Longtan Dam – Dam safety and production losses under dynamic load

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Abstract: The energy demand in China is steadily growing and large hydropower dams become more and more common. A major dam failure could cause large environmental, economic and social effects, and work concerning safety in dams is therefore essential in order to keep the utilization of hydropower at as low risk level as possible. This master thesis analyzed Longtan Dam under static and dynamic conditions with the help of a two-dimensional numerical model, built in the commercial software UDEC. Further, the production losses during an earthquake were investigated. The results showed that Longtan Dam were rather unsafe under seismic activity. When experiencing earthquake waves with amplitude above 0.4 m/s^2, the reservoir water head had to be lowered significantly in order to keep the safety at a constant level, i.e. if the initial factor of safety was to be kept at a constant value. The most critical part of the dam was the concrete-rock interface, with sliding as the most probable failure mode; a result achieved from both stability analyses by hand and stress simulations in UDEC. In means of losses in production, the results showed that these could be quite high as a consequence of the lowered reservoir water level. The most important aspect of this study were however not the achieved result, but rather the method of investigating the effects of earthquakes in a dam. Hopefully, the conclusions and recommendations could work as help and guidance for future studies and work concerning safety in hydropower dams.

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Summary

This master thesis aimed to use and analyze a method for investigating failure and losses in production, with the help of the commercial software UDEC. As a template for the numerical model, the Chinese hydropower station Longtan Dam was used. Further, the study was divided into two parts; model with static conditions and model with dynamic conditions. The static conditions incorporated water loads upstream and downstream the dam, an uplift force in the concrete-rock interface and the dam's self weight, whereas the dynamic conditions added a seismic wave to the base of the model. The losses in production during seismic activity was investigated by keeping the factor of safety constant meanwhile increasing the strength of the earthquake by increasing the amplitude of the seismic wave. The higher load was compensated by lowering the reservoir water level, hence loosing potential production.

The results from the static conditions were expected and followed basic mechanical rules, and as a consequence the dam's self weight and design were the parameters with greatest impact on the model. The two most critical parameters affecting the stability of the modeled dam were considered to be the structure and condition of the bedrock, and the size and distribution of the uplift force. Both of these two parameters will vary with time, thus changing the risk profile and safety. In addition, they proved to be the reason behind the presence of the failure mode sliding in the model, a result achieved from the analysis of the shear friction factor. A result that on the other hand showed that the dam was safe enough was the overall factor of safety with a value of 3, which indicates that the dam should be able to withstand three times the static load added to the model.

The model of Longtan Dam turned out to stand short in terms of withstanding earthquakes. Already at seismic waves with amplitudes larger than 0.4 m/s^2, the safety decreased rapidly and the reservoir water level had to be lowered drastically in order maintain the factor of safety in level with the value obtained from static conditions. At amplitudes exceeding 2.0 m/s^2 the dam failed despite a lower reservoir water level. In comparison with the regular design criteria for dams in areas with low seismic activity in China, i.e. a dam should be able to withstand dynamic loads between 0.2g – 0.3g, the result from the simulations can be somewhat explained with reference to the lower limit in the criteria. However, the results were considered to be questionable since the model could not withstand low amplitudes without lowering the reservoir water head, which should not be acceptable with the possible consequence of a dam failure in mind. Further, the time frame needed to lower the reservoir water level in the magnitudes mentioned above, are in between several days to weeks and months. The rather extreme scenario that was assumed for model, i.e. the uplift force and weak interface, could also have contributed to and somewhat explain the results. Concerning the production losses, they would be high since a significant amount of the reservoir need to be emptied.

To meet the growing energy demand in China, the development and increased utilization of hydropower is essential. Hence, the method used in this thesis could be of interest for further analysis, specifically since a number of high concrete dams are built in areas of China with complex geological conditions. The most important aspect of this thesis was not the achieved results, but the investigation of a possible method for studying the effects of earthquakes in the area of dam safety. As a method, the way of defining this model worked quite well and could be applied in risk and vulnerability analysis for gravity dams with similar construction as the Longtan Dam or work as an outline for future studies in dam safety.

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Lund, August 2012
Lars Berggren & Ludvig Wallmann

Dictionary

Compressive stress: is created when a side of an object is pushed inward to the object's center.

Concrete structure: the concrete body of the dam.

Dam failure: damage resulting from overflow due to high water levels or internal or external material failure, such as cracks in the concrete.

Dam heel: the most upstream part of the dam foundation.

Dam toe: the most downstream part of the dam foundation.

Damping: an effect that reduces vibrations by energy absorption.

Factor of safety: the ratio of maximum strength and actual load.

Flare: a part that is added to the upstream face of the dam in order to increase the resistance against the clockwise moment, see figure 5.

Overflow: a discharge section in the crest of the dam.

Rock foundation: the rock the dam is placed upon.

Shear stress: forces acting in opposite directions along a parallel plane, often critical along the dam base.

Solid section: the part of the dam which only consists of solid concrete.

Static state: is a term for simplified analysis in which the effects of an immediate change to a system is calculated, without respect to the longer term response in the system.

Tensile stress: is created when two sides of an object are moving in opposite directions, a situation that occurs frequently in the dam heel.

Nomenclature

p_w = hydrostatic water pressure

W = weight of concrete foundation

ρ_w = water density (998 kg/m^3)

g = gravitational acceleration (9.82 m/s^2)

H = height of water head upstream

h = height of water head downstream

γ_w= specific density of water

P_u= uplift pressure

T= the length of the dam section

y = distance parameter

z = distance parameter

F_o = safety factor of overturning

M_{+ve} = moments preventing overturning

M_{-ve} = moments causing overturning

$\sum$ = sign for summarization

F_{SF}= shear friction factor

c = cohesion

V= vertical force

H= horizontal force

φ = angle of internal friction

F_{SS} = sliding factor

S = the sum of loads acting on a dam

R = a dam's resistance to loads

sf = safety factor

p_f = probability of failure

P = the probability of an event

$G(x_i)$ = function on the failure mode

x_i = random variables described by a statistical distribution

Φ = cumulative distribution function of the standard normal distribution

μ_G = mean value of the state function

σ_G = standard deviation of the state function

β = safety index

F_L = factor of safety derived from loads

F_ϕ = factor of safety derived from angles

E = energy released from an earthquake

M = magnitude of an earthquake

U = uplift pressure upstream the relief drain

u = uplift pressure downstream the relief drain

F = net force

m = mass

a = acceleration

P = pressure

A = area

V = volume

L = length (same as T)

τ = shear stress

σ_z = vertical normal stress

I = the second moment of area of the plane

τ_F = shear strength

c = cohesive strength

σ = normal stress

σ_m = maximum normal stress

r = radius

E = Young's modulus (the modulus of elasticity)

G = shear modulus

K = bulk modulus

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1. Introduction

The development of the society is increasing rapidly in China, and as an effect of it the energy demand is growing as well. Today, the most common source of energy production in the country is combustion of coal, an area that is steadily expanding. However, there are disadvantages with combustion of coal such as large emissions carbon dioxide (CO_2), smoke pollutions and increased concentration of mercury in rivers. In order to meet the increasing energy demand in China, one solution is the development of its second largest energy source, hydropower, which at present contributes with 15 percent of the country's total energy production. Worth noticing is that China is the world's largest producer of energy from hydropower, in addition, there are plans for building 13 large hydropower dams where some are already under construction. The high concrete gravity dam Longtan Dam is one of the dams in the project and has recently started producing electricity.

The Longtan dam is with its 216.5 meter the highest roller-compacted concrete gravity dam in the world and has an installed effect of 6300 MW. Several risks follow from building and operating a dam of this scale, where a serious dam failure could cause devastating effects on the surrounding environment and society, followed by large economical consequences. Questions regarding safety and stability from design and construction to maintenance and operation should thus be of highest priority. Many of the dams in China are in high-intensity seismic areas, which enhance the risk for dam failure. Simulations of structures to work with questions regarding safety can provide valuable information and can help to improve dam's stability and lower construction costs. Therefore, earthquakes are an important risk to analyze even if probability of occurrence is low.

1.1.Purpose and research questions

The main theme of the project is investigating how an additional stress will affect the safety in a high concrete gravity dam through calculations of the factor of safety. Therefore, the aim and objective are to investigate critical points in order to determine what type of failure mode will occur and what effect a dam failure will have in production losses. The Longtan Dam is the target object in this thesis and will be analyzed with the help of data gained from extensive investigations performed by the Department of Civil Engineering at Shandong University. However, the most important aspect will be the methodology used in this thesis rather than the result. In order to clarify what the analysis aims to analyze, the following research questions are formulated:

1) How is the factor of safety in a dam affected by seismic activity in addition to the static conditions?

2) Where is the critical point in the dam's structure?

3) What are the production losses and what possible effects can a dam failure have on the surrounding environment?

1.2.Methods

In brief, the methods used to answer the research questions are described as followed;

- Initially, a literature study is performed in order to create a foundation regarding the area in question.

- The analysis takes its starting point in identifying Longtan Dam's static loads, including the features of the underlying bedrock. This research will work as the basis of the model that will be built for simulations in a computer software. Additional loads that can affect the dam are investigated thoroughly in order to see which failure modes that might have an effect on the dam and what influence this could have on the overall safety.

- A common commercial software (UDEC) based on the distinct element method for discontinuum modeling will be used to set up a two-dimensional numerical model. This will work as basis for the calculations of the dam's factor of safety.

- The losses in production will be estimated from investigating the measures of safety that have to be taken in order to keep a high safety, even though the dam is experiencing a higher stress level than normal.

- Finally, to highlight other consequences than the financial a small investigation concerning possible damage to surrounding environmental from a dam failure will be done.

A numerical analysis method is used in this thesis to solve the complex situation of studying a dam under seismic activity. The software UDEC is well suited for studies of deformations along discontinues and presents results that can be directly related to potential failures. Therefore, UDEC is considered to be appropriate for this type of analysis.

1.3.Limitations

The major limitation in the master thesis is the limited amount of time in China, during which simulations, model calculations and analysis of results were to be achieved. This has resulted in some assumptions and simplifications during the construction of the model. An additional aspect is that all concrete dams are unique due to local and geographical variations, which will render in a different combination of risk factors. This report will focus on risks caused by primary loads and stress analysis concerning earthquakes. There are also a wide range of dams other than the concrete gravity dam, for example arch dam and buttress dam, which are adapted and suited to withstand the loads at a location through theirs design. As a consequence part of the results in this thesis cannot be applied on other concrete gravity dams or future locations, but will however hopefully contribute with a methodology for analysis that can be used in future studies and investigations. The production losses are limited to concerning only the water level, thus leaving out technical aspects in the chain of production.

1.4.Structure of thesis

Chapter one aims to give, and has hopefully already done, a short introduction to the thesis.

Chapter two consists of a background concerning the energy situation in China, facts and figures concerning the Longtan Dam, and elementary knowledge of various types of concrete dams. The chapter ends with general thought of risk management in dam safety.

Chapter three is a chapter with theory that will help the reader to understand the static and additional stresses that affect a dam, which have to be taken into consideration when working with dam safety. Further, the most common failure modes are presented before the chapter finish with an introduction to the software that is used to build the model of Longtan Dam.

Chapter four introduces the method of work in the thesis by presenting the structure of the analysis and the assumptions made.

Chapter five presents the result of the analysis and research questions, and will follow the same structure as the previous chapter.

Chapter six consists of the discussion of the results and the thesis as a whole.

Chapter seven is the final conclusions of the thesis together with thoughts on possible future studies.

2. Background

The purpose of this chapter is to give an introduction to the use and development of hydropower in China, including a view at the present situation and the future prospects. Further, a background regarding Longtan Dam, concrete gravity dams in general and risk management in dam safety, are presented.

2.1.Energy situation in China

China is a rapidly growing economy and with its development, the demand of energy increases. Between 2001 and 2007, the annual increase in gross domestic product, GDP was 10.2 percent and the corresponding increase in primary energy consumption was 9.8 percent (Liu, Lund, Mathiesen, & Zhang, 2011). As shown in figure 1, combustion of coal is the main source of energy in China, a source that in an environmental and health perspective can be questionable due the high emissions of CO_2 and particle matter into the atmosphere. In addition, China is at present both the largest energy consumer as well as the largest CO_2 emitter in the world (Liu et al., 2011). However, an important fact to emphasize is that the energy consumption of a Chinese citizen is approximately one fourth of the one for a person from North America and in comparison with Europeans, a Chinese has half usage of energy (Energimyndigheten, 2011).

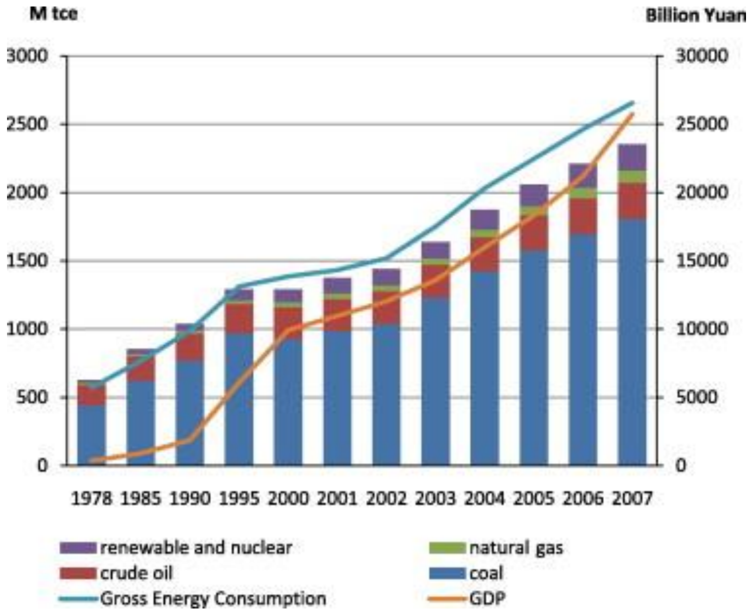

Figure 1 - The increase in gross energy consumption, GDP and produced energy in China (Liu et al., 2011).

2.1.1. Hydropower in China

The agency in charge of China’s electric power industry, The National Development and Reform Commission (NDRC) has presented a policy with the purpose to increase the hydropower, among other things (Hailun & Zheng, 2009). By increasing the amount of renewable energy sources, the growing demand can be met and the number of high concrete dams under construction in China is an example of the development initiated by NDRC’s plan (Jia, Gao, Zhang, & Ren, n.d.). Except the advantage of rendering a low quantity of emissions, hydropower also has a high efficiency and a low generation cost, which further increases the profits earned in an investment.

On a global scale, China is the largest producer of hydropower energy with 13.3 percent of the world’s entire production. Compared to Sweden’s annual generation of electricity from hydropower, 67 TWh year 2010 (Energimyndigheten, 2011), China’s production is almost ten times higher, 563 TWh year 2008 as can be seen in figure 2. The long term goal, stated in NDRC policy, is to reach a total capacity of 330 GW hydropower to the year 2020, which should result in a power generation of 1150 TWh (Vermeer, 2011).

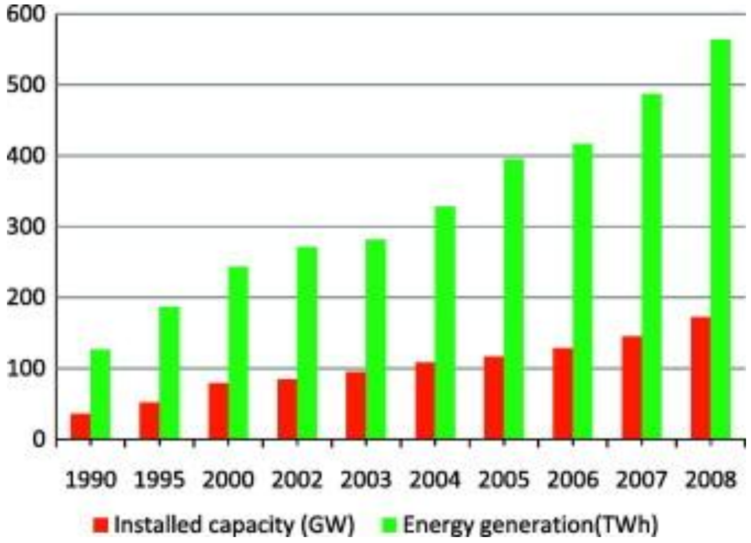

Figure 2 - The development in installed capacity and generated energy from hydropower in China during the last ten years (Liu et al., 2011).

One of the problems with the development of hydropower in China is the geographical distribution of potential sources. As figure 3 illustrates, the areas with most potential for exploitation is in the Southwestern parts of the country were the highest amounts of precipitation is. These areas are not as developed in economy, industry and infrastructure as the eastern and coastal parts of China, which makes the allocation between source and utilization uneven. In order to take advantage of the resource, high-voltage power grids for long distances transmission has to be constructed, a measure that is expensive but a necessity if the resource is to be utilized (Hailun & Zheng, 2009).

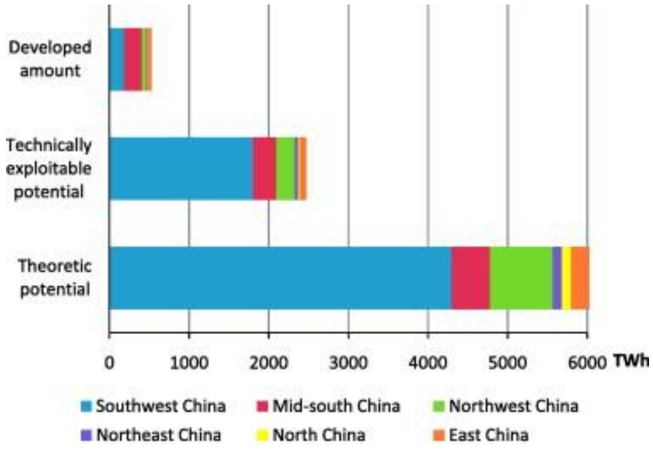

Figure 3 - The potential and geographic distribution of sources for hydropower in China (Liu et al., 2011).

2.2.Consequences of mega dams

Today, dams are built in order to serve several purposes and the social and environmental impacts have therefore become more important to investigate. Except functioning as a water supply and hydropower station, dams also provide flood and sediment control, prevent irrigation, improve the navigations of rivers and opportunities for recreation. The multipurpose has resulted in a new direction of priorities in the development of dams, where environmental, economic and social costs are taken into account in the planning phase for new projects. In a historical perspective the main purpose of dam constructions have been flood control, which will probably continue be of major importance since four out of ten of all fatalities caused by natural catastrophes in the world are due to flooding. However, the central function of dams is shifting towards generation of electricity and benefits such as flood control are seen as additional contributions. (Altinbilek, 2002)

Despite its advantages, large dams have long been met with skepticism and the main reasons are connected to damage on the surrounding environment during the construction, which effect ecosystems and the inhabitants in the area that have to be resettled. Examples of ecological damages are loss in the diversity of water life and the spread contaminations in the surface water. Other often debated topics are water losses caused by evaporation from reservoirs, spread of waterborne diseases, and the problems with damage and safety. (Altinbilek, 2002)

Between 1950 and 2000, 12.5 million people moved in order to make room for new reservoirs in China alone. According to Eduard B. Vermeer (2011) the resettlements caused numerous economic, social and psychological problems such as less area of farmland, reduced access to roads and electricity, and poorer education than the national average. New laws and policies in China require hydropower projects to develop a plan for resettlement, perform an independent environmental impact assessment and an approval before the start of a construction. As a result, both the ecological situation and questions concerning the relocation of people has improved, however at the expense of a decrease in the previous rather high development rate of new hydropower stations. Construction of dams has increasingly become more expensive and the process for approval longer, which has resulted in a trend of fewer new projects. To reach the target of 330 GW of hydropower until 2020 the development has to switch, thus more dams has to be built. The benefits with a clean source of energy are very important for the people in China, and in comparison to the combustion of coal hydropower is more environmental friendly.

2.3. Longtan Dam

The Longtan Hydropower Project started in 2001, was completed 2010 and is a part the Great Western Development Plan and the strategic project of *Power transmission from west to east*. In other words, Longtan Dam is one of many dams that are being or are going to be constructed in the southwestern and northwestern parts of China. These are areas with a complex geological bedrock and high-frequent seismic activity. (Jia, Li, & Ren, 2010) The dam investigated in this thesis is located in Hongshui River in Tian'e County of the Guangxi Zhuang Autonomous Region situated in the southwest of China. With its maximum height of 216.5 meters, Longtan Dam is the highest roller-compacted concrete (RCC) gravity dam throughout the world. The dam contains an underground hydropower system with a total power generation capacity of 6300 MW, divided into nine units. Except for the purpose of generating electricity, Longtan Dam fulfils an important function in supervision and prevention of floods in the Hongshuai River. The system for flood control includes seven surface spillways and two bottom outlets. (CHINCOLD, n.d.) Elemental facts and figures regarding the Longtan Dam can be seen in table 1.

Table 1 - A brief resume of facts and figures related to Longtan Dam.

Dam type	RCC
Height (m)	200
Span/Crest length (m)	849.44
Maximum water head for production (m)	179
Minimum water head for production (m)	102
Downstream water head (m)	15-25
Concrete volume (10^9 m^3)	7.67
Drainage area above the dam site (km^2)	98500
Reservoir storage (10^{12} m^3)	27.27, active 20.53
Maximum flood releasing capacity (m^3/s)	27 134
Mean annual discharge (m^3/s)	1610

2.4. Concrete dams

It is important to distinguish between dams according to both variations in shape and construction material, since their functions should coincide with a variety of local factors, i.e. geological- and environmental conditions, climate and shape of the valley. Based on the construction material, there are two main types of dams; embankment dams (earth fill and rock fill dams) and concrete dams. Almost nine out of ten active dams are of embankment type, which is a result from technical and economical considerations. Concrete Dams are generally much more complex to build, but has advantages when it comes to reducing risks. For instance, concrete dams are not sensitive to overtopping under extreme flood conditions and have higher ability to withstand seismic disturbance. (Novak, Moffat, Nalluri, & Narayanan, 2007) Concrete dams can through the shape of the construction be further divided into three subcategories; gravity, arch and buttress dams. Illustrations of the shape of each and one of the three categories are presented in figure 4 below.

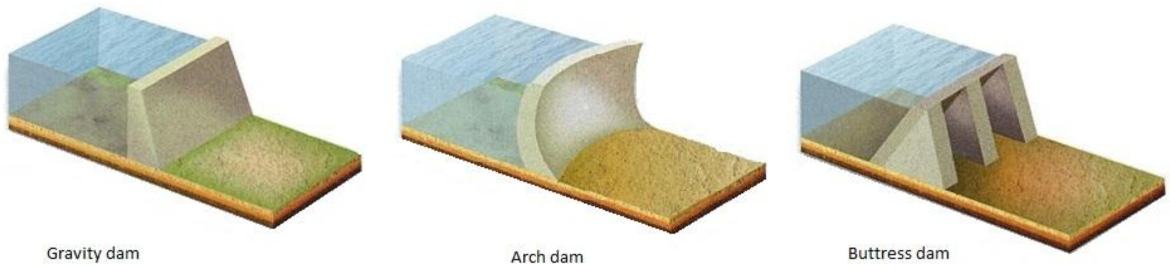

Figure 4 – Illustration of the three most common designs of concrete dams. From right to left; gravity dam, arch dam and buttress dam. (Australian Geographic, 2011)

- The most common among the three types of concrete dams is the gravity dam. In 1998, 11.3 percent of all large dams (including embankment dams) in the world were concrete gravity dams (Novak et al., 2007). The purpose with a gravity dam's design is the possibility to withstand the hydrostatic force entirely with the force of its own weight and geometrical shape. In simplicity, the structure's shape of a triangle should resist the triangular distribution of the upstream water pressure. Because of the large amount of concrete needed to build a solid construction, which is able to withstand high water loads and weathering, a concrete gravity dam is the most expensive dam to build. Therefore, in order to become economically viable a concrete gravity dam is dependent on both adequate quality and quantity. (Hamill, 2001)

- A dam that is curved and depends on an arch action for its strength is called an arch dam. The design idea with the arch shape is to withstand the high loads from the hydrostatic pressure by leading the compression in the structure into the rock foundation. Reinforced concrete is the most common construction material in arch dams and these types of designs are preferable in narrow locations with strong abutments. The distinguished benefit of an arch dam is the thin structure, which requires less material than any other kind of concrete dam and the building costs are thus reduced. However, due to the complex structure, an arch dam is more complicate to build in comparison to a gravity dam. (Hamill, 2001)

- A buttress dam is a lighter version of a concrete gravity dam, with a series of buttresses instead of solid concrete foundation. The main function of a buttress is to transfer the hydrostatic force down to the ground and the shape of the foundation wall can be flat as well as curved like an arch dam. A buttress dam only requires about 60 percent concrete in comparison to a similar gravity dam. Due to the need of reinforced concrete and the complex structure, the cost is almost in level with a gravity dam. Buttress dams are mostly used when the rock foundation is weak and/or the flood valley is too wide for a single arch dam. (Hamill, 2001)

2.4.1. Roller-compacted concrete dam

A less expensive type of a gravity dam is the roller-compacted concrete (RCC) dam, which uses a dry type of cement mix consisting fly ash. The concrete is processed with conventional construction equipment and compacted by rolling, usually with vibratory rollers. The ash is a waste product from the coal industry (Novak et al., 2007), and allows the concrete to reduce the amount of water in the construction phase, thus reduces bleeding. This two elementary steps provide significant advantages in the construction methodology and the overall building process is more rapid, durable and safer than for a normal concrete gravity dam or for an embankment dam. The benefits of RCC increase the possibility to use a wide range of equipment for construction and consequently allow a variation of locations for deployment. (U.S. Army Corps of Engineers, 1995)

2.5. Risk management in dam safety

It is hard to argue against the benefits that the development of hydropower has brought the society, enabling an economical growth through industrialization, among other things. In present time, the most obvious positive aspects with hydropower are electricity produced with high efficiency at a low generation cost and the utility of a renewable energy source. Despite the advantages, both historical and present, there have always been risks connected to dams. The question is whether the risks are tolerable or not, which comes down to factors such as economy, politics and the perception of risk in the society. In order to make certain the safety of a dam is acceptable the possible risks has to be investigated thoroughly and there are several methods at hand for a risk analysis. Hence, every unique situation will determine which approach that should be used.

2.5.1. Methods for identifying risks

There are three common methods used for identifying risks; comparative methods, brainstorming methods (HAZOP, FMEA and What-if) and analysis of logical systems (Fault tree and Event tree). In order to provide a quantitative measure of a dam's risk level, estimations of probabilities are required. Three different methods are mentioned by Hartford and Baecher (2004) for the execution of the estimation:

- **Empirical estimates** of probabilities based on occurred events, which requires a large sample of history data. The reliability of the estimation will depend on the amount of available data.

- **Logical systems** are analytical methods where the system is broken down into smaller pieces, thus creating a model based on an adverse event or outcome. This is not an estimation or assessment of the overall risk, but will instead treat events and outcomes, that affect the risk, alone or in combinations. Examples of logical systems are event tree and fault tree analysis.

- **Expert judgments** of the probability, performed by persons with experience and knowledge in the field of question. The estimations are based on subjective judgments and can easily be adapted to local conditions. Bayesian methods could be used in order to combine expert judgments with empirical data, for instance old empirical data may be updated with new information by using Bayes' formula. (Bartsch, 1997)

The quantification of risks and probabilities for geological structures is particularly difficult since they, unlike technical systems, do not have a defined chain of events, i.e. the variability in nature and changes over a period of time can result in rough and uncertain estimations. (Hartford & Baecher, 2004)

2.5.2. What is risk and vulnerability?

The definition of risk used in this report, was proposed by Kaplan and Garrick (1981) and highlights the classic triplet for the definition of risk, which are the function of the risk scenario, the probability and the consequence of the scenario. This definition is well established in literature concerning risk and the triplet simply sets out to answer the following questions:

- What can happen?
- How likely is it to happen?
- Given that it occurs, what are the consequences?

While the definition of risk is relatively well accepted in its sector, there is no established definition for vulnerability. Rausand & Utne (2009) stated that vulnerability is related to a possible loss of value that can be influenced by a limitation and reduction of vulnerability. Compared to risk, vulnerability is a more complex concept. However, a prerequisite in all vulnerability analysis is that an increased emphasis is devoted to an organization's or a system's capability of responding to and recovering from something that affects the system adversely, i.e. the system's ability to respond to a state considered not to be normal. Based on the above definition of risk, Johansson & Jönsson (2007) has defined three similar questions that should be answered in a vulnerability analysis:

- Given a stress, what can happen?
- Given a stress, how likely is it to happen?
- What are the consequences?

3. Theory

With the help of figure 5, this chapter will introduce the reader to some fundamental ideas concerning elementary dam design and the general loads and stresses a dam should be able to withstand. The dictionary and nomenclature in the preamble of the report could be of additional help.

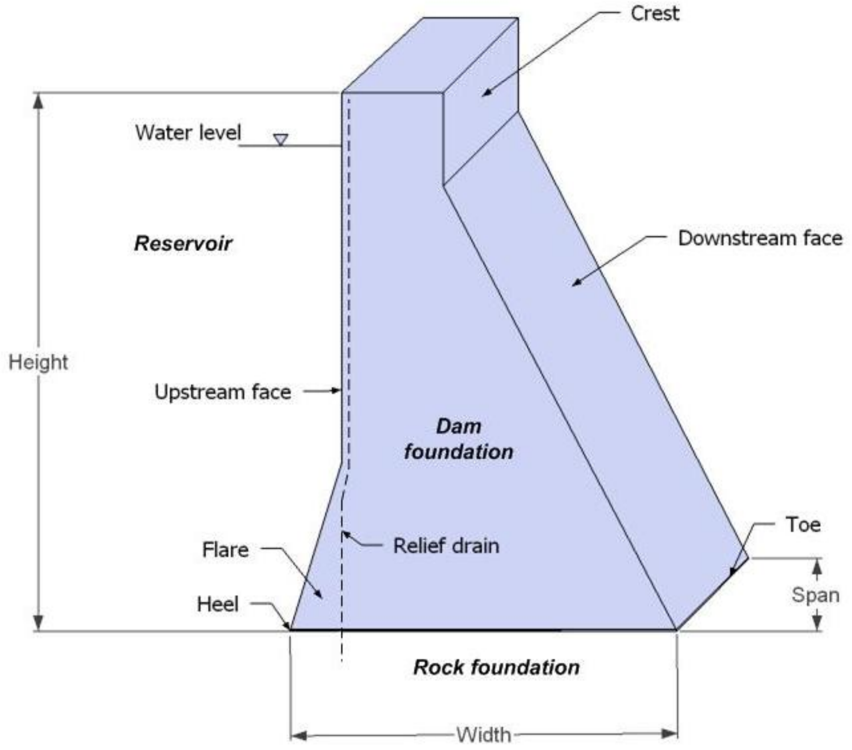

Figure 5 – The cross section of a concrete gravity dam, explaining the most fundamental parts.

3.1.Loads on a concrete gravity dam

Bedrock geology, material characteristic, flood hydrology and so forth, are all factors that result in that each and every dam is unique and must be adapted to the loads created at a specific location. However, there are always two unavoidable stresses; the hydrostatic water pressure ($\mathrm{p_w}$) caused by the upstream and downstream water loads and the weight of the concrete structure (W). The load from the hydrostatic water pressure reaches its maximum at the bottom of the dam; hence it will be distributed in the form of a triangle with the resulting force in horizontal direction one-third from the bottom. These types of loads are universally applicable for dams and are known as primary loads. Loads that develop gradually or occur temporarily are called secondary loads. The third type, exceptional loads, has limited general applicability or low probability of occurrence (Novak et al., 2007) (Westberg, 2010). The different potential loads on a concrete gravity are demonstrated in figure 6.

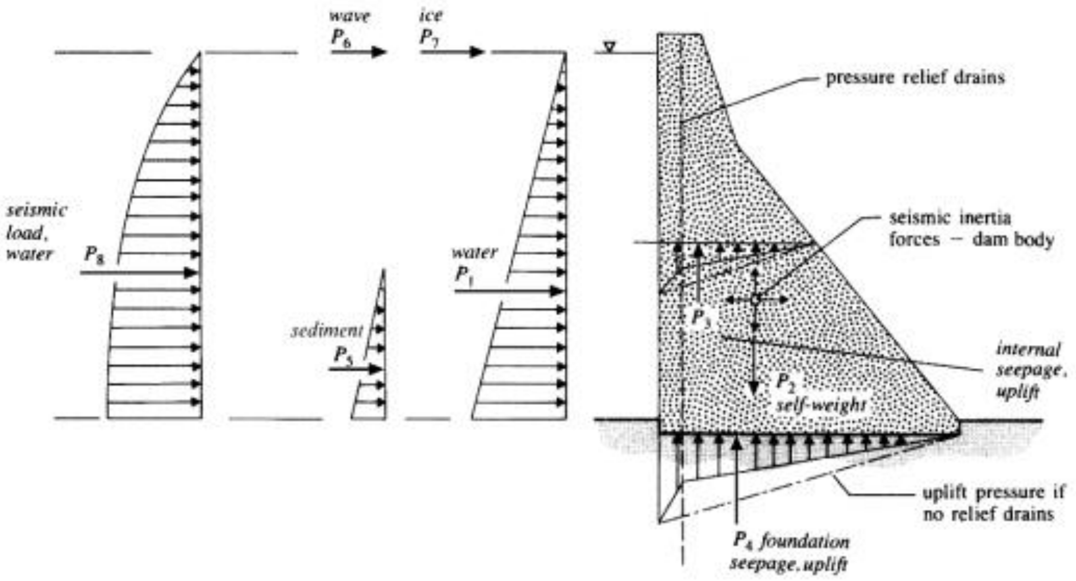

Figure 6 - Illustration of a concrete gravity dam and its loads along with pressure distributions and resultant forces (Novak et al., 2007). Note that the labels concerning the different loads will differ in the report.

3.1.1. Primary loads

3.1.1.1. Water

The water load creates the hydrostatic force, which is acting on the dam foundation in the shape of a triangle with a resultant force situated one-third up from the dam heel. The magnitude of the load is determined by the hydrostatic pressure, p_w, and can be expressed through;

$$p_w = \rho_w g h$$

where ρ_w is the density of the water, g is the acceleration of earth gravity and h is the height of the water head. An important factor to bear in mind is that the hydrostatic pressure is situated on both sides of the concrete foundation, the greater stress will however be situated on the upstream side. The water density varies with the temperature, thus the load will be season dependent. Further, the water flow is also depending on seasonal variations and the geographical location, i.e. melting snow water can cause high floods during spring whereas other areas experiences the highest flood during the autumn as a result from more precipitation.

3.1.1.2. Self weight

The load from self-weight depends on the material used in the concrete foundation and is in general calculated by the volume times the specific weight of concrete. This load creates a resulting force acting vertically downwards from the center of gravity of the concrete structure. A factor that reduces the effect of the dam’s weight is the force created from the uplift pressure, i.e. the water pressure under the foundation, which is explained in detail below. The degree of variability for the self weight is small in comparison to the variability of other loads acting on the dam and can in time decrease from a reduction in density or volume caused by mechanical damage or seepage, but these effects are considered to be negligible. However, the position of the resultant force, the volume and density could be difficult to determine since consideration to spillways and additional features in the construction design have to be taken into account.

3.1.1.3. Uplift and seepage

Seepage through pores and discontinuities, e.g. joints, cracks and fine fissures, in the dam and the concrete-rock interface creates the possibility for pressure within the concrete structure and underneath the dam. The uplift pressure is situated under the concrete foundation is as previous mentioned caused by the hydrostatic pressure and decreases towards the toe of the dam. Deviations in the distribution of the uplift force will vary with geological conditions, temperature and other loads. Damages caused by seepage are foremost cracking and internal erosion, meanwhile uplift results in instability and an increased risk for sliding. Internal uplift is controlled by pressure relief drains and the uplift in the concrete-rock interface is decreased with relief drains that are drilled into the bedrock. Without drains, the pressure is assumed to be triangular with the peak in the dam's heel, however the pressure decreases rapidly before it is flattening out if relief drains are applied. A resultant from the uplift pressure acts vertically upwards to the concrete foundation; see illustrations of the pressure distribution and resultant in figure 7. The pressure at the heel and toe is equal to the water head in the reservoir and the downstream water, respectively. In this thesis the following equation is used for determining the resultant of the uplift pressure;

$$P_u = T \cdot \gamma_w \cdot \frac{(z_1 + z_2)}{2}$$

which will be situated at the distance y_1 from the heel according to;

$$y_1 = \frac{T}{3} \cdot \frac{2 \cdot z_2 + z_1}{z_2 + z_1}$$

where T is the thickness of the base section and $y_w \cdot z$ is the value for the hydrostatic pressure.

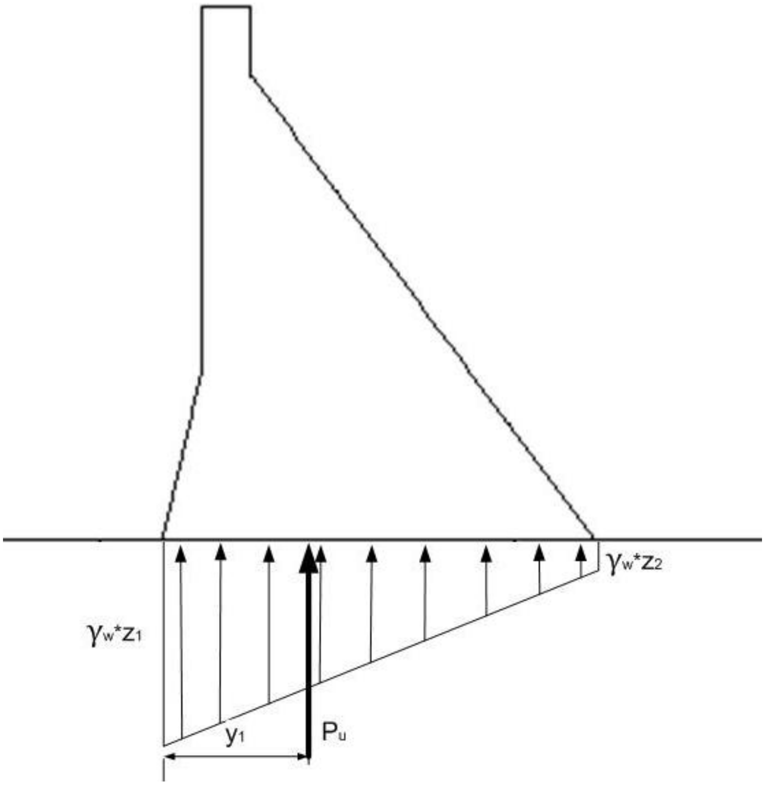

Figure 7 - Illustration of the uplift pressure in a dam without relief drains.

3.1.2. Secondary loads

3.1.2.1. Sediment

In time, rivers motion will deposit fine particles as sediment at a dam's heel. The resultant pressure from the additional load will act horizontally on the upstream face and depend on the unit weight of the matter, the sediment depth and the active lateral pressure coefficient. The sediment load is an addition to the hydrostatic pressure, but is in most cases not critical to the dam design, and is hard to determine because of factors connected to river hydrograph, characteristics of the reservoir and the concentration of sediment, etc. However, the sediment load could be critical in small flood control dams.

3.1.2.2. Hydrodynamic wave

The influence of hydrodynamic waves is random in its appearance due to local variations, is negligible in significance and is therefore in general not considered. An exceptional case are large waves caused from landslides upstream the dam, e.g. as a secondary effect from seismic activity. The dynamic behind landslide and following effects are discussed more thoroughly below.

3.1.2.3. Ice

In colder climates where ice sheets at considerable thickness occur for a longer period of time, a pressure towards the dam's crest level could be generated. The pressure varies with wind speed, temperature, fluctuations in water level and currents.

3.1.2.4. Thermal

A temperature gradient can be created throughout the dam. This is a complex and time dependent function affected by a combination of factors, which are subsequent variations in the ambient conditions, water temperature and the cooling of large pours of concrete as an effect of exothermic hydration of cement.

3.1.3. Exceptional loads

3.1.3.1. Seismic activity

An earthquake has a low probability, but could generate a high dynamic load that affects the foundation and hydrostatic pressure in both vertical and horizontal directions, if occurring. Just as the ice load the seismic load will be geographically dependent, thus consideration to such effect in design and risk assessments will vary from one project to another. The impact of earthquakes will be investigated in an upcoming chapter regarding natural hazards in dam safety.

3.1.4. Combinations of loads and parameters of resistance

A problem is the effects caused by combinations of several loads, which might not need to be considered in the design of lesser dams, but could however be of greater importance in larger constructions and thus demanding that measures have to be taken into the design. A concrete dam must be designed with respect to all loads and possible combination of them that might have a realistic probability occurrence. As already mentioned the primary loads are always present. The secondary loads are a little more complicated to take into account and can vary a lot in duration, occurrence and intensity over time. Exceptional loads are uncommon but can alone be a threat to the safety. This means that every dam has to be designed and analyzed in accordance to the specific criteria in the area and other circumstances concerning the dam, e.g. temperature régimes and anticipated flood characteristics. Therefore, the combinations of load are divided into normal, unusual and extreme depending on the purpose of the stability analyze. What is included in each category varies and depends on the conditions prevailing. (Novak et al., 2007)

3.1.5. Stress

In order to understand the impact of loads in dam failure, elementary knowledge of the stresses affecting a dam is a necessity. The loads applied will either move the object or build up different kinds of stresses within it, which can cause damage in form of cracks in the bedrock, the dam or in the interface. As mentioned previously, the loads affecting a dam is applied in a variation of directions and are adopting different distributions, consequently resulting in stresses with a variation in attributes. Horizontal stress is normally caused by the hydraulic pressures on the upstream and downstream faces of the dam, although it can also be an effect of secondary loads such as ice. In addition, earthquakes and wave pressure result in dynamic horizontal stresses. Typical vertical stresses are caused by the dam weight, the water loads on the bedrock and the uplift force in the concrete-rock interface. Concerning stresses; material properties and the unique conditions on a location are essential factors, e.g. the characteristics of concrete will vary with age, the type of cement, the cement/water ratio, etc. (Hudson & Harrison, 1997)

3.1.6. Dam failure

In figure 8, causes of dam failure are summarized up in terms of primary and secondary causes. The first five causes are all due to foundation, which is the most frequent cause of dam failure. The next three causes are due to failure in concrete and the upcoming three are effects from unforeseen actions or actions of exceptional magnitude. Finally, the last three columns are causes from structural behavior.

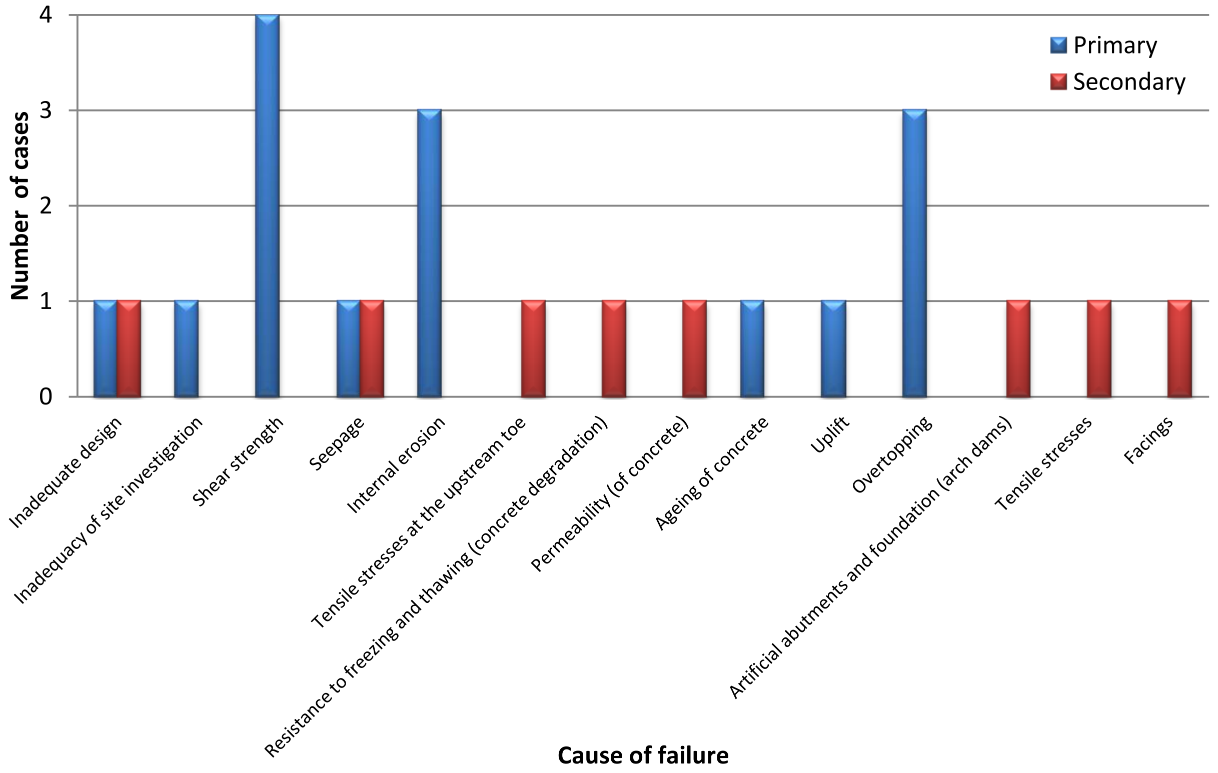

Figure 8 - Causes of dam failure in concrete dams, after data from the International Commission on Large Dams, ICLOD, (Westberg, 2010).

As can been seen in the figure above, there are several critical factors in a dam's construction that can cause a failure and the interface between the rock and the dam is one of the most important. According to Jia, Gao & Li (2011) this is a result from that the force that are binding rock and dam together is small and weathering in the rock foundation surface and joints in the rock bed. This interface and its forces of resistances against stresses are of importance in avoiding failure in a dam.

3.2.Stability analysis for dams

3.2.1. Failure modes

There are three major types of failure modes in concrete dams according to Novak et al. (2007) and Westberg (2010);

- Overturning
- Sliding
- Overstress and material failure.

Each of the failure modes are essential and work as criteria when designing or performing an assessment on a dam. The three failure modes, or criteria, mentioned are presented in more detail below.

3.2.1.1. Overturning

The weight of the dam functions as a force resisting the loads acting upon it and if the force from the self weight is less than the other forces, overturning could occur. In order to prevent overturning one of the two criteria; *normal load case or exceptional load case* should be fulfilled. Both of the criterion are regarding the resultant force in the dam; in the first case it should fall in the mid third and the latter the $3/5^{th}$ of the dam's base area. The second criterion is used as a safety factor, F_o, derived from the ratio of the moments of the resisting and overturning forces, i.e.

$$F_o = \frac{\sum M_{+ve}}{\sum M_{-ve}}$$

where $\sum M_{+ve}$ are the sum of moments stabilizing the dam (prevents the dam from overturning) and $\sum M_{-ve}$ are the sum of moments overturning the dam (including the uplift pressure). In order to ensure a desirable resistance to overturning F_o should be larger than 1.5. Overstress and material failure are connected to overturning, which is an effect from that the moments created by the water loads affect the stress levels in the dam. This results in that the concept of overturning becomes more complex. In addition, a decrease of the capacity in resistance to overturning can in turn increases the stresses at the dam's toe as well as the tensile stresses at the dam's heel, resulting in a higher risk for sliding. The failure modes are thus connected.

3.2.1.2. Sliding

Sliding can occur in the interface between rock and concrete, in the bedrock or in the concrete body. It happens when the shear capacity, i.e. the resisting force preventing sliding, is less than the forces acting on the concrete dam. Therefore, sliding is an essential aspect and need to be considered when designing a dam as well as in evaluations during the building process and in the maintenance. The most common method used in analysis regarding the risk for sliding has its origin in the notion of a dam as rigid body that can only slide in its critical surfaces, which are the concrete-rock interface and horizontal joints in the concrete foundation caused during the construction or in joints within the bedrock which are connected to geological factors. In these areas the shear strength will reach its minimum level and as pointed out earlier, sliding will occur when the driving forces exceed the shear resistance. This definition is based on the Mohr-Coulomb failure criteria (see Appendix A) where the effective normal stress and the shear stress are integrated over the sliding plane and is called the shear friction factor, F_{SF}. The shear friction factor is one of three common definitions that is used for evaluate the factor of safety or stability against sliding, and is expressed as;

$$F_{SF} = \frac{c * T + \sum V \tan \varphi}{\sum H}$$

where c is the cohesion in the concrete-rock interface and φ the internal friction angel, which both are two factors of major importance in the sliding stability. $\sum H$ and $\sum V$ is the summations of all horizontal loads respectively all vertical loads, and T is the length of the contact or the sliding area. Recommended shear frictions factors for the concrete-rock interface is 3.0 under a normal load and should exceed 1.0 under extreme load (Novak et al., 2007).

An easier way to evaluate the factor of safety against sliding is by the sliding factor:

$$F_{SS} = \frac{\sum H}{\sum V}$$

The stability against sliding is here expressed as a function of sliding over a plane where neither the cohesion nor the frictional components are accounted for. Under normal load the sliding factor should not be permitted to exceed 0.75 and the corresponding value for a situation with extreme load is 0.9 (Novak et al., 2007). A problem with this factor is that no consideration is taken to the conditions in the bedrock, i.e. a weak rock foundation could require a lower limit for F_{ss}.

3.2.1.3. Overstress and material failure

If the materials in a dam's body or in the rock foundation experience stress exceeding the components capacities, there will be an overstress. Although, a total dam failure is not in general caused by overstress it can be the initial factor, which in the future may cause a major failure.

3.3. Reliability analysis

One way to describe the safety of a dam is to estimate its reliability. In this thesis the reliability is expressed as the probability that the dam will remain fully functional throughout its life time. The main principle to calculate the reliability of a dam is rather uncomplicated and the approach is basically that the resistance, R, should be greater than the actions (loads), S, acting on the dam. The contingency associated with a reliability analysis is however somewhat more complicated to handle, e.g. information concerning the bedrock is hard to define. In order to avoid major consequences it is a necessity to present a factor of safety, sf. The factor of safety provides a measure of how high loads a structure should be able to withstand without overstepping its resistance and a margin of safety. The principle of reliability and safety in elementary dam design could be expressed by;

$$S \leq \frac{R}{sf}$$

The probability of failure, p_f, can be expressed as a function of the failure mode, $G(x_i)$, where x_i are random variables described by a statistical distribution, according to;

$$p_f = P[G(x_i) \leq 0] = \int_{g(x_i)\leq 0} f_x(x)dx$$

where $G(x_i) < 0$ corresponds to failure and $f_x(x)$ is the joint probability density function of x. Different failure modes, such as sliding, overturning and overstress, can be calculated from the probability of failure. With normalized distributed and independent variables, the function of the probability of failure can be written as;

$$p_f = \Phi\left(\frac{0 - \mu_G}{\sigma_G}\right) = \Phi(-\beta)$$

where β is the safety index and Φ is the cumulative distribution function of the standard normal distribution. μ_G and σ_G are the mean value and standard deviation of the state function, respectively. Additional information about the procedure can be studied in Westberg (2010) and Jeppsson (2003). For a given probability of failure, the safety index is given by the inverse of the standard normal distribution, i.e.:

$$\beta = -\Phi^{-1}(p_f) = \frac{\mu_G}{\sigma_G}$$

An increased β corresponds to an improved safety and among the possible results from a probability analysis the safety index is essential for an estimation of the risks. Further, it is also a good measure to compare and find critical components with. Even if an exact probability of failure is calculated, it is important to note that factors such as human errors and interventions will affect the result. Moreover, it is also important to notice that different types of safety index cannot be compared with one another.

The simulations in this thesis follow the distinct element method that is used in software UDEC, with the aim to calculate and analyze the factor of safety for Longtan dam. The simulations are performed under both a normal load and an additional dynamic load. The factor of safety is determined in several ways in UDEC, where the following two can work as examples:

$$F_L = \frac{failure\ load}{design\ load}$$

and

$$F_\phi = \frac{tan\ (actual\ friction\ angle)}{tan\ (friction\ angle\ at\ failure)}$$

The method is called *the strength reduction method* (for further knowledge see Chang & Huang (2005)), which systematically changes factors throughout the model until a failure occurs. A failure is indicated when the distinct element method does not converge to a solution, i.e. an equilibrium cannot be reached in the model. As a result, the factor of safety will correspond to the most critical failure. (Itasca, 2005)

3.4.Natural hazards in dam safety

As previously mentioned are large dams representing a rather high potential risk for the downstream area, even though they also provide positive effects such as preventing floods. The main factors behind the high risk can be divided into two categories (Carmo & Carvalho, 2011):

1. Natural hazards (e.g. storms, earthquakes and landslides).
2. Human behavior, errors, simple mistakes and operational mismanagement.

In this report, focus will be on the first category of risks and in particular problems caused by earthquakes.

3.4.1. Earthquakes in China

Briefly explained, earthquakes are vibrations caused by ground motion, where movements in tectonic plates are the most important source and other are volcanism, landslides, rock bursts, and anthropogenic sources such as explosions. An earthquake with its origin from movements in tectonic plates is created from accumulated strain energy, which in time have overcome the existing resisting forces, thus the energy is released throughout the ground. (Scawthorn, 2002) These types of disturbances generate transient dynamic loads and are essential to consider in the design of all major dams. High concrete dams should be designed to withstand an appropriate maximum earthquake and resonance. (Novak et al., 2007) Earthquakes are of a stochastic nature, hence there will always be a degree of uncertainty in the data and these uncertainties has to be estimated. In a historical perspective the probability for a dam failure during a strong earthquake is low, even though surrounding buildings have been damaged or destroyed. This should not be taken as a guarantee of a safe dam, since unforeseen secondary effects such as wave generation from seismic activity can be the additional force that causes a dam failure with the possibility of a catastrophe as an effect. (Carmo & Carvalho, 2011)

China is affected by movements with the origin in two tectonic plates; the Indian plate and the Philippine plate, which is resulting in stresses from two directions. The seismicity, an expression emphasizing the likelihood of occurrence of an earthquake and the probable intensity, is therefore high and is an essential factor for consideration in engineering and construction designs. In roughly the last century, China's mainland has experienced 15 earthquakes with a magnitude exceeding seven on the Richter scale. (Wang, 2009) In figure 9, records from more than 4000-years of history data of seismicity in China is shown.

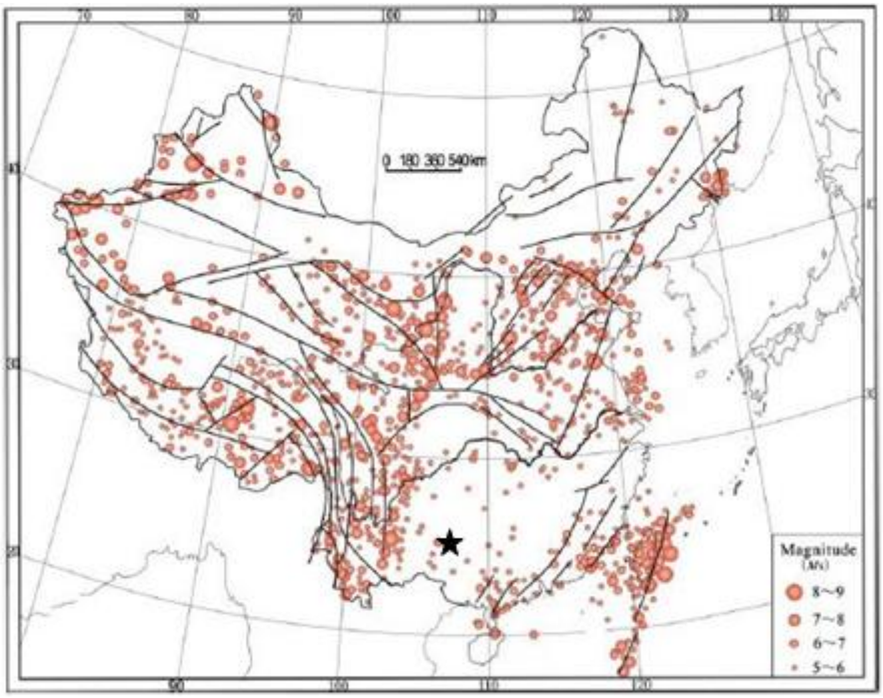

Figure 9 - Distribution of earthquake (Richter <5) epicenter in China from 2300 B.C. to 2000 A.D. (Wang, 2009). The black star indicates the location of Longtan Dam.

Earthquakes propagate different types of waves, which are separated by their speed, the way they put material particles into motion and if they are travelling in the ground surface or down in the ground. There are four kind of waves; S-wave, P-wave, Rayleigh-wave and Love-wave. The first two are created when stress and strain sets the ground into motion and the latter two types of waves differ by only appearing in the ground surface. P-waves (Primary waves) pass through the ground with the highest speed, thus reaching any location first meanwhile spreading energy by push- and pull motions. S-waves (Secondary waves) are slower and the energy is transmitted through shear action in the perpendicular direction of the wave propagation. In terms of damaged caused, S-waves are of higher significance as a result of the magnitude of horizontal motion that are created in the ground surface. The surface-waves are separated by their oscillations; Rayleigh- and Love waves oscillate vertically and horizontally, respectively. (Towhata, 2008) (Scawthorn, 2002) In figure 10, the four different waves created from an earthquake are illustrated.

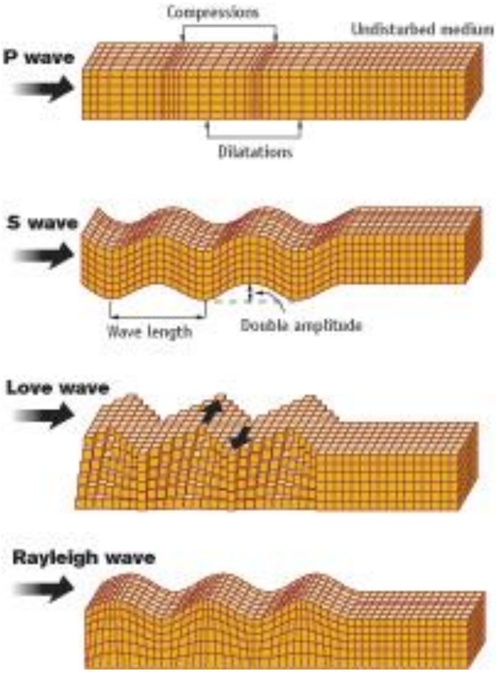

Figure 10 - An illustration of the propagation of earthquake waves and the motion of particle matter (IRIS, 2008).

The energy from an earthquake can have a negative impact on a dam in two ways. The first affects the dam in horizontal direction and is caused by an additional hydrodynamic water load in the reservoir. The second way is from waves propagating in the ground and is associated with a vertical acceleration in the foundation, which will reduce the mass of the dam. (Novak et al., 2007)

Earthquakes are measured in two different quantities; intensity and magnitude. The energy released from an earthquake, E, is derived from the magnitude and can be expressed by;

$$\log_{10} E = 11.4 + 1.5 \cdot M$$

where the magnitude, M, is in the unit of Richter, and the equation is an empirically compiled relationship (Scawthorn, 2002). The most common way of expressing the magnitude is in terms of the Richter scale, which has a range from $M = 1.0$ to $M = 9.0$ (Novak et al., 2007). In section 4.3.2.1. Dynamic load, a record of an earthquake is presented, which could provide a connection between amplitude and magnitude of earthquakes. A limitation with using the magnitude as a measurement of an earthquake is that it is measured at the hypocenter i.e. the source of where the energy is released. In order to estimate the effects on buildings, other constructions and the surrounding environment at a certain distance, the intensity of the motion must be quantified. There are different scales used for estimating the intensity, but since it is connected with the motion it will nevertheless depend on the following factors (Towhata, 2008):

- The distance from the source of motion.
- The rupture zone's (fault) size.
- The amount of strain energy released into the rock.
- The formation of geology that lies between the source and the object of consideration.
- The local soil condition and topography.

3.4.2. Landslide

There are several different factors that can provoke a landslide; erosion is one important and another is earthquakes. In the case with earthquakes, landslides are seen as secondary effects, i.e. a consequence of the original incident and is according to Jian et al. (2010) one of the most important hazards from earthquakes. The process of erosion weakens the soil and rock in the area of a reservoir and could consequently in combination with an earthquake provoke a landslide. Both human and natural processes are sources for erosion, were human influences are overgrazing, forest fires, deforestation and changes in vegetation toward plants that are reducing the soil stability (Carmo & Carvalho, 2011). Approximately 50 percent of the landslides are caused by effects from rainfall events (precipitation and snow melt) and the remaining 50 percent are induced by earthquakes. Furthermore, mountain areas are the most common location for landslides. (Kuo, Tsang, Chen, & Shieh, 2011).

Landslides occur in areas with high seismicity and larger landslides seem to coincide with major seismic faults. A landslide could, as previously mentioned, create hydrodynamic waves, which can be of different types and have a significant effect on a dam by amplifying the horizontal pressure on the upstream face. Hence, secondary effects from earthquakes could in combination with other loads be the source of a dam failure creating a catastrophe to the downstream environment and societies. Landslide induced waves can vary in form and effect, and there are three major aspects determining the outcome (Carmo & Carvalho, 2011):

- The volume of the sliding mass.
- The impact velocity of the mass into the reservoir.
- The size and depth of the reservoir.

3.5.UDEC and the distinct element method

UDEC is an abbreviation for the Universal Distinct Element Code and is a numerical program developed by the ITASCA Consulting Group (Itasca, 2005). The program allows numerical modeling for advanced geotechnical analysis in two dimensions of soil, rock and structural support, and is based on the distinct element method. The distinct element method is similar to the finite element method (FEM), with the difference in that the first allows block to interact with each other. The spacing between the blocks, such as joints, is called discontinuum elements (see figure 11).

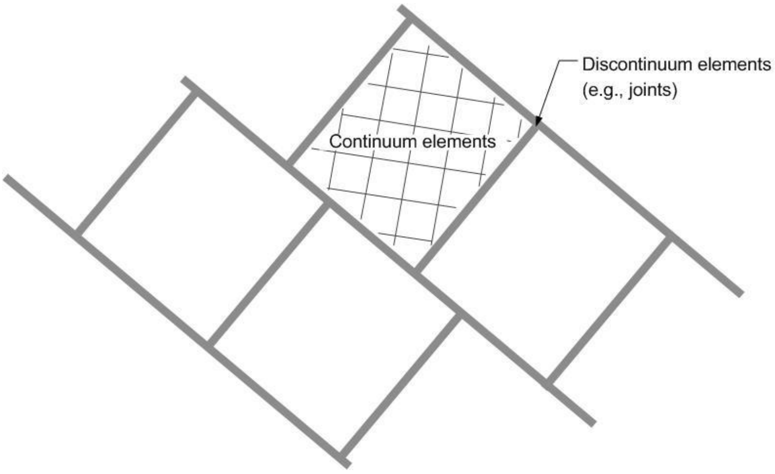

Figure 11 – The design of the elements within a model and the structure of the distinct element method.

In UDEC the model can be subject to either static or dynamic loading. The software’s ability to incorporate a large number of fractures in materials makes it ideal for analysis in rock engineering projects and studies of failure modes. The rock mass is simulated through the creation of a group of blocks, which are linked together through cohesion, tensile strength and friction at the block’s edges, thus permitting sliding of blocks and particles. In a simplified point of view; if a bond breaks a failure is caused, i.e. a simulation of the strength in the modeled rock mass can be analyzed. UDEC is best suited for studies where the availability of geological information is good and well defined. Another application area of the software is in the field of earthquake engineering, a feature that is be used in this thesis. The software manual (Itasca, 2005) gives a more detailed description of the program and the possible applications in different areas and problems.

4. Method

There are three major failure modes in dams; sliding, overstress and overturning. They can occur if loads are added, increased or dramatically changed. In this thesis the effect of seismic activity on a concrete gravity dam with high upstream water levels is investigated. Earthquakes are not common in the area of Longtan Dam, but are however more frequent in the Northwestern parts of China where the majority of the country's future large hydropower plants are being built or projected. By investigating the effects caused by seismic activity this report can work as a basis for further studies on dam safety in areas with high seismicity. As an example this study can be used in the design of new dams, in particular when it comes to decision concerning the size of a dam and acceptable reservoir water level.

4.1.Procedure of method, analysis and results

The method, analysis and results are performed according to the following steps of procedure:

Method

1) Find relevant information concerning the dam and surrounding area
2) Description of case and assumptions
3) Simulate and calculate the factor of safety in UDEC for the different load conditions
4) Calculated the stability for overturning and sliding by hand

Analysis and Results

5) Present and analyze the results
6) Define critical areas and components in the dam
7) Investigate the loss in production under extreme conditions as a function of decreased reservoir water head

4.2.Input data

The software UDEC is brought into the thesis in order to enable a demonstration of the effects of static- and dynamic loads on Longtan Dam. The model is simplified and only consists of four elements; a concrete foundation that is assumed to be made of solid concrete, a rock foundation, intersecting joints in the bedrock and finally a discontinuity along the concrete-rock interface. An illustration of the UDEC-model of the Longtan Dam is shown in figure 12.

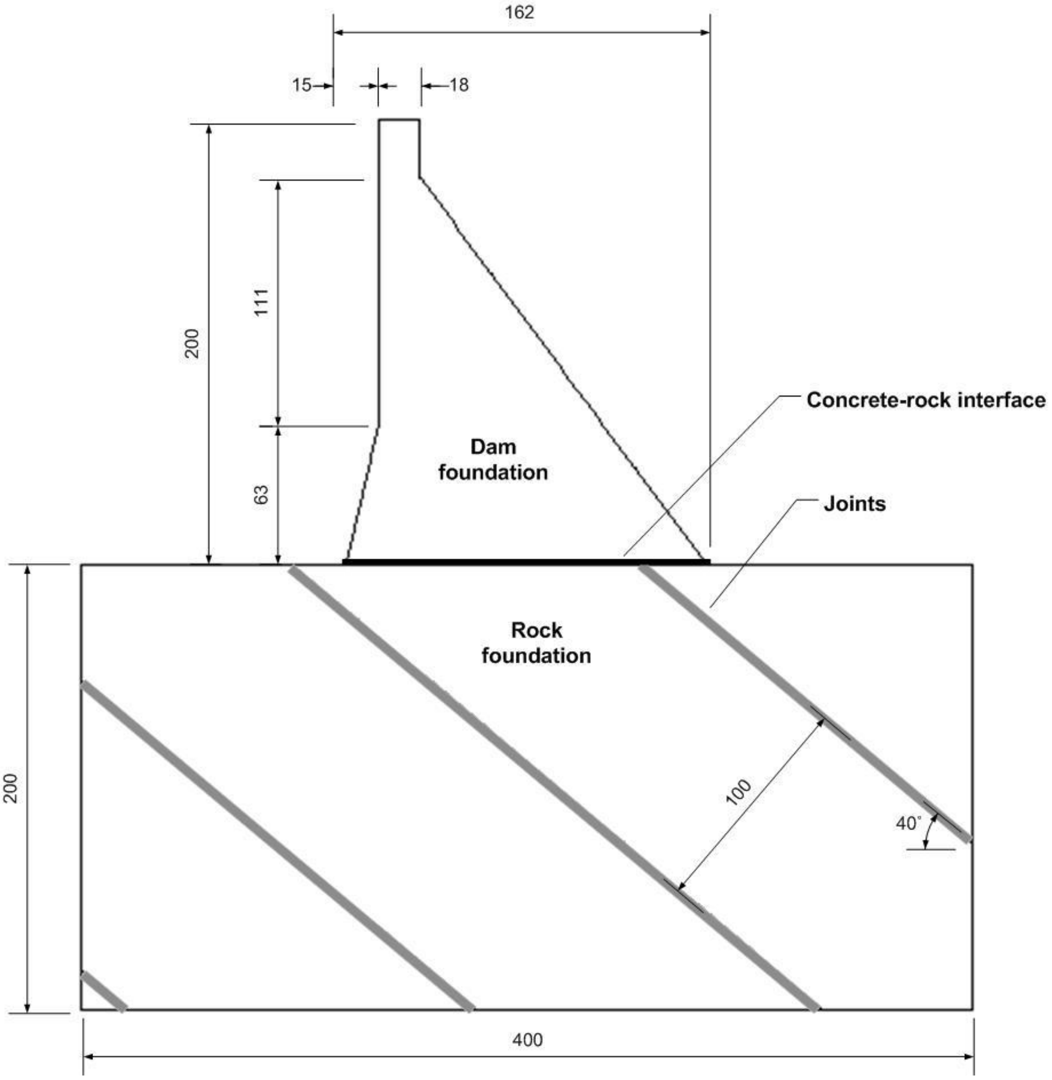

Figure 12 – The UDEC-model of Longtan Dam and its dimensions. The dimensions of the dam structure are based on existing data, while the dimensions of the rock foundation are estimated to suit this model.

Figure 12 also shows the dimensions of the dam, which are based on data from measurements of the Longtan Dam. Information concerning the Longtan Dam has already been presented in table 1 and will also be used in the simulations with a water load.

In the simulations in this research, the model of the Longtan Dam will follow the Mohr-Coulomb's model for plasticity; hence certain material properties are required as input parameters in UDEC. The full list of input parameters is presented in table 2. Three of the parameters needed; the bulk modulus, the shear modulus and the friction angel, are calculated from the given data according to the formulas in Appendix B. The remaining data in table 2 are provided by the Department of Civil Engineering at Shandong University, China, and represent measurement from analysis made in the Longtan Dam with surroundings. Methods used for calculations of the distribution of loads are presented in Appendix B. In the following sections are more assumptions introduced together with descriptions of the different cases.

Table 2 – Material data for the Longtan Dam with surroundings, that are used in the UDEC model (Jia, Unpublished document concerning Longtan Dam, 2012).

	Concrete (normal)	Concrete-rock interface	Rock	Rock joint
Elastic modulus, E (MPa)	19600	13000	12000	11000
Joint shear stress (MPa)	20000[a]	20000[a]	20000[a]	20000[a]
Poisson's ratio	0.167	0.3	0.27	0.27
Bulk density (kN/m^3)	24	24	0	0
Density, ρ (kg/m^3)	2444	2444	0	0
Peak shear strength - Friction, f	1.20	0.70	1.1	1.0
Peak shear strength - Cohesion, c (MPa)	2.50	0.10	1.48	1.20
Tensile strength (MPa)	1.57	0	0.6	0.5
Compression strength (MPa)	18.5	18.5	9	9
Shear modulus, G (MPa)	9810[b]	10833[b]	8696[b]	7971[b]
Bulk modulus, K (Mpa)	8398[b]	5000[b]	4724[b]	4331[b]

a: estimated value, b: calculated value

4.3.Description of case and assumptions

The first simulation in this study is concerning the effects of an empty reservoir; hence the model is only affected of the gravity and the present in-situ stress. In the next stage of simulations are the hydrostatic pressures, upstream and downstream, added along with a pressure for the uplift. A value of the factor of safety for the dam is calculated in this stage in order to get a reference value of a natural state as a comparison for the further analysis. The third simulation inserts a dynamic load to the base boundary of the bedrock in the model, with the intention to study potential effects caused by earthquakes. Additional simulations are done to investigate the production losses from a dynamic load. This is done by decreasing the reservoir water level while increasing the dynamic load and keeping the factor of safety in level with the reference value from earlier simulations. By keeping the factor of safety constant the influence of a dynamic load can easily be observed. The procedure of the case is described in figure 13.

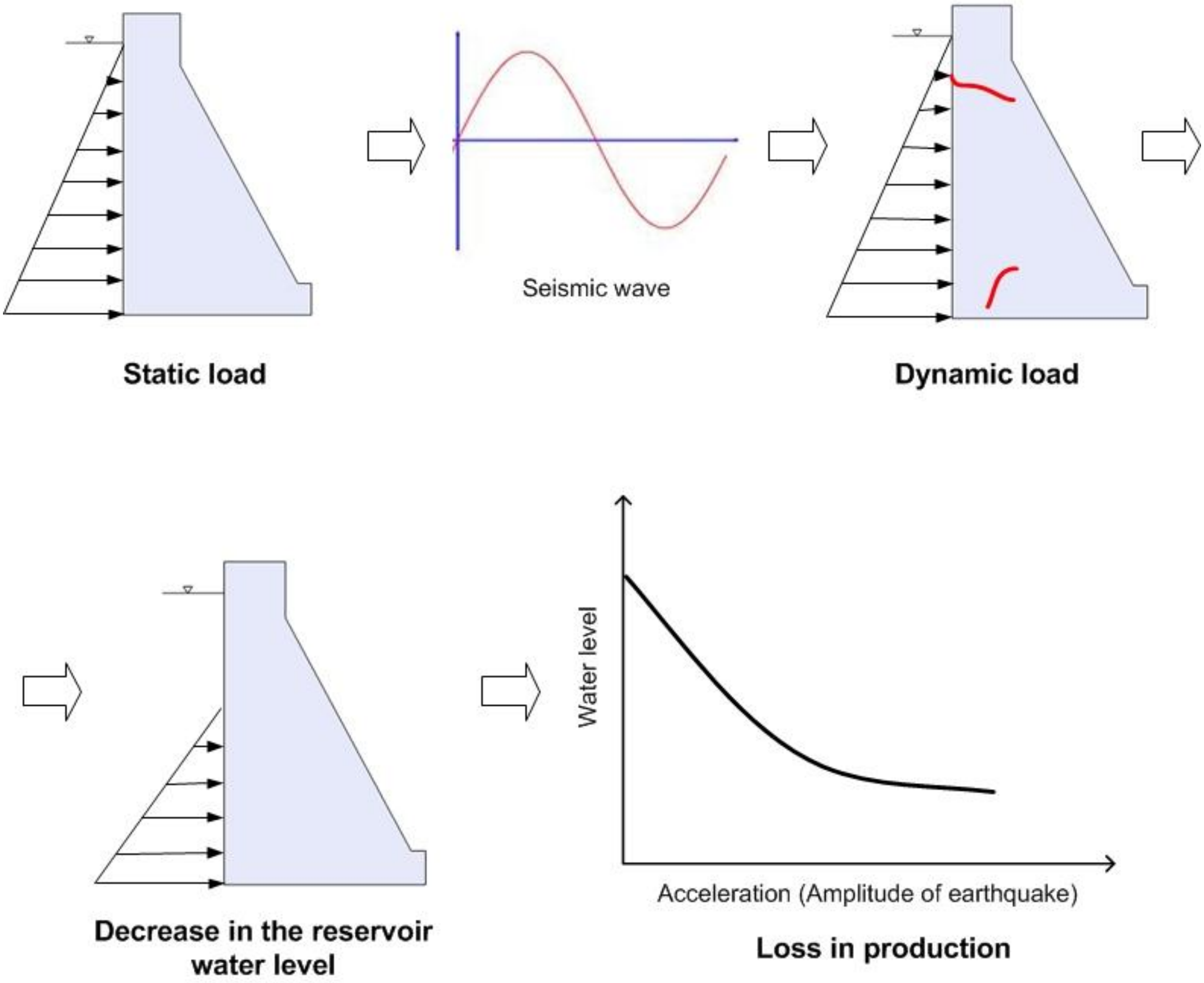

Figure 13 – The procedure in this thesis is divided into four stages; in-situ stress and full reservoir, failure after dynamic load, decrease in hydrostatic pressure in order to maintain the factor of safety and finally, a presentation of the water level as a function of the amplitude of an earthquake.

The numerical analysis in UDEC can be divided into four stages, where each and every of the first three add stresses to the previous stage. One additional stage (stage 4) is added to simulate the consequence of dynamic load and the effect in loss of energy, i.e. the loss in production. In short, the different stages are; an empty and full reservoir, dynamic load, decline in water head and loss in production. Assumptions and conditions for each stage are presented below, and the code for the UDEC model can be found in Appendix C.

4.3.1. Static conditions

4.3.1.1. Empty Reservoir

The first case in this stage is an analysis over the in-situ stress in the model together with the dam's self weight. A predetermined in-situ stress was applied in the rock mass and the reservoir and downstream water levels was assumed to be zero. Origo is in the center of the dam base with the x-axis in the vertical direction and y-axis in horizontal. The in-situ stress is taken from an example concerning a similar dam in the UDEC manual (Itasca, 2005). In the model all the boundaries were assumed to be impermeable, i.e. no horizontal displacement was allowed along the sides of the model and no vertical displacement was could occur along the bottom boundary of the model. This is important when gravity is introduced and will prevent the model from moving.

The model was assumed to follow plastic conditions according to the parameters in table 2. Further, the joints was put into the model with a spacing 100 meters and in a direction of -40 degrees compared to the x-axis, see figure 12. Note that some data in the UDEC code are not implemented into the model at this stage. For instance, the properties for a viscous boundary, which represents a non-reflection boundary in the dynamic model are introduced in the code in this stage but are implemented into the model in a later stage. Because of lack of information, the properties of the viscous boundary were also taken directly from the example in the UDEC manual. A way to ensure that the forces in the model are at equilibrium, thus reached a steady state, is the history command, which creates a record for a certain variable during the time stepping. Examples could be plots of the shear stress in a certain point or the maximum unbalanced force in the model.

4.3.1.2. Full reservoir

The second case in the first stage adds water loads and an uplift force in the concrete-rock interface. Hydrostatic pressures were set on both the upstream and the downstream face of the concrete foundation. The upstream face is fully saturated at 179 meters and the corresponding number downstream was set to the average value, 20 meters, according to table 1. According to the dam design the water loads will affects the concrete foundation both horizontally and vertically as functions of the hydrostatic pressure and the weight of the water, respectively. The third load, the uplift force, is a secondary effect from the hydrostatic pressures. The uplift force were controlled in the model by introducing an interior stress, which allowed simulations with a pressure relief drain situated 15 meters from the dam heel. The pressure relief drain was assumed to reduce the uplift force with 70 percent. Below is an explanation of how the uplift force with distribution was assumed to be in this model.

The uplift, U and u, is equal to the maximal hydrostatic water pressure for the present water head, H or h, and is calculated by;

$$U = \rho_w \cdot g \cdot H$$

for the pressure at the dam heel and

$$u = \rho_w \cdot g \cdot h$$

for the corresponding value at the dam toe. As can be seen in figure 14 below, the distribution of the uplift force will vary along the concrete-rock interface.

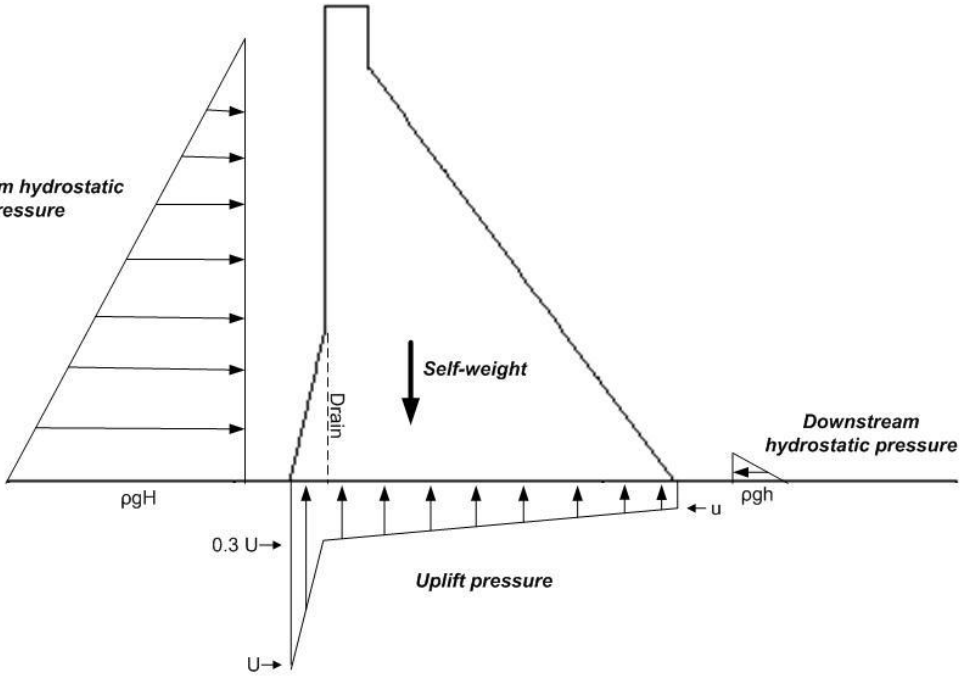

Figure 14 – A schematic model of the applied forces, not according to scale. Note; the hydrostatic pressure also acts in the vertical direction.

4.3.2. Dynamic conditions

4.3.2.1. Dynamic load

Several simulations were done with a variation in the dynamic load, a process described further in stage3, while this stage's focus is on the general process of a adding a dynamic load in UDEC and the assumptions made in this thesis. When applying dynamic conditions into a model in UDEC, consideration should be taken to the following factors:

1) Dynamic loading and boundary conditions.
2) Mechanical damping.
3) Wave transmission through model.

Since the effects from a variation in the dynamic load were to be investigated, a sinusoidal curve with a constant frequency and duration was chosen; hence the only factor causing variations in the load was the amplitude. The dynamic input can be added in either the x- or y-directions, or in the both directions as a xy-stress (shear stress), which was the case in this model. Worth notation is that the earthquake is simplified due to limitations in the software. An earthquake will normally vary in both magnitude and frequency over time, as well as in direction. Typical result in form of graphs from measurement from a real earthquake is illustrated in figures 15 and 16. The figures present data in form of the frequencies in the x- and y-direction from the Koyna earthquake, which happened 1967 and had a magnitude of 6 on the Richter scale.

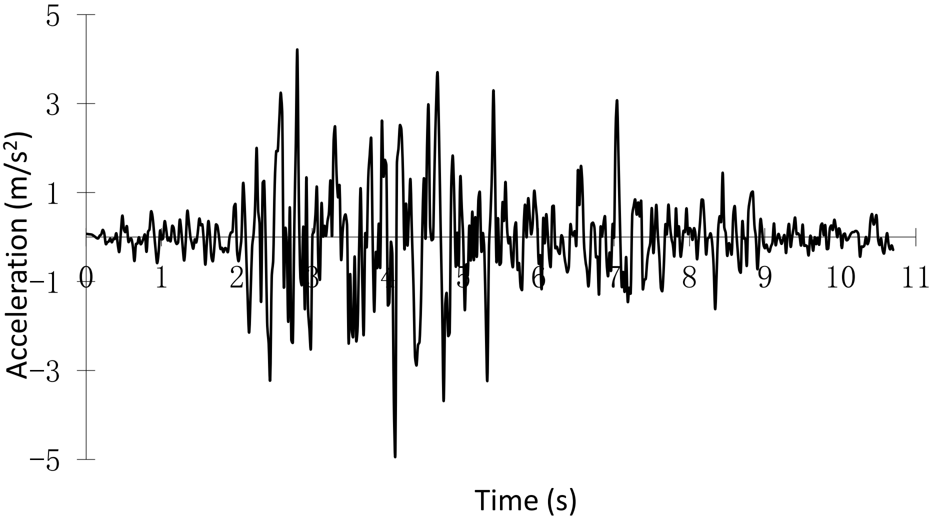

Figure 15 – The frequency in the x-direction of the Koyna earthquake year 1967.

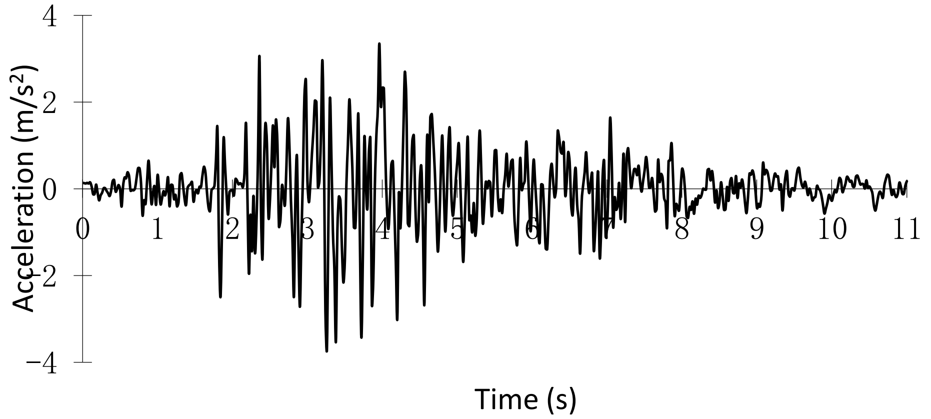

Figure 16 – The frequency in the y-direction of the Koyna earthquake year 1967.

In order to avoid problems with reflections of the seismic waves back into the model from the outer boundaries, they were set to viscous in the x-direction, which create a non-reflecting boundary. Also, a free-field was added to the same boundaries. The function of a free-field is to simulate the behavior of the motion of a wave in the non-existing medium outside the model boundaries.

Natural systems usually consist of some form of damping of the energy from vibrations; hence a damping is needed in the model in order to reproduce the losses of energy from a dynamic load. In lack of information and knowledge of the in-situ system, a damping was chosen from the same UDEC example as before (Itasca, 2005).

A dynamic load was added along the baseline of the model in the form of a sinusoidal wave of velocity with a frequency of 5 Hz and duration of 5 seconds, and a shear stress calculated from predetermined amplitudes in the form of acceleration. The method of calculations can be seen below in stage 4. Worth mentioning is that the curve could be set as either a sine or cosine curve, and as already mentioned a sine curve was selected for the simulations in this thesis. However, the possible difference in result caused from choosing a sine curve over a cosine curve are considered minimal, since the duration time compensate for possible effects from the shift of phases.

4.3.2.2. Decrease in reservoir water level

In order to keep the factor of safety at the same level as the reference value derived from case with all static loads, the upstream hydrostatic pressure has to decrease. This is a safety procedure that in real dams is operated by opening spillways and represents the third stage of simulations in this report. When the hydrostatic pressure is declined it is important to take into consideration that the uplift force will follow. In stage 3, the dynamic load described in stage 2 was applied for a series of amplitudes for which the reservoir water head was systematically changed (along with the uplift force) with the target of finding a factor of safety in level with the reference value. These values are then used to show the loss in production, which represent the fourth stage in the method.

The conversion of amplitudes in the form of acceleration to stresses was in this thesis done according to the following procedure and assumptions.

Newton's second law states:

$$F = m \cdot a$$

A stress, τ, seen as a pressure can be calculated from:

$$P = \frac{F}{A} = \frac{m \cdot a}{A}$$

The mass can be derived from the density, ρ, and the volume, V, according to:

$$m = \rho \cdot V$$

Since the model is in 2-D the following simplifications can be done:

$$V \rightarrow A$$

$$A \rightarrow L$$

The new formula for the stress then becomes:

$$\tau = \frac{\rho \cdot A \cdot a}{L}$$

The stress caused by the earthquake was assumed to only affect the dam in the model, hence:

$$\tau = \frac{\rho_{concrete} \cdot A_{dam} \cdot a}{L_{dam\ base}} = \frac{2444.0 \cdot 15295.5 \cdot a}{162} = 0.230754333 \cdot a\ [MPa]$$

As can be seen in the final equation the pressure will vary with the acceleration of the amplitude, allowing an investigation of how the size of an earthquake will influence the reservoir water level.

4.4. Calculations by hand

4.4.1. Moments

The static loads will when summarized result in a resultant force, F, which will be situated in a certain point and create a moment in the structure. With a value of the moment and a magnitude of the different forces acting in vertical and horizontal direction, a stability analysis and a stress analysis can be performed. In figure 17 the arrows represents the forces from the static loads. Some simplifications were done; the horizontal force from the upstream and downstream hydrostatic pressures do not account for the flare and the sloping surface, respectively. Since the slopes are quite steep, the simplifications are considered to not affect the calculations significantly.

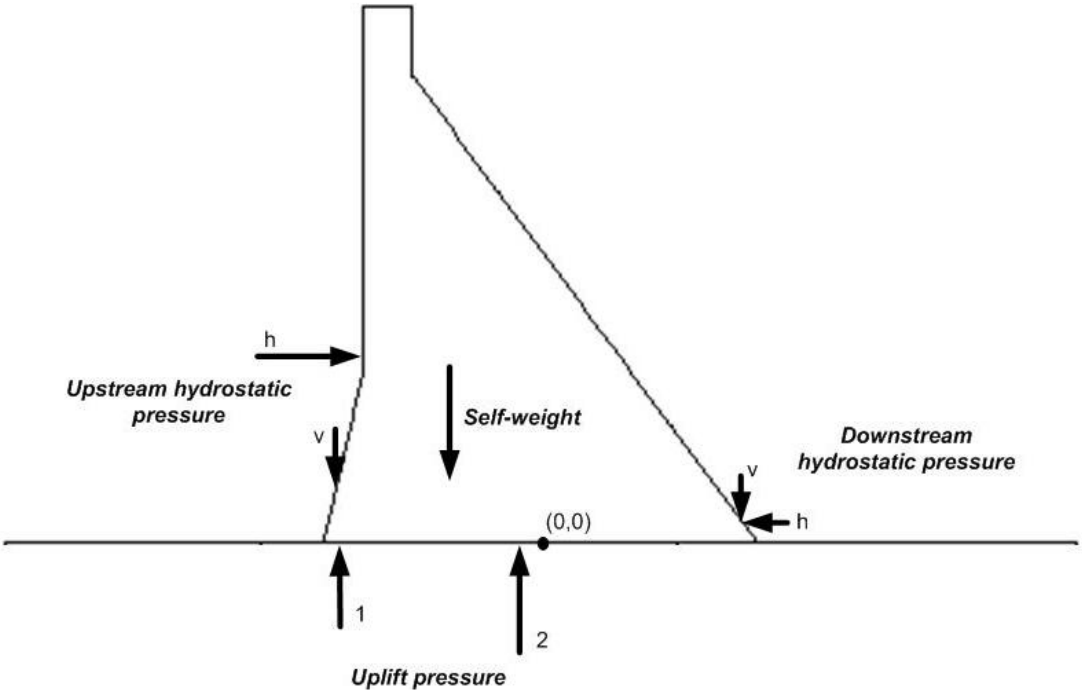

Figure 17 – The positions of the static loads that are used in order to validate the result from the UDEC model of Longtan Dam.

4.4.2. Stability analysis

In chapter 3.3 *Stability analysis for dams*, three different factors concerning the stability are presented; overturning factor, shear friction factor and sliding factor, together with the recommended values for each factor. These factors were calculated in order to analyze the stability of the dam with the static conditions, and find the most critical failure mode and the weakest parameter in the model. For calculating the overturning factor and the sliding factor no more than the moment round the dam heel, and the magnitude and direction of the forces are needed. According to table 2 the cohesion and the internal friction angle in the concrete-rock interface are 0.1 MPa and 0.7, respectively- Both of the parameters are needed in the calculation of the shear friction factor.

4.4.3. Stress analysis

By calculating the normal stress caused by the moment, reference values that can verify the simulations of the UDEC model of Longtan Dam are obtained.

On any horizontal plane, assuming that the normal stresses are linear distributed over a section, the vertical normal stress, σ_z, can be derived from;

$$\sigma_z = \frac{\sum V}{A} \pm \frac{\sum M \cdot y'}{I}$$

where I, the second moment of area of the plane with respect to the centroid, can be expressed as:

$$I = \frac{L^3}{12}$$

If the two equations above are combined and in addition are adjusted for 2-D system, the following expression for the normal stress is derived;

$$\sigma_z = \frac{\sum V}{L} \pm \frac{12 \cdot \sum M \cdot y'}{L^2}$$

where $\sum V$ is the summation of vertical loads, $\sum M$ is the summation of the moments, y' is the distance from origo to the point where the normal stress are to be calculated and L is the width of the dam.

In the endpoints of the dam's base the stress can be calculated with;

$$\sigma_{z,heel} = \frac{\sum V}{L} + \frac{\sum M}{L^2} \cdot 6$$
$$\sigma_{z,toe} = \frac{\sum V}{L} - \frac{\sum M}{L^2} \cdot 6$$

which follows from that $y' = \frac{L}{2}$ at both of the distances when calculating the moment relative to origo.

5. Analysis and results

5.1.Static conditions

5.1.1. UDEC-model

The first results are from the simulation with an empty reservoir, which were performed in order to create a comparison for the upcoming simulations with the complete set of static loads, but also to investigate the importance of the dam's self weight. Two figures are used to recapture the results and are here represented by plots of the displacement vectors and the contours of the xy-strain (see figures 18 and 19). A dam is designed to withstand high hydrostatic loads at the upstream face. Therefore, the absence of water results in a construction with a tendency of being "front-heavy" in upstream direction, which is illustrated by the displacement vectors in figure 18.The figure is also illustrating the distribution of the displacement in the bedrock and the impact of the weak layers represented by joints. As should be, the direction of the displacement vector is mostly vertical downwards and somewhat in the negative x-direction; hence a counterclockwise is created in the dam. A vector of displacement indicates the final direction and motion of a certain point's motion.

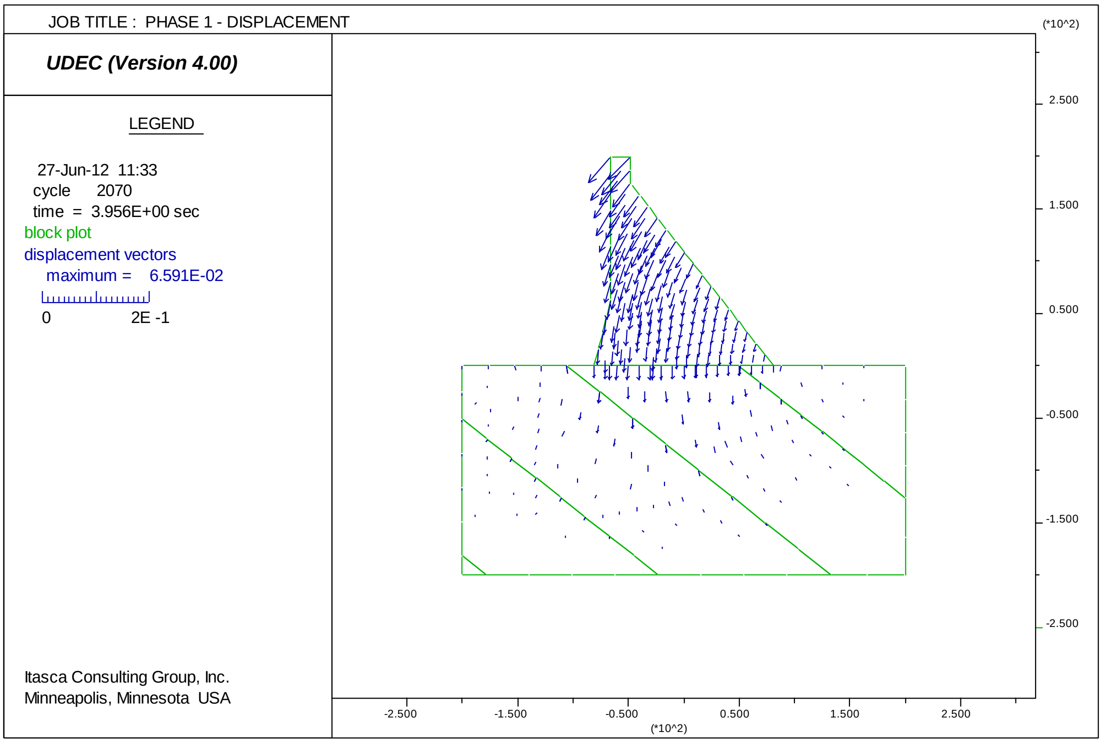

Figure 18 – Illustration of the displacement vectors (blue arrows) caused by the dam's self weight.

Figure 19 illustrates the xy-strain contours and the shear displacement in joints. A positive number indicates tensile stresses and consequently a negative number corresponds to compressive stresses. The results show that the dam's heel experiences compressive stresses meanwhile there are tensile stresses in the toe. This corresponds to the indications from the displacement vectors that the dam's design results in a counter clockwise moment. The critical points will be situated where the stresses are at their maximum; in the concrete-rock interface at the dam's heel and toe. In order to study the effects on the joints and the concrete-rock interface more closely, the shear displacement in the mentioned areas are included in figure 19. The red lines indicate shear displacement, which can be seen in the concrete-rock interface at both the heel and toe, and in the rock joint vertical downwards from the center of gravity of the dam. There are two main factors creating these conditions; the counter clockwise moment caused by the elementary dam design and the self weight.

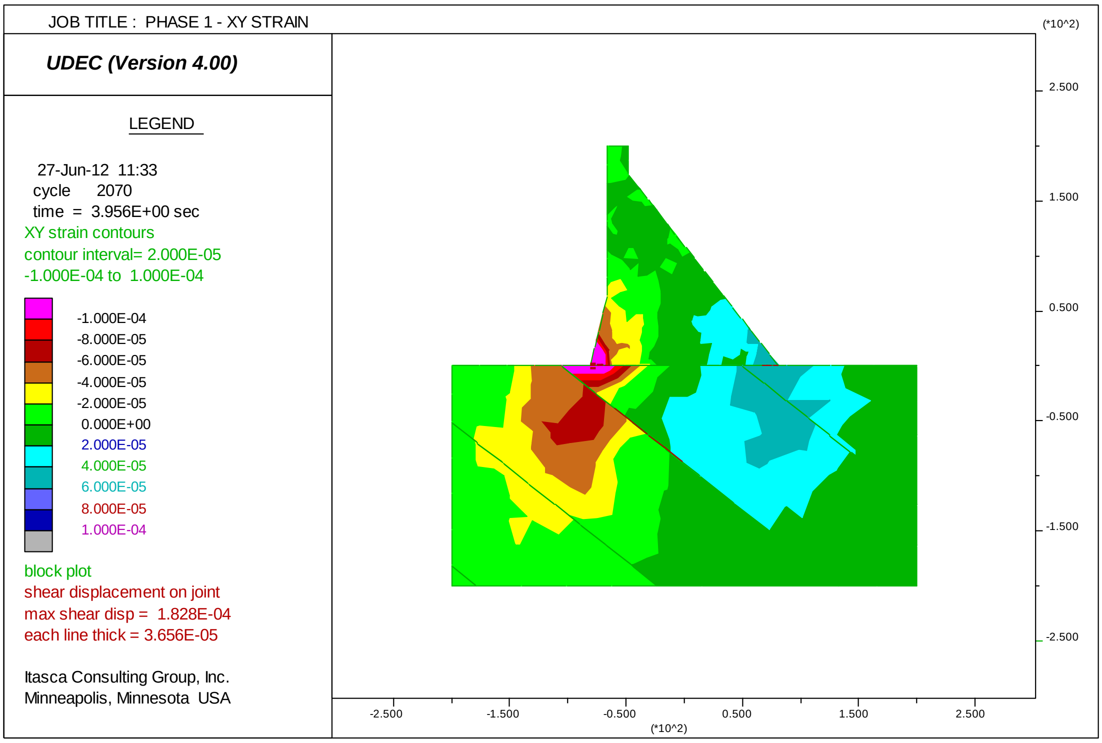

Figure 19 – Illustration of xy-strain contours and the shear displacement in joints (red lines) after the first phase of simulations. Negative numbers indicates compressive stress and positive numbers indicates tensile stress.

In this phase of simulations the remaining static loads are added to the model, i.e. the hydrostatic pressures at the upstream and downstream sides are added together with an uplift pressure distributed along the concrete-rock interface. Illustrations of the displacement and xy-strain contour for the new condition in the model are shown in figures 20 and 21. The displacement is similar to the one in the previous simulation, shown in figure 19, with the addition of the impact of the vertical water pressure on the flare. After exposing the dam to all the static loads, the result still indicates that the self weight is of major importance, but also that the flare will have a contribution. The displacement in the bedrock has increased and the effects from the added water can be seen in the larger vectors in the bedrock upstream the dam and in the change in direction of the vectors under the dam. The latter is an effect from the water pressure on the flare.

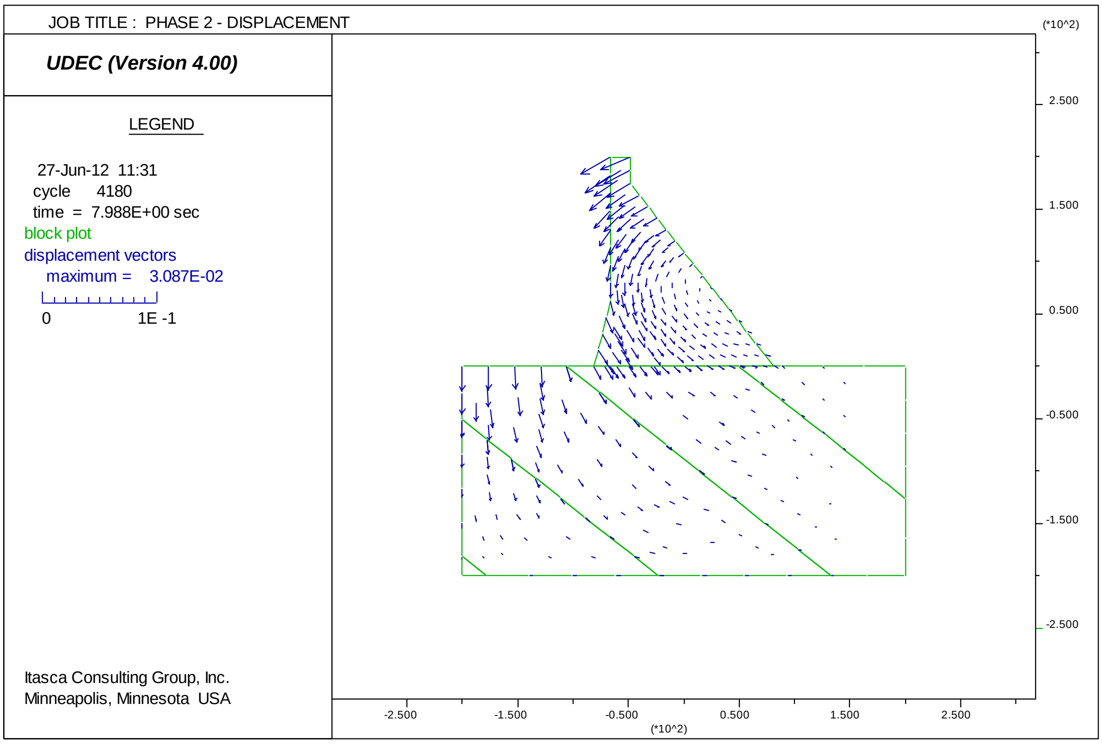

Figure 20 – The displacement after adding all static loads.

According to figure 21 there are primarily tensile stresses upstream the dam; hence the effect from the dam's self weight and the water pressure on the flare is reduced by the uplift force. At the dam toe is it the opposite situation, where there are compressive stresses and shear displacement in the concrete-rock interface. Sliding is indicated after the second stage of simulations, which can be seen from the shear displacement in the rock-concrete interface (the red colored line in figure 21). However, the dam is still safe since the factory of safety is larger than 1. The factor of safety has decreased in comparison with the first phase of simulations, resulting in a value of 3.00. This value will be used as a reference value for the dam's safety in the upcoming stages with dynamic conditions.

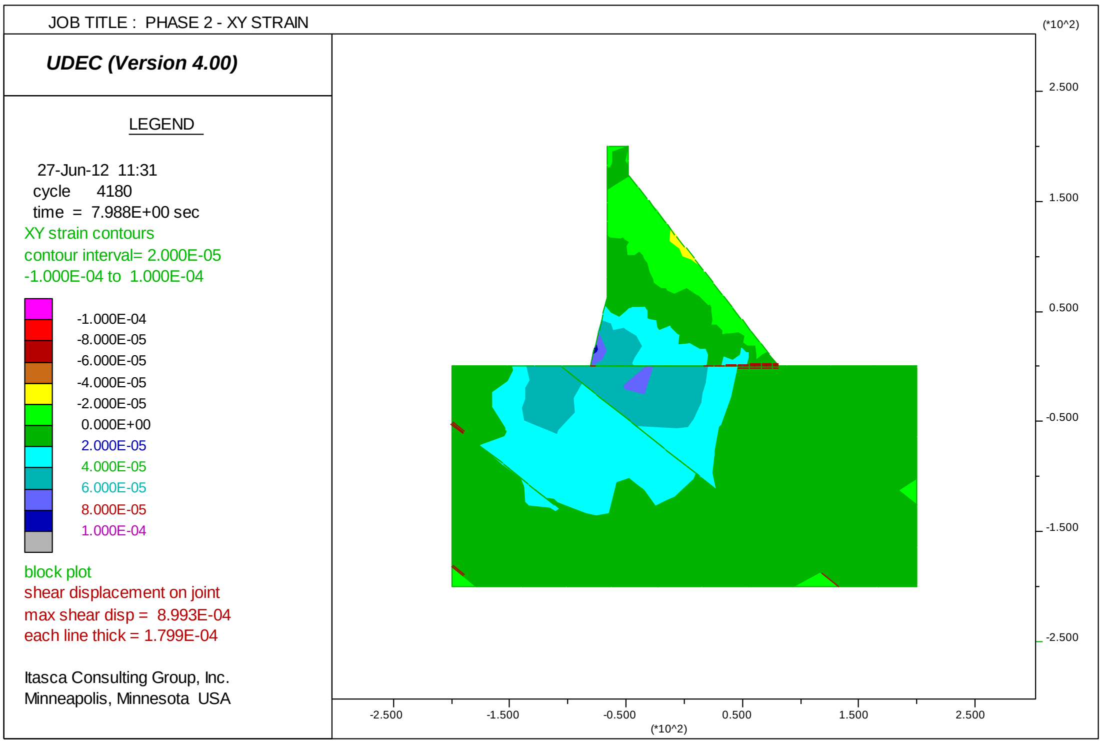

Figure 21 – Illustration of xy-strain contours and the shear displacement in joints (red lines) after the second phase of simulations. Negative numbers indicates compressive stress and positive numbers indicates tensile stress.

A study over the displacement and the factor of study as function of the reservoir water level during the static conditions was executed and the result can be seen in figures 22 and 23. The result shows that the factor of safety keeps a rather constant value, with a small decrease when the water level reaches its maximum. The maximal displacement will on the other hand experience an increase, while the displacement in the dam heel decreases, which can be explained by that the flare will stabilize the dam in this point with a higher water load. As can be seen in the figures, there are fluctuations in the graphs, which are explained with that the different loads and the dam design will operate in different manner when acting together. The result of the investigation of the static conditions shows the importance of the self weight and that a relationship between the size of the displacement and the factor of safety can be interpreted. This connection can be important to bear in mind to the upcoming result where the effect of dynamic conditions on the reservoir water level is analyzed.

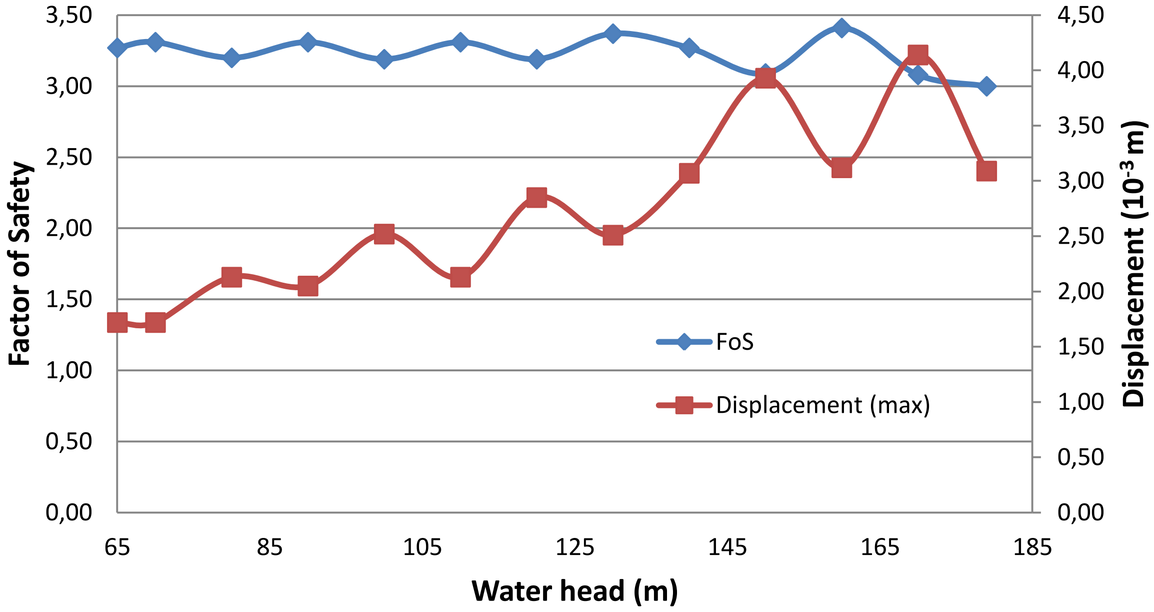

Figure 22 – The maximal displacement and the Factor of Safety in the model as a function of the reservoir water level.

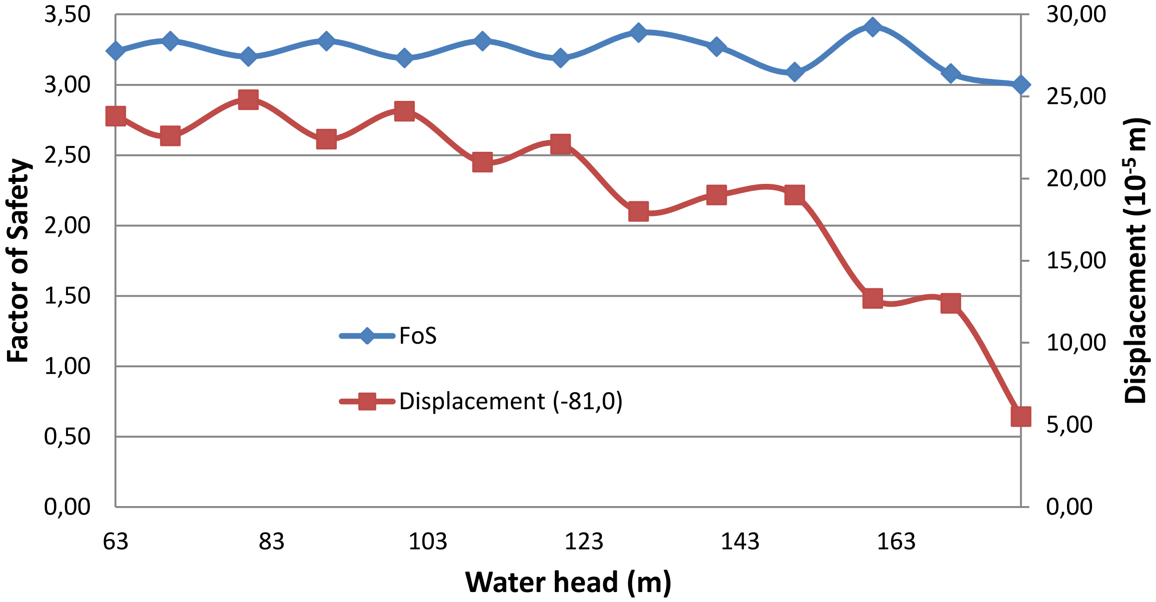

Figure 23 – The displacement in the dam heel (-81,0) and the Factor of Safety in the model as a function of the reservoir water level.

5.1.2. Stability and stress analysis

In tables 3 and 4 below, the forces created from the static loads are presented together with their moment arms, from which the moments were calculated. The two tables (3 and 4) only differ in the point in the model that the moment is relative to. Where the stability analysis uses the dam toe as reference point, the stress analyze uses the center of the dam's base. The calculations are done according to the equations in chapter 3.2 *Loads on concrete gravity dams* and chapter 4.4 *Calculations by hand*.

Table 3 – The forces created from the static loads together presented together with respectively moment arm and moment. The moment is relative to the dam toe. H = horizontal, V = vertical, CW = clockwise and CCW = counterclockwise.

Loads	**Moment arm (m)**		**Vertical force (MN)**		**Horizontal force (MN)**		**Moment (MNm)**	
	←	↑	↑ (-)	↓ (+)	→ (-)	← (+)	CW (-)	CCW (+)
Self weight	100.2			367.1				36810
Upstream (H)		59.67			157.3		9387	
Flare (V)	155.0			21.73				3368
Downstream (H)		6.670				1.964		13.1
Downstream (V)	4.94			1.455			7.189	
Uplift (1)	155.9		17.14				2671	
Uplift (2)	99.70		53.19				5303	
Sum			70.33	390.3	157.3	1.964	17369	40194

To analyze the stability of the dam, three different factors were calculated by inserting the result from table 3. The different factor of safety calculated is only regarding overturning and sliding, and cannot be compared to the factor of safety calculated in UDEC, which is the factor of safety for any given point in the dam being most critical.

$$F_o = 2.31\ (> 1.5)$$

$$F_{SF} = 1.55\ (> 3.0)$$

$$F_{SS} = 0.49\ (< 0.75)$$

According to Novak et al. (2007), see recommended criteria in the brackets above, the value of the shear friction factor, F_{SF}, is not acceptable under normal conditions which indicates that the Longtan dam is not stable against sliding. Worth notation is that the cohesion and the internal friction seems to be of major importance for the dam safety, since the dam proves to be able to withstand according to the sliding factor, F_{SS}. Concerning overturning, the calculated value for the overturning factor, F_o, is higher than what is required.

Table 4 – The forces created from the static loads together presented together with respectively moment arm and moment. The moment is relative to the centroid. H = horizontal, V = vertical, CW = clockwise and CCW = counterclockwise.

Loads	**Moment arm (m)**		**Vertical force (MN)**		**Horizontal force (MN)**		**Moment (MNm)**	
	←	↑	↑ (-)	↓ (+)	→ (-)	← (+)	CW (-)	CCW (+)
Self weight	19.28			367.1				7078
Upstream (h)		59.67			157.3		9387	
Flare (v)	74.03			21.73				1609
Downstream (h)		6.670				1.964		13.10
Downstream (v)	76.06			1.455			110.7	
Uplift (1)	74.85		17.14				1283	
Uplift (2)	18.70		53.19				994.7	
Sum			70.33	390.3	157.3	1.964	11775.6	8699.2

In order to verify the model before adding the dynamic conditions, calculations for a stress analysis over the static conditions were executed. By inserting the results from table 4 into the earlier presented equations, the vertical normal stress was determined to $\sigma_{z,heel} = -1{,}27$ MPa and $\sigma_{z,toe} = -2{,}68$ MPa. The values differ slightly from the stress values achieved in the UDEC model; see the illustration of the stresses of the UDEC model in figure 24. The difference between the software's values and the values calculated by hand is a result of simplifications made in the latter. The most important result of the stress analysis is that the model can be assumed to be valid.

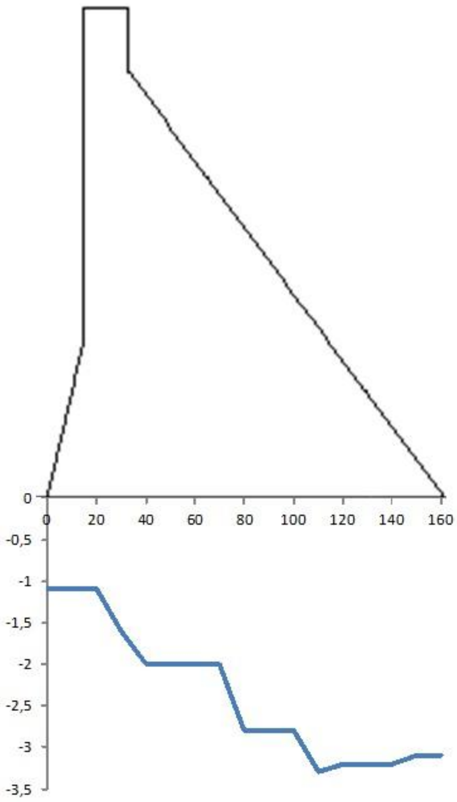

Figure 24 – The vertical normal stress [MPa] along the dam base calculated in UDEC. The figure is an illustration, made by the authors, based on the result in UDEC.

5.2.Dynamic conditions

This stage of simulations investigates the effects of adding dynamic conditions to the previous stage with static conditions. The result shows values for the reservoir water level when the factor of safety is kept at a constant level corresponding reference value from the static conditions (FoS = 3.0) and the earthquake's amplitude is systematically increased. By varying the acceleration of the sinus wave the safety of the dam can be tested for an increased stress level, and through decreasing the hydrostatic pressure the dam will be able to withstand a higher dynamic load. The result is presented in figure 25 - 28, presenting the reservoir water level, displacement and xy-strain.

Below, figure 25 illustrates the reservoir water level as a function of the amplitude of an earthquake when the factor of safety is kept constant. The chosen accelerations were in magnitudes between 0 m/s^2 and 10 m/s^2. The result only presents values in the range of 0 and 2 m/s^2 since the dam will experience a failure for values exceeding the interval. The values of the factor of safety are seen to be in level with the reference value with the margin of ± 0.15.

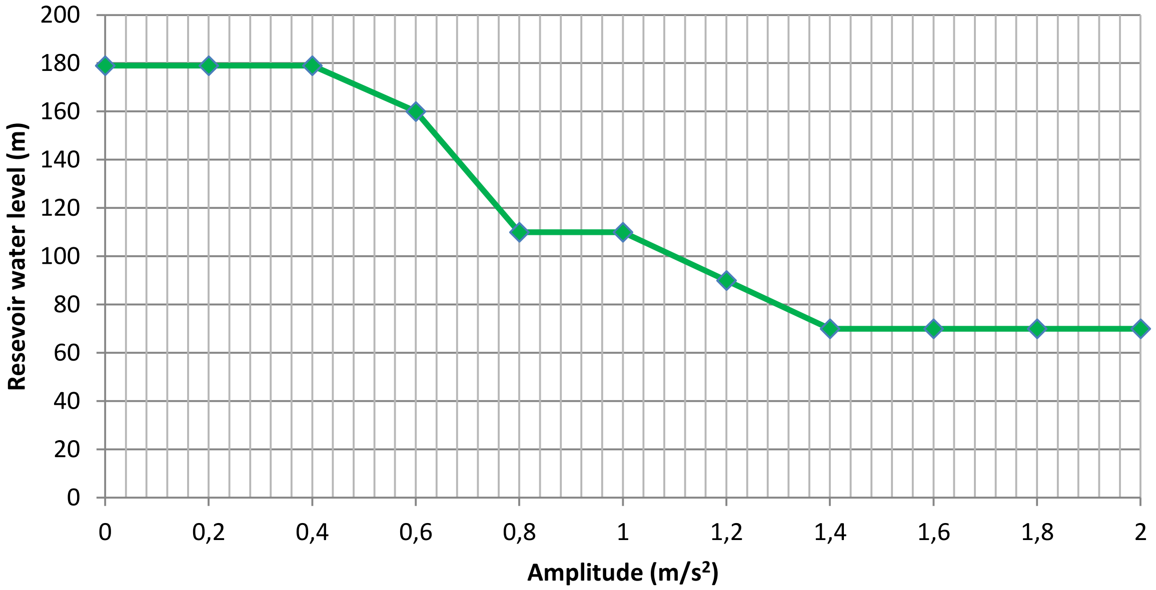

Figure 25 – The reservoir water level as function of the amplitude of an earthquake with the frequency 5 Hz and a duration of 5 seconds.

From figure 27 it can be concluded that the dam experiences four different stages depending on the size of the dynamic load. First, the dam safety decreases rapidly when the amplitude is exceeding 0.4 m/s^2. Between 0.8 and 1.0 m/s^2 the concrete-rock interface come into a steady state that represents the second stage. In order to preserve the safety the reservoir water level has to be lowered to 110 meters at this point. If the acceleration increases any further, the failing part will expand and the safety will start to decrease again, which represents the third stage. Another steady state will occur for values exceeding 1.4 m/s^2, seen in figure 27 as a leveled out graph, and finally for amplitudes above 2.0 m/s^2 the dam safety will fail. The failure is shown as a deformation in dam structure of the model and therefore the values are neglected in the analysis of the result. At this point the dam safety will have no relation with the reservoir water level. Even if the graph levels out at two occasions, the displacement increases according to figures 26 and 27. The increasing displacement for higher amplitudes is probably the reason for the failure in the model.

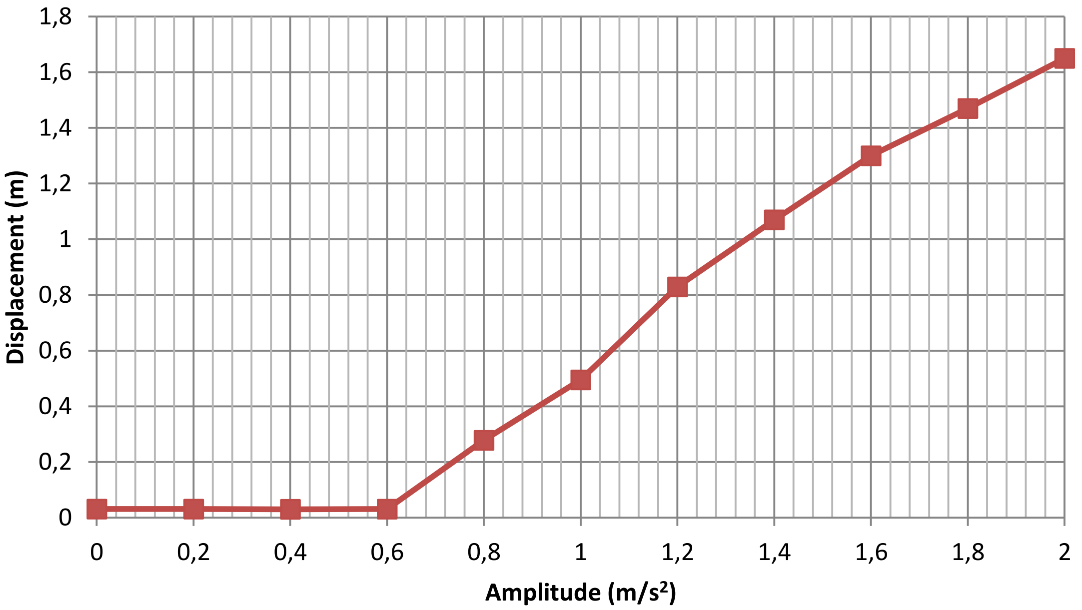

Figure 26 – The maximal displacement in the dam as a function of the amplitude of an earthquake with a frequency of 5 Hz and duration of 5 seconds.

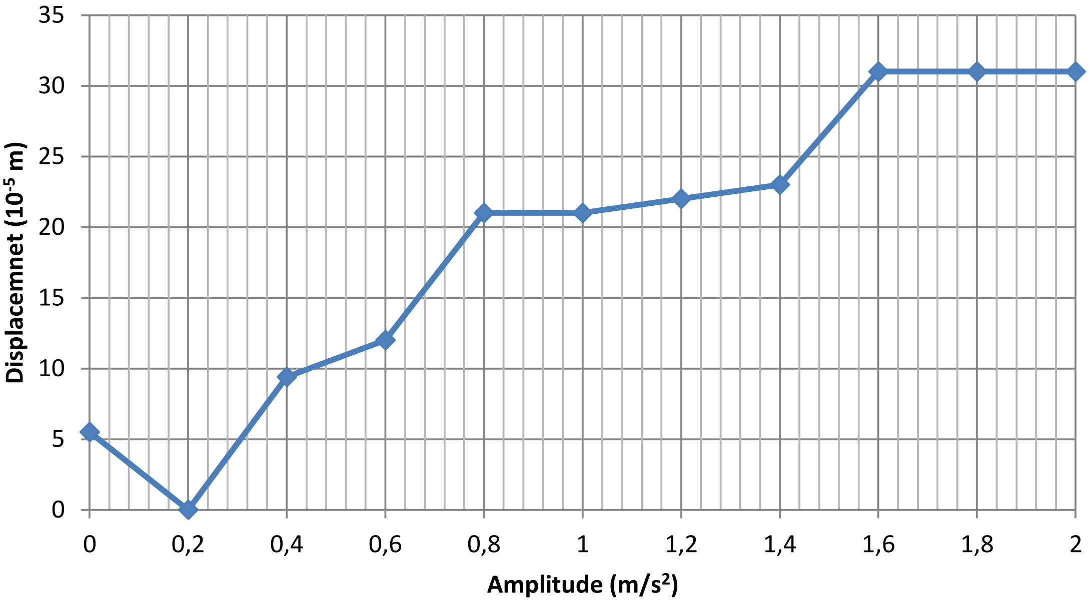

Figure 27 – The displacement in the dam heel (-81,0) as function of the amplitude of an earthquake with a frequency of 5 Hz and duration of 5 seconds.

At accelerations over 0.6 m/s^2 the displacement increases rapidly even if the reservoir water level is decreased. This is a result of the amplitude of the earthquake, but also indicates that the force from the self weight is significantly larger than the upstream hydrostatic force. The main failure will be sliding along the concrete-rock interface; a circumstance that can be concluded from the xy-strain contour plot in figure 28, together with that the factor of safety throughout the model will reach its minimum in this interface. Figure 28 shows the xy-strain contour for a simulation with the amplitude 1.0 m/s^2 and a reservoir water level at 110 meters. At this stage the displacement is steadily increasing, thus increasing the stress in the dam. Similar to previous plots of the xy-strain contours, there is a shear displacement in the dam toe. An interesting observation is the high stress level at the top of the dam, which could be an effect from a lower water level, thus leaving the highest parts of the dam without the possible support from the water mass against vibrations.

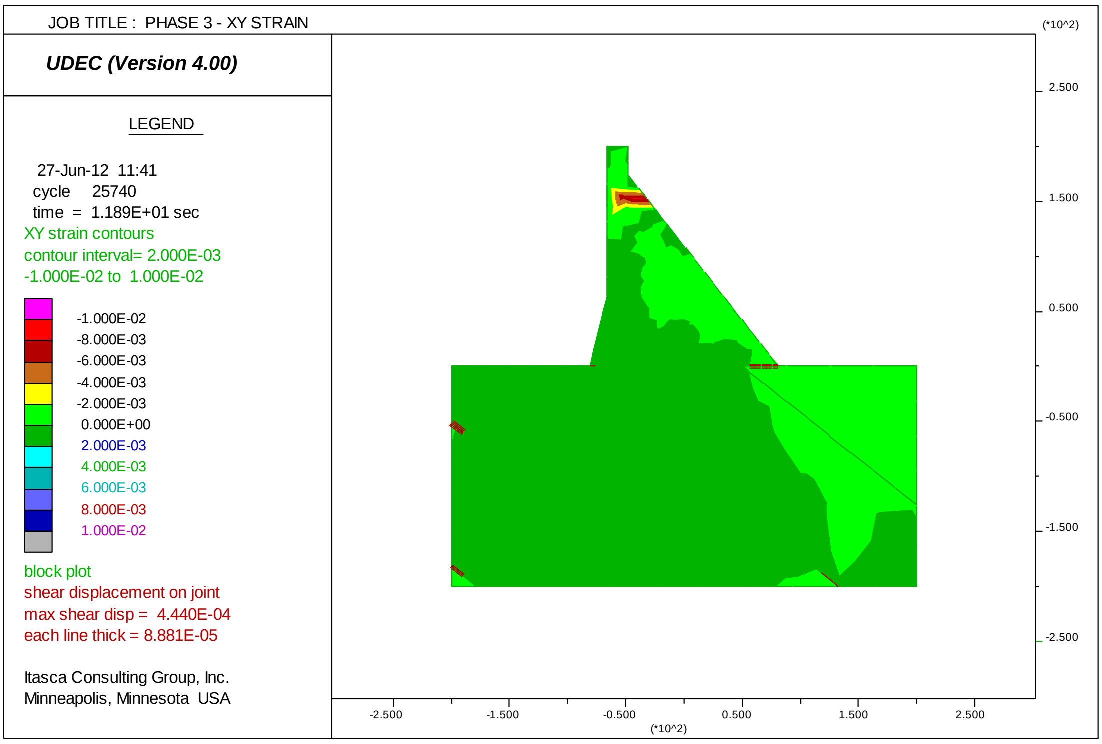

Figure 28 – Illustration of xy-strain contour plot of the model after dynamic conditions. The reservoir water level is 110 meters and the amplitude 1.0 m/s^2. Note that the contour interval is larger than the interval for the two other XY-strain plots.

5.3. Production losses

The direct production losses can be seen as the volume of water that is lost in order to keep the safety at the same level for the dynamic conditions as for the static conditions. This might not be the correct way of measure the production losses since the water level cannot be lowered directly in connection with an earthquake, but will require a period of time from weeks to months. Theoretically, if the watered could be lowered instantly, the production loss would be high since a great amount of water would be lost in order to keep the dam safe, which is illustrated in figure 25. The water level will finally even pass the minimum water level for production (102 meters), a situation occurring already after an amplitude of 1 m/s^2.

6. Discussion

Two major purposes can be pointed out in this thesis. The first purpose was to understand how a combination of loads affects the model of Longtan Dam, describe the elementary dam design, and with the help of the obtained knowledge investigate possible risks and critical points. The second purpose was to analyze how the dam safety is affected by seismic activity and from the result give a measure of the vulnerability of Longtan Dam from earthquakes. Therefore, the discussion has been divided into two parts; model with static conditions and model with dynamic conditions, corresponding to stage 1-2 and stage 3-4, respectively.

The third research question specified in the introduction of the report was concerning the production losses and possible effects on the surrounding environment from a dam failure. Unfortunately, the question was not fully answered in frame of this thesis. The loss in production is answered by figure 27, where the decrease in the reservoir water level can be directly related to losses in production. In order to investigate possible effects on the surrounding environment a deeper analysis would have to be made, which could not be performed in thesis on the basis of poor availability of information and lack of time. The magnitude of such an investigation could be a master thesis of its own. However, there is always the possibility to speculate about consequences to downstream areas, but this report will stop at the section in the background chapter.

6.1. Model with static conditions

The results from the model with static conditions are expected and follow basics mechanics rules. Noticeable is the importance of the dam's self weight, which comes from the purpose in design of a gravity dam that is to withstand external loads with its own weight. Another important part of the Longtan Dam is the flare; a feature added to increase the resistance against the moment causing overturning as an effect from the uplift force and hydrostatic pressure. The flare enhances the concrete-rock contact area and uses the weight of the water column above to press the dam heel downwards, which together prevents the dam from sliding along the interface. These features of the dam are all illustrated in the figures under the static conditions in the result chapter. In the figures regarding XY-stresses the most critical point can be determined as the point of the dam heel where the concrete of the dam foundation meet the underlying bedrock.

The model is assumed to have solid foundation of concrete, which in reality is not the case since the dam construction consists of reinforcements, spillways among other thing. However, the proportion of the additional structures within the dam are small, thus assuming the dam as solid concrete body represent the situation well enough. Representative values obtained from measurements in the Longtan Dam have been used as input data for the bedrock in the model. Even though the model is based on an existing hydropower station there will always be natural variations in materials and in the surrounding environment that is hard to take into account, but would have been preferable to consider in an analyze like this. The two most critical parameters in the model are considered to be the structure of the bedrock and the size and distribution of the uplift force. Both of the parameters will vary with time, thus creating new conditions that will change the risk profile and influence the safety of the dam. As an example, the drainage system could become plugged over time if not maintained properly, which will be followed by an increased water pressure and thereby reduce the sliding stability of the dam. Another simplification in the model is that a dam could in a degree of variation be affected by several more loads than those taken into consideration in this thesis. In addition, loads that could be taken into consideration are for instance stresses caused by sediment and ice, but since the proportions of other loads are either low or not existing in the geographical area of the dam, they are neglected. However, it can be important to consider a variation in the set of loads if the procedure of this thesis is used for other dams.

The water flow was turned off throughout the simulation and the uplift force was applied to the model manually in order to create a situation with a maximal uplift controlled by a relief drain. The effects from water flow through rock joints were however lost. In the end the main reason for not choosing the situation with flow were to ensure a condition with maximal uplift controlled by a relief drain. The loss of the effect from bedrock can be discussed, but since the rock-concrete interface were believed to be the most critical point in the safety of the dam, this part were considered more important.

As expected the failure mode of sliding proved to be the most critical, a result that was shown both by calculations and simulations. Sliding is an effect on unsatisfactory connection between the concrete and rock, allowing seepage path in the interface and internal erosion. Worth mentioning again is that the factor of safety can be calculated according to different procedures and the values obtained in this thesis from UDEC should and cannot therefore be compared with other values in literature or guidelines. Even though, the values will be of interest since they give a hint of if the dam is safe. A problem encountered during simulations in UDEC has been the sensitivity in the calculations of factor of safety and some of the values in the result from the dynamic conditions are hard to explain, with an unexpected variation in the factor of safety. Therefore, calculations of the static conditions were done by hand in order to control the validity of the model and the result indicated that the UDEC-model was correct and the values of the safety factors proved that the most expected failure mode is sliding.

Other simplifications worth notation are that the model is built in a 2-D plane and that it is assumed to follow Mohr-Coulomb's model for plasticity. The main reasons for using a 2-D model instead of one in 3-D are a mix of the time limit and a lack of knowledge. However, the sources of error have been minimized by discussions with supervisors. Effects that follow from assuming a 2-D model are that it is independent of variations along the dam's crest and no consideration is taken into factors such as spillways and variations in height. The material assigned to a model in UDEC could either be considered to follow elastic or plastic deformation. By assuming Mohr-Coulomb's model for plasticity a certain number of input parameters have to be specified and all of them could not be obtained from the in-situ investigation of the Longtan Dam. The missing values were instead approximations made with the help of the personnel at Shandong University. Accurate values from the location are always to preferable, but are however not always a possibility.

6.2.Model with dynamic conditions

To evaluate the dam safety under dynamic condition the water level in the reservoir were decreased in order to compensate for a higher dynamic loading. In reality this would be impossible since it would take weeks or even months to lower the water level in the magnitudes that are investigated in this thesis. To lower the water level in advance with the aim to compensate for a dynamic load would not be a possibility, which comes from the fact that earthquakes cannot be foreseen. Preparation for earthquake is done by building proper constructions in areas that have history of high seismic activity. Another interesting study could have been to investigate the difference in result when applying a seismic load to two in design similar concrete gravity dams, which only differs in size. This way a relationship between the size and load could be been determined and used in future designs. Due to the lack of time this was not performed in this thesis, but could be of interest in future research. Hopefully, there are some use of the study done in this thesis, although they are more connected to an economically risk perspective from loss in production and dam failure.

The effect on the reservoir water level shows a rapid decrease in height as a function of an increase in amplitude. In the interval between 0 and 0.4 m/s^2 the model of Longtan Dam will withstand an earthquake without having the reservoir water level lowered. In China are some of the dams usually designed to withstand earthquakes under 0.2g-0.3g, and from this point of view the result can be somewhat explained with reference to the lower limit of the interval. The need to lower the water level in the reservoir in order avoid a dam failure if an earthquake occur is however questionable. Longtan dam is not situated in an area with high seismicity, which explains the dam's poor ability to withstand earthquakes. It may also be a consequence of the high probability of sliding proved in the stability analyze under static conditions. Another more likely reason is the input parameters for the earthquake, which are more thoroughly discussed below. However, as pointed out earlier there are obvious problems with connecting the result of this investigation to dam safety, which are the time it will take to lower the water and knowing when an earthquake occurs.

Some simplifications are done when adding the dynamic load in UDEC. The earthquake is added as a shear stress, an assumption made in accordance with an example in the UDEC manual concerning a recommended procedure for similar problems with an idealized representation of gravity dam as a template. The size of the dynamic load is only assumed to be an effect from the weight of the dam, which was a simplification suggested by our supervisor at Shandong University. A more accurate scenario might also have considered the weight of the underlying bedrock in the model, but this would on the other hand have involved other difficulties. The frequency and duration of the earthquake, 5 Hz and 5 seconds respectively, are also assumptions made after discussions with our supervisor. Further and complementary experiment could investigate the effects of adding a historical record of an earthquake, which could confirm or discard the assumptions made in this study. It is also of importance to study the possibility for an earthquake in the dam area further.

7. Conclusions and future research

Longtan Dam turns out to be rather unsafe in terms of withstanding an earthquake with amplitude above 0.4 m/s^2, which may depend on a number of reasons that have already been pointed out in this report. Earthquakes are rare in the area where the hydropower station is situated and this is probably the most important factor behind the result, together with the rather extreme scenario assumed in the simulations, i.e. the uplift force and weak interface. This report point out the most critical areas, but more investigations has to be done before giving any recommendation about the safety. A major dam failure could cause large environmental, economic and social effects, and therefore work concerning safety in dams must continue and be further developed so that the utilization of hydropower renders as low risk as possible and will have as small impact on the surrounding environment as possible. The positive advantages that hydropower brings to a developing country as China must also be taken into consideration into an analysis. For this reasons it is hard to give any recommendations for the Longtan Dam on the basis of the results in this thesis. Important to remember is that the probability and consequence always must be weighed against each other and also that it is unreasonable to be prepared for all risks.

As mentioned before the most important aspect in this study is not the achieved result, but the method of investigating the effects of earthquakes in a dam, and hopefully it could work as a template for future research. As method, the way of defining this model works quite well and could be applied in risk and vulnerability analysis for gravity dams with similar construction as the Longtan Dam. By take account of the probability of an earthquake in the method performed the analysis can be more up against a risk-based analysis rather than an analysis from a vulnerability perspective. It is also important to note that it is not enough to design a strong dam structure, it is equally important to check the conditions at hand; from the bedrock to geographical features. Finally, we hope that the research project *Longtan high concrete dam stability research in China*, which this thesis is a part of, will lead to better dam safety in the Longtan Dam as well as in future hydropower stations in China.

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Appendix A

Mohr-Coulomb's criteria

Mohr-coulombs criteria are used in the simulations to identify the critical areas in the dam and rock foundation, by investigating the relationship between the shear stress and the normal stress at a failure. The available shear strength, τ_F, also mention the Mohr-Coulombs failing criteria, can be expressed by the equation;

$$\tau_F = c + \sigma_n \cdot \tan(\varphi)$$

where the shear strength is a function of the cohesive strength, c, the angel of internal friction, φ, and the normal stress, σ_n. The relationship is linear, hence the cohesive strength will be equal to the shear strength in the rock if no normal stress is applied and the internal friction is frictional resistant to shearing. (Hudson & Harrison, 1997)

The Mohr diagram, figure 24, describes the stress envelope for a specific element graphically, by the relationship between the shear stress and the normal stress at a failure. According to the figure the maximum shear stress, τ_m, is given by:

$$\tau_m = \frac{\sigma_1 - \sigma_3}{2}$$

The maximum shear stress is equal to the radius of the circle with center in the maximum normal stress, σ_m;

$$\sigma_m = \frac{\sigma_1 + \sigma_3}{2}$$

where $\sigma_1$and σ_3 represent the maximum principle stress respectively the minimum principle stress. The maximum shear stress is however not equal to the point where failure occurs. Instead failure will occur if the principal stresses are in such magnitude that the circle (Mohr circle) in the Mohr diagram touches the linear Mohr envelop. (Hudson & Harrison, 1997) In UDEC the strength of the stress state is represented by a circle where the maximum principle stress is increased or decreased until the circle is in contact with the Mohr envelope. The ratio of the radius of the two circles is equal to the strength/stress ratio for deformable blocks. If the “original” circle has the radius r_a and the “new” circle has the radius r_b the strength/stress ratio is expressed by;

$$F = \frac{r_b}{r_a} = \frac{(\sigma_3 - \sigma_{1b})}{(\sigma_3 - \sigma_{1a})}$$

where F also can be expressed as the failure index or the factor of safety. (Itasca, 2005)

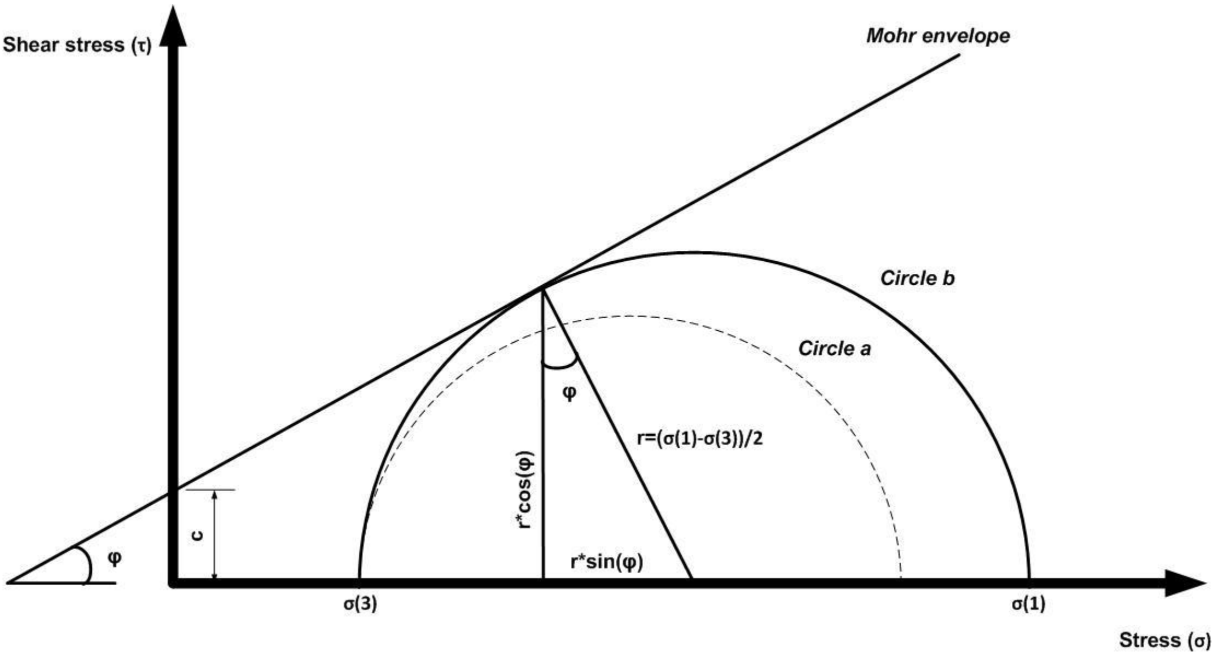

Figure 29. Figure illustrating the Mohr diagram and the method to point out a failure that is used in the software UDEC.

Appendix B

UDEC model

The following parameters should be considered in the UDEC model:

- Density, ρ
- Bulk modulus, K
- Shear modulus, G
- Friction angle, φ
- Cohesion, c
- Dilation angle, ψ
- Tensile strength

The parameters above are used for assigning properties to the different materials in the blocks of the model and authentic values for all parameters except for the dilation angle, which is set to zero degrees, are used in this thesis. Only the first three parameters have to be considered in an elastic model. The joints follow the Coulomb slip-model, in which the materials are treated as elastic-perfectly plastic. The list below summarizes the parameters needed in the model:

- Normal stiffness (Young's modulus), E
- Shear stiffness
- Friction angle, φ
- Cohesion, c
- Dilation angle, ψ
- Tensile strength

Just as in the case with the previous mentioned parameters for block material, the dilation angle is set to zero and the shear stiffness is also assumed to be 20 GPa.

Calculations of input parameters

Young's modulus (E), also called the elastic modulus, can together with Poisson's ratio (ν) be used to calculate an additional set of parameters describing stresses in various materials. The bulk modulus (K) can be derived through following equation:

$$K = \frac{E}{3(1-2\nu)}$$

Another parameter of interest is the shear modulus (G), which can be calculated as followed:

$$G = \frac{E}{2(1+\nu)}$$

In order to calculate the friction angle, the following equation is used;

$$\varphi = \tan^{-1}(f)$$

where φ is the friction angle and f is the friction coefficient.

Calculations of stress gradients

Input of stresses in UDEC can be done in three directions according to:

$$stress - sxxo\ sxyo\ syyo$$

All stresses that are distributed over a boundary can be set to vary over a distance by introducing a gradient, which are done by using one of the following two commands:

$$xgrad - sxxx\ sxyx\ syyx$$

$$ygrad - \ sxxy\ sxyy\ syyy$$

For a linearly varying boundary stress ($sxxo$, $sxyo$ or $syyo$) with origin in (0,0) can one of the following equations be used in order to calculated the stress gradient:

$$sxx = sxxo + (sxxx \cdot x) + (sxxy \cdot y)$$

$$sxy = sxyo + (sxyx \cdot x) + (sxyy \cdot y)$$

$$syy = syyo + (syyx \cdot x) + (syyy \cdot y)$$

A wetting fluid pressure can be incorporated into the model in order to control the fluid flow in joints and can just as the stresses presented above vary over a boundary with the help of the commands:

$$pxgrad - fpwx$$

$$pygrad - fpwy$$

The stress gradient is calculated with the following equation:

$$pw = fpw + (fpwx \cdot x) + (fpwy \cdot y)$$

Appendix C

UDEC code

```
; ____________________________________________________________
; PHASE 1 – MODEL, SELF WEIGHT and IN-SITU CONDITIONS
; ____________________________________________________________
;
; Input parameters are in [MPa], [m], [s] and [Gg]
;
; --- MAT=1 : dam foundation ---
prop mat=1  d=0.00244  g=8398  k=9810  fr=50.2  coh=2.5  tens=1.57
prop jmat=1  jkn=19600  jks=20000  jfr=50.2  jcoh=2.5  jtens=1.57
;
; --- MAT=2 : rock foundation ---
prop mat=2  d=0.00275  g=4724  k=8696  fr=47.7  coh=1.48  tens=0.6
prop jmat=2  jkn=12000  jks=20000  jfr=45.0  jcoh=1.2  jtens=0.5
;
; --- JMAT=3 : concrete-rock interface resp. joint ---
prop mat=3  d=0.00244  g=5000  k=10833  fr=35  coh=0.1  tens=0
prop jmat=3  jkn=13000  jks=20000  jfr=35.0  jcoh=0.1  jtens=0
;
; --- MAT=4 : viscous boundarys ; JMAT=4 : joint (cohesion) ---
prop mat=4  d=0.00265  g=11111  k=11680
prop jmat=4  jkn=1000  jks=1000  jfr=30  jcoh=2
;
round  0.5
; Set minimum edge length
set  edge=8.0
; Set minimum contact length
set  clemin=5.0
;
; Create and set the size of the model
block  -200,-200 -200,200 200,200 200,-200
;
; --- Structure : gravity dam ---
crack  -201,0 201,0
crack -81,-1 -66,63
crack -66,63 -66,201
crack -66,201 -48,201
crack -48,201 -48,174
crack -48,174 81,0
delete  range -200,-81 0,200
delete  range  81,200 0,200
;
; --- Structure : Joints ----
jregion id=1 -200,-200 -200,0 200,0 200,-200
jset -40,0  800,0 0,0  100,0 (50,0)  range jreg 1
;
; --- Apply concrete and rock materials ---
```

```
change mat=1  cons=3  range -81,81 0,200
change mat=2  cons=3  range -200,200 -200,0
;
; --- Generate triangle-shaped finite different zones within blocks ---
; Edge works with both elastic and plastic : edge length = 60 resp. 20
generate edge  40  range -200,200 -200,0
generate edge  20  range -81,81 0,200
;
; --- Apply joint and interface materials ---
; Rock joints
change jmat=2   range -210,210 -210,10
; Concrete-rock interface
change jmat=3   range -81,81 -1,1  ang=-5,5
;
; --- Boundary conditions : lateral x-fixed, bottom y-fixed
bound xvel=0   range  -201,-199 -201,1
bound xvel=0   range  199,201 -201,1
bound yvel=0   range  -201,201 -201,-199
;
; --- Set fluid density (for in-situ domain pressures) ---
fluid  dens 0.001  bulk 0.0
set flow off
;
; --- Set gravity : gravitational acc. in x- resp. y-directions ---
grav 0 -9.8
;
; --- In-situ stress conditions ---
insitu -210,210 -210,0  ygrad 0.017885, 0, 0.025970  zgrad 0 0.017885    ywtab=0
;
; --- History ---
; Maximal unbalanced force
hist  unbal
; Displacement at dam toe
hist  xdis=-81,0  ydis=-81,0
; Velocity at dam toe
hist  xvel=-81,0  yvel=-81,0
;
; --- Damping : damping parameters are set automatically ---
damp auto
;
solve rat 1e-8
;
; ______________________________________________________________
; PHASE 2 - WATER LOADS AND UPLIFT (ALTERNATIVELY WATER FLOW)
; ______________________________________________________________
;
; No fluid flow by setting : fluid  dens 0.001  bulk 0.0
; Dynamic domain pressure is also possible by setting : fluid  dens 0.001  bulk 2000.0
;
reset dis  jdis  hist
;
; --- Flow properties : rock foundation resp. viscous boundarys ---
```

```
prop jmat=2  jperm=3.0e8  azero=0.001  ares=0.0005
prop jmat=4  jperm=0  azero=0.001  ares=0.0005
;
; --- Flow properties : concrete-rock interface ---
prop jmat=3  jperm=3.0e8  azero=0.0002  ares=0.0001
;
; --- Set maximal aperture (maximum size of joint openings) ---
set caprat=2.0
;
; Set lateral and bottom boundary contacts to zero permeability
change jmat=4  range -201,-199 -201,1
change jmat=4  range 199,201 -201,1
change jmat=4  range -201,201 -201,-199
;
; --- Upstream water head : calculate pressure with water head=h [m] ---
def pressure
        h=179 ; Define head [m]
        P_h=h*0.00982 ; Pressure head [MPa]
        P_f=(h-63)*0.00982 ; Pressure at flare top [MPa]
        P_d=20*0.00982 ; Downstream pressure with water head at 20 m [MPa]
        neg_P_h=-P_h ; Negative values for compressive stresses [MPa]
        neg_P_f=-P_f ; Negative values for compressive stresses [MPa]
        neg_P_d=-P_d ; Negative values for compressive stresses [MPa]
        h_h=h+0.1 ; Overlap for horizontal load [m]
end
pressure
;
; Fix head upstream of dam
bound pp=P_h  range -201,-80.9 -1,1
;
; Apply vertical water load upstream dam
bound stress 0,0,neg_P_h  range -201,-80.9 -1,1
;
; Apply horizontal load to dam
bound stress neg_P_f,0,0  ygrad 0.00978,0,0  range -66.1,-65.9 62.9,h_h
;
; Apply vertical and horizontal load at the flare
bound stress neg_P_h,0,neg_P_h  xgrad 0,0,0.0411  ygrad 0.00978,0,0  range -81.1,-65.9 -0.1,63.1
;
; --- Downstream of dam : minimum head=7 m ---
; Fix head downstream of dam
bound pp=P_d  range 80.9,201 -1,1
;
; Apply vertical load downstream of dam
bound stress 0,0,neg_P_d  range 80.9,201 -1,1
;
; Apply vertical and horizonal load on dam
bound stress neg_P_d,0,0  xgrad 0,0,-0.0132 ygrad 0.00978,0,0  range 75.7,81.1 -0.1,7.1
;
; --- Uplift pressure : function of water loads and relief drain at (-66,0) ---
def uplift
        P_r=0.3*P_h ; Reduction in pressure with 70% from a relief drain [MPa]
```

```
            x_grad1=(P_r-P_h)/15 ; X-grad for uplift_1
            x_grad2=(P_d-P_r)/150 ; X-grad for uplift_2
end
uplift
;
bound pp P_h  pxgrad x_grad1  range -81.1,-65.9 -0.1,0.1
bound pp P_r  pxgrad x_grad2  range -66.1,81.1 -0.1,0.1
;
; --- Fix lateral boundaries : horizontally ---
bound xvel=0  range -201,-199 -201,1
bound xvel=0  range 199,201 -201,1
bound yfree  range -201,-199 -199,-1
bound yfree  range 199,201 -199,-1
;
; --- History ---
; Maximal unbalanced force
hist unbal
; Displacement at dam heel
hist xdis=-81,0  ydis=-81,0
Velocity at dam heel
hist xvel=-81,0  yvel=-81,0
; Flowrate into concrete-rock interface
hist flowrate(-81,0)
;
; --- Fluid properties : non-zero bulk modulus ---
fluid dens 0.001  bulk 2000.0
;
; Switch on fast flow logic
set flow steady
;
solve rat 1e-8
;
; Factor of Safety in dam foundation and concrete-rock interface
solve fos include mat 1 jmat 3
;
; Display all variables
print fish
;
; _________________________________________________________________
; PHASE 3 - DYNAMIC LOADING WITH SHEAR WAVE AT BASE OF MODEL
; _________________________________________________________________
;
; Free-field lateral boundaries with constant domain pressures
; No fluid flow by setting : fluid  dens 0.001  bulk 0.0
; Dynamic domain pressure is also possible by setting : fluid  dens 0.001  bulk 2000.0
; The dynamic solution is less conservative and predicts less movement
;
; Switch off flow
fluid dens 0.001  bulk 0.0
set flow off
;
; Generate free-field (20 nodes) ; cohesion below y=-150 ; fixed bottom
```

```
ffield gen yrange (-200,0)  np 20
ffield change  mat=2  cons=3  range -200,0
;
def field
        f=neg_P_h/100
end
field
;
; Insitu=UDEC example
ffield ini sxx 0 0.017885
ffield ini szz 0 0.017885
ffield ini syy 0 0.025970
ffield ini pp 0 f
;
; Fix bottom
ffield base  xvel=0
ffield base  yvel=0
;
; Cycle with FF not applied to grid in order to verify that FF stresses are at equilibrium
reset time  hist
cycle 100
save dam3.sav
reset time  hist
;
; --- Boundary conditions : apply viscous boundaries and free-field ---
bound mat=4
bound ff  range -201,-199 -201,1
bound ff  range 199,201 -201,1
bound xvisc  range -201,201 -201,-199
;
; --- Earthquake ---
;Calculate stress from amplitude of shear wave
def amplitude
        a=0.5 ; Define the amplitude with its acceleration [m/s^2]
        A=0.230754333*a ; Calculate the amplitude as a pressure [MPa]
        P=2*A ; Add a factor 2 in order to compensate for the viscous boundaries [MPa]
end
amplitude
;
; Amplitude of shear wave : P [MPa] ; frequency = 5 [Hz] ; time = 5 [s]
bound stress 0,P,0  hist=sin(5.0,5.0)  range -201,201 -201,-199
;
; Fix y-velocity at bottom
bound yvel=0  range  -201,201  -201,-199
;
; Boundary conditions at the base of free-field
ffield base  sxy=P  hist=sin(5.0,10.0)
ffield base  xvisc
ffield base  yvel=0
;
; --- History ---
; Maximum unbalanced force
```

```
hist unbal
; Maximum velocity
hist vmax
; Displacement in x- and y-directions at dam heel
hist xdis(-81,0) ydis (-81,0)
;
; --- Dynamic damping ---
damp 0.10 2.0 mass
;
; No mass scaling
mscale off
;
solve rat 1e-5
;
; Factor of Safety in dam foundation and concrete-rock interface
solve fos include mat 1 jmat 3
;
; Display all variables
print fish
```