1.getValue() * B1.getValue() / 2; // valu
4      float value2 = U_W_c.getValue() * H_d.getValue() * b.getValue(); // value2:
5      float value3 = U_W_c.getValue() * H3.getValue() * B3.getValue() / 2; // valu
6
7      float value4 = value1 * ((B1.getValue()/3) + b.getValue() + B3.getValue());/
8      float value5 = value2 * ((b.getValue()/2) + B3.getValue()); //value5: moment
9      float value6 = value3 * (B3.getValue() * 2/3); //value6: moment of W3 about
10
11     float value7 = value1 + value2 + value3;// value7: self-weight load of dam-b
12     float value8 = value4 + value5 + value6; // value8: moment of self-weight lo
13
14     W_c.setValue(value7);
15     M_w_c.setValue(value8);
16 }
```

Figure A-8.22. Script to compute self-weight load of gravity dam

8.2.1.2. Reservoir load (P)

Reservoir load (P) is the most major external force acting on a dam. Water applies pressure with a linear variation with depth. The deeper the water, the more horizontal pressure it exerts on the dam. So at the surface of the reservoir, the water is exerting no pressure, and at the bottom of the reservoir, the water is exerting maximum pressure. The total load exerted by the triangle equals the intergal of pressure; thus:

$$P = \frac{1}{2}\gamma_w H_{res}^2$$

where,

P : Reservoir load (kN)

γ_w : unit weight of water = 10 kN/m^3

H_{res} : Reservoir level (m)

Reservoir load acts at (1/3)H_{res} from the base.

Moment of reservoir load about the toe of the dam is given as:

$$M_r = (-)\ P * H_{res}/3$$

where,

M_r: Moment of reservoir load about the toe of the dam (kNm)

P: Reservoir load (kN)

H_{res} : Reservoir level (m)

Rule to calculate reservoir load and its moment about the toe of the dam:

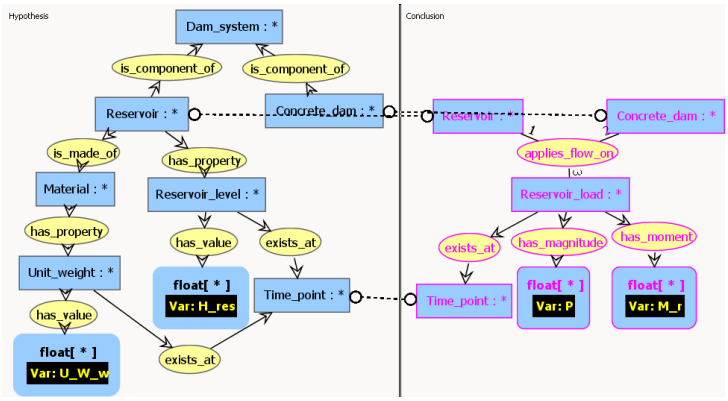


Figure A-8.23. Rule to calculate the reservoir load

Rule | Associated script

```
1  void after()
2  {
3      float value1 = U_W_w.getValue() * Math.pow(H_res.getValue(), 2.0);
4      float value2 = value1 * H_res.getValue()/3;
5
6      P.setValue(value1); // P: hydrostatic load
7      M_r.setValue(value2); // Moment of load
8  }
```

Figure A-8.24. Script of the rule calculating the reservoir load

The resulting graph (Figure A-8.23) shows an interaction between the reservoir and the concrete dam in a dam system. The resulting load is computed based on the properties of the reservoir. The condition for this interaction is expressed as **if** *Reservoir* and *Concrete dam* are components of *Dam system*, **then** *Reservoir load* will be exerted on *Concrete dam*. The time point of the resulting load is the time point of *Reservoir*. Figure A-8.24 shows the associated script.

8.2.1.3. Uplift load (U)

Uplift load is the second significant external load acting on a dam. Water penetrating along the cracks, fissures of the foundation material, or water seeping through the dam and then to the bottom through the joints between the dam and its foundation at the base; exert an uplift load on the base of the dam. Such an uplift load reduces the self-weight load of the dam and hence, acts against the dam stability (Garg, 2005).

The process of creating the uplift load is divided into two steps:

1. Water seeps into the foundation;

2. The seepage exerts a load on the dam's base, which considers as the interaction between the foundation and the dam.

The distribution of load through a horizontal section of the dam is assumed to vary linearly from a full hydrostatic head at the upstream face to zero at the downstream face, provided the dam has no drains or unlined water passages.

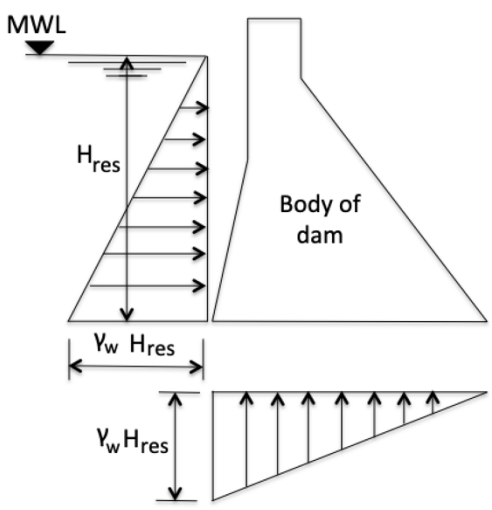


Fig (a) Uplift pressure diagram when no drainage gallery is provided

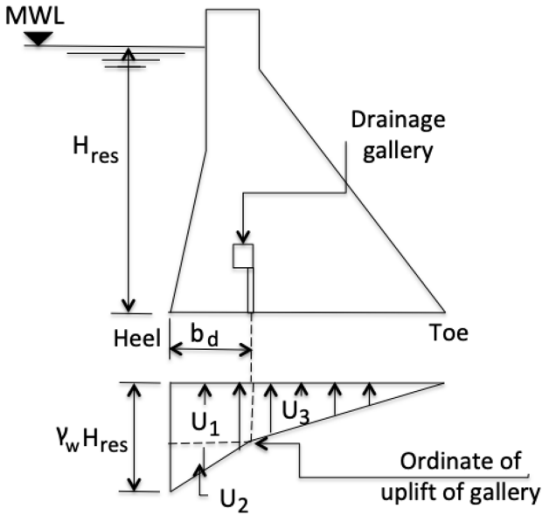


Fig (b) Uplift pressure diagram when drainage gallery is provided

Figure A-8.25. Uplift pressure

The equation to compute uplift load for dam without gallery drainage (Figure A-8.25a) is used:

$$U = ½\ \gamma_w * H_{res} * B$$

where, U : Uplift load (kN)

H_{res} : Reservoir level (m)

B : Base width of dam (m)

γ_w : unit weight of water = 10 kN/m^3

When drainage galleries are provided to relieve the uplift built up under the dam, the magnitude of the uplift pressure at the face of the gallery is equal to the hydrostatic pressure at the toe plus 1/3rd the difference the hydrostatic pressure at the heel and toe.

Uplift pressure at gallery

$$= \frac{1}{3}\gamma_w . H_{res}$$

with the assumption that there is no tailwater on the downstream side.

Uplift load when drainage is provided is calculated as follow :

$$U_d = U_1 + U_2 + U_3$$

$$U_1 = \frac{1}{3}\gamma_w . H_{res} . b_d$$

$$U_2 = \frac{1}{2} . \frac{2}{3}\gamma_w . H_{res} . b_d = \frac{1}{3}\gamma_w . H_{res} . b_d$$

$$U_3 = \frac{1}{2}(B - b_d) . \frac{1}{3}\gamma_w . H_{res} = \frac{1}{6}\gamma_w . H_{res} . (B - b_d)$$

Moment of uplift load about toe when drainage gallery is provided as follow:

$$M_{ud} = M_{u1} + M_{u2} + M_{u3}$$

$$M_{u1} = (-)\, U_1 . (B - \frac{b_d}{2})$$

$$M_{u2} = (-)\, U_2 . (B - \frac{b_d}{3})$$

$$M_{u3} = (-)\, U_3 . \frac{2}{3} . (B - b_d)$$

Moment of uplift load about toe is given as:

$$M_u = (-)\, U * 2/3\, B$$

where,

M_u: Moment of uplift load about the toe of the dam

U: Uplift load (kN)

B: Base width of dam (m)

Rule to calculate uplift load and its moment about the toe of the dam:

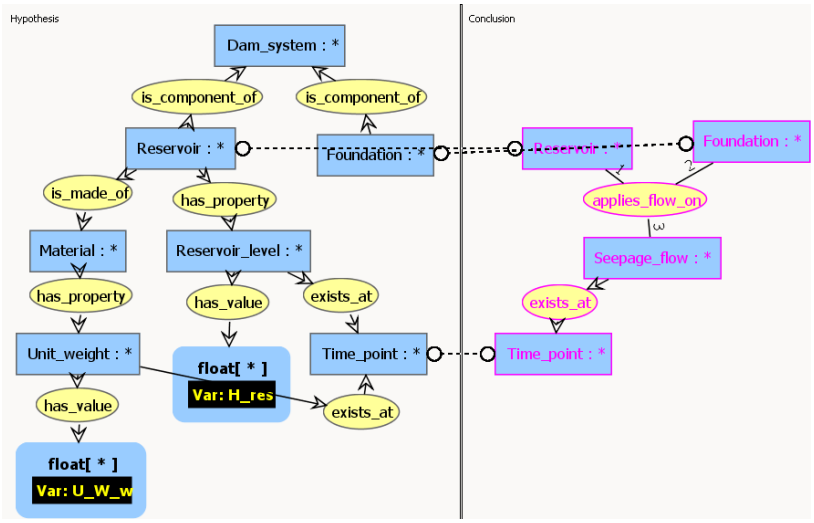


Figure A-8.26. The rule of the seepage flow in the foundation

Figure A-8.26 shows a rule graph of the interaction between the reservoir and foundation in a dam system. The graph can be explained as **if** *Reservoir* and *Foundation* are components of *Dam_system*, **then** *Reservoir* applies *Seepage flow* on *Foundation*. The quantity of the seepage flow is computed based on the properties of the reservoir. The time of the resulting flow is the time of the reservoir level.

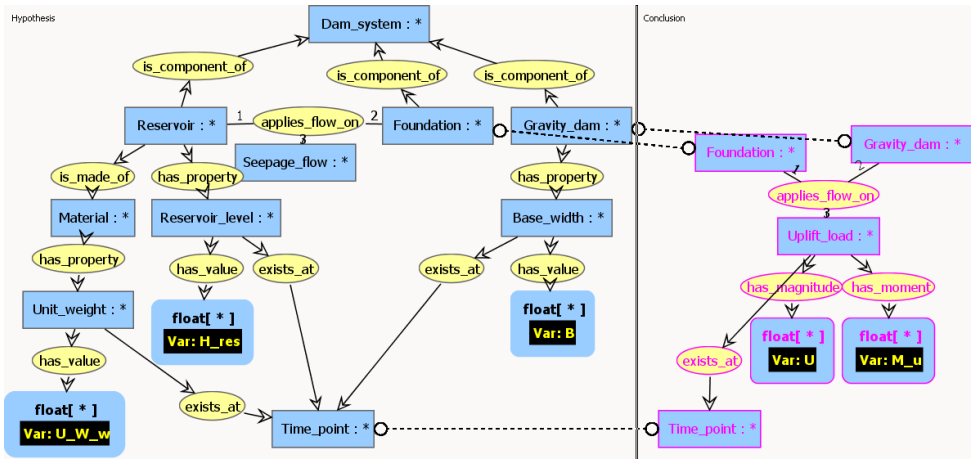


Figure A-8.27. The rule to compute the uplift load

The rule graph (Figure A-8.27) shows the interaction between the foundation and the gravity dam under the impact of the seepage flow in the foundation. The rule graph can be expressed in natural language as **if** *Reservoir* applies *Seepage flow* on *Foundation*, and *Reservoir*, *Foundation*, and *Gravity_dam* are components of *Dam_system*, then *Foundation* applies *Uplift_load* on *Gravity dam*. The uplift load is computed based on the relevant properties of the reservoir. The time of the resulting load is the time of the reservoir and the dam. Figure A-8.28 shows the associated script.

Rule | Associated script

```
1  void after()
2  {
3
4      float value1 = U_W_w.getValue() * H_res.getValue() * B.getValue()/2;
5      float value2 = value1  * (B.getValue() * 2/3);
6
7      U.setValue(value1);
8      M_u.setValue(value2);
9
10 }
```

Figure A-8.28. The script computing the uplift load

8.3. Failures of concrete dam

A concrete dam may fail in the following ways:

- By overturning (or rotating) about the toe
- By crushing
- By sliding or shear failure

8.3.1. Overturning

If the resultant of all the loads acting on a dam at any of its sections pass outside the toe, the dam shall rotate and overturn about the toe. The ratio of the righting moments about toe (anti-clockwise) to the overturning moments about toe (clock-wise) is called the factor of safety against overturning. Its value generally varies between 2 to 3.

The factor of safety against overturning as equal to

$$\frac{\sum Stabilising\ momen\ (+)}{\sum Disturbing\ moment\ (-)}$$

(+) sign is used for anti-clockwise moments

(-) sign is used for clockwise moments

Stabilizing moment: the moment of self-weight load (M_{w_c})

Disturbing moments: are included:

- Moment of reservoir load (M_r)
- Moment of uplift load (M_u)
- Moment vertical earthquake load (M_{e_v})
- Moment horizontal earthquake load (M_{e_h})
- Moment of earthquake hydrodynamic load (M_{e_d})

$$\text{Factor of safety against overturning} = \frac{M_{w_c}}{M_r+M_u+M_{e_v}+M_{e_h}+M_{e_d}}$$

Rule to calculate the measured level of the factor of safety against overturning:

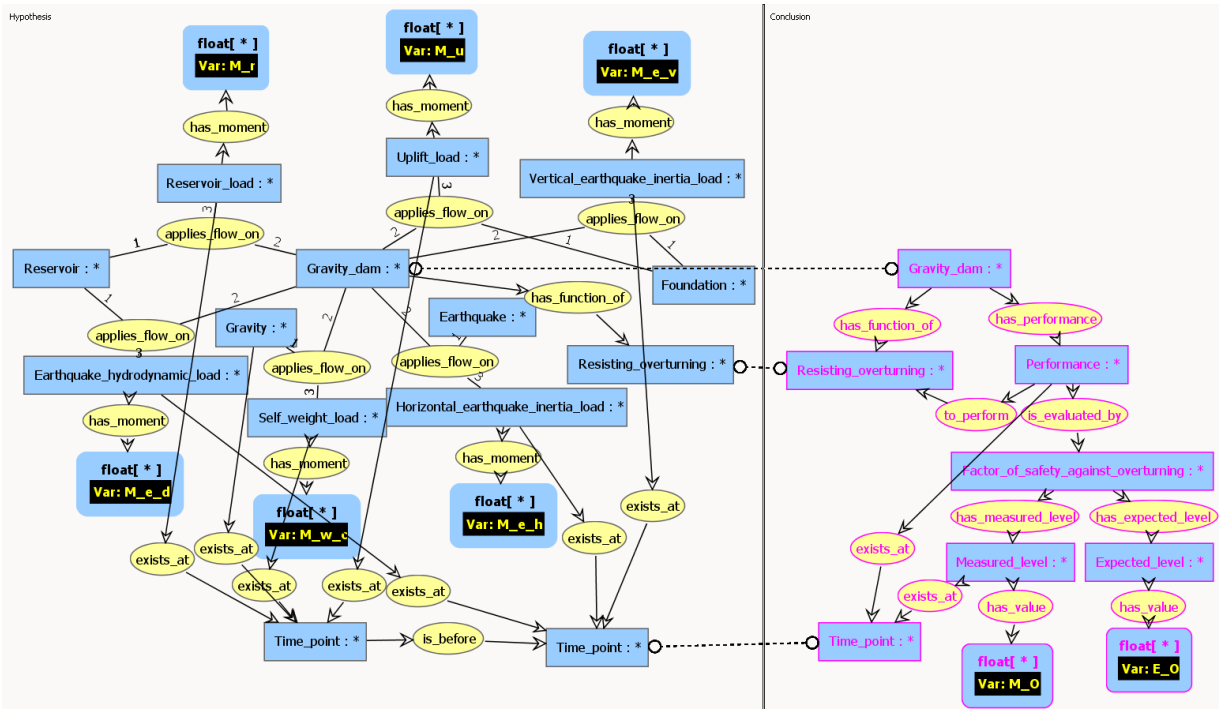


Figure A-8.29. Rule to calculate the measured level of the factor of safety against overturning

Figure A-8.29 shows a rule graph for calculating the measured level of the factor of safety against overturning. The measured level is computed based on moments of reservoir load, uplift load, vertical earthquake inertia load, earthquake hydrodynamic load, self-weight load, and horizontal earthquake inertia load. The time of the measured level and performance is

the time of the earthquake. The conclusion graph illustrates a graph for evaluating the performance of the function *Resisting overturning* of the gravity dam. Figure A-8.30 shows the associated script.

Script to calculate the measured level of factor of safety against overturning:

Rule | Associated script

```
1
2  void after()
3  {
4      float value = M_w_c.getValue()/(M_r.getValue()+ M_e_h.getValue() + M_u.getValue() + M_e_v.getValue() + M_e_d.getValue());
5      M_O.setValue(value);
6  }
```

Figure A-8.30. Script to calculate the measured level of factor of safety against overturning:

Overturning stability performance:

Overturning stability performance of the dam is considered by the factor of safety against overturning, which is the ratio of the stabilizing moments about toe (anti-clockwise) to the overturning moments about toe (clock-wise). If the value measured of the factor of safety less than the selected limit value, the dam will fail.

Rule to evaluate overturning stability performance:

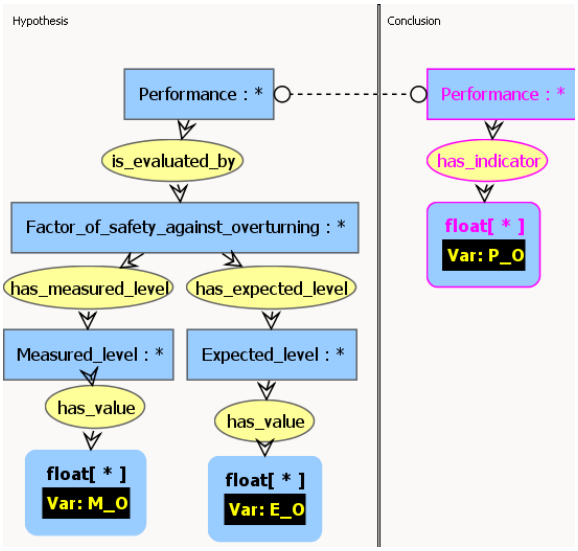


Figure A-8.31 Rule to identify the performance to resist overturning

Figure A-8.31 illustrates the identifying of the performance of a gravity dam to resist overturning. The rule graph can be explained as **if** *Performance* is evaluated by *Factor of safety against overturning* which has *Measured level* and *Expected level*, **then** *Performance* has an indicator".

Script to evaluate the overturning stability performance:

Rule | Associated script

```
1  void after()
2  {
3      if (M_O.getValue() < E_O.getValue()){
4          P_O.setValue(0);
5      }
6      else {
7          P_O.setValue(1);
8      }
9  }
```

Figure A-8.32. Script to identify the performance to resist overturning

8.3.2. Compression or crushing

A dam may fail by the failure of its materials, i.e., the compressive stresses produced may exceed the compressive strength, and the dam-material may get crushed. The vertical direct stress distribution at the base is given by the equation:

$$\text{p} = \text{Direct stress} + \text{Bending stress}$$

$$p_{\frac{max}{min}} = \frac{\sum V}{B}\left[1 \pm \frac{6e}{B}\right]$$

where, e = Eccentricity of the resultant load from the center of the base

ΣV: Total vertical load

B = Base width

$$e = \frac{B}{2} - \bar{x}$$

where $\bar{x}$ is the distance from the resultant load to the toe, determines the location of the resulting load.

$$\bar{x} = \frac{\sum M}{\sum V}$$

where,

ΣM: The algebraic sum of the moments of all loads about the toe.

ΣV: The algebraic sum of all the vertical loads acting on the dam.

The positive sign will be used for calculating vertical stress at the toe since the bending stress will be compressive there, and a negative sign will be used for calculating vertical stress at the hee. The maximum compressive stress occurs at the toe, and for safety, this should not be greater than the allowable compressive stress for the material.

For concrete, the compressive strength was taken as 3000 kN/m^2.

Rule to calculate vertical stresses:

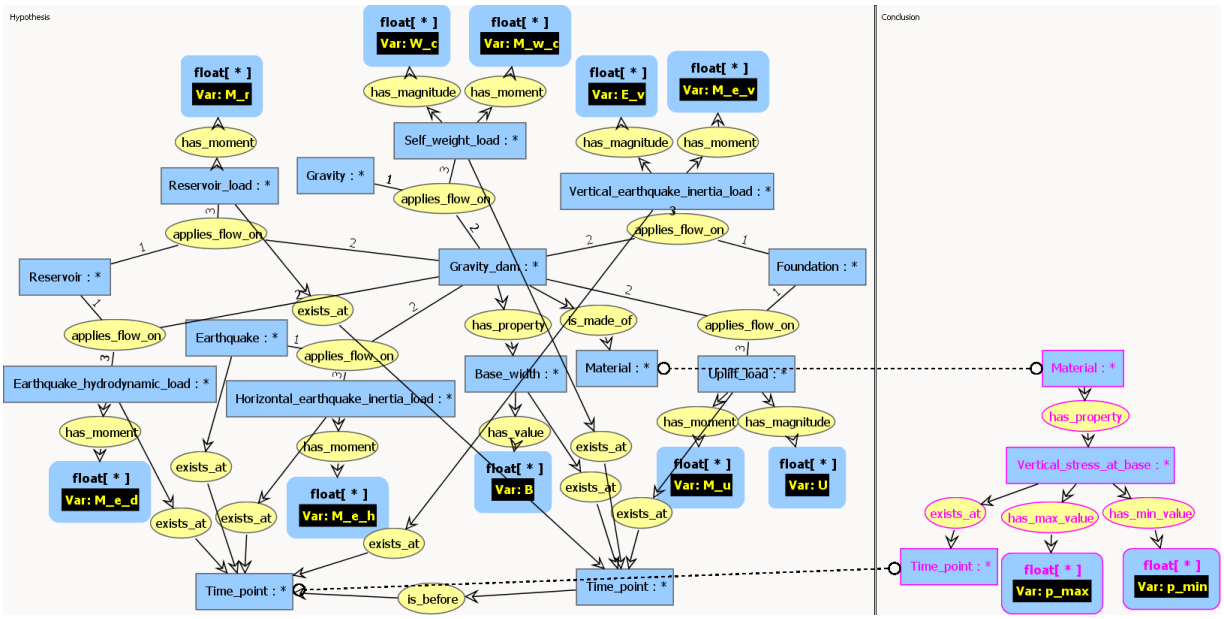


Figure A-8.33. Rule to calculate vertical stress

The rule graph is shown in Figure A-8.33 calculating vertical stress at the base of the gravity dam. The vertical stress is computed based on reservoir load, self-weight load of dam, vertical earthquake inertia load, uplift load, horizontal earthquake inertia load, earthquake hydrodynamic load, and base width of the gravity dam. The time of stress is the time of the earthquake. The rule graph can be expressed as:

If *Gravity dam* subjects to *Reservoir load* and *Earthquake hydrodynamic load* from *Reservoir*, *Vertical earthquake inertia load* and *Uplift load* from *Foundation*, and *Gravity dam* has *Self-weight load*, **then** *Material* constituted the dam has *Vertical stress at the base*. Figure A-8.34 exposes the associated script.

Rule | Associated script

```
1  void after()
2  {
3      float M = M_w_c.getValue() - M_r.getValue() - M_e_d.getValue() - M_u.getValue() - M_e_v.getValue() - M_e_h.getValue();
4      float V = W_c.getValue()- U.getValue()-E_v.getValue();
5      float x = M/V;
6      float e = (B.getValue()/2)-x;
7
8      p_max.setValue(V/B.getValue()*(1+6*e/B.getValue()));
9      p_min.setValue(V/B.getValue()*(1-6*e/B.getValue()));
10 }
```

Figure A-8.34. Script to calculate vertical stress

Principal stress at the toe

The vertical stress intensity, $p_{max,}$ or p_{min} is not the maximum direct stress produced anywhere in the dam. The maximum normal stress will be the significant principal stress that will be generated on the significant principal plane.

Consider an elementary triangular section at either the heel or the toe of the dam section such that stress intensity may be assumed to be uniform on its faces. The face of the dam will act as a principal plane because the water pressure acts on it in the perpendicular direction, with no accompanying shear stress. Since the principal plane is at right angles to

each other, the plane AB drawn at right angles to the face AC will be the second principal plane.

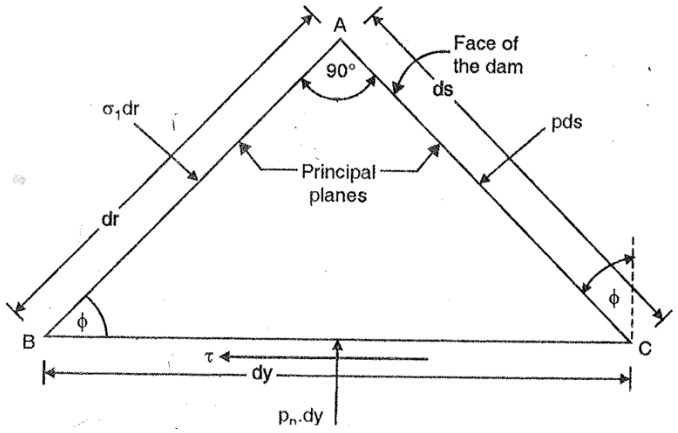


Figure A-8.35. Elementary triangular section

Consider an elementary triangular section at either the heel or the toe of the dam section such that stress intensity may be assumed to be uniform on its faces. The face of the dam will act as a principal plane because the water pressure acts on it in the perpendicular direction, with no accompanying shear stress. Since the principal plane is at right angles to each other, the plane AB drawn at right angles to the face AC will be the second principal plane.

The principal stress is given by:

$$\sigma = p_v . sec^2_{\emptyset}$$

Principal stress at the toe is

$$\sigma = p_{max} . sec^2_{\emptyset}$$

where,

p_v: vertical stress

p_{max}: maximum vertical stress

$\emptyset$: the angle which the downstream face of the dam makes with vertical

Rule to calculate the principal stress at toe:

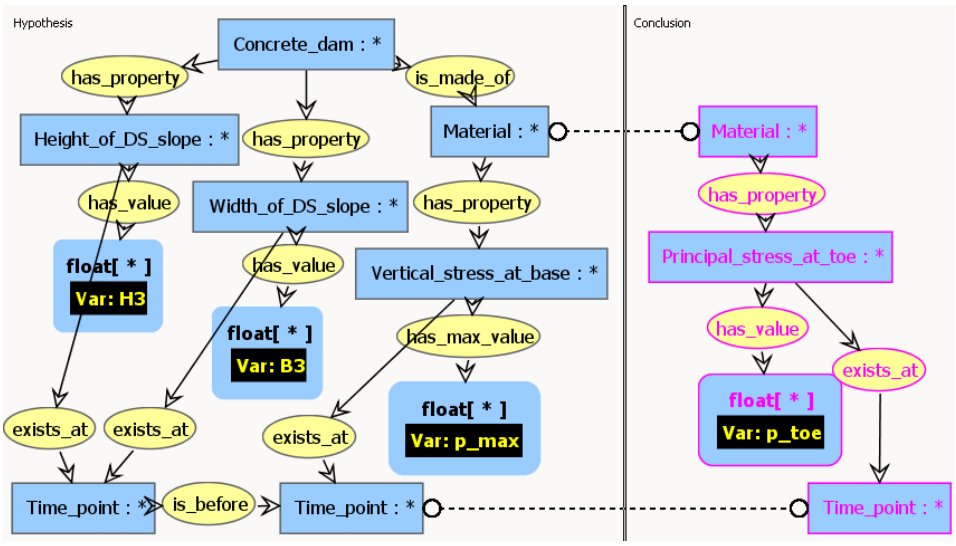


Figure A-8.36. Rule to calculate the principal stress at toe

The rule graph in Figure A-8.36 computes the principal stress at the toe of the gravity dam. It can be explained as **if** *Concrete dam* has *Downstream_angle* and *Material* has maximum *Vertical stress at the base*, then *Material* has *Principal stress at the toe*. The time point of the principal stress is the time point of properties of the gravity dam. Figure A-8.37 shows the associated script.

Rule | Associated script

```
1  void after()
2  {
3      float value1 = p_max.getValue()* (1+ Math.pow((B3.getValue()/H3.getValue()),2));
4
5      p_toe.setValue(value1);
6
7  }
```

Figure A-8.37. Script to calculate the principal stress at the toe

Since $sec_{\emptyset}^{2}$ is always more than 1, it follows that principal stress will be more than normal stress. The principal stress, which is the maximum produced anywhere in the dam, should not be allowed to exceed the maximum allowable compressive stress of dam material.

Factor of safety against compression

$$\text{F.S.C} = \frac{Principal\ stress}{Compressive\ strength}$$

Limit condition for compression resistance:

if measured F.S.C > Limit F.S.C = 1: the dam may crush and fail by crushing.

if measured F.S.C ≤ Limit F.S.C = 1: no compression take place

Rule to calculate the measured level of the factor of safety against compression:

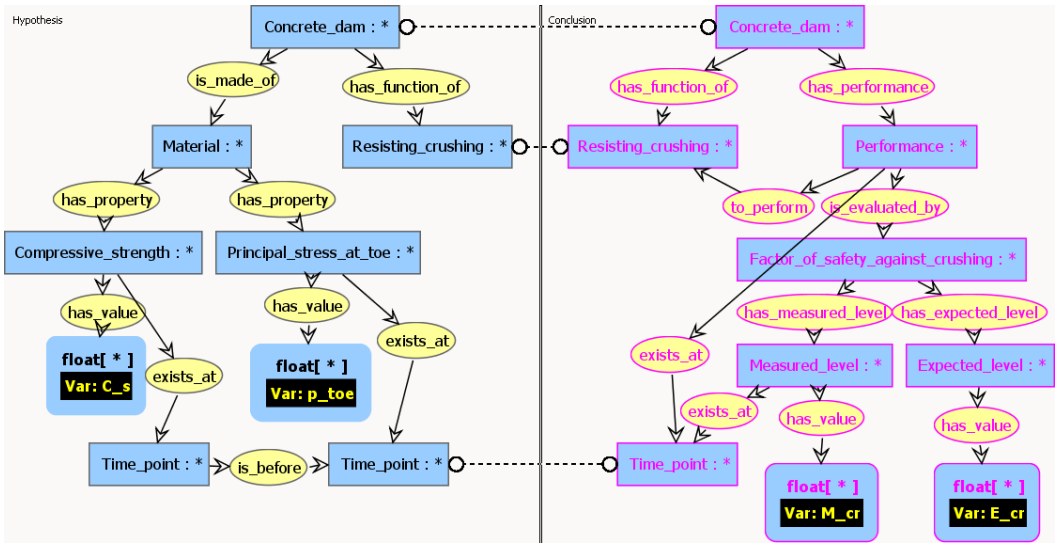


Figure A-8.38. Rule calculating the measured level of F.S against compression

Figure A-8.38 shows a rule graph for calculating the measured level of the factor of safety against crushing. The measured level is computed based on compressive strength and vertical stress at the base. The rule graph can be interpreted as **if** *Concrete dam* is made of *Material* with *Compressive strength* and *Principal stress at toe*, and *Concrete dam* has the function of *Resisting crushing* **then** *Performance* to perform *Resisting crushing* is evaluated by *Factor of safety against crushing* which has *Measured level* and *Expected level*. Figure A-8.39 exposes the associated script.

Rule | Associated script

```
1  void after()
2  {
3      float value = p_toe.getValue() / C_s.getValue();
4      M_cr.setValue(value);
5  }
```

Figure A-8.39. Script calculating the measured level of F.S against compression

Performance of the dam to resist crushing:

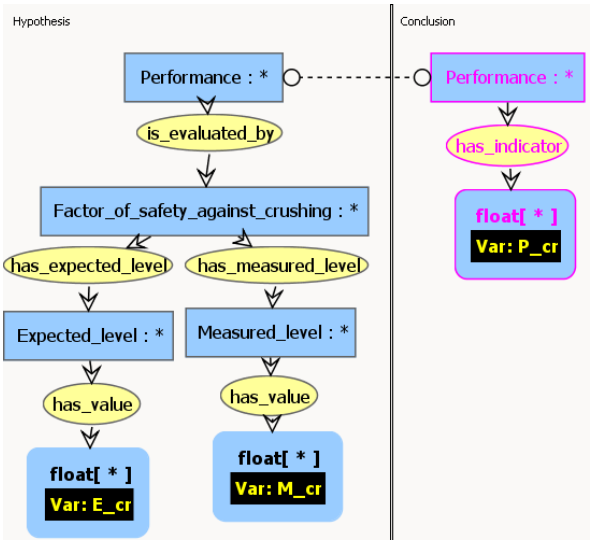


Figure A-8.40. Rule to evaluate performance resisting crushing

Figure A-8.40 shows the performance of the factor of safety against crushing. The rule graph can be expressed as **if** *Performance* is evaluated by *Factor of safety against crushing* which has *Expected level* and *Measured level*, then *Performance* has an indicator. Figure A-8.41 shows the associated script.

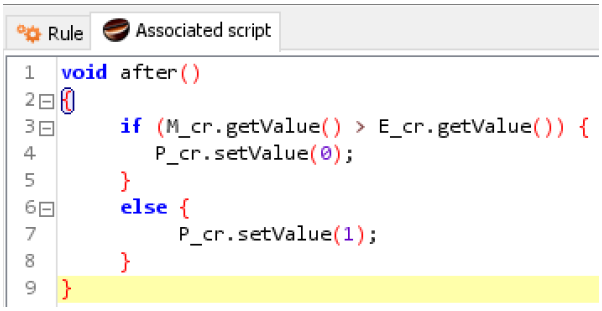


Figure A-8.41. Script to evaluate performance resisting crushing

8.3.4. Sliding

Sliding (or shear failure) will occur when the friction angle of material developed at the interface of the dam base and the foundation exceeds the limit frictional angle.

Forces apply :

- Uplift load : U
- Self-weight load : W
- Hydrostatic pressure : P
- Earthquake hydrodynamic load: E_{dr}
- Horizontal earthquake inertia load: E_h
- Vertical earthquake inertia load: E_v
- Resultant force: R'

The resultant force is the component applied by the foundation on the dam base, which refers to the effective value as the uplift load is taken a part. One could also write :

$$\vec{U} + \dot{\overrightarrow{R'}} = \vec{R}$$

$$\overrightarrow{W} + \vec{P} + \vec{U} + \overrightarrow{R'} = 0$$

$$\tan \alpha = \frac{R_{hor}}{R_{ver}} \Rightarrow \alpha = \arctan\left(\frac{R_{hor}}{R_{ver}}\right) = \arctan\left(\frac{P+E_{dr}+E_h}{W-U-E_v}\right)$$

The measured level of factor of safety against sliding $= \frac{\alpha}{\beta}$

where,

α: friction angle of material developed at the interface of the dam base and the foundation

β: limit frictional angle

The measured level of factor of safety against sliding

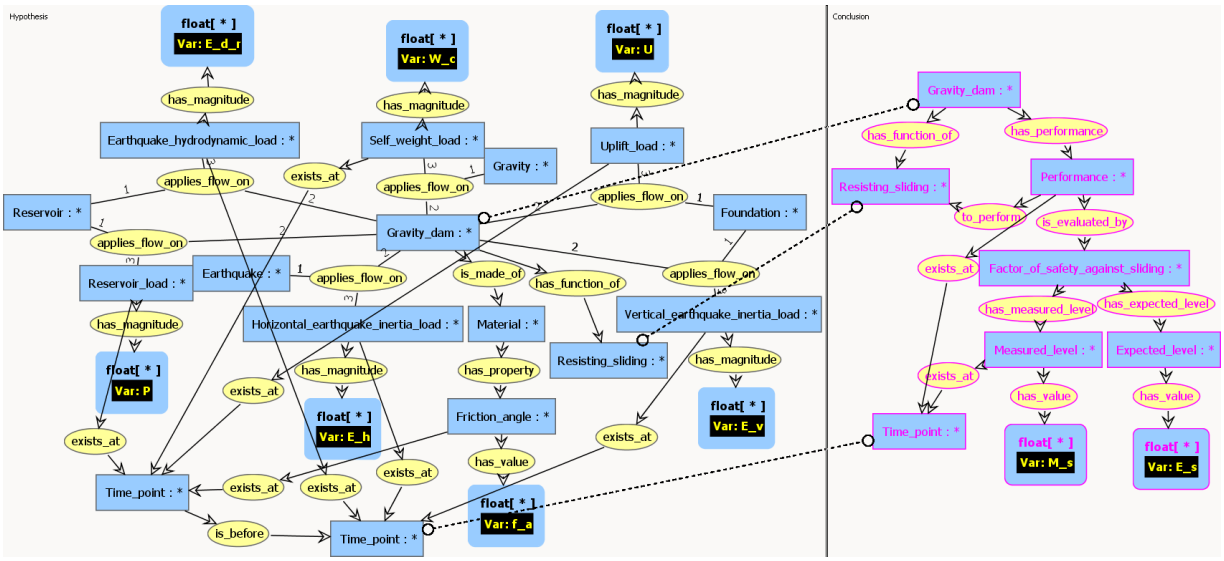


Figure A-8.42. Rule to calculate the measured level of factor of safety against sliding

The rule graph in Figure A-8.42 shows a rule calculation of the measured level of factor of safety against sliding. The factor is computed based on Reservoir load, earthquake hydrodynamic load, self-weight load, uplift load, vertical earthquake inertia load, horizontal earthquake inertia load, and friction angle of the material. The time of performance and measured level is the time of the earthquake. Figure A-8.43 shows the associated script.

Rule | Associated script

```
1  void after()
2  {
3      rad=Math.atan((P.getValue() + E_d_r.getValue() + E_h.getValue()) /(W_c.getValue()-U.getValue() - E_v.getValue()));
4
5      float value1 = rad*180/Math.PI; // measured friction angle
6      float value2 = value1/f_a.getValue(); // measured level
7      M_s.setValue(value2);
8  }
```

Figure A-8.43. Script to calculate the measured level of factor of safety against sliding

Sliding stability performance

Limit condition for sliding stability:

if $\frac{\alpha}{\beta} > 1$: dam fail by sliding

if $\frac{\alpha}{\beta} < 1$: no sliding take place

Rule to calculate the performance of the gravity dam to resist sliding

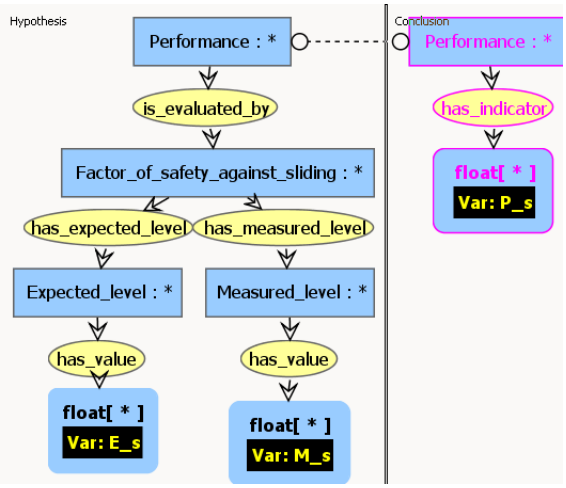


Figure A-8.44. Rule to calculate the performance of the gravity dam to resist sliding

Figure A-8.44 shows the calculation of the indicator of the performance of gravity to resist sliding. It is computed based on the expected level and measured level of the factor of safety against sliding. The rule graph can be expressed as **if** *Performance* is evaluated by *Factor of safety against sliding,* which has *Expected level* and *Measured level*, then *Performance* has an indicator. Figure A-8.45 shows the associated script**.**

Rule | Associated script

```
1  void after()
2  {
3      if (M_s.getValue() > E_s.getValue()) {
4          P_s.setValue(0);
5      }
6      else {
7          P_s.setValue(1);
8      }
9  }
```

Figure A-8.45. Script to calculate the performance of the gravity dam to resist sliding

8.4. Interactions and performances of embankment dam

8.4.1. Phreatic line and self-weight load for a homogeneous dam with a horizontal filter and area of the dam section

Line of seepage or phreatic line or saturation line is defined as the line within the dam section below which there are positive hydrostatic pressures in the dam.

The hydrostatic pressure on the phreatic line is equal to the atmospheric pressure and hence, equal to zero.

Determining the position and shape of the phreatic line will enable us to determine a divider line between the dry (or moist) and submerged soil. The soil above the seepage line will be taken as dry, and the soil below the seepage line shall be taken as submerged for computation of shear strength of the soil.

Let consider the graphical method of the determination of the phreatic line by the Casagrande method. Casagrande assumed the phreatic line to be a base parabole focusing at F, taking at the left end of the horizontal filter and as the origin.

AB is the upstream face. Its horizontal projection is L. The directrix HD of the parabola is located by the principle that distance from focus and directrix must be equal.

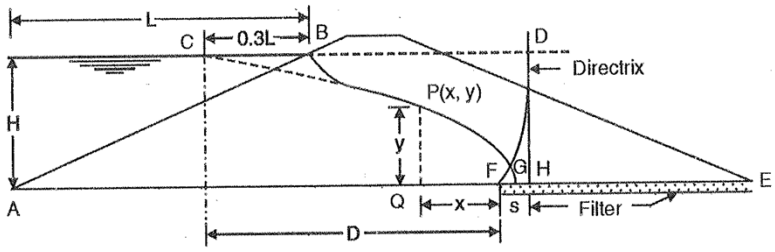


Figure A-8.46. The phreatic line of the homogeneous dam with horizontal drainage

The equation of the base parabola is given by

$$\sqrt{x^2 + y^2} = x + S$$

where S is the distance of the point (x,y) from the directrix, called focal distance

x,y : are the co-ordinates of any point on the parabola

a) Determine the start-point of the parabola: point C

The parabola cuts the reservoir water surface at point C in such a way that

$$BC = 0.3\ L$$

Plot point C at a distance 0.3L from B (fig. 1).

The coordinates of the point C concerning F as origin are:

x_C = AE – EF = Base width of dam - Filter width

y_C = Reservoir level

b) Determine the vertex G of the parabola:

From the equation of the base parabola: $\sqrt{x^2 + y^2} = x + S$

$$\Rightarrow \quad S = \sqrt{x^2 + y^2} - x \qquad [2]$$

⇨ The vertex (G) of the base parabola shall be situated at a distance equal to $\frac{S}{2}$ or $\frac{\sqrt{x^2+y^2}-x}{2}$ beyond the point F.

The directrix shall be at a distance ($\sqrt{x^2 + y^2} - x$) from F, as shown in Fig.1.

At point F, $x_F = 0$, $y_F = S$.

Locating the intermediate points on the parabola using the principle that their distance from the focus is equal to their distance from the directrix. Joint all these points to draw the

base parabola and correct the entry point B so that the phreatic line comes ⊥ to the upstream face of the dam.

c) Compute area of the dam section

The total area of dam section : = ½ (B + b) * H

where,

B: Base width of dam (m)

b: Top width of dam (m)

H: Height of dam (m)

The phreatic line separates the saturated and unsaturated zones. The area below the seepage line is approximately the area of triangle ABG (fig. 1)

$$= \frac{1}{2} AG * H_{res}$$

$$= \frac{1}{2}\left(B - Filter\ width + \frac{S}{2}\right) * H_{res} \qquad [4]$$

where,

H_{res} : Reservoir level (m)

S: Focal distance (m)

The area above the seepage line = Total area of dam section – Area below the phreatic line

$$= ½ (B + b) * H - \frac{1}{2}\left(B - Filter\ width + \frac{S}{2}\right) * H_{res}$$

Weight of the dry portion of the dam section = Area above the phreatic line * γ_{dry}

where,

γ_{dry} : Dry unit weight of the soil in the dam (kN/m^3)

Weight of the submerged portion of the dam section = Area below the phreatic line * γ_{sub}

where,

γ_{sub} : Submerged unit weight of the soil in the dam (kN/m^3)

Submerged unit weight of soil (γ_{sub}) is defined as the unit weight of saturated soil minus the unit weight of water.

Submerged (Buoyant unit weight)

γ_{sub} = Weight of soil inside the water / Total volume

The dry unit weight of soil (γ_{dry}) is defined as the unit weight when the moisture content of the soil is 0.

Saturated soil when the volume of water is equal to the volume of voids in a soil mass.

Total weight of dam

= Area above the phreatic line * γ_{dry} + Area below the phreatic line * γ_{sub}

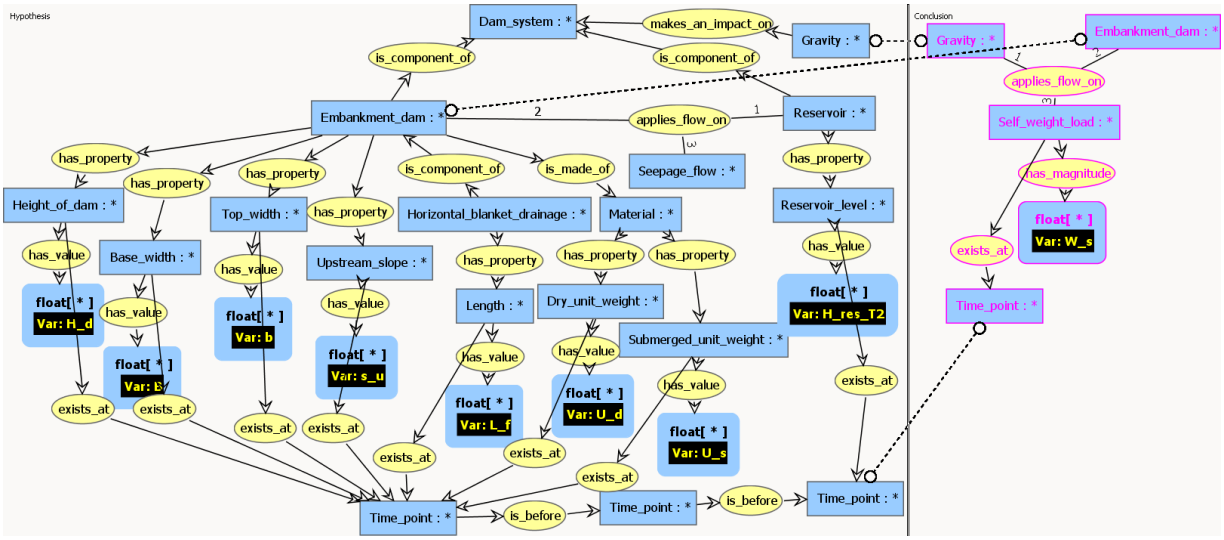


Figure A-8.47. Rule to calculate the self-weight load of a homogeneous dam with horizontal blanket drainage

Figure A-8.47 shows the calculation of the self-weight load of an embankment dam with horizontal blanket drainage. The self-weight load is computed based on geometrical parameters of the embankment dam, horizontal blanket drainage, and reservoir, and properties of embankment material. The rule graph can be expressed as **if** *Embankment dam* and *Reservoir* are components of *Dam system*, *Embankment dam* applies *Seepage flow* on *Reservoir*, and *Gravity* makes an impact on *Dam_system*, then *Gravity* applies *Self-weight load* on *Embankment dam*. The time point of the load is the time point of the reservoir property. Figure A-8.48 shows the associated script.

Rule | Associated script

```
void after()
{
    float value1 = H_res_T2.getValue() * s_u.getValue(); // value1 = L
    float value2 = (B.getValue() - (0.7*value1) - L_f.getValue()); // value2 = x_C
    float value3 = (Math.sqrt(Math.pow(value2,2) + Math.pow(H_res_T2.getValue(),2))) - value2;

    float value4 = (B.getValue() + b.getValue()) * H_d.getValue()/2; // value4 = Total area of
    float value5 = (B.getValue() - L_f.getValue() + value3/2) * H_res_T2.getValue()/2; // value
    float value6 = value4 - value5; // value6 = Dry area

    float value7 = value5 * U_s.getValue(); // value7 = selfweight of submerged area (kN)
    float value8 = value6 * U_d.getValue(); // value8 = selfweight of dry area (kN)
    float value9 = value7 + value8; // value 9 = Total selfweight of dam (kN)

    W_s.setValue(value9);
}
```

Figure A-8.48. Script to calculate the self-weight load of a homogeneous dam with horizontal blanket drainage

8.4.2. Phreatic line and self-weight load for a homogeneous dam without horizontal blanket drainage

The phreatic line can be determined on the same principles as was done for a dam with a horizontal drainage filter case.

The focus (F) of the parabola will be the lowest point of the downstream slope.

The base parabola will cut the downstream slope at J and extend beyond the dam toe up to the point G (i.e., the vertex of the parabola)

The seepage line will, however, emerge out at K, meeting the downstream face tangentially there. The portion KF is known as discharge face and always remains saturated. The correction JK (say Δa) by which the parabola is to be shifted downward can be determined.

Let α be the angle which the discharge face makes with the horizontal.

(a + Δa) is the distance J_oH. a and Δa can be connected by a general equation

$$\Delta a = (a + \Delta a)\left[\frac{180^0 - \alpha}{400^0}\right]$$

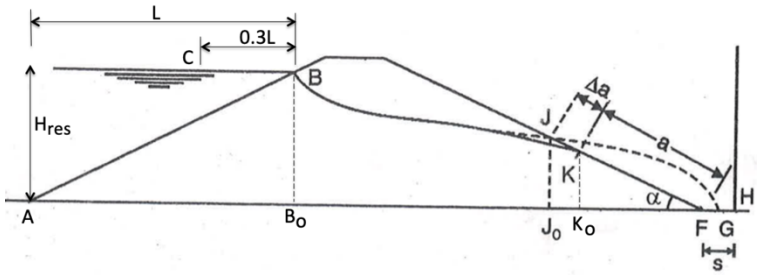


Figure A-8.49. Phreatic line for homogeneous dam without filter

If $\alpha < 30^o$: $a = \frac{b\prime}{cos\alpha} - \sqrt{\frac{b\prime^2}{cos^2\alpha} - \frac{H_{res}^2}{sin^2\alpha}}$

If $30^o \leq \alpha < 60^o$: $a = \sqrt{b^2 + H_{res}^2} - \sqrt{b^2 - H_{res}^2 cot^2\alpha}$

The area below the seepage line is approximately a total of

Area of triangle KK_oF + Area of triangle ABB_o + Area of trapezoid BB_oK_oK

The area of $ABB_o = \frac{1}{2}\, AB_o * BB_o = \frac{1}{2} H_{res}^2 * s_u$

where,

H_{res} : Reservoir level (m)

s_u : Upstream slope

The area of $KK_oF = \frac{1}{2} KK_o * K_oF$ = ½ (a.sinα * a.cosα)

where,

a is the distance KF

S : Focal distance (m)

α : is the angle which the discharge face makes with the horizontal

The area of trapezoid BB_oK_oK

$= \frac{1}{2}(KK_o + BB_o)B_oK_o$ = ½ [a.sinα + (B - L - a.cosα)]

where,

B: Base width of dam (m)

The area below the phreatic line

$= \frac{1}{2}H_{res}^2 * s_u$ + ½ (a.sinα * b.cosα) + ½ [a.sinα + (B-L-a.cosα)]

The total area of dam section = ½ (B + b) * H

where,

b: Top width of dam (m)

H: Height of dam (m)

The area above the phreatic line:

= The total area of dam section - area below the phreatic line

= ½ (B + b) * H - $\frac{1}{2}H_{res}^2 * s_u$ + ½ (a.sinα * a.cosα) + ½ [a.sinα + (B – L - a.cosα)]

Weight of the dry portion of the dam section

= Area above the phreatic line * γ_{dry}

where,

γ_{dry} : Dry unit weight of the soil in the dam (kN/m^3)

Weight of the submerged portion of the dam section

= Area below the phreatic line * γ_{sub}

where,

γ_{sub} : Submerged unit weight of the soil in the dam (kN/m^3)

Total weight of dam

= Area above the phreatic line * γ_{dry} + Area below the phreatic line * γ_{sub}

Rule to calculate self-weight load for a homogeneous dam without filter

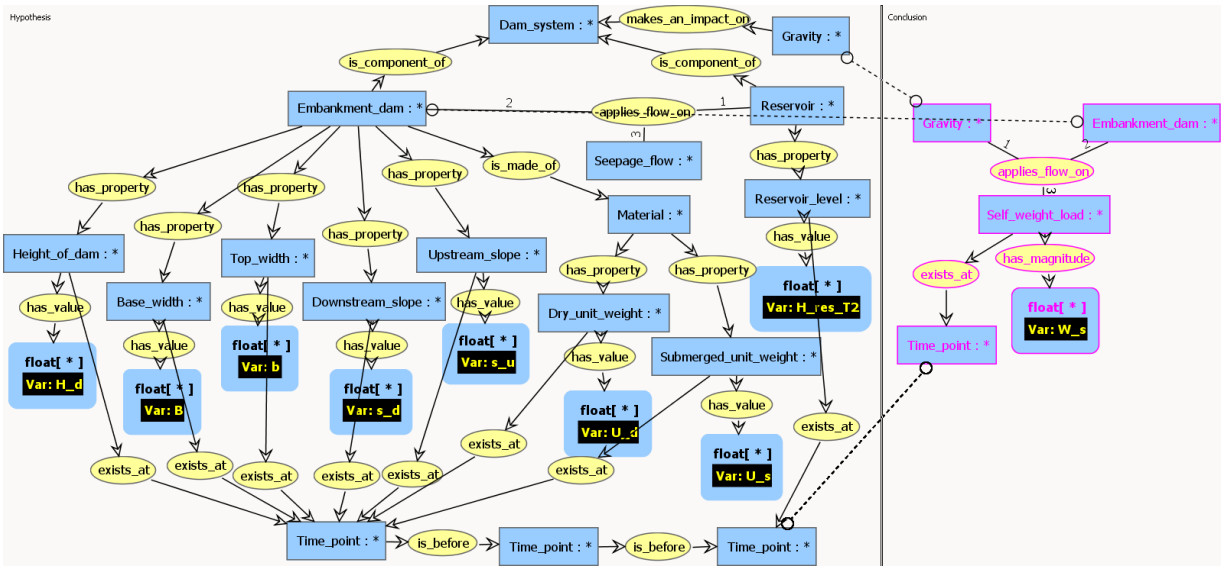
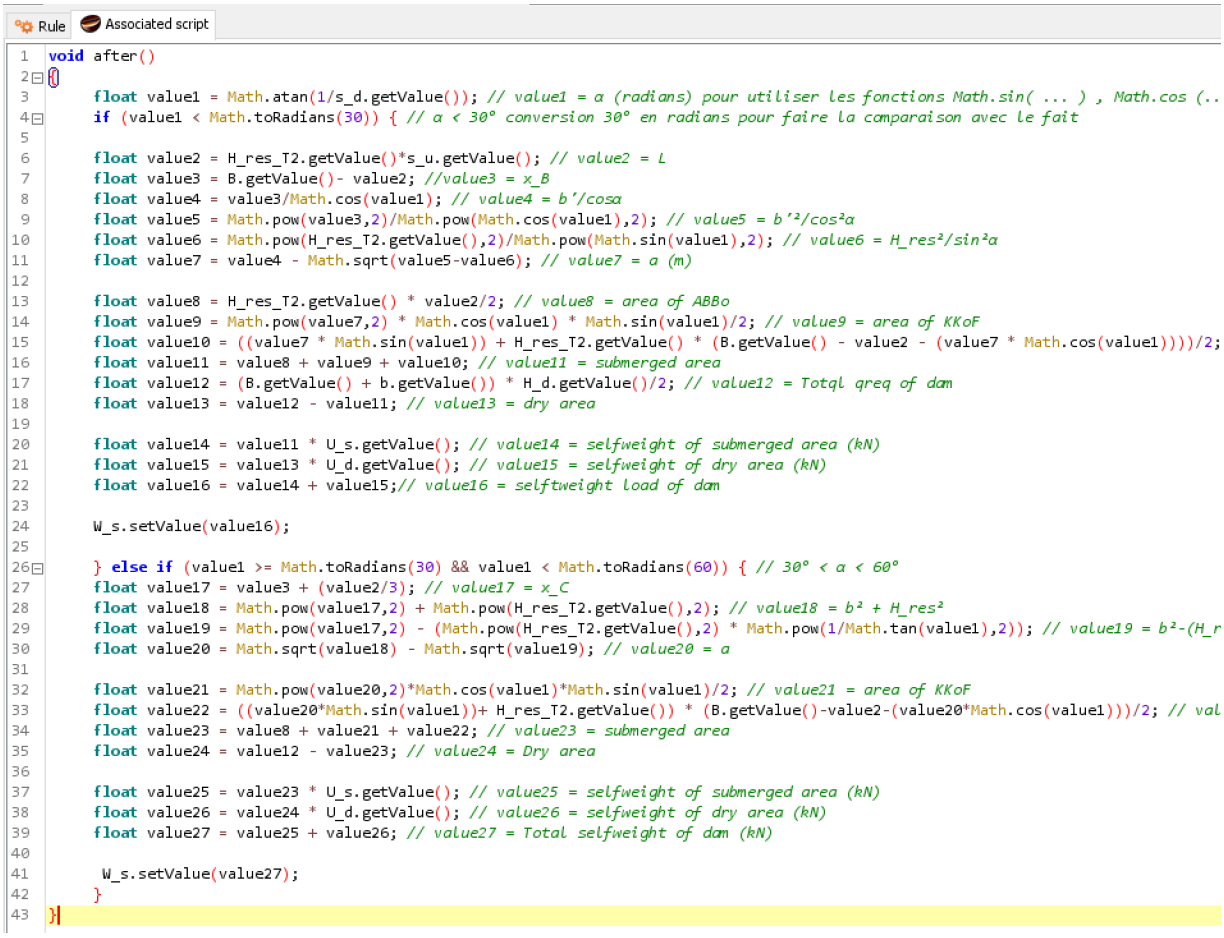


Figure A-8.50. Rule of the self-weight load of homogeneous without horizontal blanket drainage

The rule graph in Figure A-8.50 shows the self-weight load of an embankment dam without horizontal blanket drainage. The load is computed based on the relevant geometrical parameters of the embankment dam and properties of embankment material, with the level of the reservoir. The rule graph can be explained as **if** *Embankment dam* and *Reservoir* are components of *Dam system*, *Reservoir* applies *Seepage flow* on *Embankment dam*, and *Gravity* makes an impact on Dam *system*, then *Gravity* applies *Self-weight load* on *Embankment dam*. The time of load is the time of reservoir level. Figure A-8.51 shows the associated script.



```
Rule  Associated script
1  void after()
2  {
3      float value1 = Math.atan(1/s_d.getValue()); // value1 = α (radians) pour utiliser les fonctions Math.sin( ... ) , Math.cos (..
4      if (value1 < Math.toRadians(30)) { // α < 30° conversion 30° en radians pour faire la comparaison avec le fait
5
6      float value2 = H_res_T2.getValue()*s_u.getValue(); // value2 = L
7      float value3 = B.getValue()- value2; //value3 = x_B
8      float value4 = value3/Math.cos(value1); // value4 = b'/cosα
9      float value5 = Math.pow(value3,2)/Math.pow(Math.cos(value1),2); // value5 = b'²/cos²α
10     float value6 = Math.pow(H_res_T2.getValue(),2)/Math.pow(Math.sin(value1),2); // value6 = H_res²/sin²α
11     float value7 = value4 - Math.sqrt(value5-value6); // value7 = a (m)
12
13     float value8 = H_res_T2.getValue() * value2/2; // value8 = area of ABBo
14     float value9 = Math.pow(value7,2) * Math.cos(value1) * Math.sin(value1)/2; // value9 = area of KKoF
15     float value10 = ((value7 * Math.sin(value1)) + H_res_T2.getValue() * (B.getValue() - value2 - (value7 * Math.cos(value1))))/2;
16     float value11 = value8 + value9 + value10; // value11 = submerged area
17     float value12 = (B.getValue() + b.getValue()) * H_d.getValue()/2; // value12 = Totql qreq of dam
18     float value13 = value12 - value11; // value13 = dry area
19
20     float value14 = value11 * U_s.getValue(); // value14 = selfweight of submerged area (kN)
21     float value15 = value13 * U_d.getValue(); // value15 = selfweight of dry area (kN)
22     float value16 = value14 + value15;// value16 = selftweight load of dam
23
24     W_s.setValue(value16);
25
26     } else if (value1 >= Math.toRadians(30) && value1 < Math.toRadians(60)) { // 30° < α < 60°
27     float value17 = value3 + (value2/3); // value17 = x_C
28     float value18 = Math.pow(value17,2) + Math.pow(H_res_T2.getValue(),2); // value18 = b² + H_res²
29     float value19 = Math.pow(value17,2) - (Math.pow(H_res_T2.getValue(),2) * Math.pow(1/Math.tan(value1),2)); // value19 = b²-(H_r
30     float value20 = Math.sqrt(value18) - Math.sqrt(value19); // value20 = a
31
32     float value21 = Math.pow(value20,2)*Math.cos(value1)*Math.sin(value1)/2; // value21 = area of KKoF
33     float value22 = ((value20*Math.sin(value1))+ H_res_T2.getValue()) * (B.getValue()-value2-(value20*Math.cos(value1)))/2; // val
34     float value23 = value8 + value21 + value22; // value23 = submerged area
35     float value24 = value12 - value23; // value24 = Dry area
36
37     float value25 = value23 * U_s.getValue(); // value25 = selfweight of submerged area (kN)
38     float value26 = value24 * U_d.getValue(); // value26 = selfweight of dry area (kN)
39     float value27 = value25 + value26; // value27 = Total selfweight of dam (kN)
40
41      W_s.setValue(value27);
42     }
43 }
```

Figure A-8.51. Script of a self-weight load of homogeneous without horizontal blanket drainage

8.5. Failures of embankment dam

8.5.1. Sliding of a dam at the base

When the foundation of the earth dam is made of soft soils, such as fine, silt, soft clay, etc., the entire dam may slide over the foundation. Sometimes, seams of fissured rocks, shales, or soft clay, etc., may exist under the foundation, and the dam may slide over some of them, causing its failure. In this type of failure, the top of the embankment gets cracked and subsides, the lower slope moves outward, forming large mud waves near the heel.

Excessive pore water pressure in confined seams of sand and silt, artesian pressure in abutments, or hydrostatic excess developed due to consideration of clay seams embedded between sands or silts, etc. may reduce the shear strength of the soil, until it becomes incapable of resisting the induced shear stresses, leading to the failure of the dam foundation without warning. Loose sand foundations may fail by the liquefaction or flow slides.

Shear resistance of the dam at the base

$$R = C + W \tan \phi$$

where,

C : Total cohesive strength of the soil at the base = (c * B * 1) (kN)

B: Base width of dam (m)

c : Cohesion of soil of dam (kN/m^2)

ϕ : Friction angle of soil in the dam

W : Total weight of dam (kN)

Rule to calculate shear resistance of the dam at the base

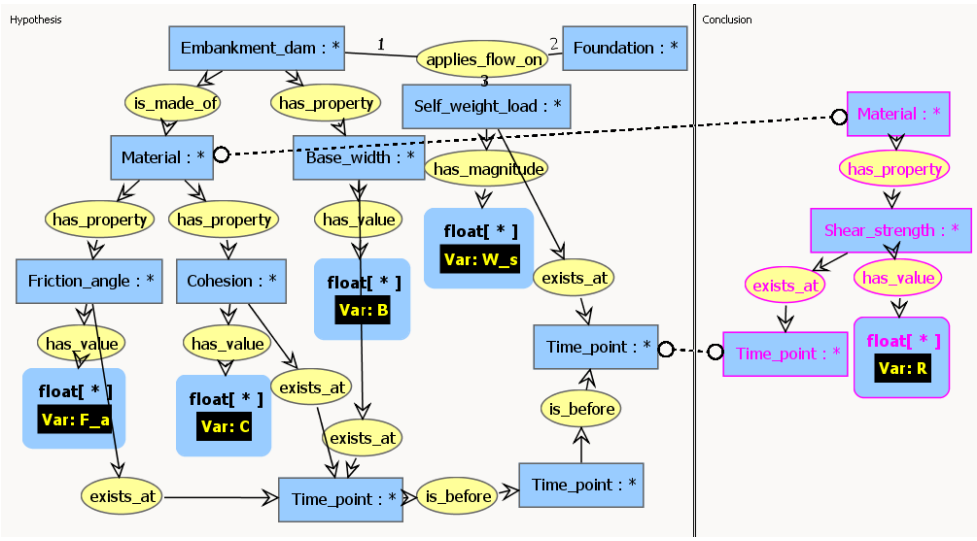


Figure A-8.52. Rule of shear resistance of the dam at the base

Figure A-8.52 shows the calculation of shear strength of embankment material. The shear strength is computed based on the relevant properties of embankment material and the base width of the dam. The rule graph can be expressed as **if** *Embankment dam* applies *Self-weight load* on *Foundation*, **then** *Material* has *Shear strength*. The time of shear strength is after the time of the embankment. Figure A-8.53 shows the associated script.

Rule | Associated script

```
1  void after()
2  {
3      float value = (C.getValue() * B.getValue()) + (W_s.getValue() * Math.tan(Math.toRadians(F_a.getValue())));
4      R.setValue(value);
5  }
```

Figure A-8.53. Script of shear resistance of the dam at the base

Horizontal forces = Reservoir load

$$P = \frac{1}{2}\gamma_w H_{res}^2$$

where,

P : Reservoir load (kN)

γ_w : unit weight of water = 10 kN/m^3

H_{res} : Reservoir level (m)

Rule to calculate reservoir load

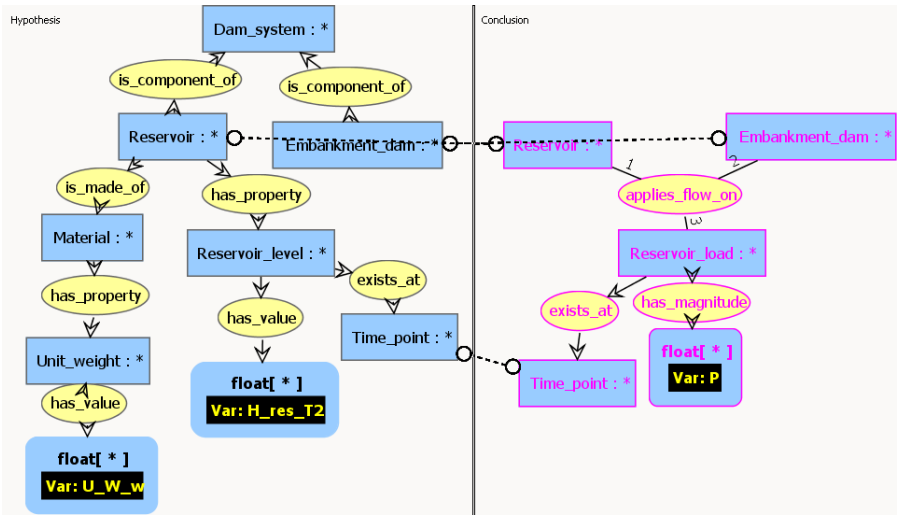


Figure A-8.54. Rule of reservor load

The rule graph shown in Figure A-8.54 illustrates the calculation of reservoir load. The reservoir load is computed based on the properties of the reservoir and its material. The rules graph can be expressed as **if** *Reservoir* and *Embankment dam* are components of *Dam system*, **then** *Reservoir* applies *Reservoir load* on *Embankment dam*. The time of the reservoir load is the time of the reservoir level. Figure A-8.55 shows the associated script.

Script to calculate reservoir load

Rule | Associated script

```
1  void after()
2  {
3      float value = U_W_w.getValue() * Math.pow(H_res_T2.getValue(), 2.0)/2;
4      P.setValue(value);
5  }
```

Figure A-8.55. Script of reservor load

Factor of safety against failure due to horizontal shear at base:

$$\text{F.S against sliding} = \frac{R}{P}$$

Limit condition for foundation sliding stability:

if $\frac{R}{P} >$ Limit factor of safety = 1.3 : no sliding take place

if $\frac{R}{P} <$ Limit factor of safety = 1.3 : foundation slide

Rule to calculate the measured level of Factor of safety against sliding:

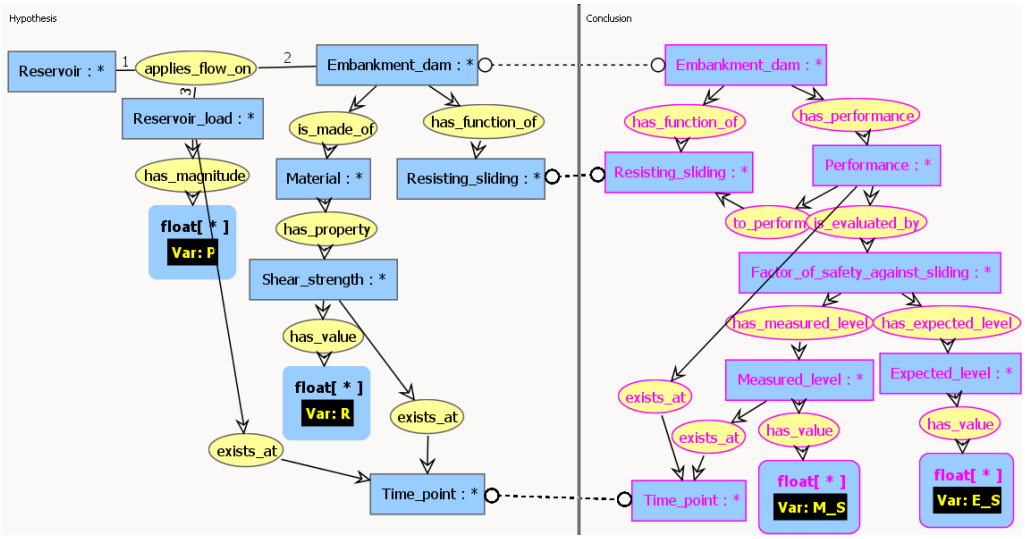


Figure A-8.56. Rule of measured level of factor of safety against sliding at the base

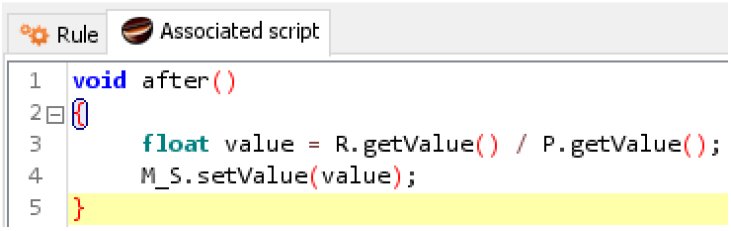


Figure A-8.57. Script of measured level of factor of safety against sliding at the base

Rule to calculate the performance of sliding stability of the dam at the base

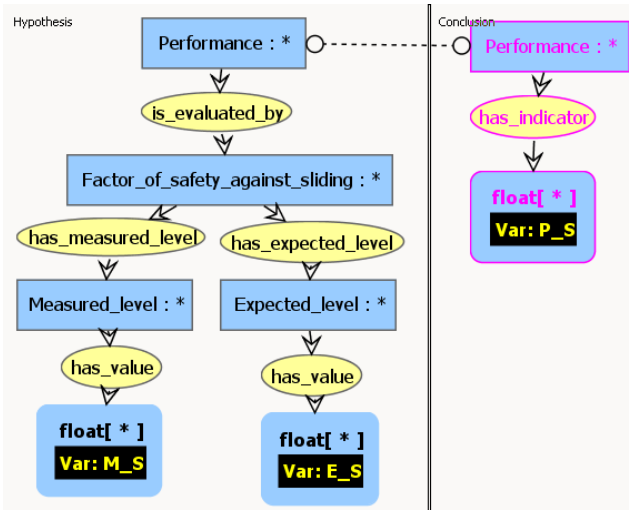


Figure A-8.58. Rule of performance of sliding stability of embankment dam

Script to calculate the performance of sliding stability of the dam at the base

Rule | Associated script

```
1  void after()
2  {
3      if (M_S.getValue() < E_S.getValue()){
4          P_S.setValue(0);
5      }
6      else {
7          P_S.setValue(1);
8      }
9  }
```

Figure A-8.59. Script of performance of sliding stability of embankment dam

8.5.2. Downstream slope slide during steady seepage

The most critical condition of the slide of the downstream slope is most likely to slide, then the reservoir is full, and percolation is at its maximum rate. The pore water pressure acting on the soil mass below the phreatic line reduces the effective stress responsible for mobilizing shearing resistance.

The factor of safety against the horizontal shear forces can be evaluated on the same principles as was done for the u/s slope.

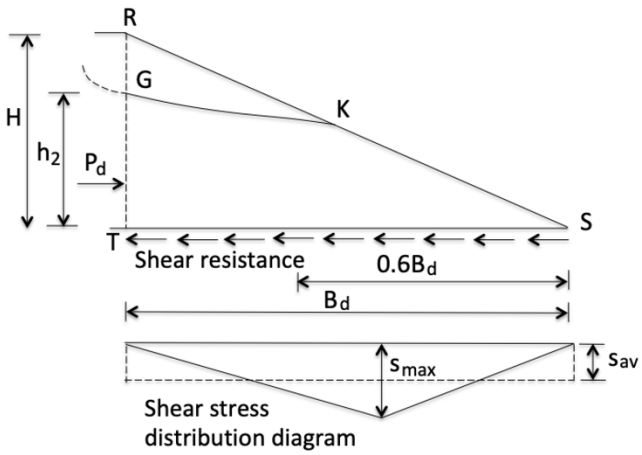


Figure A-8.60. Shear resistance

The horizontal shear force P_d is given by

$$P_d = \left[\frac{\gamma_2 H^2}{2}\tan^2\left(45 - \frac{\phi}{2}\right) + \gamma_w \frac{h_2^2}{2}\right]$$

where γ_2 is the weighted density at the center of the triangular shoulder downstream and is given by

$$\gamma_2 = \frac{\gamma_{sub}.h_2 + \gamma_{dry}.(H - h_2)}{h}$$

γ_{sub} : Submerged unit weight of the soil in the dam (kN/m^3)

γ_{dry} : Dry unit weight of the soil in the dam (kN/m^3)

H: height of dam body (m)

ϕ: Angle of internal friction of soil in the dam

Rule to calculate the horizontal shear force P_d with horizontal blanket drainage

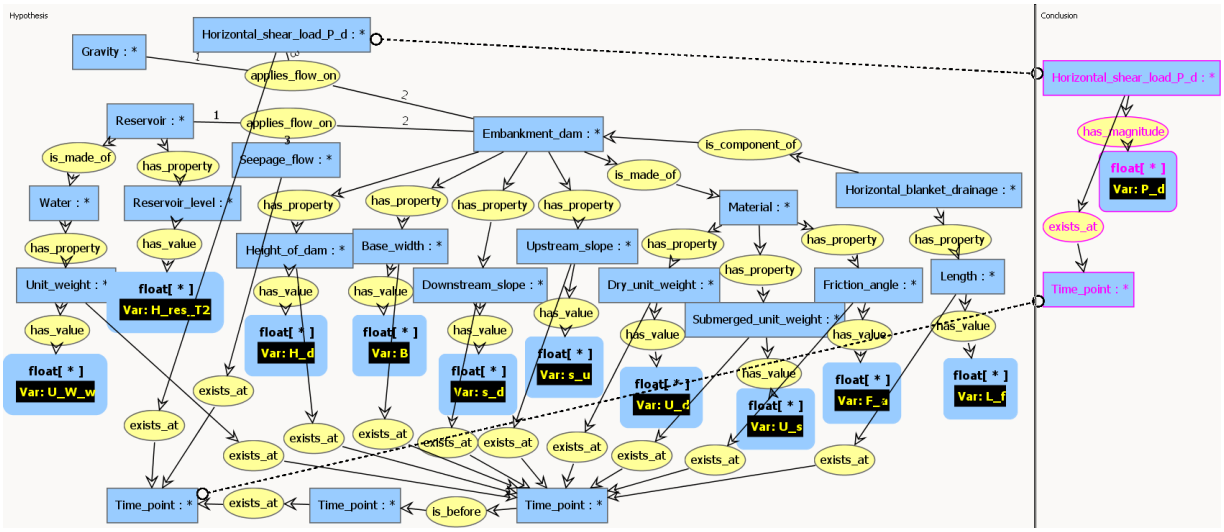


Figure A-8.61. Rule of the horizontal shear load P_d

Figure A-8.61 shows the calculation of the horizontal shear load P_d of the embankment dam. The shear load is computed based on properties of the reservoir, properties of the dam, and its material, length of the horizontal drainage. The rule graph can be expressed as **if** *Reservoir* applies *Seepage flow* on *Embankment dam*, *Gravity* applies *Horizontal shear load* on *Embankment dam*, *Horizontal blanket drainage* is component of *Embankment dam*, **then** *Horizontal shear load* P_d has a magnitude. The time of the load is the time of the reservoir level. Figure A-8.62 shows the associated script.

Rule | Associated script

```
void after()
{
    float value1 = H_res_T2.getValue() * s_u.getValue(); // value1 = L
    float value2 = (B.getValue() - (0.7*value1) - L_f.getValue()); // value2 = x_C
    float value3 = (Math.sqrt(Math.pow(value2,2) + Math.pow(H_res_T2.getValue(),2))) - value2; // value3 = S: Focal distanc

    float value4 = Math.sqrt(Math.pow(value3,2) + 2*((s_d.getValue()*H_d.getValue())- L_f.getValue())*value3); // value4 = 
    float value5 = (U_s.getValue()*value4 + U_d.getValue()*(H_d.getValue()-value4))/H_d.getValue(); // value5 = γ_2 unit we

    float value6 = (value5 * Math.pow(H_d.getValue(),2)/2) * Math.pow(Math.tan(Math.toRadians(45-(F_a.getValue()/2)) ) ,2);
    float value7 = U_W_w.getValue()*Math.pow(value4,2)/2; // γ_water * h_2²/2
    float value8 = value6 + value7; // value8 = Horizontal shear force P_d

    P_d.setValue(value8);
}
```

Figure A-8.62. Script of the horizontal shear load P_d

Rule to calculate the horizontal shear force P_d without horizontal blanket drainage

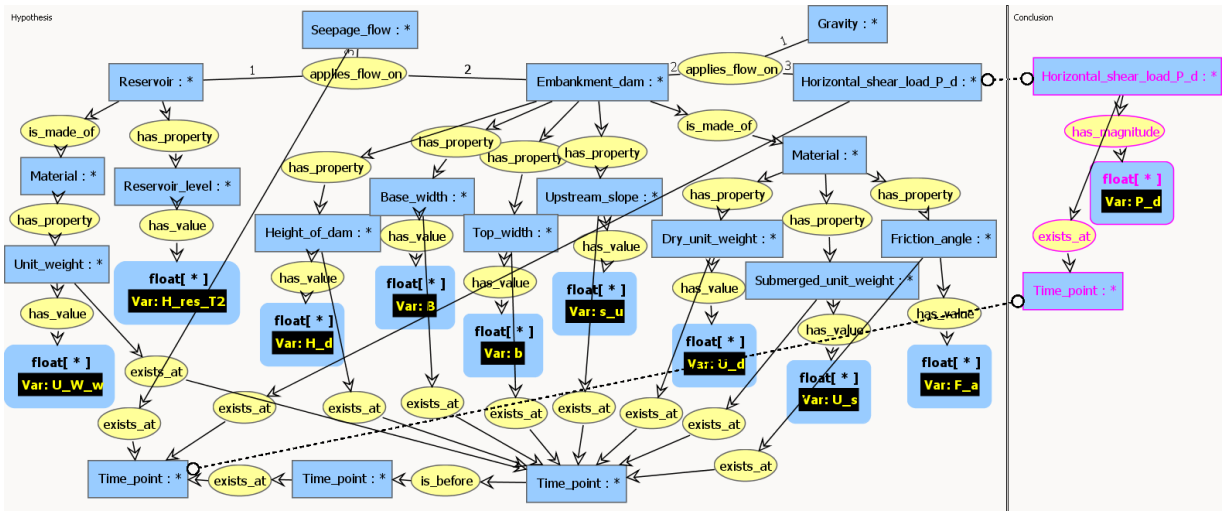


Figure A-8.63. Rule of the horizontal shear load P_d without horizontal blanket drainage

Figure A-8.63 shows the calculation of the horizontal shear load P_d of the embankment dam. The shear load is computed based on properties of the reservoir, properties of the dam, and its material. The rule graph can be expressed as **if** *Reservoir* applies *Seepage flow* on *Embankment dam*, *Gravity* applies *Horizontal shear load* on *Embankment dam*, *Horizontal blanket drainage* is component of *Embankment dam*, **then** *Horizontal shear load* P_d has a magnitude. The time of the load is the time of the reservoir level. Figure A-8.64 shows the associated script.

Rule | Associated script

```
1  void after()
2  {
3      float value1 = (H_res_T2.getValue() / s_u.getValue()); // value1 = L
4      float value2 = B.getValue() - (0.7 * value1); // value2 = x_C
5      float value3 = (Math.sqrt(Math.pow(value2,2) + Math.pow(H_res_T2.getValue(),2))) - value2; // value3 = S: Focal distance
6
7      float value4 = B.getValue() - (H_d.getValue()/s_u.getValue()) - b.getValue(); // value4 = x of h_2
8      float value5 = Math.sqrt(Math.pow(value3,2) + 2 * value4 * value3); // value5 = h2 = sqrt(S²+2xS)
9      float value5 = (U_s.getValue()*value4 + U_d.getValue()*(H_d.getValue()-value4))/H_d.getValue(); // value5 = γ_2 unit wei
10
11     float value6 = (value5 * Math.pow(H_d.getValue(),2)/2) * Math.pow(Math.tan(Math.toRadians(45-(F_a.getValue()/2)) ) ,2);
12     float value7 = U_W_w.getValue()*Math.pow(value4,2)/2; // γ_water * h_2²/2
13     float value8 = value6 + value7; // value8 = Horizontal shear force P_d
14
15     P_d.setValue(value8);
16 }
```

Figure A-8.64. Script of the horizontal shear load P_d without horizontal blanket drainage

Shear resistance (R_d) of the downstream slope portion of the dam developed at the base is given by

$$R_d = C_d + W_d \tan \phi$$

where, W_d = the weight of the d/s triangular shoulder of the dam, ΔRST (Fig. 5)

C_d = The total cohesive force developed at the base

If c_{dam} is the unit cohesion of the dam soil, then $C = c_{dam} * (TS * 1)$.

The triangular profile RTS of the d/s slope portion of the dam has an area of dry soil above the seepage line and the area of submerged soil below the seepage line. The weight of the d/s slope triangular shoulder can be calculated as follow:

$W_d = \gamma_{dry}$. Area above the seepage line + γ_{sub} . The area below the seepage line

$= \gamma_{dry} . \Delta RGK + \gamma_{sub} . GKST$

Rule to calculate the shear strength R_d of the downstream portion

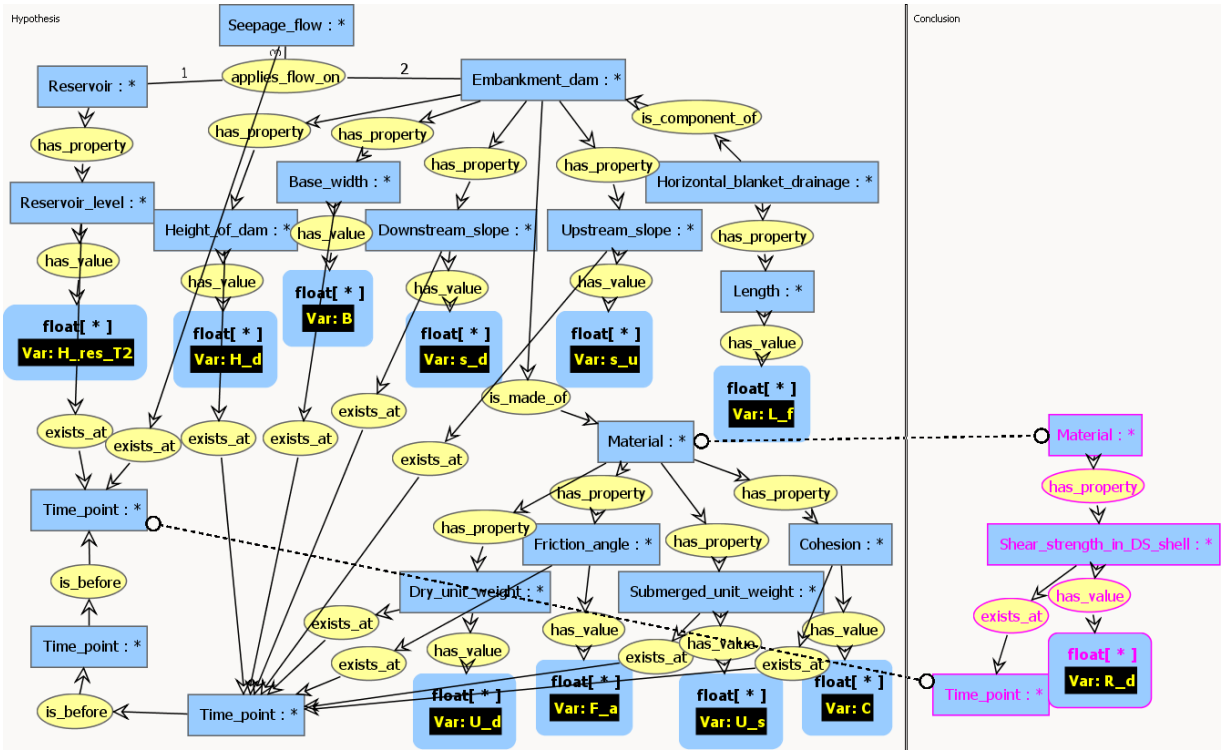


Figure A-8.65. Rule for calculating shear strength R_d of downstream shell

Rule | Associated script

```
void after()
{
    float value1 = H_res_T2.getValue() * s_u.getValue(); // value1 = L
    float value2 = (B.getValue() - (0.7*value1) - L_f.getValue()); // value2 = x_C
    float value3 = (Math.sqrt(Math.pow(value2,2) + Math.pow(H_res_T2.getValue(),2))) - value2; // value3 = S:
    float value4 = Math.sqrt(Math.pow(value3,2) + 2*((s_d.getValue()*H_d.getValue())- L_f.getValue())*value3);

    float value5 = value4 * (s_d.getValue()*H_d.getValue()- L_f.getValue()+ (value3/2))/2; // value4 = Submerg
    float value6 = H_d.getValue() * s_d.getValue()*H_d.getValue()/2; // value6 = Downstream area
    float value7 = value6 - value5; // value7 = Dry area

    float value8 = value5 * U_s.getValue() + value7 * U_d.getValue(); // value8 = Total weight of downstream

    float value9 = C.getValue()*H_d.getValue()*s_d.getValue();
    float value10 = value8 * Math.tan(Math.toRadians(F_a.getValue()));

    float value11 = value9 + value10;

    R_d.setValue(value11);
}
```

Figure A-8.66. Script of the shear strength R_d of downstream shell

The factor of safety against shear can be determined as

$$\text{Factor of safety against shear in downstream shell} = \frac{R_d}{P_d}$$

Limit condition for sliding stability of the d/s slope portion at base:

if $\frac{R_d}{P_d} >$ Limit factor of safety = 2: no sliding take place

if $\frac{R_d}{P_d} <$ Limit factor of safety = 2: d/s slope slid

The factor of safety at the point of maximum shear stress

The maximum intensity of shear stress occurs at a distance 0.6 B_d from the toe (i.e., 0.4 B_d from the top shoulder) and is equal to 1.4 times the average shear intensity.

The average shear intensity is

$$\tau_{av} = \left(\frac{P_d}{B_d.1}\right)$$

Maximum shear stress induced

$$= \tau_{max} = 1.4 \left(\frac{P_d}{B_d}\right)$$

which is developed at the point = 0.6 B_d.

Rule to calculate maximum shear stress induced is given below:

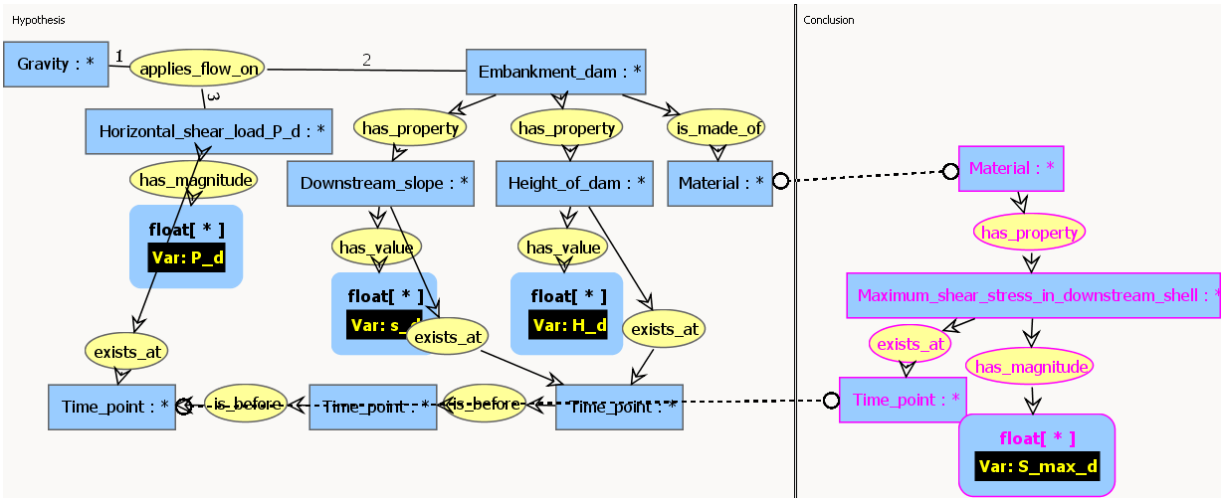


Figure A-8.67. Rule of maximum shear stress in the downstream shell

Rule | Associated script

```
1  void after()
2  {
3      float value = (1.4 * P_d.getValue()) / (H_d.getValue()*s_d.getValue());/
4      S_max_d.setValue(value); // kN/m²
5  }
```

Figure A-8.68. Script of maximum shear stress in the downstream shell

The unit shearing resistance developed at this point of maximum shear stress is given by

$$\tau_f = c + h'\gamma_{sub}.tan\,\phi$$

$$= c + 0.6\ h\ .\ \gamma_{sub}.tan\ \phi$$

Factor of safety against maximum shear

$$\text{Factor of safety} = \frac{\tau_f}{\tau_{max}}$$

Limit condition for sliding stability at the point of the maximum shear stress:

if $\frac{\tau_f}{\tau_{max}}$ > Limit factor of safety = 1: no sliding take place

if $\frac{\tau_f}{\tau_{max}}$ < Limit factor of safety = 1: d/s slope slid

Rule to calculate the measured level of the factor of safety of the downstream shell at the point of the maximum shear and base:

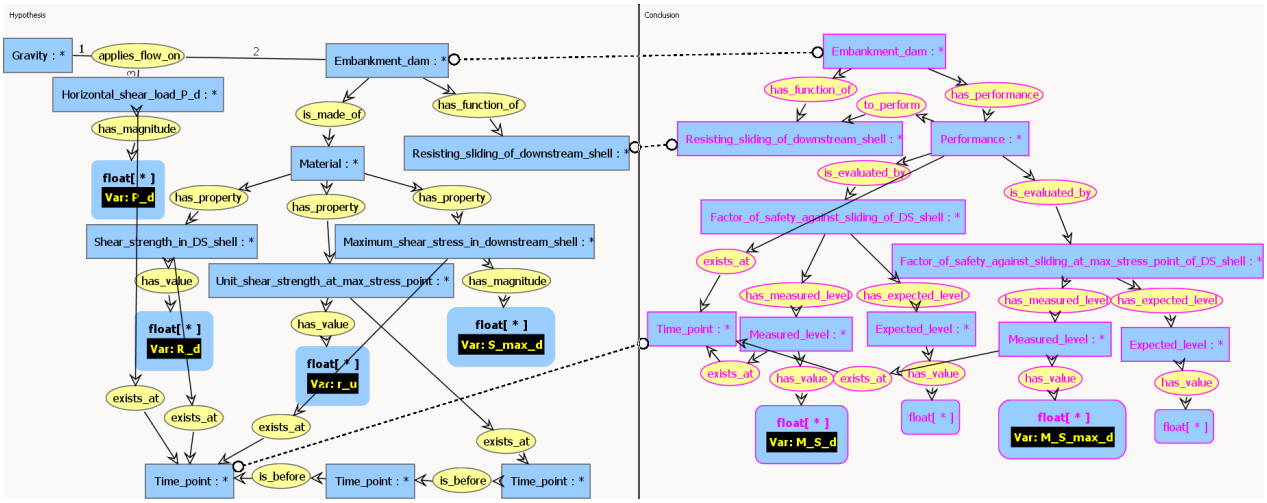


Figure A-8.69. Rule of measured level of factor of safety against sliding of downstream shell

The rule graph in Figure A-8.69 shows the calculation of measured levels of factor of safety against sliding of downstream shell and at the point of maximum stress of downstream shell. The measured level of two factors is computed based on Horizontal shear load P_d and properties of embankment material. The rule graph can be expressed as **if** *Gravity* applies *Horizontal shear load* P_d on *Embankment dam*, **then** *Performance* to perform the function of *Resisting sliding of downstream shell* is evaluated by *Factor of safety against sliding of downstream shell* and *Factor of safety against sliding at max stress point of downstream shell*, with their *Measured level* and *Expected level*. The time of performance and measured levels is the time of load P_d. Figure A-8.70 shows the associated script.

Rule | Associated script

```
1  void after()
2  {
3      float value1 = R_d.getValue() / P_d.getValue();
4      float value2 = r_u.getValue() / S_max_d.getValue();
5
6      M_S_d.setValue(value1);
7      M_S_max_d.setValue(value2);
8  }
```

Figure A-8.70. Script of measured level of factor of safety against sliding of downstream shell

Performance of sliding stability of the d/s slope portion of the dam during steady seepage is calculated based on two conditions:

- Limit condition for sliding stability at the base of the downstream slope portion

- Limit condition for sliding stability at the point of the maximum shear stress

If either of these conditions is not assured, the downstream performance of sliding stability of the d/s slope portion will not be assured.

Rule to calculate the performance of sliding stability of the downstream shell of the dam during steady seepage is given below:

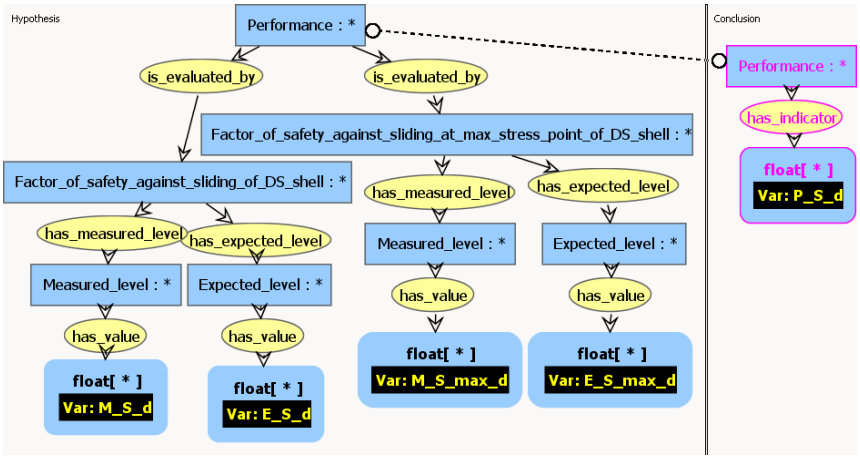


Figure A-8.71. Rule of performance of downstream shell against shear load during steedy seepage

The rule graph in Figure A-8.71 shows the performance to resist sliding of the downstream shell. The *Performance* is evaluated by two factors: *Factor of safety against sliding of downstream shell* and *Factor of safety against sliding at max stress point of DS shell.* Figure A-8.72 shows the associated script.

Rule | Associated script

```
1  void after()
2  {
3      if (M_S_max_d.getValue() < E_S_max_d.getValue() && M_S_d.getValue() < E_S_d.getValue())  {
4
5          P_S_d.setValue(0);
6      }
7      else {
8          P_S_d.setValue(1);
9      }
10 }
```

Figure A-8.72. Script of performance of downstream shell against shear load during steedy seepage

8.5.3. Foundation slides

When the earth dam has a foundation of fine silt or soft soil, it can slide wholly. Applying an approximate method for determining the factor of safety against the foundation shear is

based on the assumption that soil has an equivalent liquid unit weight, which would produce the same shear stress as the soil itself.

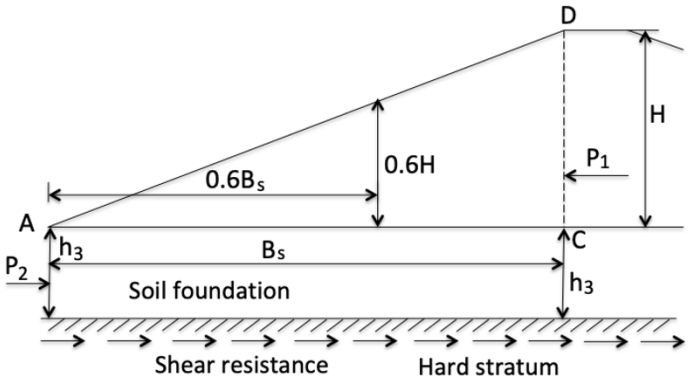


Figure ***A-8.73.*** Shear resistance in the foundation

Horizontal shear force (P_f)

The total horizontal shear force (P), under a slope of the dam is equal to the difference between the lateral thrust on a vertical through the top shoulder of the slope and a vertical through the toe of the slope.

$$P = P_1 - P_2 = \frac{\gamma_{eq}(h+h_3)^2}{2} tan^2\left(45 - \frac{\phi_1}{2}\right) - \frac{\gamma_{eq} h_3^2}{2} tan^2\left(45 - \frac{\phi_1}{2}\right)$$

$$\text{or } P = \gamma_{eq}\left[\frac{(h+h_3)^2 - h_3^2}{2}\right].\left[tan^2\left(45 - \frac{\phi_1}{2}\right)\right]$$

where, h_3 = the depth of foundation soil below the dam base, overlying the hard stratum below it.

γ_{eq} = the equivalent unit weight of dry soil in foundation and dam. It is given by

$$\gamma_{eq} = \frac{\gamma_{dry}\ for\ dam\ material\ .h + \gamma_{dry}\ for\ foundation\ material\ .h_3}{h + h_3}$$

ϕ_1 = the equivalent angle of internal friction and is given by

$$\phi_1 = tan^{-1}\left[\frac{c_f + \gamma_{eq}(h + h_3)\tan\phi_f}{\gamma_{eq}.(h + h_3)}\right]$$

c_f and ϕ_f are the values of unit cohesion and angle of internal friction for the soil in the foundation.

Rule to calculate the total horizontal shear force P_f

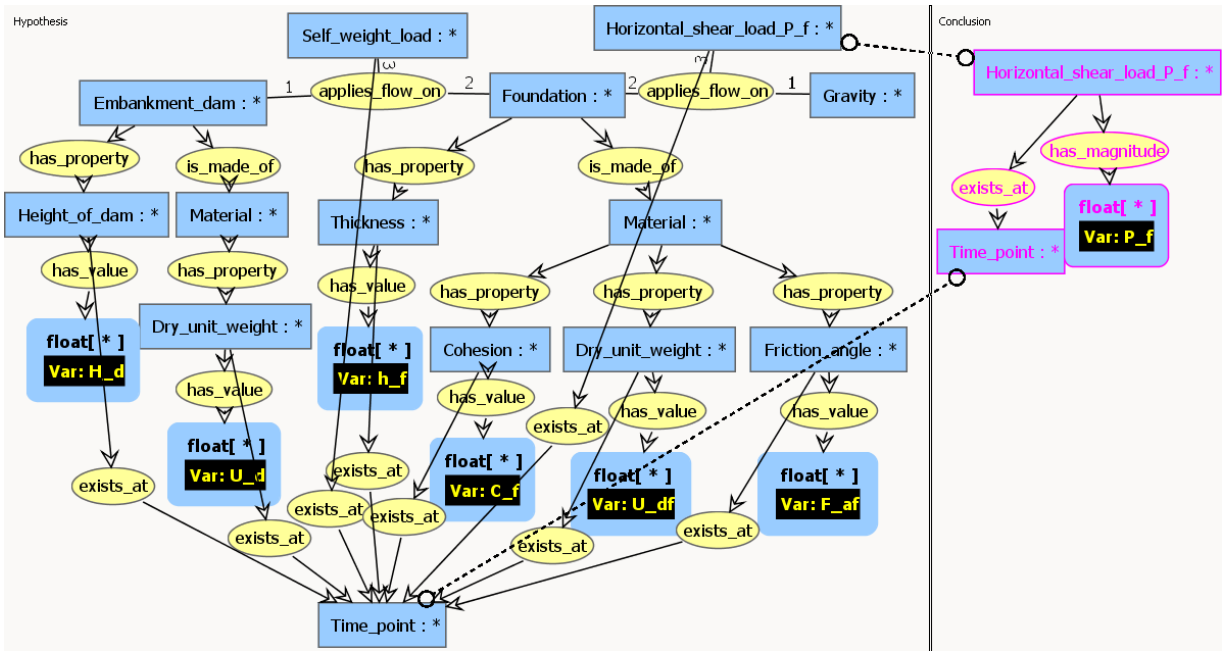


Figure A-8.74. Rule of total horizontal shear force P_f

Figure A-8.74 shows the calculation of the horizontal shear load P_f of the foundation. The shear load is computed based on properties of the embankment dam and foundation, and properties of material constituted them. The rule graph can be expressed as **if** *Embankment dam* applies *Self-weight load* on *Foundation*, and *Gravity* applies *Horizontal shear load* P_f on *Foundation*, **then** *Horizontal shear load* P_f has a magnitude. Figure A-8.75 shows the associated script.

Rule | Associated script

```
1  void after()
2  {
3      float value1 = (U_d.getValue() * H_d.getValue() + U_df.getValue()* h_f.getValue()) / (H_d.getValue() + h_f.getValue());
4      float value2 = C_f.getValue() + (value1* (H_d.getValue() + h_f.getValue()) * Math.tan(Math.toRadians(F_af.getValue())));
5      float value3 = value1 * (H.getValue() + h_f.getValue()); // value3 = γ_eq.(h+h_3)
6      float value4 = value2 / value3; //
7      float value5 = Math.toDegrees(Math.atan(value4)); // value5 = ∅_1 = the equivalent angle of internal friction
8
9      float value6 = value1 * (Math.pow((H_d.getValue() + h_f.getValue()),2) - Math.pow(h_f.getValue(),2)) / 2; // value6 = γ_
10     float value7 = Math.pow(Math.tan(Math.toRadians(45- (value5/2)) ) ,2); // value7 = tan²(45-∅_1/2)
11     float value8 = value6 * value7; // value8 = Horizontal shear load P_foundation
12
13
14     P_f.setValue(value8);
15 }
```

Figure A-8.75. Script of the total horizontal shear force P_f

Shear stress induced at base

The average shear stress at the base of the slope

$$\tau_{av} = \left(\frac{P}{B_s}\right)$$

where B_s is the base width below the slope.

Rule to calculate shear stress induced at base:

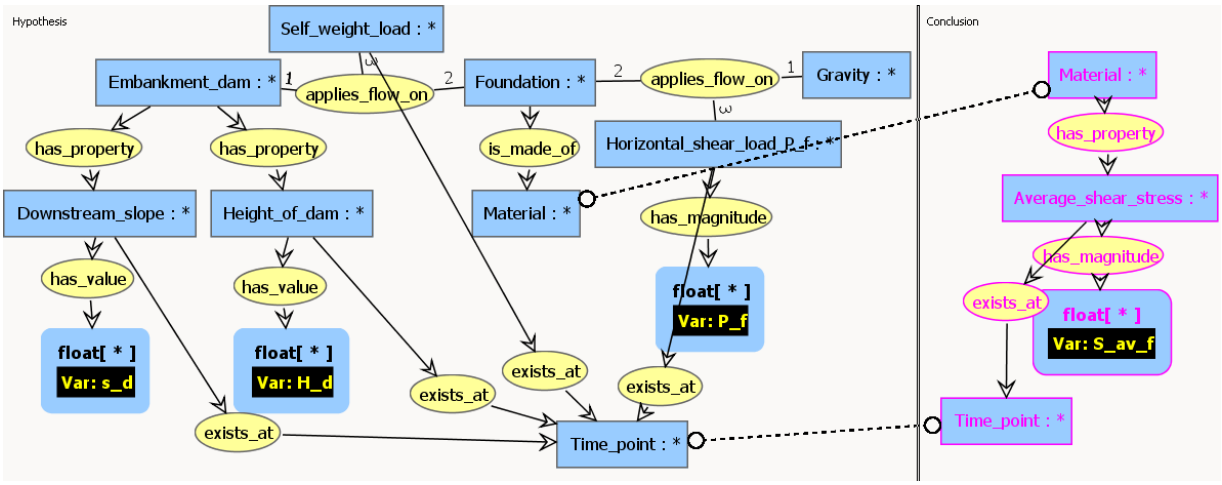


Figure A-8.76. Rule of shear stress at the base

The rule graph shows in Figure A-8.76 illustrates the calculation of average shear stress in the foundation. The average shear stress is computed based on properties of the embankment dam and the horizontal shear load $P_{f,}$ which gravity applies to the foundation. The rule graph can be expressed as **if** *Embankment dam* applies *Self-weight load* on *Foundation*, and *Gravity* applies *Horizontal shear load* P_f on *Foundation*, then *Material* constituted Foundation has *Average shear stress.* Figure A-8.77 shows the associated script.

Rule | Associated script

```
1  void after()
2  {
3      float value = P_f.getValue() / (s_d.getValue()*H_d.getValue());
4
5      S_av_f.setValue(value);
6  }
```

Figure A-8.77. Script of shear stress at the base

Maximum stress is 1.4 times the average stress, and it occurs at a distance of 0.6 B_s from the toe of the slope

$$\text{or } \tau_{max} = 1.4\left(\frac{P}{B_s}\right)$$

Rule to calculate maximum shear stress is given below:

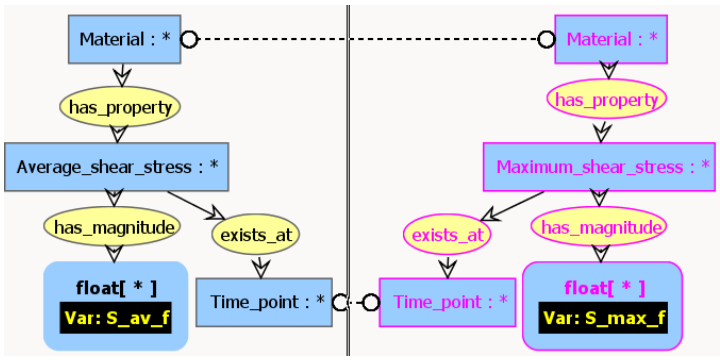


Figure A-8.78. Rule of maximum shear stress

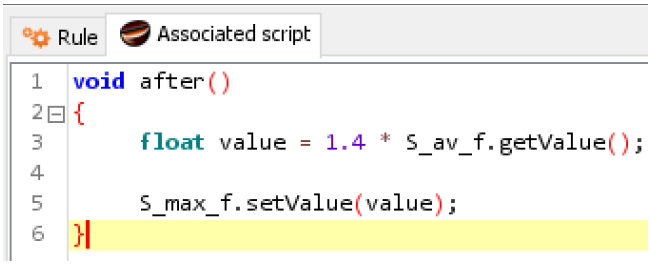


Figure A-8.79. Script of maximum shear stress

Shear resistance of the foundation soil below the dam

The unit shear resistance of the foundation soil below at the toe

$$= \tau_{f1} = \left[c_f + \gamma_f . h_3 \, . \tan \phi_f\right]$$

where γ_f is the unit weight of foundation soil.

The unit shear resistance of the soil vertically below the upper point of the considered slope is given by τ_{f2}

$$= \tau_{f2} = \left[c_f + \gamma_3 . (h + h_3) \, . \tan \phi_f\right]$$

where γ_3 = the equivalent unit weight of soil in the dam and foundation at the point N_1 and is given by

$$\gamma_3 = \frac{\gamma_f . h_3 + \gamma_{dam} . h}{h + h_3}$$

The values of γ_f and γ_{dam} may be taken as their dry unit weight or submerged unit weight depending upon the possibility of soils is impervious or submerged.

The average shear resistance

$$= \tau_f = \frac{\tau_{f1} + \tau_{f2}}{2}$$

Rule to calculate the average shear strength is given below:

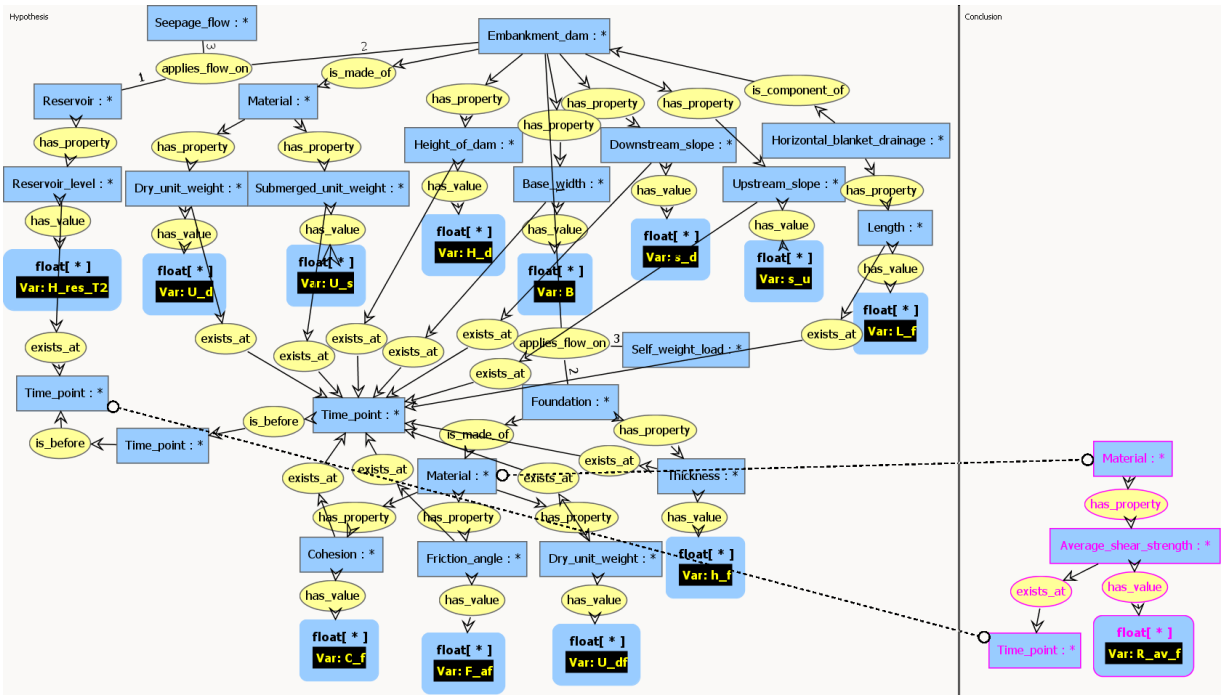


Figure A-8.80. Rule of the average shear strength

Figure A-8.80 illustrates a rule graph calculating the average shear strength of a material in the foundation. The average shear strength is calculated based on reservoir level, properties of embankment material, geometrical parameters of the dam, thickness of foundation, and properties of foundation material. The rule graph can be interpreted as **if** *Reservoir* applies *Seepage flow* on *Foundation*, and *Embankment dam* applies *Shelf-weight load* on *Foundation*, then *Material* constituted foundation has *Average shear strength*. The time point of the average shear strength is the time point of the reservoir level. Figure A-8.81 exposes the associated script.

Rule | Associated script

```
void after()
{
    float value1 = H_res_T2.getValue() * s_u.getValue(); // value1 = L
    float value2 = (B.getValue() - (0.7*value1) - L_f.getValue()); // value2 = x_C
    float value3 = (Math.sqrt(Math.pow(value2,2) + Math.pow(H_res_T2.getValue(),2))) - value2; // value3 = S: Focal dista
    float value4 = Math.sqrt(Math.pow(value3,2) + 2*((s_d.getValue()*H_d.getValue())- L_f.getValue())*value3); // value4

    float value5 = U_s.getValue()*value4 + U_d.getValue()*(H_d.getValue()-value4) + U_df.getValue()*h_f.getValue();
    float value6 = H_d.getValue()+ h_f.getValue();
    float value7 = (value5 / value6); // value7 = γ_3 = equivalent unit weight of soil in the dam and foundation at base

    float value8 = C_f.getValue() + (value7*(H_d.getValue()+ h_f.getValue())* Math.tan(Math.toRadians(F_af.getValue())));
    float value9 = C_f.getValue() + (U_df.getValue() * h_f.getValue() * Math.tan(Math.toRadians(F_af.getValue()))); // va

    float value10 = (value8 + value9)/2; // value10 = The average shear strength at base

    R_av_f.setValue(value10); // kN/m²
}
```

Figure A-8.81. Script of the average shear strength

The overall factor of safety

$$\text{Factor of safety against sliding of foundation} = \frac{\tau_f}{\tau_{av}}$$

Limit condition for stability of the foundation against Shear :

if $\frac{\tau_f}{\tau_{av}}$ > Limit factor of safety = 1.5 : no sliding take place

if $\frac{\tau_f}{\tau_{av}}$ < Limit factor of safety = 1.5 : failure

The factor of safety at the point of maximum shear is calculated as below

The unit shear resistance at the point of maximum shear

$$= \tau_{f(max)} = \left[c_f + \gamma_4 . (h_3 + 0.6H) . \tan \phi_f\right]$$

where γ_4 is the equivalent weight of soil in dam and foundation and is given by

$$\gamma_4 = \frac{\gamma_f . h_3 + \gamma_{dam} . (0.6H)}{h_3 + 0.6h}$$

The values of γ_f and γ_{dam} may be taken as their dry unit weight or submerged unit weight depending upon the possibility of soils is impervious or submerged.

Rule to calculate the unit shear resistance at the point of maximum shear is given below:

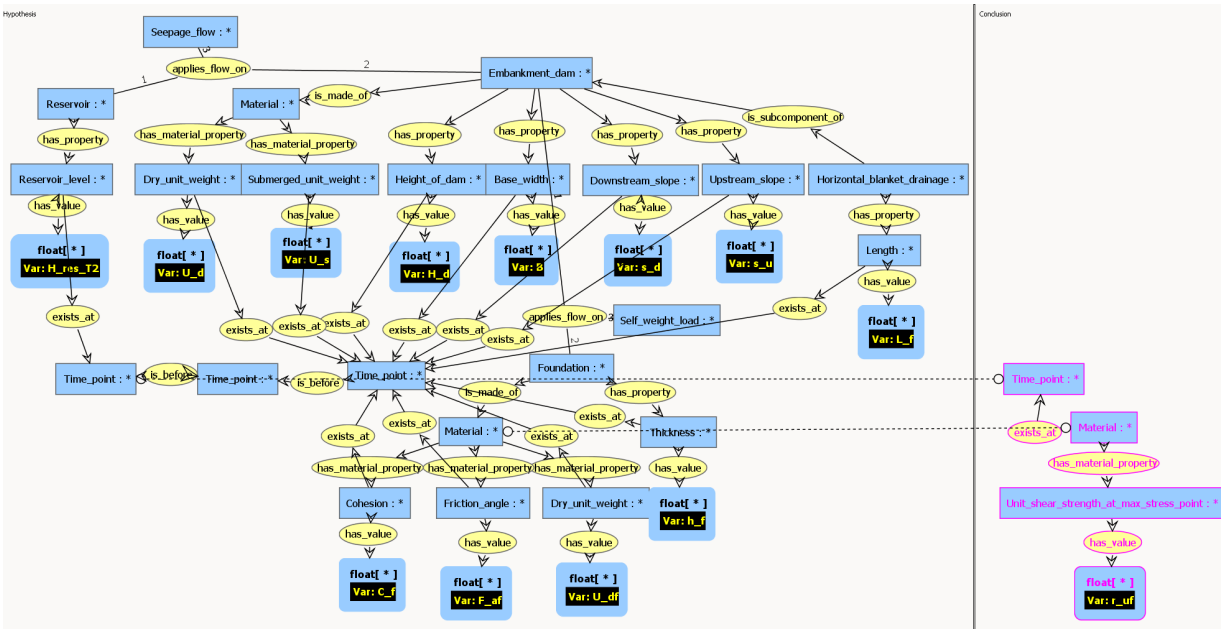


Figure A-8.82. Rule of the unit shear resistance at the point of maximum shear

Figure A-8.82 illustrates a rule graph calculating unit shear strength at the point of maximum shear stress in the foundation. The unit shear strength is calculated based on reservoir level, properties of embankment material, geometrical parameters of the dam, the thickness of foundation, and properties of foundation material, length of horizontal drainage. The rule graph can be interpreted as **if** *Reservoir* applies *Seepage flow* on *Foundation*, *Embankment dam* applies *Shelf-weight load* on *Foundation*, and Horizontal blanket drainage is component of Embankment dam, then *Material* constituted foundation has *Unit shear strength at max stress point*. The time point of the unit shear strength is the time point of the reservoir level. Figure A-8.83 shows the associated script.

Rule | Associated script

```
void after()
{
    float value1 =  H_res_T2.getValue() * s_u.getValue(); // value1 = L
    float value2 = (B.getValue() - (0.7*value1) - L_f.getValue()); // value2 = x_C
    float value3 = (Math.sqrt(Math.pow(value2,2) + Math.pow(H_res_T2.getValue(),2))) - value2; // value3 = S: Focal distance (
    float value4 = Math.sqrt(Math.pow(value3,2) + 2*(0.6*s_d.getValue()*H_d.getValue()- L_f.getValue()+(value3/2))*value3); //

    float value5 = U_s.getValue()*value4 + U_d.getValue()*(0.6*H_d.getValue()-value4) + U_df.getValue()*h_f.getValue();
    float value6 = 0.6*H_d.getValue() + h_f.getValue();
    float value7 = (value5 / value6); // value7 = γ_4 = equivalent unit weight of soil in the dam and foundation at the point

    float value8 = C_f.getValue() + (value7*(0.6*H_d.getValue()+ h_f.getValue())* Math.tan(Math.toRadians(F_af.getValue())));

     r_uf.setValue(value8); // kN/m²
}
```

Figure A-8.83. Script of the unit shear resistance at the point of maximum shear

F.S. = Factor of safety at the point of maximum shear

$$\text{F.S} = \frac{\tau_{f(max)}}{\tau_{max}}$$

Limit condition for stability at the point of maximum shear:

if $\frac{\tau_{f(max)}}{\tau_{max}} >$ Limit factor of safety = 1 : no sliding take place

if $\frac{\tau_{f(max)}}{\tau_{max}} <$ Limit factor of safety = 1: failure

Rule to calculate measured F.S. for stability against shear in the foundation at the point of the maximum shear and foundation level:

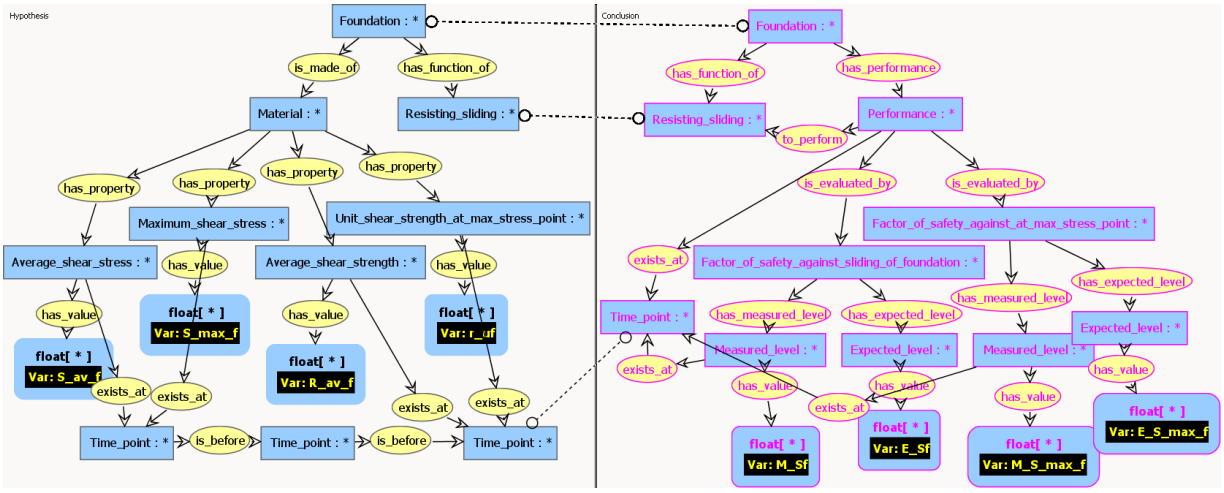


Figure A-8.84. Rule calculating the measured level of factor of safety against sliding in the foundation

Figure A-8.84 shows a rule graph for calculating the measured levels of factor of safety against sliding of foundation and factor of safety against sliding at the point of maximum stress in the foundation. The measured levels are computed based on the relevant properties of the foundation material. The coref relation between two *Resisting sliding* concept nodes shows that with one *Resisting sliding* function, the foundation can have different performances created to perform it. The rule graph can be interpreted as **if** *Foundation* is made of *Material* that has its properties, and *Foundation* has the function of *Resisting sliding* **then** a new *Performance* is created to perform *Resisting crushing*, which is evaluated by

Factor of safety against sliding of foundation and *Factor of safety against sliding at max stress point* with their *Measured level*s and *Expected levels*. Figure A-8.85 shows the associated script.

Rule | Associated script

```
1  void after()
2  {
3      float value1 = R_av_f.getValue() / S_av_f.getValue();
4      float value2 = r_uf.getValue() / S_max_f.getValue();
5
6      M_Sf.setValue(value1);
7      M_S_max_f.setValue(value2);
8  }
```

Figure A-8.85. Script of the measured level of factor of safety against sliding of foundation

Performance of stability against Shear of the foundation is calculated based on two conditions:

- Limit condition for stability against Shear at foundation level

- Limit condition for stability at the point of the maximum shear stress

If either of these conditions is not assured, the performance of stability against Shear of the foundation will not be assured.

Rule to calculate the performance of stability of the against Shear of foundation

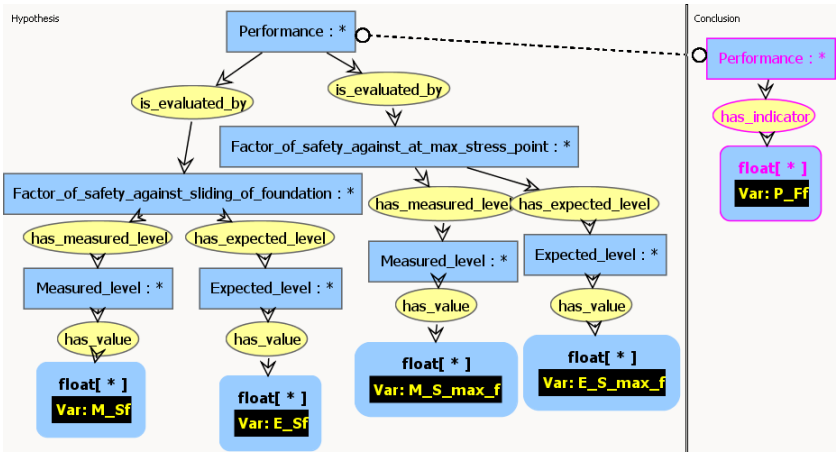


Figure A-8.86. Rule of performance resisting sliding in the foundation

Rule | Associated script

```
1  void after()
2  {
3      if (M_S_max_f.getValue() < E_S_max_f.getValue() && M_Sf.getValue() < E_Sf.getValue())  {
4
5          P_Ff.setValue(0);
6      }
7      else {
8          P_Ff.setValue(1);
9      }
10 }
```

Figure A-8.87. Script of performance resisting sliding in the foundation

8.5.4. Backward erosion piping

Backward erosion piping (BEP) occurs when soil erosion (particle detachment) begins at a seepage exit point and erodes backward (towards the impounded water), supporting a "pipe" or "roof" along the way.

As the erosion continues, the seepage path gets shorter, and flow concentrates in plan view, leading to higher gradients, more flow, and higher potential for erosion to continue. This process can continue until the head of piping reaches the upstream slope, where the surface soil over the piping hole is too thin to withstand its weight, and complete failure occurs suddenly as the reservoir breaks through. (Figure …)

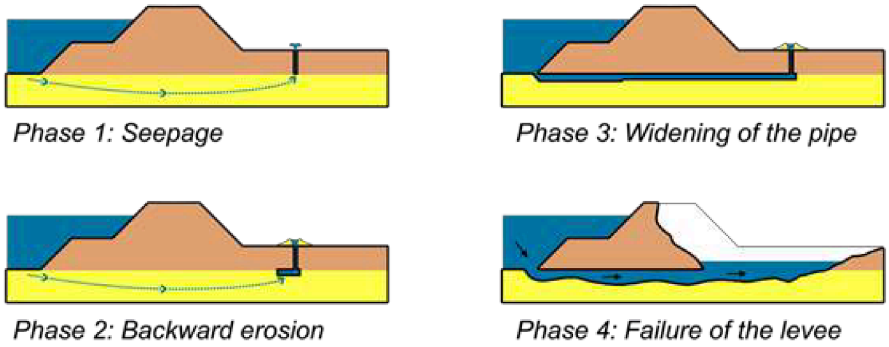


Figure A-8.88. Backward erosion piping (USBR, 2018)

Critical Gradient for Initiation of a Pipe

Backward erosion piping will initiate when a "heave" or zero effective stress condition occurs in soils subject to upward through-seepage. The heave equation or critical exit gradient from Terzaghi (1996) is given by:

$$i_{cr} = \frac{\gamma_b}{\gamma_w}$$

where:

γ_w = unit weight of water

γ_b = buoyant unit weight of the soil (USBR, 2018)

Rule to compute the critical gradient for initiation of a pipe is given below:

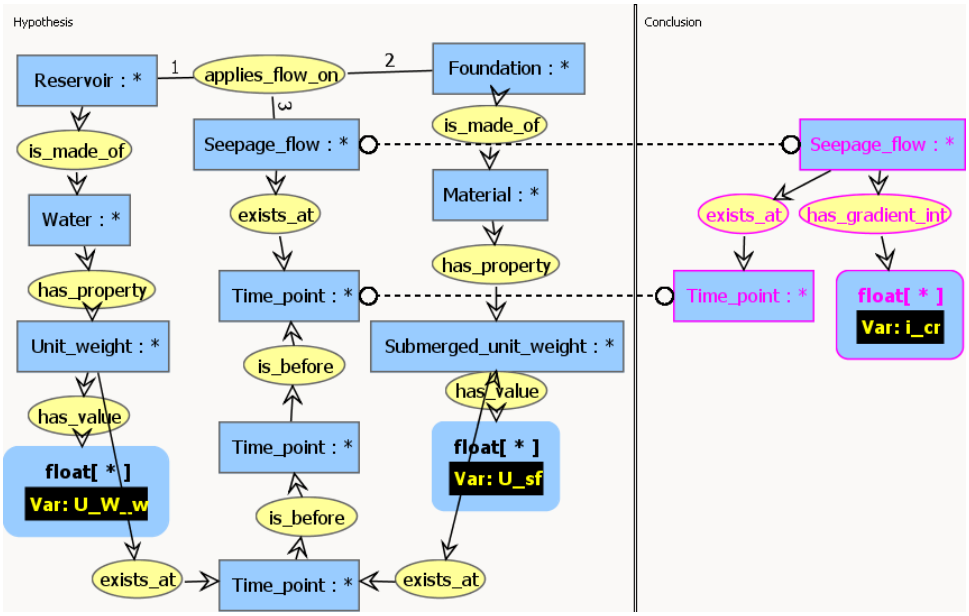


Figure A-8.89. Rule of the critical gradient for initiation of a pipe

Figure A-8.89 illustrates the calculating of the critical gradient for initiation of a pipe. The critical gradient is calculated based on the unit weight of water and the submerged unit weight of the material of the foundation. The rule graph can be expressed as **if** *Reservoir* applies *Seepage flow* on *Foundation*, **then** *Seepage flow* has a value of critical gradient. The time point of the gradient is the time point of the seepage flow. Figure A-8.90 exposes the associated script.

Rule | Associated script

```
1  void after()
2  {
3      float value1 = U_sf.getValue() / U_W_w.getValue();
4      i_cr.setValue(value1);
5
6  }
```

Figure A-8.90. Script of the critical gradient for initiation of a pipe

The simplified relationship for the critical vertical exit gradient can also be expressed as the condition when the pore water pressure equals the submerged unit weight of the soil, and thus the effective stress is zero.

Rule of the measured level of the factor of safety against piping is given as follow:

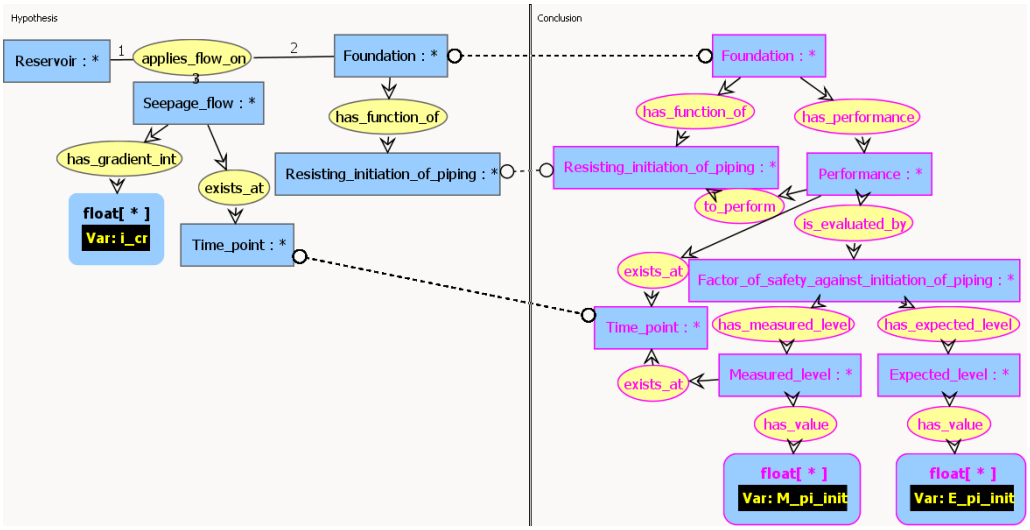


Figure A-8.91. Rule of the factor of safety against piping initiation

Figure A-8.91 shows a rule graph for calculating the measured level of the factor of safety against initiation of piping. The measured level is computed based on the value of the critical gradient of seepage flow for piping initiation at a time point. The rule graph can be interpreted as **if** *Reservoir* applies *Seepage flow* which has critical gradient on Foundation, **then** *Performance* to perform *Resisting initiation of piping* is created, which evaluated by *Factor of safety against initiation of piping* that has *Measured level* and *Expected level*. The coref relation between two *Resisting initiation of piping* concept nodes shows that with one *Resisting initiation of piping* function, the foundation can have different performances created to perform it. The time point of performance is the time point of the seepage flow.

Rule | Associated script

```
1  void after()
2  {
3      float value = i_cr.getValue();
4
5      M_pi_init.setValue(value);
6  }
```

Figure A-8.92. Script of factor of safety against piping initiation

Limit condition for piping initiation:

if $\frac{\gamma_b}{\gamma_w}$ < Limit factor of safety = 1: piping initiation

if $\frac{\gamma_b}{\gamma_w}$ > Limit factor of safety = 1: no piping initiation

Rule to evaluate the performance of resisting piping initiation:

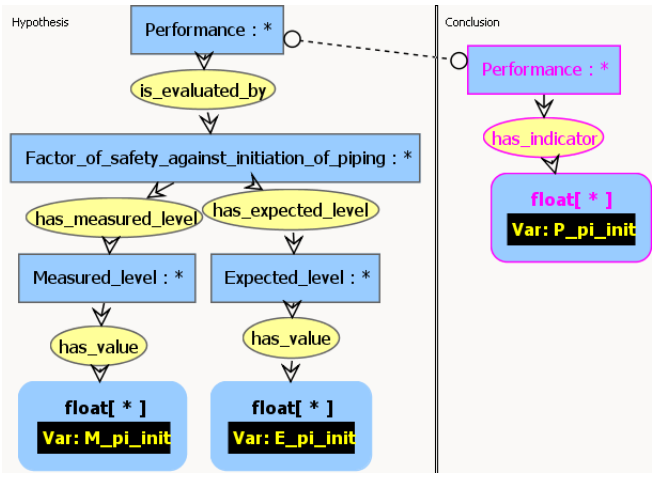


Figure A-8.93. Rule of performance of resisting piping initiation

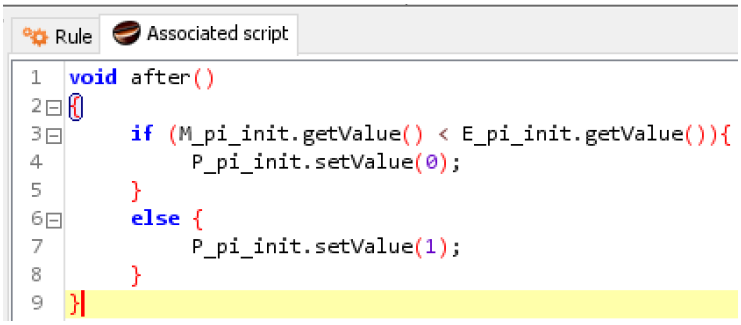


Figure A-8.94. Script of performance of resisting piping initiation

Critical Gradient for Progression of a Pipe

To assess the likelihood of the hydraulic condition for the progression of backward erosion piping, the global or horizontal gradient in the foundation can be compared to the critical gradient for the progression of a pipe.

Line-of-creep methods such as Bligh (1910) and Lane (1935) are used for screening-level assessment of the critical gradient for the progression of a pipe. For application to embankment dams, the seepage path length would be beneath the roof-forming material, including upstream and downstream blankets or berms, cutoff walls, cutoff or inspection trenches, etc. The creep ratio is calculated as the total seepage path length divided by the hydraulic head difference. For Lane's method, the horizontal seepage path lengths are weighted three times less than the vertical seepage path lengths.

$$C_w = \frac{\frac{(L_1 + W + L_2)}{3} + 2d}{h}$$

where,

L_1 = length of upstream blanket or berm;

W = width of base of embankment;

L_2 = length of downstream blanket or berm; and

d = depth of vertical structure (e.g., cutoff or weir).

Minimum Creep Ratios

Piping Material	Lane (1935)
Very fine sand or silt	8.5
Fine sand	7.0
Medium sand	6.0
Coarse sand Fine	5.0
Fine gravel	4.0
Medium gravel	3.5
Gravel and sand	#N/A
Coarse gravel, including cobbles	3.0

The creep ratio is the reciprocal of the average gradient in the foundation for the reservoir level under consideration (i_{avf}), and the minimum creep ratio is the reciprocal of the critical gradient for progression of a pipe ($i_{adv} = 1/C$ or $i_{adv} = 1/C_w$)

Rule to calculate critical gradient for progression of a pipe:

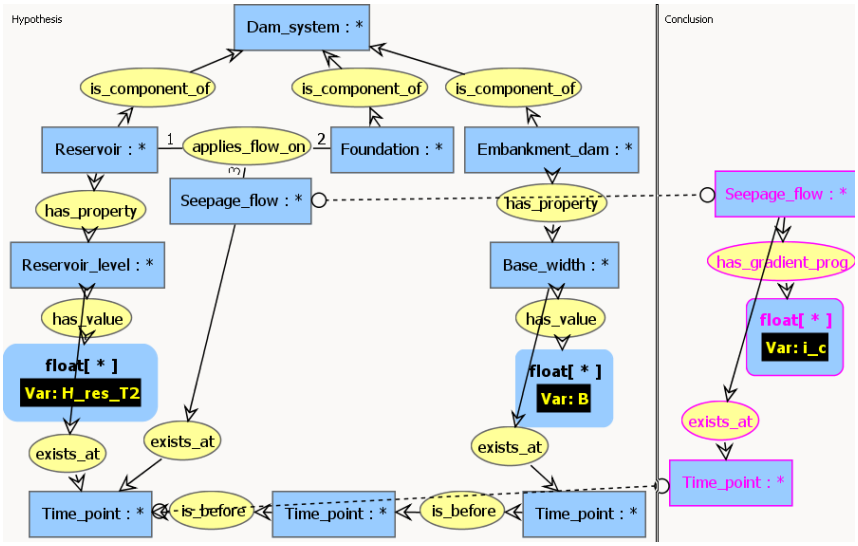


Figure A-8.95. Rule of the critical gradient for the progression of a pipe

Figure A-8.95 illustrates the calculating of the critical gradient for the progression of a pipe. The critical gradient is calculated based on reservoir level and base width of the embankment dam. The rule graph can be expressed as **if** *Reservoir* applies *Seepage flow* on *Foundation*, and *Reservoir*, *Foundation*, and *Embankment dam* are components of *Dam_system*, **then** *Seepage flow* has a value of critical gradient for progression of a pipe. The time point of the gradient is the time point of the seepage flow. Figure A-8.96 shows the associated script.

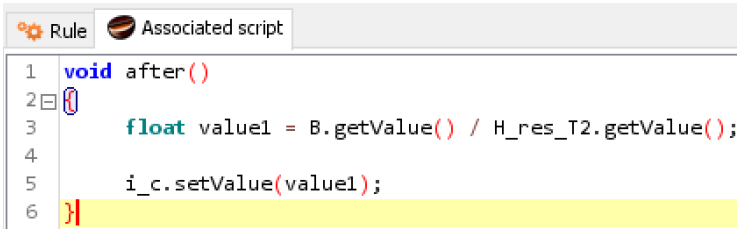


Figure A-8.96. Script of the critical gradient for progression of a pipe

Factor of safety against piping progression (F.S piping) $= \frac{i_c}{C_w}$

where, i_c : critical gradient for progression of a pipe

C_w: Minimum Creep Ratios

Rule to compute the measured level of the factor of safety against piping progression:

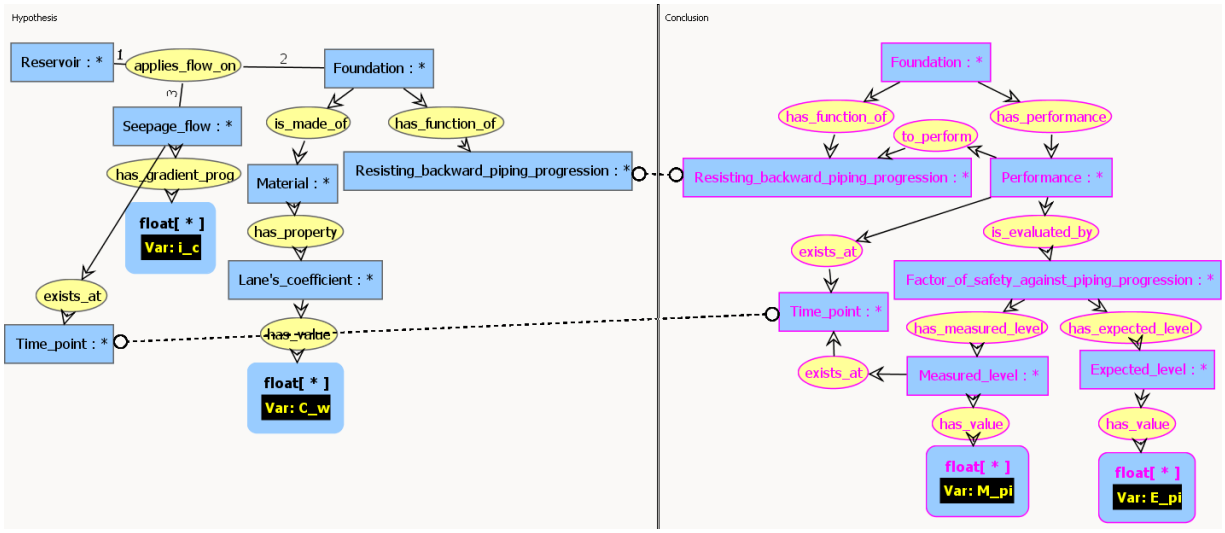


Figure A-8.97. Rule of measured level of the factor of safety against piping progression

Figure A-8.97 shows a rule graph for calculating the measured level of the factor of safety against the progression of piping. The measured level is computed based on the value of the critical gradient of seepage flow for piping progression at a time point and Lane'scoefficient of foundation material. The rule graph can be interpreted as **if** *Reservoir* applies *Seepage flow* which has critical gradient on Foundation, **then** *Performance* to perform *Resisting backward piping progression* is created, which evaluated by *Factor of safety against piping progression* that has *Measured level* and *Expected level*. The coref relation between two *Resisting backward piping progression* concept nodes shows that with one *Resisting backward piping progression* function, the foundation can have different performances created to perform it. The time point of performance is the time point of the seepage flow. Figure A-8.98 shows the associated script.

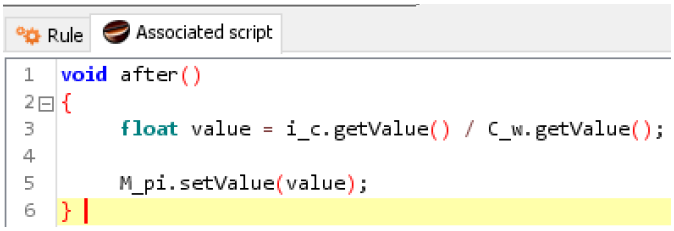


Figure A-8.98. Script of measured level of factor of safety against piping progression

Limit condition for piping progression:

if $\frac{i_c}{C_w}$ < Limit factor of safety = 1: no piping progression

if $\frac{i_c}{C_w}$ > Limit factor of safety = 1: piping

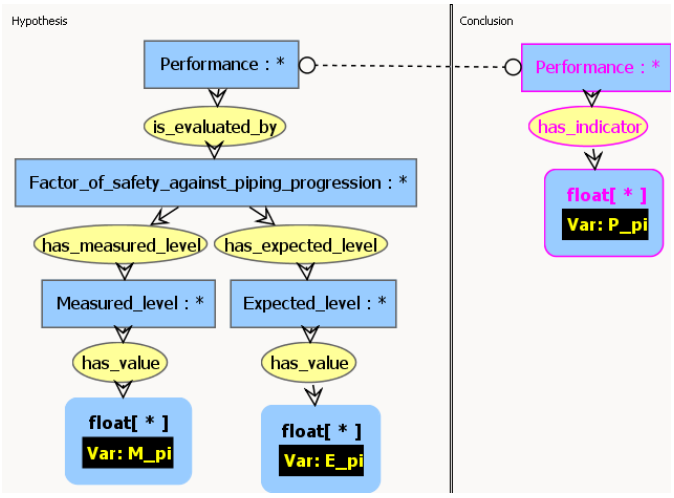


Figure A-8.99. Rule of piping progression performance

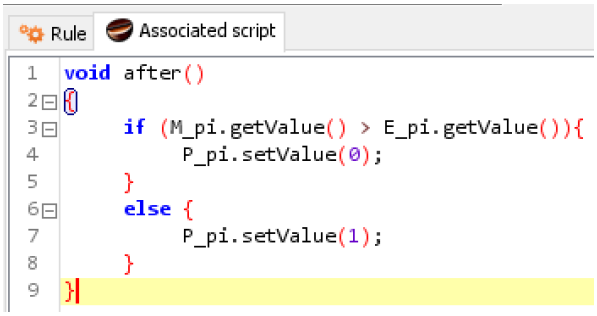


Figure A-8.100 Script of piping progression performance

8.5.5. Sloughing:

Sloughing is caused by seepage flow that leads to saturation, excessive seepage forces, and/or excessive uplift. Under the full reservoir condition, the d/s portion of the dam becomes saturated and continuously remains in the same state, causing the softening and weakening of soil mass. This usually occurs when the phreatic lines cuts the downstream face. Seepage forces acting in the direction of flow may produce erosion and slump at the downstream toe. The slump will leave a steeper face, which gets eroded due to seepage and form slump again. This progressive removal of saturated soil is called sloughing.

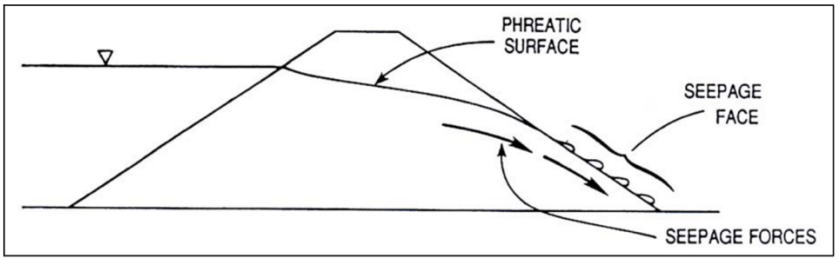


Figure A-8.101. Seepage through an embankment dam (Cheng, Draper and An, 2014)

Conditions for the failure of sloughing include:

- Saturation of embankment dam

- Factor of safety against sloughing

Saturation of the dam occurs when the phreatic line cuts the downstream face of the dam. It means that the discharge face or seepage face is greater than 0.

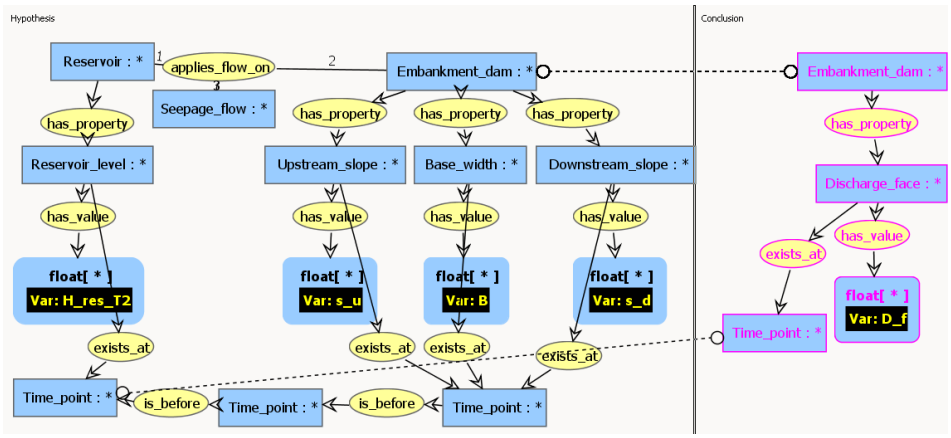


Figure A-8.102. Rule calculating discharge face

The rule graph in Figure A-8.102 shows the calculating of discharge face of the embankment dam. It is computed based on reservoir level and relevant geometrical parameters. The rule graph can be expressed as **if** *Reservoir* applies *Seepage flow* on *Embankment dam*, then *Embankment dam* has *Discharge face*. The time point of the discharge face is the time point of the reservoir level. Figure A-8.103 shows the associated script.

Rule | Associated script

```
1  void after()
2  {
3      float value1 = Math.atan(1 / s_d.getValue());
4      float value2 = H_res.getValue() * s_u.getValue(); // value2 = L
5      float value3 = B.getValue() - value2; //value3 = x_B
6      float value4 = value3 + (value2/3); // value8 = x_C
7      float value5 = Math.pow(value4,2) + Math.pow(H_res.getValue(),2); // value5 = b² + H_res²
8      float value6 = Math.pow(value4,2) - (Math.pow(H_res.getValue(),2) * Math.pow(1/Math.tan(value1),2));
9      float value7 = Math.sqrt(value5) - Math.sqrt(value6); // value7 = a
10
11      D_f.setValue(value7);// (m);
12     }
```

Figure A-8.103. Script calculating discharge face

The measured level of the factor of safety against saturation of embankment dams is:

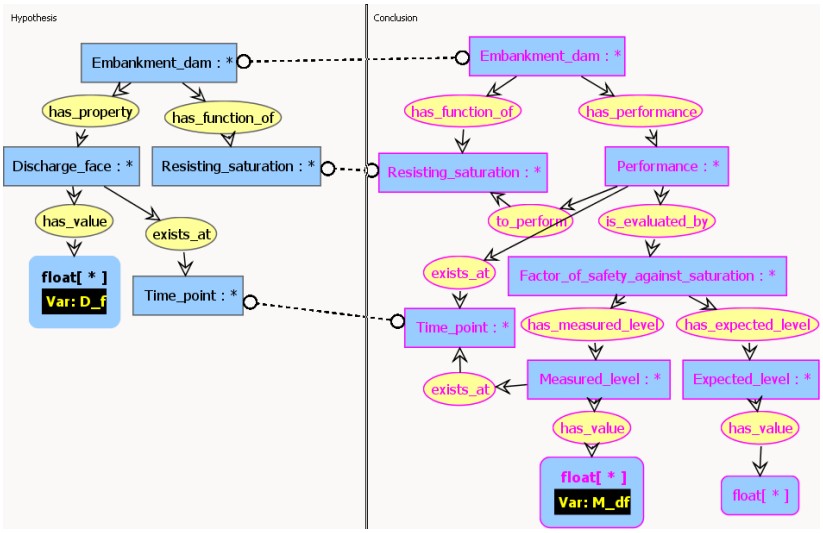


Figure A-8.104. Rule of measured level of factor of safety against saturation

Figure A-8.104 shows a rule graph for calculating the measured level of the factor of safety against saturation. The measured level is computed based on the value of the discharge face. The rule graph can be interpreted as **if** *Embankment dam* has *Discharge face* at a time point, and *Embankment dam* has the function of *Resisting saturation*, **then** *Performance* to perform *Resisting saturation* is created, which evaluated by *Factor of safety against saturation* that has *Measured level* and *Expected level*. The coref relation between two *Resisting saturation* concept nodes shows that with one *Resisting saturation* function, the dam can have different performances created to perform it. The time point of the new performance is the time point of the discharge face. Figure A-8.105 shows the associated script.

Rule | Associated script

```
1  void after()
2  {
3      float value = D_f.getValue();
4
5      M_df.setValue(value);
6  }
```

Figure A-8.105. Script of measured level of factor of safety against saturation

Performance of embankment to resist saturation:

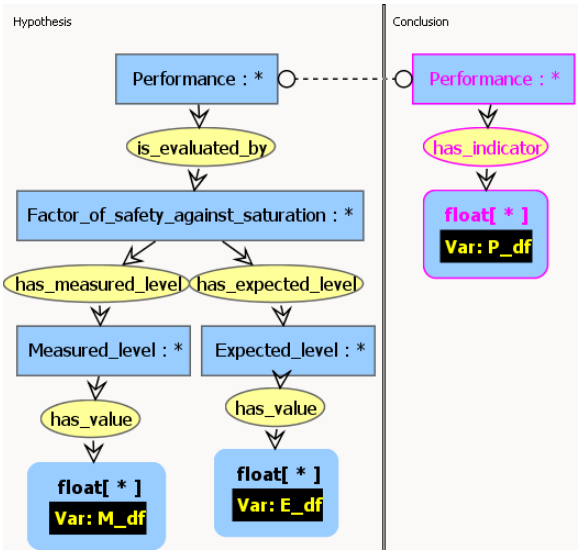


Figure A-8.106. Rule of performance of the dam against saturation

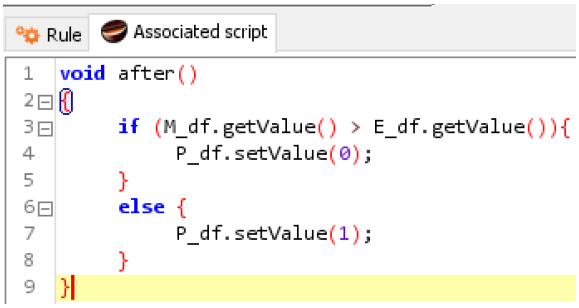


Figure A-8.107. Script of performance of the dam to against saturation

Performance of the dam to resist sloughing:

The safety factor against a sloughing failure using the tangents of the slope angle and the internal friction angle of the soil to predict the safety factor of the saturated slope. These are termed infinite slope equations (Lambe, etal., 1968) and (Venkatramaiah, 2006).

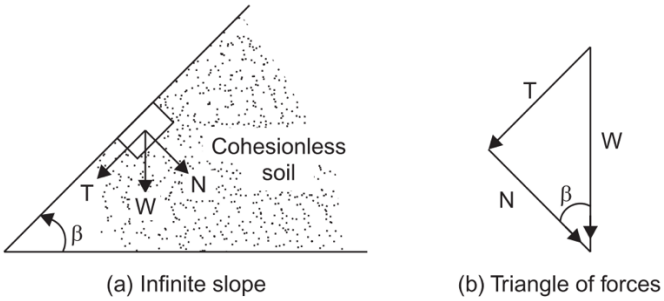


Figure A-8.108. Infinite slope in cohesionless soil (Venkatramaiah, 2006)

The factor of safety against sloughing is given by:

$$F = \frac{\text{Restraining force}}{\text{Sliding force}} = \frac{W\cos\beta\tan\varphi}{W\sin\beta} = \frac{\tan\varphi}{\tan\beta}$$

For limiting equilibrium (F = 1),

$$\tan \beta = \tan \varphi$$

$$\text{or} \qquad \beta = \varphi$$

where, φ is the angle of internal friction

β is the angle between the downstream slope and the horizontal

Rule of the measured level of the factor of safety against sloughing is given as follow:

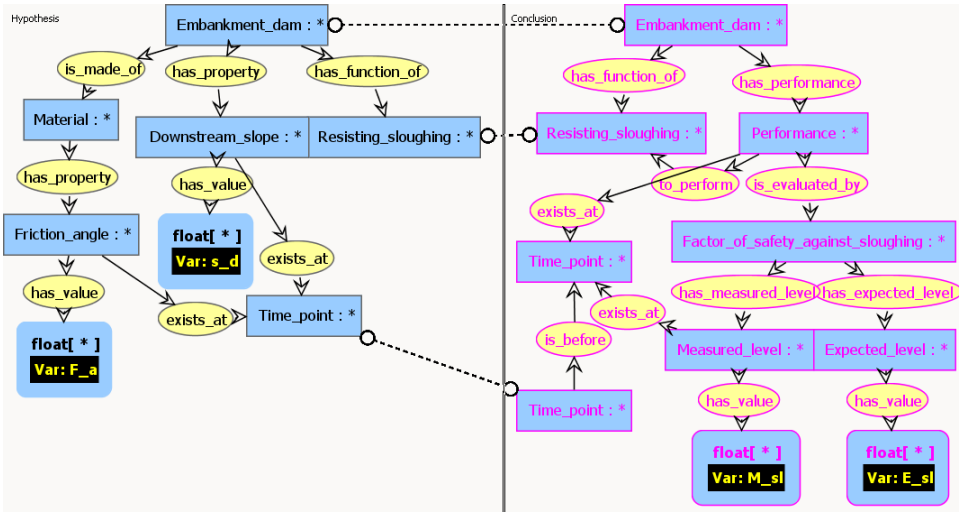


Figure A-8.109. Rule of measured level of factor of safety against sloughing

Figure A-8.109 shows a rule graph for calculating the measured level of the factor of safety against sloughing. The measured level is computed based on a friction angle of embankment material and downstream slope. The rule graph can be interpreted as **if** *Embankment dam* is made of Material that has Friction angle, Embankment dam has Downstream slope, and has the function of Resisting sloughing, **then** *Performance* to perform *Resisting sloughing* is created, which evaluated by *Factor of safety against sloughing* that has *Measured level* and *Expected level*. The coref relation between two *Resisting sloughing* concept nodes shows that with one *Resisting sloughing* function, the dam can have different performances created to perform it. The time point of the new performance is after the time point of the friction angle. Figure A-8.110 shows the associated script.

Rule | Associated script

```
1  void after()
2  {
3
4      float value1 = Math.toRadians(F_a.getValue());
5      float value2 = Math.atan(1 / s_d.getValue());
6      float value3 = value1 / value2;
7
8      M_sl.setValue(value3);
9
10     }
```

Figure A-8.110. Script of measured level of factor of safety against sloughing

Performance of embankment against sloughing

The performance of embankment against sloughing is evaluated based on two conditions:

If the dam is saturated, i.e., the indicator performance has a value of 0

and $\frac{\tan\varphi}{\tan\beta} <$ Limit factor of safety = 1

Then sloughing occurs

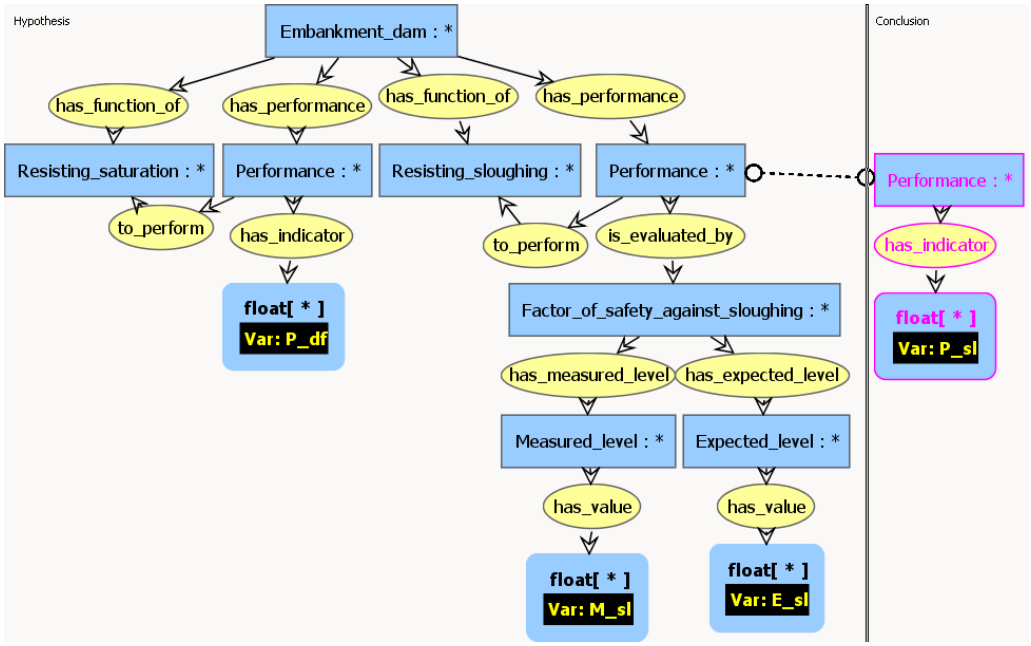


Figure A-8.111. Rule of performance of dam to against sloughing

Figure A-8.111 shows a rule graph to identify the performance indicator of a dam. It is computed based on the measured level of the factor of safety against sloughing and the performance indicator resisting saturation. The rule graph can be expressed as **if** *Embankment dam* has *Measured level* of *Factor of safety against sloughing* and *Performance* performing *Resisting saturation*, then *Performance* to perform *Resisting sloughing* has an indicator. Figure A-8.112 shows the associated script.

Rule | Associated script

```
1  void after()
2  {
3      if (M_sl.getValue() < E_sl.getValue() && P_df.getValue()==0) {
4
5          P_sl.setValue(0);
6      }
7      else {
8          P_sl.setValue(1);
9      }
10 }
```

Figure A-8.112. Script of performance of dam to against sloughing

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