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FEM MODELING OF CONCRETE GRAVITY DAMS

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SUMMARY

This thesis is an analysis of two different concrete gravity dams. One of the dams, the Baozhusi Hydropower Station, is a fully functional concrete gravity dam situated in the Sichuan province in the Peoples Republic of China. This dam reopened again after its upgrading, which was finished in 1998. The dam has three main purposes: irrigation, flood control and power extraction. Our analysis in this thesis is to prove or disprove, by results given by the Finite Element Method (FEM), the safety of the dam due to Chinese standards. The section which we have analyzed is in one of the dam's turbine sections.

The second dam is under construction, situated in the Kuchin province in Myanmar. In spite of the dam's location it's partly a Chinese project. The Qipei Hydropower Project is going to dam up the Irrawaddy River with the main purpose of generating power but also provide flood control for the region. We are in this thesis analyzing the safety of the dam due to Chinese standards in one of the dam's solid sections.

Both dams are analyzed in a static state, in a usual and an unusual load case state, meaning that we have considered a normal water flow and higher flow simulating a flood.

Key words: Baozhusi Station, Qipei Project, irrigation, flood control, power extraction, FEM, turbine section, solid section, static state and load cases.

SAMMANFATTNING (SWEDISH)

Den här avhandlingen är en analys av två olika gravitationsdammar av betong. En av dammarna, Baozhusi Vattenkraftverk, är en fullt fungerande gravitationsdam som ligger i Sichuan provinsen i Kina. Dammen kom åter i drift efter dess uppgradering som var klar 1998. Baozhusi gravitationsdamm har tre huvudsakliga uppgifter: bevattning, översvämningskontroll och energiutvinning. Vår analys i den här avhandlingen är gjord för att bevisa eller motbevisa, genom resultat inskaffade med hjälp av Finita Element Metoden (FEM), dammens säkerhet enligt kinesisk standard. Vi har analyserat en turbinsektion i den här dammen.

Den andra dammen är under arbete, den ligger i Kuchin provinsen i Myanmar (Burma). Trots dammens lokalisering är det delvis ett kinesiskt projekt. Qipei vattenkraftverk kommer att dämma upp floden Irrawaddy med huvudanledning att producera el men också att kontrollera översvämningarna som drabbar området. Vi analyserar säkerheten i dammen utifrån kinesisk standard i en av dammens solida sektioner.

Båda dammarna är statiskt analyserade, med en vanlig och en ovanlig typ av last, vilket betyder att vi har övervägt både ett normalt vattenflöde och ett högre flöde som ska simulera en översvämning.

Nyckelord: Baozhusi Vattenkraftverk, Qipei Vattenkraft Projekt, konstbevattning, översvämningskontroll, el utvinning, FEM, turbin sektion, solid sektion, statisk last och lasttyper.

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This project, managed by James Yang, is founded by Elforsk AB within the frame of dam safety, where Mr. Cristian Andersson is the program director of hydropower. Some funding is even obtained from the Royal Institute of Technology (KTH) which facilitates the accomplishments of the projects.

We would also like to thank our examinator Professor Hans Bergh from Land and water resources at the Royale Institute of Technology (KTH), Sweden.

1. TABLE OF CONTENT

SYMBOLS AND DICTIONARY

Symbols

a = reduced gravity acceleration	[m/s^2]
c = cohesion	[N/m^2]
E= elasticity	[Pa]
g = acc. of modulus gravity	[m/s^2]
K = safety factor	[-]
L = Length	[m]
α = angle	[º]
μ = friction coefficient	[-]
σ = normal stress	[Pa]
τ = shear stress	[Pa]
ϱ = density	[kg/m^3]
K_T = safety factor for tension	[-]
K_c = safety factor for compression	[-]

Dictionary

Batter: an optional sloped extension at the dam heel.

Dam heel: the most upstream part of the dam foundation

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

Discharge section: a part of the dam where the spillway is located

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

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

Static state: is a term for simplified analysis wherein the effect of an immediate change to a system is calculated without respect to the longer term response of the system to that change.

Turbine section: a part of the dam where the turbines for generating power are located

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INTRODUCTION

1.1. Introduction of the projects

1.1.1. *Baozhusi hydropower project*

The Baozhusi hydropower station is located in the Sichuan province in the central southern part of the Peoples Republic of China. It is located in the lowland of the Sichuan plain displayed in figure 1, lowland anyway in comparison to the highland just to the west, the Tibetan plateau. Since the plain has an altitude of 200 to 700 meters above sea level a lot of rain falls here due to the cooling of the air travelling against the western plateau. The annual precipitation is over 1000 millimeters (www.bbc.co.uk).

The Baozhusi dam is a concrete gravity dam, which means that it is supposed to withstand the loads caused by water simply because of its own weight. The dam crest is located 595 meters above sea level making the maximum height of the dam 132 meters. The length of the dam is 525 meters (Ministry of Water Recourses and Electric Power of People's Republic of China, 1979).

The Bailonghu reservoir has a capacity of containing 2.2 billion cubic meters of water and an area of 80 thousand square kilometers. The dam has been operational since 1998, eleven years after the decision to construct the dam (Ministry of Water Recourses and Electric Power of People's Republic of China, 1979).

There are three different types of sections in the dam: solid section, overflow discharge section and turbine section. In both figure 2 and 3, these sections can be seen, with the turbine sections in the center, surrounded by discharge sections and the solid sections connected to the dam on both sides. The model on which the calculations and the analysis are conducted in the Baozhusi case is from the turbine section unlike in the Qipei case, presented below, where a solid section is modeled.

Figure 1 Map showing the Peoples Republic of China, Sichuan in red and Baozhusi highlighted (www.samsays.com).

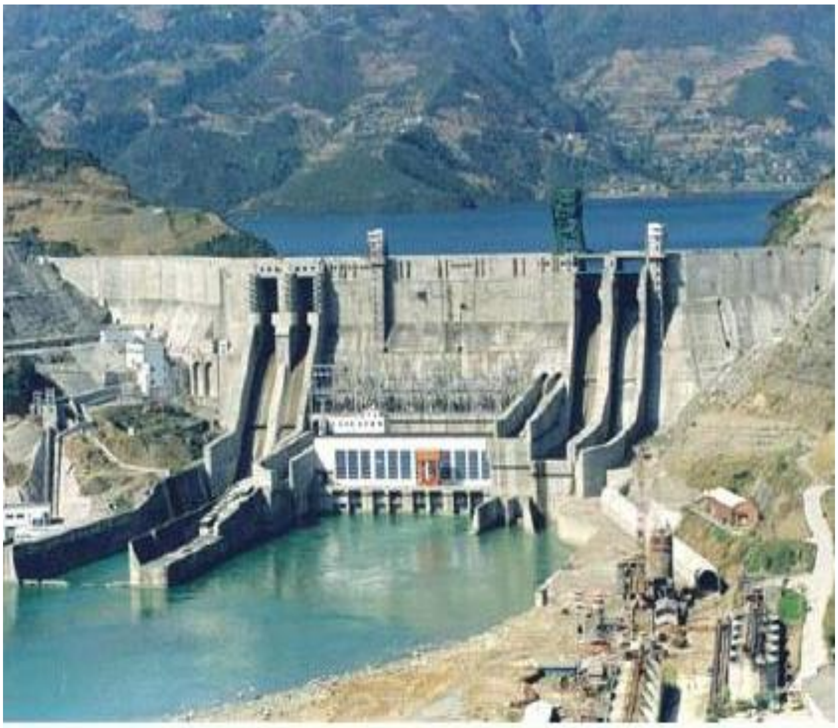


Figure 2 Baozhusi Hydropower Station, picture taken from downstream (www.cryptome.org).

For the hydropower extraction the dam has four large Francis turbines, each of them with a capacity of 175 MW, adding up to a total capacity of 700 MW (Ministry of Water Recourses and Electric Power of People's Republic of China, 1979).

1.1.2. *Qipei hydropower project*

The Qipei hydropower project is to be constructed in the Irrawaddy River, which partly flows through China, but as it finds its way to the Indian Ocean it flows into the Chinese neighbor country of Myanmar where the dam will be located. It will be constructed 104 km upstream of the city Myitkyina the capital of the Kachin province in Myanmar, shown in figure 4.

Despite the project being located in Myanmar, it is partly a Chinese project. In fact the project is a coalition between China's state-owned China Power Investment Corporation (CPI) and Myanmar's private Asia World Company (www.reuters.com).

One objective for the dam is to generate electricity, which because of the origin of the project primarily will be rerouted back to China. The capacity of the hydropower station will be 3400 MW. A second reason, still a very important one, is flood control (Ministry of Water Recourses and Electric Power of People's Republic of China, 1979).

There have been two different alternatives how to construct the dam, the difference between them is the location. Both of the suggested outlines cross the main river. The first alternative is a dam with an axis length of 1200 meters and a crest elevation of 408 meters above sea level creating a maximum height of 215 meters.

Figure 3 An aerial photo of the Baozhusi Dam and Hydropower Station (www.cryptome.org).

The dam will have a non-overflow section on the western side and a channel spillway section on the eastern side (Ministry of Water Recourses and Electric Power of People's Republic of China, 1979).

The second alternative, which is the one studied in this thesis, has a dam axis length of 1333 meters and the same crest elevation as alternative one. This alternative consists of two dams, a main dam, 893 meters of length has a maximum height of 201 meters and an auxiliary dam, 440 meters of length which has a maximum height of 60.5 meters. The auxiliary dam is east of the main dam. Both alternatives have a crest width of ten meters (Ministry of Water Recourses and Electric Power of People's Republic of China, 1979).

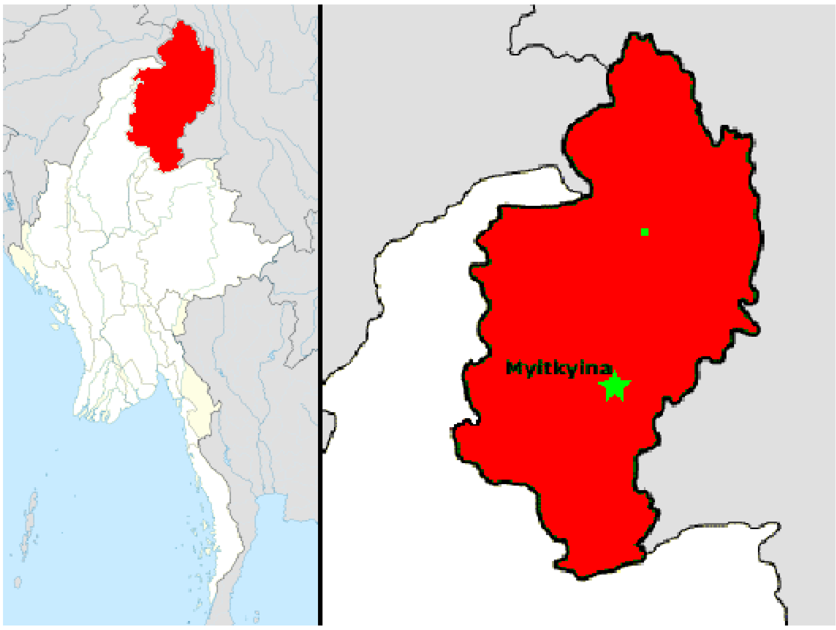


Figure 4 Map showing Myanmar to the left and the Kachin province to the right with province capital and Oipei dam highlighted (www.wikimedia.org).

1.2. The purpose of the thesis

The purpose of this thesis consists in drawing, modeling and analyzing a section from the concrete dams described above in a static state according to Chinese standards. The analyses are performed with the Finite Element Method (FEM). The purposes of the analyses are to calculate the capacity of the dams regarding:

- Sliding stability
- Tension stress
- Compressive stress
- Displacement

There are some parts of the dam and the foundation that are more vulnerable due to the hydrostatic as well as other external pressures. These parts need to be analyzed very thoroughly, and chosen with great care so a risk of future failure can be properly reduced.

1.3. Dams in general

1.3.1. ***Main dam types***

There are two main types of dams, embankment dams and concrete dams. Embankment dams can either be rockfill or earthfill dams. The method of construction is similar in both cases, with just the main type of material differentiating, an example is shown in figure 5. Embankment dams are often very inexpensive to build, at least if material from the surrounding environment can be used. It is sensitive to erosion and cannot support any overflow sections (Armstrong, 1988).

Concrete dams are superior in constructing massive overflow discharge sections, and are therefore often used in areas where floods are common. A lot less material is used compared to an embankment dam but concrete is usually more costly. It is also easier to connect a hydropower station to a concrete dam (Golze, 1977). Different concrete dams are displayed in figure 6.

Three different height spans exsist when concrete dams are considered and they are defined as: low dams (up to 30 meters), medium height dams (30-90 meters) and high dams (90 meters and above). This is a measurement of the difference in elevation between the lowest constructed part of the dam foundation and the walkway at the dam crest (Golze, 1977).

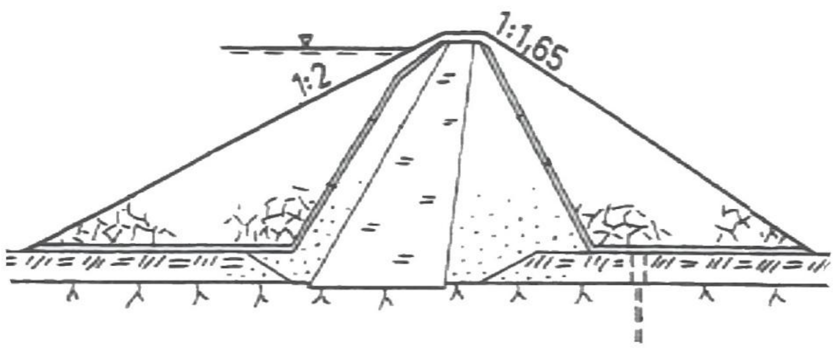
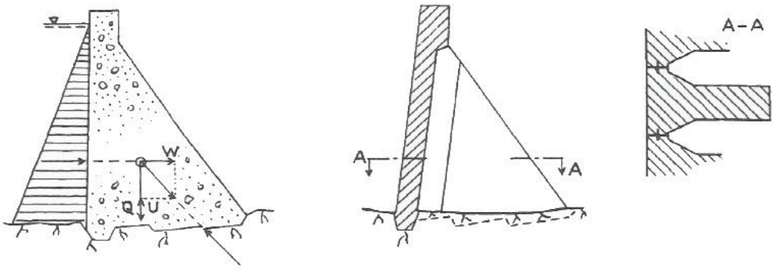
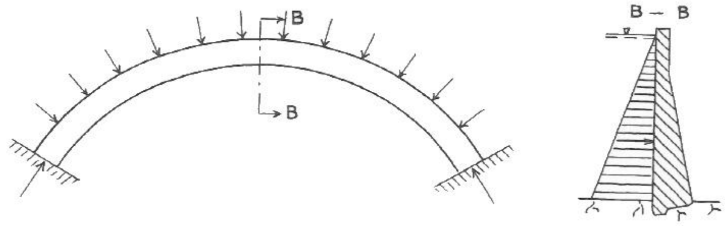


Figure 5 Embankment dam (Bergh, 2009).



Gravity dam

Buttress dam



Arch dam

Figure 6 Different types of concrete dams (Bergh, 2009).

1.3.2. ***Concrete dams***

There are different types of concrete dams based on the principal for the transfer of the hydrostatic pressure.

- Gravity dams, figure 7
- Buttress dams, figure 8
- Arch dams, figure 9

Figure 7 Concrete gravity dam north of Irkutsk, Russian Federation (www.hydroelecritc.energy.blogspot.com).

Gravity dams will be described in the following paragraphs. They, the different types of dams exists both as independent and as combined dams due to changes in the topography or other factors in the surroundings such as the bottom of the river or the composition of the underlying ground.

The theory behind **gravity dams** is that their own weight should be sufficient to withstand the hydrostatic pressures affecting them. This means that gravity dams are usually massive and therefore require a lot of construction material. With the amount of concrete required, this dam type may be somewhat expensive but on the other hand, it is very versatile. Another advantage is that it can possess substantial overflow discharge capacity (Golze, 1977).

Buttress dams, shown in figure 8, are similar to gravity dams with the distinction that they also use the gravity of the reservoir water instead of only the gravity of the dam itself. Because of this, the dam body does not need to be as massive and use buttresses instead of a solid downstream part of the dam. Being less solid on the downstream side, buttress dams have the advantage of being a lot less affected by the water uplift force (Golze, 1977).

Arch dams, shown in figure 9, are curved around a vertical cord to resist the hydrostatic pressure by arching thus transferring the pressure into the canyon walls. For this transfer to be possible and cost effective the width to height ratio should not exceed 5:1, although in some cases arch dams has been built with a ratio as high as 10:1. Another criteria which is important for arch dams is the shape of the canyon, if it is symmetrical an arch dam is often very suitable. If the canyon is a little less symmetrical, an arch dam with influences of a gravity dam may be constructed. If the canyon is extremely asymmetric, another dam type may be preferred (Golze, 1977).

Figure 8 One of the buttresses in the Manic-Ceng buttress dam in Québec, Canada (www.dappolonia.com).

Figure 9 Arch dam in Zernez, Switzerland, view from side, (www.commandatastorage.googleapsis.com).

2. CONCRETE GRAVITY DAMS

2.1. Loads

There are several types of forces acting on dams, the eight that are commonly used are listed and explained in this chapter. In figure 10 the forces acting on a gravity dam are shown:

- Dead weight
- Hydrostatic pressure from reservoir
- Hydrostatic pressure from tail water
- Internal hydrostatic pressure (uplift pressure)
- Sand and silt
- Ice
- Temperature
- Earthquake

Dead weight is the gravity affecting the dam itself, since we are dealing with compact, heavy structures this is a major factor. This is a static load as well as the others, except for earthquake (Golze, 1977).

Hydrostatic pressure from reservoir is the pressure created by the upstream water.

Hydrostatic pressure from tail water affects the dam the same way as the hydrostatic pressure caused by reservoir water does, with the only difference that it is the pressure from the water downstream of the dam (Golze, 1977).

Internal hydrostatic pressure is what we also call uplift pressure. This is the pressure from the water in the foundation and in the dam body that will push the dam body upward, causing an enhanced risk of sliding. This is especially problematic for gravity dams since they cover a greater area than other types of concrete dams (Golze, 1977).

Sand and silt is the load applied as an earth pressure from eroded material at the upstream face of the dam. It is usually reasonably small compared to the hydrostatic reservoir pressure (Golze, 1977).

Ice load affects the upstream face of the dam, as the surface of the water freezes. If the ice gets thick enough it will cause a significant load. The load is concentrated to a small surface where the dam body is thinnest (Golze, 1977).

Temperature is a concern both during the construction phase and the entire lifespan of the dam. The hardening of the concrete causes severe temperature variations that will lead to strains. Depending on where in the world the dam is located the temperature changes may continue, during the entire lifespan of the dam, to be an important issue (Golze, 1977).

Earthquake is a dynamic load. This load is, unlike the other seven, very hard to predict but is very important to consider in earthquake affected regions (Golze, 1977).

2.2. Load cases

From the loads mentioned above it is possible to create load cases. In the present study we use these three load cases.

- Usual
- Unusual
- Extreme

A usual load case occurs often, or even all the time. For example the combination of dead weight, sand and silt load, uplift pressure, hydraulic pressures from reservoir and tail water at a normal level.

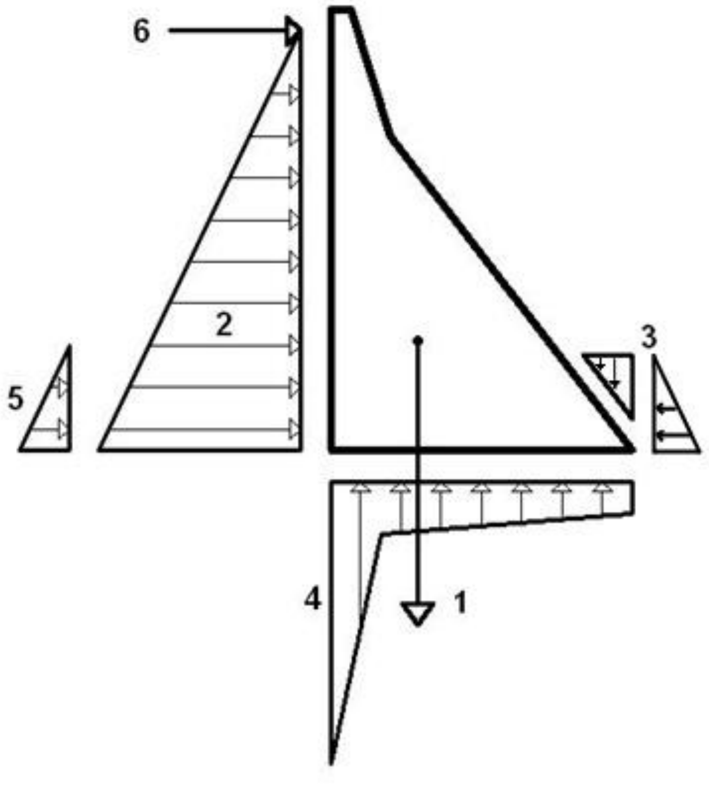


Figure 10 Forces acting on a gravity dam: 1. Dead weight, 2. Hydostatic pressure from the Reservoir, 3. Hydrostatic pressure from the Tailwater, 4. Internal hydrostatic pressure, 5. Sand and silt, 6. Ice. Temperature and seismic loads are not displayed in this picture.

An unusual load case may be the usual case from above with added ice load and lowest possible temperature.

An extreme load case could be a combination of the worst scenario in all eight load-types, including a nearby earthquake.

The reason to use these load cases is to be able to estimate and calculate safety factors, the more usual a load case is, the higher the safety factor should be. This is just an example of how different scenarios can be predicted, in reality these different cases are very thoroughly evaluated, with a lot of different combinations (Golze, 1977).

2.3. Stability criteria

The loads listed in chapter 2.1 will create different types of stresses in the dam body. Although every dam project is unique, problems with these stresses will often occur in the same areas. Figure 11 shows these general critical areas. To create a clear overview of the figure none of the applied loads are displayed (Golze, 1977).

To evaluate ***shear stress*** in the different, carefully chosen, areas in and below the dam foundation, information about the friction coefficient both in concrete, rock and between the two is needed. The cohesion in concrete and rock is also needed. With the vertical stress, the shear stress, the friction coefficient and the cohesion a safety factor, K can be calculated. This safety factor is calculated according to Mohr-coulomb failure criterion, this criterion is Eq. 1 shown in appendix 8.2. Unstable sliding surfaces can occur in numerous places in the dam and the foundation. Therefore it is important to single out the areas where the greatest risk of damage exists. For example such surfaces could be cracks in the ground, where a change of rock material occurs and in various places in the dam, the two most obvious of such being in the foundation plane just in the contact surface with the underlying rock and the horizontal plane where the slope of the downstream side of the dam body starts to flatten out shown in figure 11 (China water press, 1979a).

According to the Chinese standards for constructing dams the safety factor for a sliding surface should be 3.0 for the usual state, 2.5 for the unusual state and in the extreme state the factor must be 2.3 (China water press, 1979b).

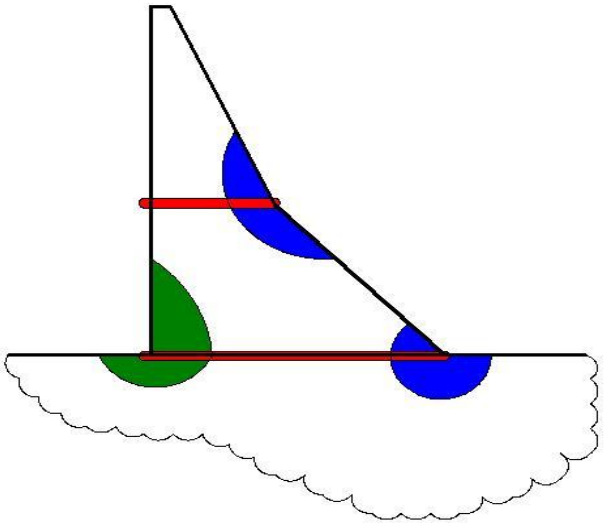


Figure 11 Simple dam model showing critical areas for compressive (blue), tensile (green) and sliding (red).

When constructing a concrete gravity dam according to Chinese standards only seven per cent of the length of the dam is allowed to be exposed to tension stresses. Tension stress is as shown in figure 11 usually found in the dam heel, this area is therefore treated with extra care when conducting a stress analysis (China water press, 1979a).

According to Chinese standards the compressive stress value of concrete should be divided by three and compared to the highest value of compressive stress in the model for usual load case. Compressive stress control is of course very important to check as well as the tension stress. It is important to get an overview of the compression situation in the foundation but it is equally important to see the areas affected by the stresses (China water press, 1979b).

According to Chinese standards, no requirements for how big displacements in a concrete gravity dam can be. Compared to other dams in China of the same magnitude displacements up to ten centimeters are not unusual but in case the model indicate higher values than that further investigation about the problem should be done (Personal communication Ph. D. M.X. Zhong 2010).

3. FEM ANALYSIS PROCESS

FEM means Finite Element Method and it is a way of turning real life objects, such as a dam construction, to a computable model. In the FEM the object is divided into smaller elements which are calculated separately, preferably by a computer. It is the density and shapes of these elements that determines the accuracy of the FEM-model.

There is one very important issue we need to understand about making models, not just FEM models but models in general. From advanced mathematical models to simple models made of for example clay, they are still just models. Models can be more or less accurate, but they will never behave exactly as reality would.

3.1. FEM modeling of concrete gravity dams

3.1.1. *Modeling the dam*

The four types of controls listed in chapter 1.3 are of course something we need to consider when creating the FEM-models. Knowing what to look for helps a lot to make the model as accurate as possible.

- Sliding stability
- Tension stress
- Compressive stress
- Displacement

Sliding stability; To make sure the calculations are accurate, the element standards, described later in this chapter, will be considered when creating elements inside and around the critical areas, especially close to the dam foundation and in the batter (Zhang et al., 2001).

Tension stress often occurs, in the region around the dam heel, therefore we put extra care in forming the elements in this region. In addition to this we make the elements smaller the closer they are to the sensitive area, also for enhancing accuracy. When analyzing the tension stress we use a simplification for FEM modeling that states that the number of elements with tension in the bottom layer of the dam cannot exceed seven per cent of the total amount of elements in that layer. The reason that we can use this simplification is that the elements in the foundation have roughly the same size, which leads to that the percentage of tension elements is considered the same as the percentage of area with tension. The reason that we have to use the simplification is that FEM modeling has a tendency to create stress concentrations, for example in the dam heel. This means looking at just the maximum tension in the model is a very inaccurate method (Zhang et al., 2001).

Compression stresses are handled by looking at the whole model and then determine where the greatest risk for compressive failure appears. Material characteristics have to be evaluated and compared to the computed compressive stresses (China water press, 1979a).

Displacement control is based on the entire model. Since for example the displacement in the top of the dam depends on the displacement in the bottom part of the dam there is not really one area to focus on to receive good displacement results (Personal communication Ph. D. M.X. Zhong 2010).

3.1.2. *Modeling the elements*

The size and shape of elements is utterly important, and some basic standards have been set up to make it easier to create well-functioning elements. The two most common types of two-dimensional elements are quad and tri elements. Tri elements are made from three different nodes and contain only one integration point while quads, as implied by their name, are made of four nodes and contain four integration points. Therefore quad elements are more accurate and are to be preferred. In our models we use only quad elements as displayed in figure 12.

The height-width relation should not exceed three to one, for the quad elements, and no interior angle should be less than 45 degrees (Zienkiewicz & Taylor, 2000).

In practice the limit may be reduced to 30 degrees and the result will still be acceptable. According to the two shape standards above, the most precise element has the height-width ratio of one to one and all interior angles 90 degrees, the perfect square. In the dam (to the right) in figure 12, there are a lot of elements that almost achieve this (Personal communication Prof. F. Jin 2010).

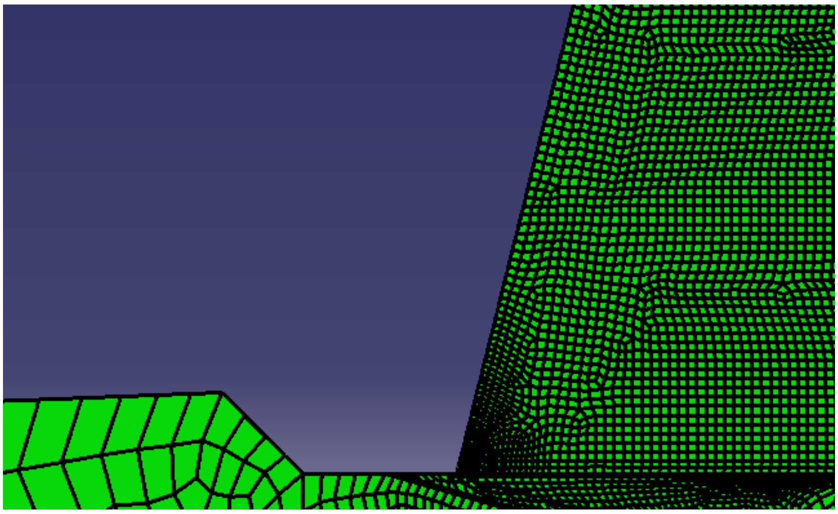


Figure 12 A screenshot from the Oipei dam model displayed in Abaqus.

Usually, fitting all elements into these standards is impossible and not even that important, a small percentage of the elements may remain distorted. The element standards in critical regions of the model where the mesh may also possibly be denser, is of course more important (Personal communication Prof. F. Jin 2010).

Minor alteration in the model's geometry can be made, in such a way that they generate no significant difference in the results. These alterations should be done so the elements could form a better shape, given height-width relation and their interior angle (Personal communication Prof. F. Jin 2010).

3.2. Strain and stress in FEM

The elements used in FEM processes can either be plane stress or plane strain elements. In both plane stress and plane strain analyses there are three components that need consideration in the xy-plane. Two of these components are normal stresses, one horizontal and one vertical, the last of the components is shear stress. However there are differences between the stress and strain. In plane stress analysis all components of stress, except the three mentioned, are zero which leads to no addition to the internal work in the elements. In the case of plane strain analysis, the stress orthogonal the xy-plane can vary. However because of the definition of plane strain, the strain in that perpendicular direction to the plane does not exist. Given this correlation of these contributions to the internal work in the elements will not be affected. This makes it comparable to plane stress. The benefit of this is that the xy-plane can be evaluated with the three main stress components at the end of all computations (Zienkiewicz & Taylor, 2000).

3.3. Special FEM methods

A few creative "tricks" were applied to create the FEM-models, some of them were of great importance for the modeling and are explained here.

3.3.1. *Pressure uplift*

The method used to model the water uplift pressure, like figure 13, was to reduce the gravity on some elements in the dam; the total volume of those elements leads to a pressure equivalent to the total internal water pressure. To accomplish this a new group of elements was created from the dam that put together have the same shape and approximate area as the water uplift, but rotated 180 degrees around the horizontal axis.

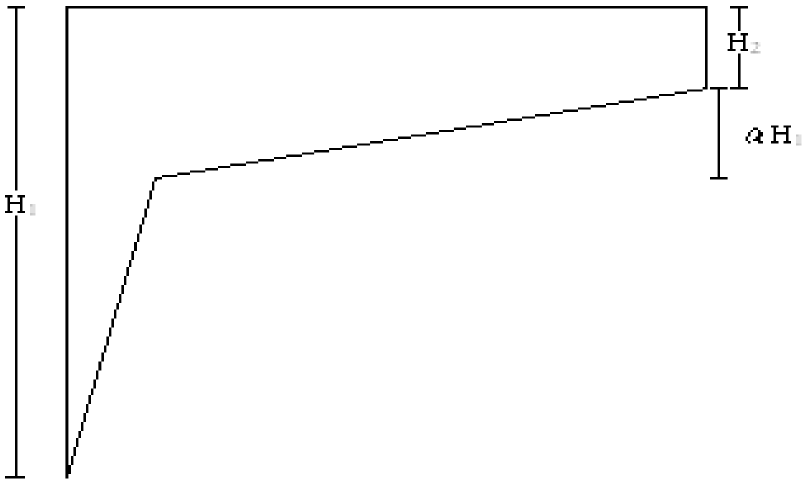


Figure 13 A model for calculating the internal hydrostatic pressure.

After that acceleration was applied and directed upwards on the chosen elements.

H_1= Upstream water level

H_2 = downstream water level

α = 0.2

The model in figure 13 is a simple model of the hydrostatic pressure on a concrete gravity dam with an impervious water shield located in the foundation close to the dam heel. The shield is used to reduce water flow and erosion under the dam body. If this were not used, the increase of pressure would be constant from the dam toe to the dam heel.

The reduced "gravity" on the element field is about 5.7 m/s^2 instead of 9.81 m/s^2.

$$a = \frac{\rho_c - \rho_w}{\rho_c} * g \qquad \text{Eq. 4}$$

In this equation ρ_w represents the density of water, ρ_c the density of concrete, g the acceleration constant and a is the reduced acceleration constant (Personal communication Prof. F. Jin 2010).

3.3.2. *Ground tension*

To get an accurate model of the ground's conditions it was necessary to simulate the displacements and stress before the dam is introduced in the model. To get the ground's pretension from those displacements the model was first analyzed without any influence of the dam or the external loads. Then the different stress data from the calculation in Abaqus was saved, without the displacement. Then it was possible to use these stress values in the model of the whole dam, applying them into the input file using Ultraedit, adding gravity on the dam and the foundation again. This is a simple way of getting an accurate enough model of the ground pretension (Personal communication Prof. F. Jin 2010).

3.4. Special FEM methods used in the Baozhusi dam

The FEM processing steps conducted in the Baozhusi dam section, in addition to the steps presented in chapter 3.3.

3.4.1. *Penstocks*

The tubes leading the water to the turbines must be considered when creating the model. Since the model is only two dimensional a tube running through the dam body cannot be modeled accurately. This is solved by reducing the gravity acceleration affecting the tube according to the relationship between concrete and water density with the same principle as the water uplift reduction. This relationship leads to a reduction of one fifth of the original gravity acceleration, thus leaving the reduced area with a "gravity" of 7.7 m/s^2. This is a geometric reduction, the volume of the tubes is divided equally through the dam sections containing penstocks (Personal communication Prof. F. Jin 2010).

3.4.2. *Turbine room*

In the downstream end of the model of the Baozhusi dam the turbine room is located. This area of the model can not to be regarded as solid concrete and must, in the same way as the penstocks, be given a reduced gravity. In this section we reduced with a third of the gravity acceleration, which is an estimation of the density of empty void, turbine, water and concrete in this area. The "gravity" in this section was then 6.6 m/s^2 in the model. The calculation of the reduced gravity is shown in appendix 8.2 (Personal communication Prof. F. Jin 2010).

3.4.3. *Sliding surface*

Precise drawings of the foundation made it possible to estimate where the biggest risk for sliding due to shear stress failure would occur. These sliding surfaces modeled 0.5 meters wide so only one element in width could fit in. These elements were put into a new group so an analysis concerning shear stress could be preformed (Personal communication Prof. F. Jin 2010).

3.5. Special FEM methods used in the Qipei dam

In this chapter follows a description of the FEM processing steps conducted in the Qipei dam section, in addition to the steps taken in both processed sections, presented in chapter 3.3.

3.5.1. *Sliding surfaces*

Under the Qipei dam, no major ruptures were detected in the preconstruction surveys. Therefore the foundation was considered equivalent to solid rock. This does not mean that the rock can be fully trusted yet, so the risks in the foundation were taken under consideration during the creating of the model. The way of doing this is to use sliding surfaces (Personal communication Prof. F. Jin 2010).

The risk of sliding was calculated by selecting only the elements in the sliding surface, and looking for the stress orthogonal to the plane of the sliding surface. Comparing that to the shear stress (τ) and with some geological data it is possible to calculate whether there is risk of sliding or not. (The definition of the safety factor, K, can be found in appendix 8.2.)

4. RESULTS

In this section only results are presented, associated equations are presented in appendix 2 for enhanced understanding. In chapter 1.2, we introduce the different criteria for the different controls and their associated safety factors.

4.1. Sliding stability

The safety factors regarding the sliding stability are calculated by using Eq. 1 (shown in appendix 2).

In each section of the dam we have made calculations for two conditions and four sliding surfaces described in figure 14. The first condition is normal water flow, and the second load case we have evaluated is the flood condition, as described in chapter 2.2.

Table 1. Calculated safety factors for sliding stability

Baozhusi normal	Inside dam	Dam base	Found. 1	Found. 2
Safety factor, K_s	5.6	3.6	28.3	27.4

Baozhusi flood	Inside dam	Dam base	Found. 1	Found. 2
Safety factor, K_s	4.7	4.2	29.8	28.6

Qipei normal	Inside dam	Dam base	Found. 1	Found. 2
Safety factor, K_s	3.7	3.6	5.9	10.9

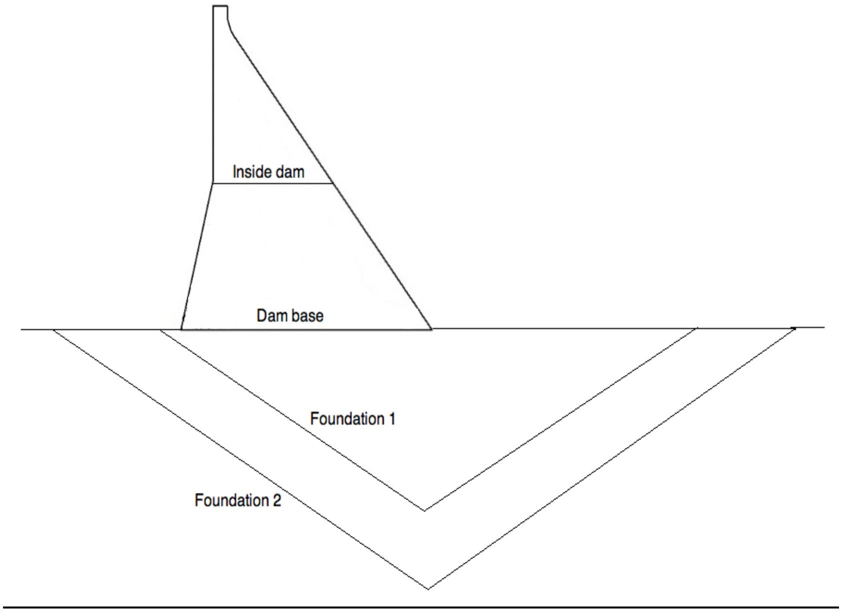


Figure 14 The different sliding surfaces.

4.2. Tension stress control

The results for tension stress control are presented in figure 15, 16 and 17. The percentage of the area with tensile stress in the bottom layer is zero, therefore the risk of tension cracks occurring and leading to severe dam failure is neglected. A safety factor, K is impossible to present (K will thus be infinite) because there is no tension in the bottom layer.

Reading the figures: Tension stresses are defined in the pictures as above zero. Therefore reading the figures it is understood that there is no need for concern due to tension stress. Especially vulnerable places in the dam foundation is the dam heel, the upstream part of the dam. But as figures 15 to 17 show there exists no tension stresses there or anywhere else in the dam.

Table 2. Tension stress in dam foot

Baozhusi normal	**Tension in dam foot (% of area)**
	0 % of elements

Baozhusi flood	**Tension in dam foot (% of area)**
	0 % of elements

Qipei normal	**Tension in dam foot (% of area)**
	0 % of elements

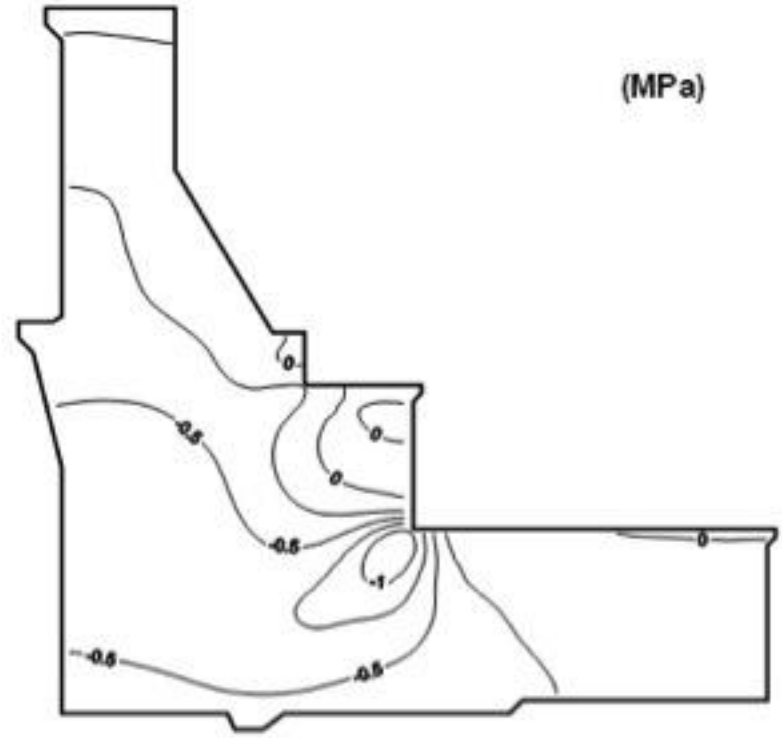


Figure 15 Tension stresses in the Baozhusi dam at normal water level (tension is defined as >0).

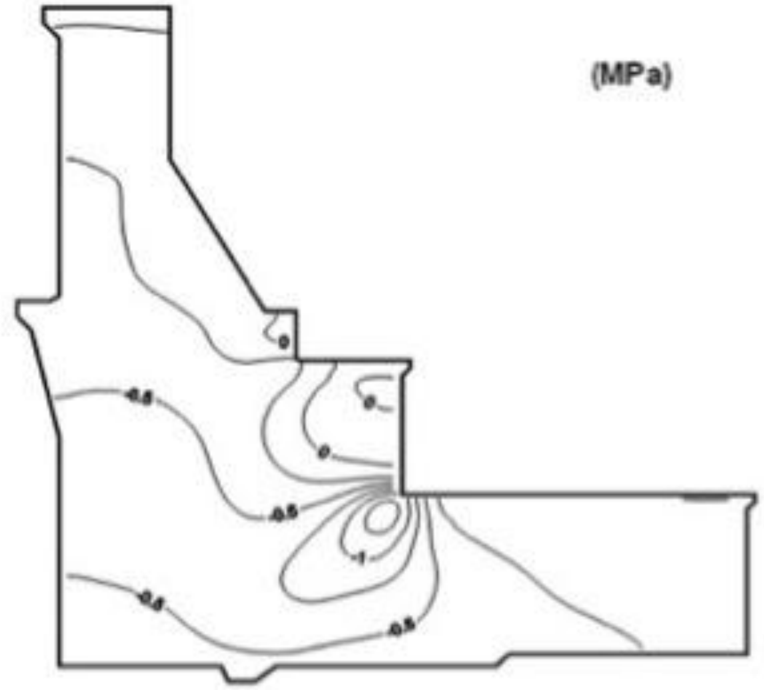


Figure 16 Tension stresses in the Baozhusi dam during flood (tension is defined as >0).

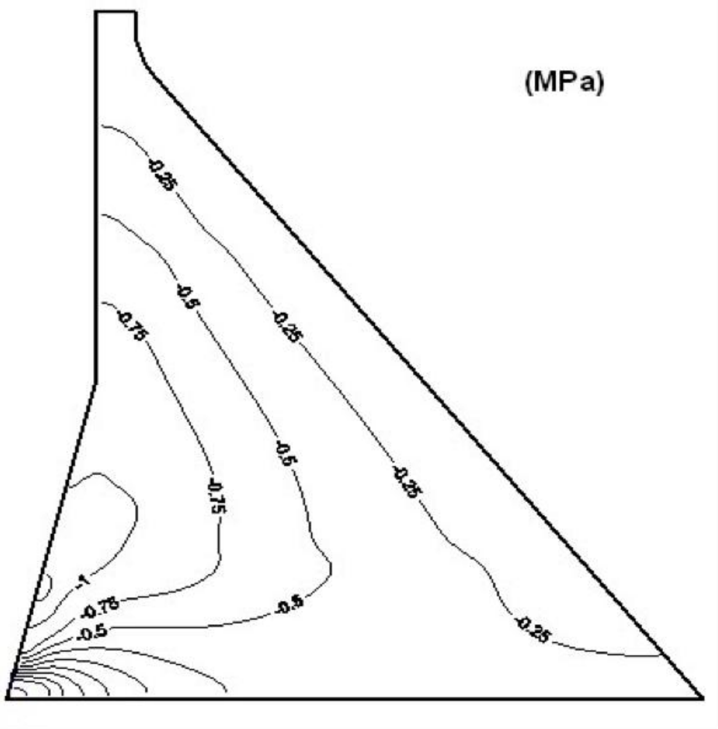


Figure 17 Tension stresses in the Oipei dam at normal water level (tension is defined as >0).

Compressive stress control

Results from compressive control from the different types of concrete used in the Baozhusi and the Qipei dams are shown in the tables below. The results are displayed in figures 18, 19 and 20 as well. In the table the calculated safety factors are numbers which would be considered good, especially for the Qipei dam where the safety factor only once falls under 7. One should also remember that at the time of calculating the Qipei dam was only in the first steps of construction in difference from the Baozhusi dam which had been standing reconstructed since 1998. Comments about them will be found in the discussion chapter.

Table 3. Calculated safety factors for compressive control. The abbreviations (R150, RII, CIV and so on) refer to types of concretes used in the two dams.

Baozhusi normal water level	R150	R200	R250
Safety factor, K_c	1.8	5.7	3.7

Baozhusi flood	R150	R200	R250
Safety factor, K_c	1.6	7.3	3.8

Qipei normal water level	RI	RII	RIII	RIV	RV	CI	CIV
Safety factor, K_c	13.1	9.9	10.3	14.8	9.9	6.8	9.9

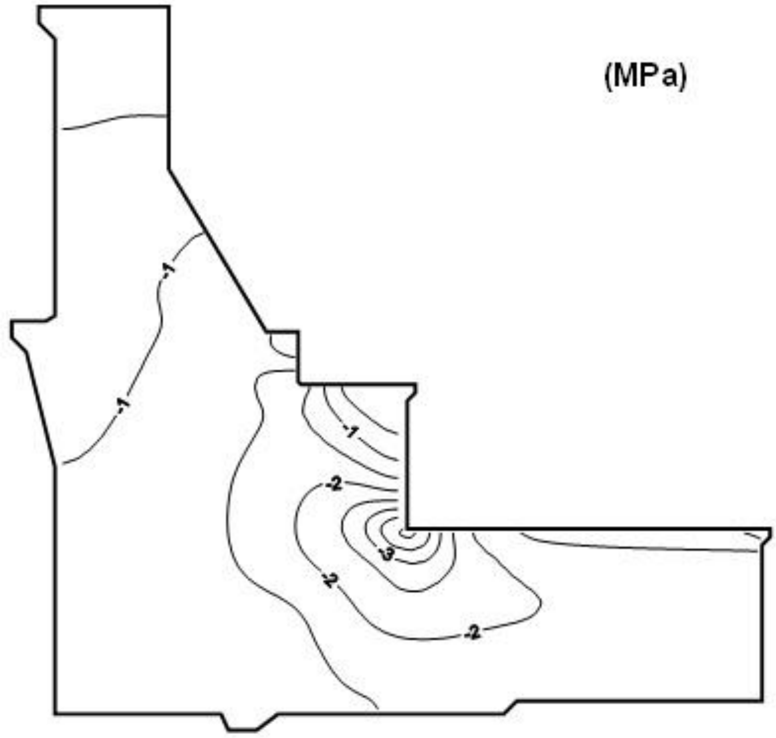


Figure 18 The minimum in-plane principle stress in the Baozhusi dam during normal conditions (tension is defined as >0).

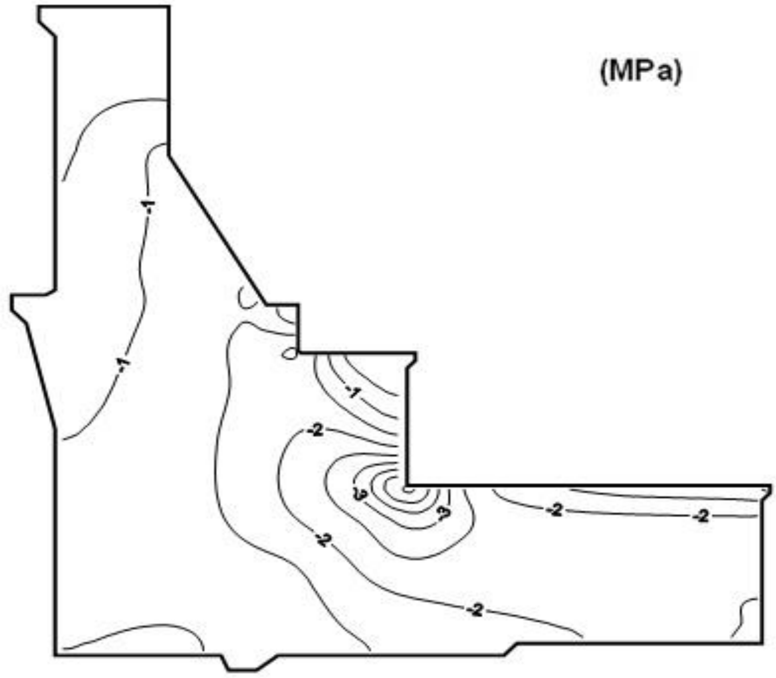


Figure 19 The minimum in-plane principal stress in the Baozhusi dam during flood conditions (tension is defined as >0).

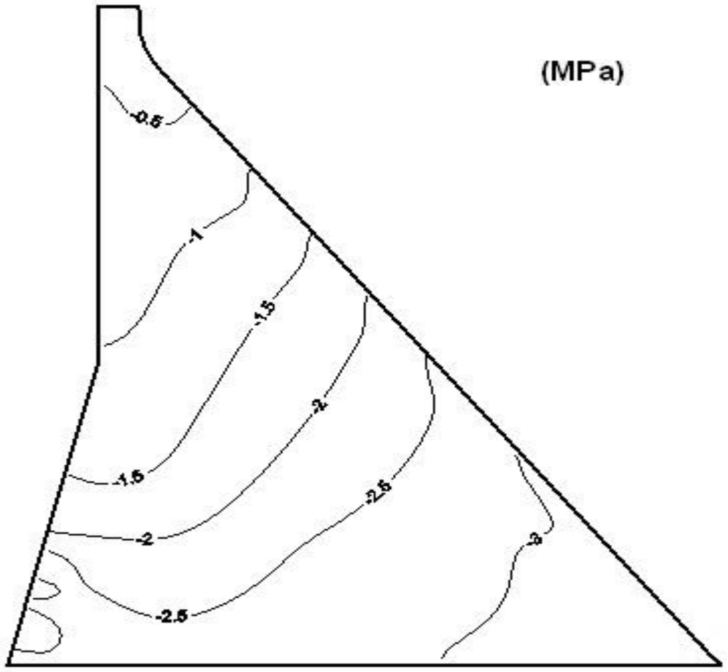


Figure 20 The minimum in-plane principal stress in the Qipei dam (tension is defined as >0).

4.3. Displacement control

The displacement control of the dam is a little different from the other controls. There is no defined limit for accepted displacemen, therefore we only present the values calculated in Abaqus in figures 21, 22 and 23.

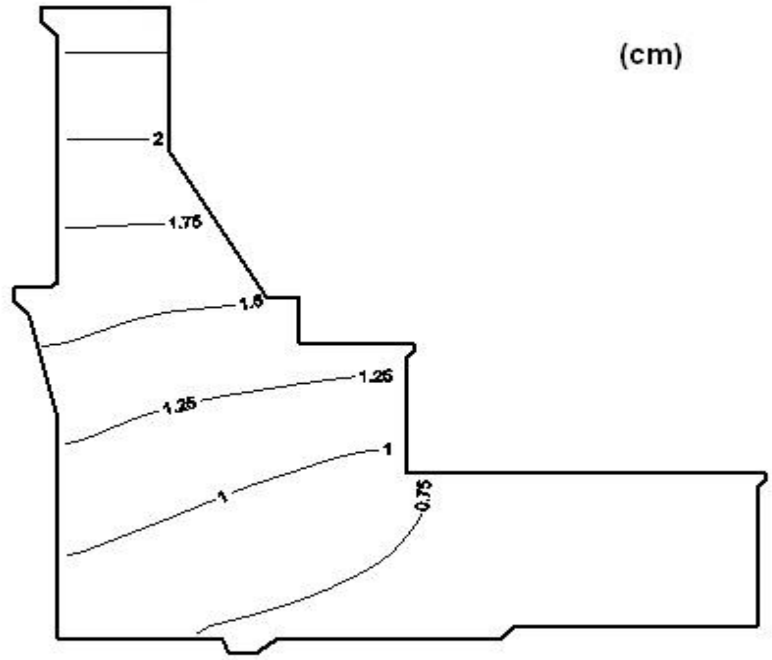


Figure 21 Horizontal displacements in the Baozhusi dam during normal conditions. The positive direction is set to the right (downstream) in the figure.

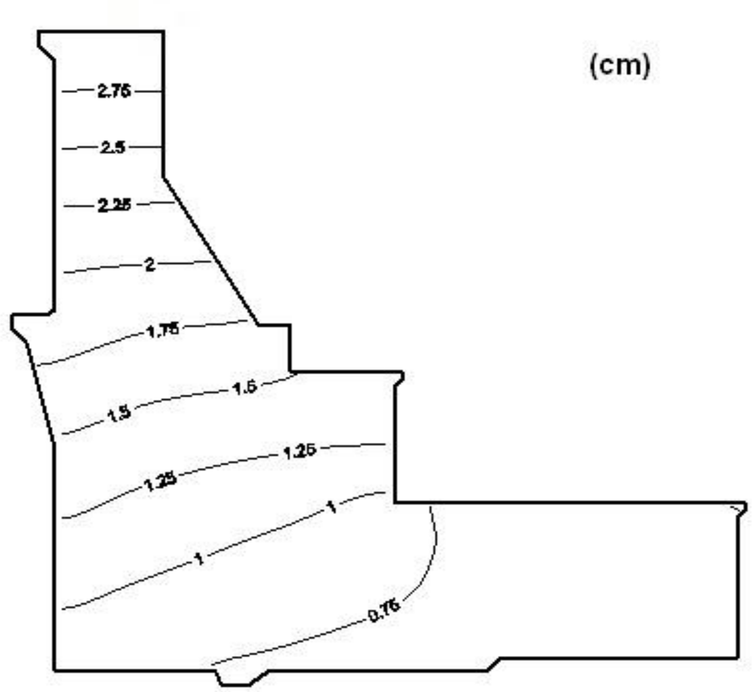


Figure 22. Horizontal displacements in the Baozhusi dam during flood conditions. The positive direction is set to the right (downstream) in the figure.

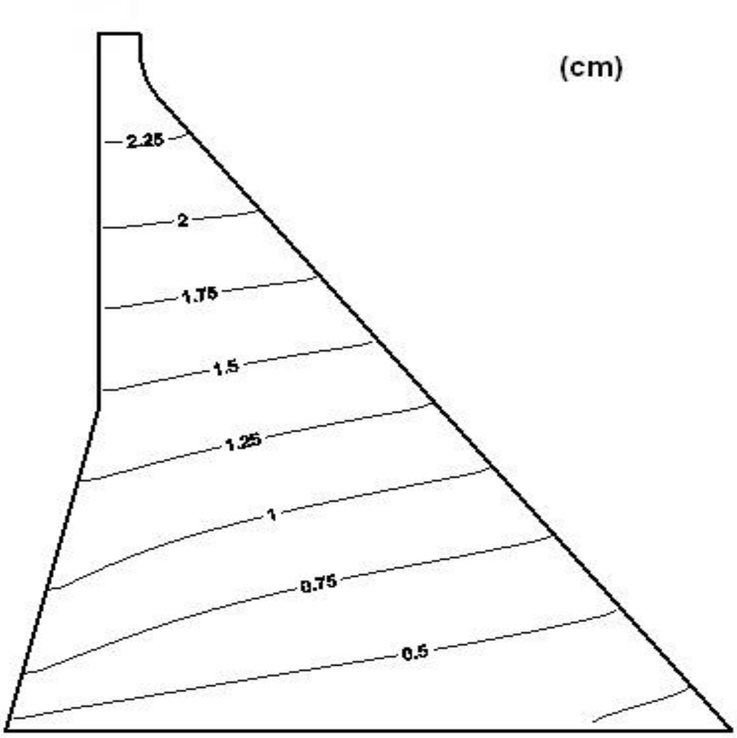


Figure 23. Horizontal displacements in the Qipei dam. The positive direction is set to the right (downstream) in the figure.

5. DISCUSSION

5.1. General

FEM modeling of concrete gravity dams is a method with a lot of advantages compared to traditional structural dynamics and scale modeling. Compared to scale modeling the time and cost issue is the main factor, it is a lot cheaper to construct a virtual model than a physical one. Also the convenience of computer based models compared to the location and rarity of scale models provide a significant advantage.

Compared to structural mechanics FEM has a big advantage in the alteration of both construction and external loads. Once a dam has been modeled in FEM it is possible to experiment and change details about it without the need to restart the whole process.

We thought that the software we used were easy to apply and despite the fact that they did not reveal much of the actual FEM process it provides the useful tools needed to perform such a task as ours. We were glad to work with software so compatible with each other.

This is still just an analysis of a single section in a static state of a dam; a lot of aspect is because of that limitation not dealt with at all. Examples of these aspects are: discharge capacity, temperature changes, cracks, earthquakes and fatigue of the concrete.

5.2. Baozhusi

According to Chinese standards section 17 of the Baozhusi Hydropower Station is capable of withstanding the loads applied to it in a static state, both for the usual and the unusual load case we have modeled. In a lot of aspects, the stresses in the concrete and hence the risks were lower in the load case considering flood conditions. This is probably because the water level downstream of the dam was raised dramatically, providing some extra stability.

The risk considered the most important in the static state is the tension in the dam heel, because of concretes natural sensitivity to tensile stress. The high values of compressive stress in the downstream face of the dam are also something that needs to be explained.

5.3. Qipei

Our analysis of the Qipei Hydropower Project shows that the greatest risk in this dam project are the tension stresses in the lower upstream dam face. However we still feel that this dam should have no problem withstanding the pressures caused by the different loads applied to it in either the usual or the unusual load case in the static state which we have modelled. Our results presented in chapter 4 indicate that no problems are likely to occur in the dam.

According to the simplifications in chapter 3, the percentage of area with tensile stresses in the bottom layer of the dam is zero: therefore the risk of tension cracks occurring and leading to severe dam failure is neglected. However in one node, the one furthest upstream in the dam foot, the modelled tension stress returns a far too high value, more than 10 MPa. This tension is concentrated at not even a whole element, and is therefore considered a “stress concentration” caused by the FEM software. Stress concentrations like this do not occur in the dam in reality, if they would do that the concrete would crack. Conclusions

6. CONCLUSIONS

To summarize the benefits of FEM modeling, a lot different reasons adds up to the superior cost effectiveness in FEM. Is this method as convenient when we need to consider all the other aspects mentioned in the last paragraph in chapter 5.1. Another risk is for the modelers to lose the understanding of dam engineering; the FEM process has a tendency to demand more programming skills than engineering skills.

About the high stress values modeled we feel that there is no need to be alarmed even though some of these stresses are very high because the concentrations of the stresses are in such small areas. As explained in chapter 2.2, to just look at the maximum stress is a very inaccurate method. In the static state we see no reasons for failure in neither of the dams.

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Zhou, Meng Xia: Ph.D. student at the Department of Hydraulic Engineering, Tsinghua Univesity, Beijing. Personal communication June 2010 to October 2010BBC main webpage: www.bbc.co.uk

CAD Mechanical webpage: www.autodesk.com

Golden Software main webpage: www.goldensoftware.com

Microsoft main webpage: www.microsoft.com

MSC Software main webpage: www.mscsoftware.com

Reuter main webpage: www.reuters.com

Simulia main webpage: www.simulia.com

Ultraedit text editor webpage: www.ultraedit.com

APPENDIXES 1 TO 8

1. DATA CONCERNING THE DAMS

Baozhusi dam
Crest elevation: +595 m.a.s.
Crest width: 25m (section 17)
Crest length: 524.5m
Maximum dam height: 132m (section 17)
Maximum dam width: 132m (section 17)
Upstream:
Normal water level: 123m (+588m)
Flood water level: 126m (+591m)
Sand pressure level: 58m (+523m)
Downstream:
Normal water level: 20m (+487m)
Flood water level: 36m (+503m)

Qipei dam
Crest elevation: +408 m.a.s.
Crest width: 10m
Crest length: 1333m
Maximum dam height: 200m
Maximum dam width: 179m
Upstream:
Normal water level: 192m (+400m)
Flood water level: 192m (+400m)
Sand pressure level: 57m (+265m)
Downstream:
Normal water level: 36m (+244m)
Flood water level: 60m (+268m)

2. EQUATIONS

Sliding stability

Safety factor, K

$$K_s = \frac{\sum(\mu_i * \sigma_i + c_i)L_i}{\sum \tau_i * L_i} \qquad Eq. 1.$$

μ_i = friction coefficient
σ_i = principal stress (vertical)
c_i = cohesion
L_i = element length
τ_i = shear stress

Tension control

Safety factor, K_T

$$K_T = \frac{Number\ of\ elements\ in\ the\ dam\ foot}{Number\ of\ elements\ with\ tension} \qquad Eq. 2$$

Compressive control

Safety factor, K_c

$$K_c = \frac{Characteristic\ value\ for\ compressive\ stress}{Calculated\ value\ for\ compressive\ stress} \qquad Eq. 3$$

Other calculations

Reduced gravity acceleration, a

$$\mathrm{a} = \frac{\rho_c - \rho_w}{\rho_c} * \mathrm{g} \qquad \mathrm{Eq.}\ 4$$

3. DRAWINGS

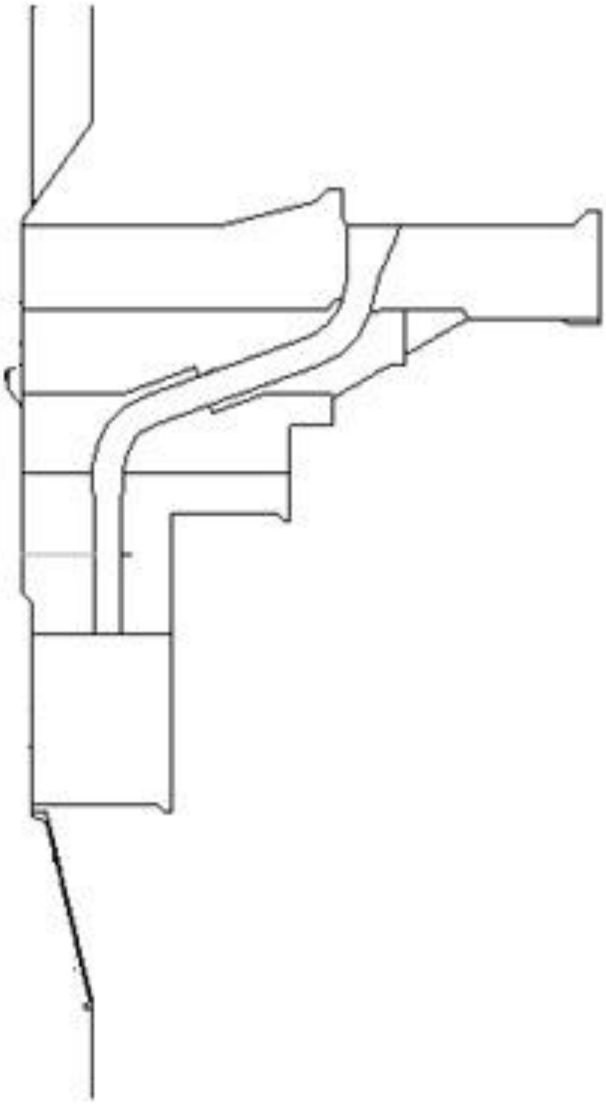

Fig. 24. CAD drawing of Baozhusi.

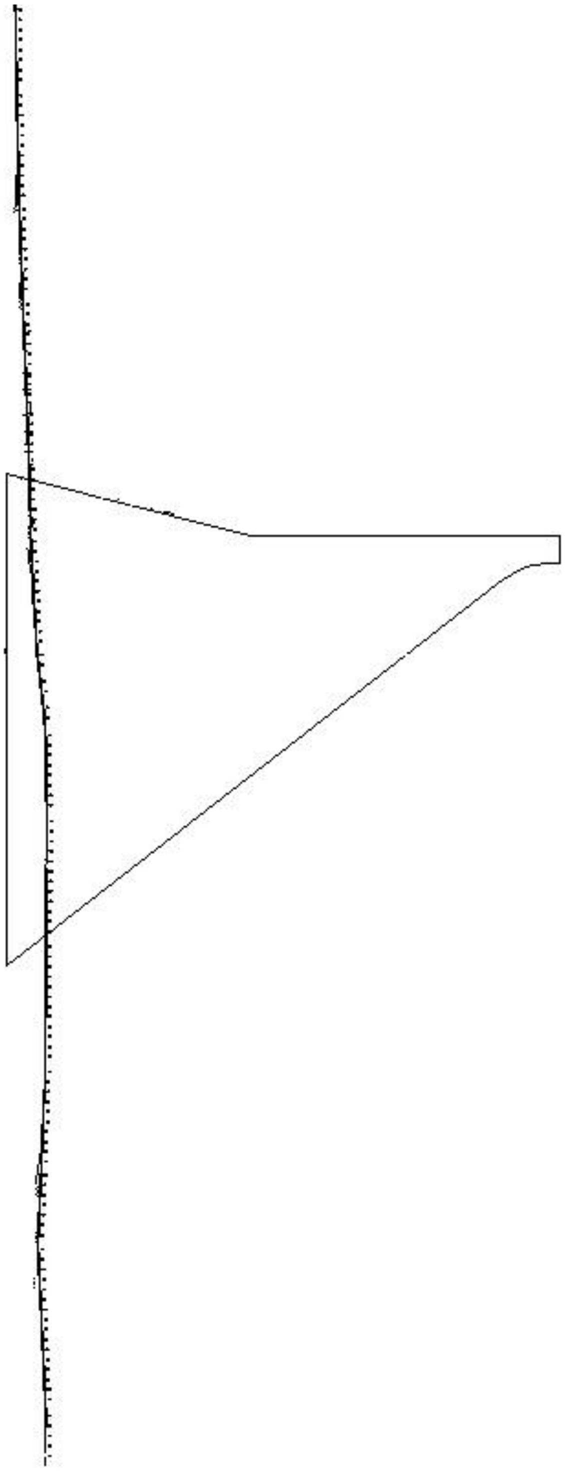

Fig. 25. CAD drawing of Oipei.

4. MATERIAL DATA

Baozhusi dam				
Foundation data				
	Rock 1 (0_2^{2-1})	Rock 2 (0_2^{2-2-2})	Rock 3 (0_2^{2-3})	
Density	2650	2650	2650	[kg/m^3]
Elastic modulus	80	20	12	[GPa]
Poisson's ratio	0.27	0.18	0.25	[-]
Cohesion	969350	969350	969350	[N/m^2]
Coef. of friction	1	1	1	[-]
Concrete data				
	R_{90}150	R_{90}200	R_{90}250	
Density	2400	2400	2400	[kg/m^3]
Elastic modulus	21.5	25.0	27.6	[GPa]
Poisson's ratio	0.167	0.167	0.167	[-]
Comp. strength	14.72	19.62	24.53	[MPa]
Cohesion	969350	969350	969350	[N/m^2]
Coef. of friction	1	1	1	[-]

Qipei dam				
Foundation and concrete data				
	Rock	CIV		
Density	2750	2400		[kg/m^3]
Elastic modulus	100	30.0		[GPa]
Poisson's ratio	0.20	0.167		[-]
Comp. strength	---	30.0		[MPa]
Cohesion	969350	969350		[N/m^2]
Coef. of friction	1	1		[-]
	RI	RII, RIV, CI	RIII, RV	
Density	2400	2400	2400	[kg/m^3]
Elastic modulus	22.0	25.5	28.0	[GPa]
Poisson's ratio	0.167	0.167	0.167	[-]
Comp. strength	19.6	25.5	28.0	[MPa]
Cohesion	969350	969350	969350	[N/m^2]
Coef. of friction	1	1	1	[-]

5. TEXT FILES

Here we present a shortened version of one of our text files. This text file is created by Patran then edited by us in Ultraedit. The part of the file that we show here is mainly what we have written or changed in to the original file. Our different full length text files vary between 30000 and 40000 lines. All listing of elements and nodes have been removed.

This is the text file from Baozhusi at normal water level. The symbol * is usually followed by a definition of for example a material parameter. The symbol ** is just for making comments in the code file, everything on a line that starts with ** is discarded by the computer when conducting calculations.

Listing of approximately 16000 nodes and 12000 elements together with all groups containing both elements and nodes have been removed and been replaced with these three lines.

```
**----------------------------------PROPERTIES---------------------------------
** Rock_1
*SOLID SECTION, ELSET=EL_ROCK_1_0,
MATERIAL=ROCK_1_0
        1.,
**---------------------------------------------------
** Rock_3
*SOLID SECTION, ELSET=EL_ROCK_3_0,
MATERIAL=ROCK_3_0
        1.,
**---------------------------------------------------
** Rock_2
*SOLID SECTION, ELSET=EL_ROCK_2_0,
MATERIAL=ROCK_2_0
        1.,
**---------------------------------------------------
** C_150
*SOLID SECTION, ELSET=EL_C_150_0, MATERIAL=C_150_0
        1.,
**---------------------------------------------------
** C_200
*SOLID SECTION, ELSET=EL_C_200_0, MATERIAL=C_200_0
        1.,
**---------------------------------------------------
** C_250
*SOLID SECTION, ELSET=EL_C_250_0, MATERIAL=C_250_0
        1.,
**----------------------------------MATERIALS-------------------------------------
** Rock_1
** Date: 09-Aug-10          Time: 15:05:58
**
*MATERIAL, NAME=ROCK_1_0
**
*DENSITY
```

```
      2650.,
**
*ELASTIC, TYPE=ISO
      8.E+9,        0.27
**------------------------------------------------
*MATERIAL, NAME=ROCK_2_0
**
*DENSITY
      2650.,
**
*ELASTIC, TYPE=ISO
     2.E+10,        0.18
**------------------------------------------------
*MATERIAL, NAME=ROCK_3_0
**
*DENSITY
      2650.,
**
*ELASTIC, TYPE=ISO
    1.2E+10,        0.25
**------------------------------------------------
*MATERIAL, NAME=C_150_0
**
*DENSITY
      2400.,
**
*ELASTIC, TYPE=ISO
   2.15E+10,       0.165
**------------------------------------------------
*MATERIAL, NAME=C_200_0
**
*DENSITY
      2400.,
**
*ELASTIC, TYPE=ISO
    2.5E+10,       0.165
**------------------------------------------------
*MATERIAL, NAME=C_250_0
**
*DENSITY
      2400.,
**
*ELASTIC, TYPE=ISO
   2.76E+10,       0.165
**------------------------BOUNDARY CONDITIONS-----------------------
```

```
*Boundary
**Fixed nodes at bottom of model (x, y)
GROUND_FIX, 1, 2
**Fixed nodes at sides of model (x, x)
GROUND_LATERAL_FIX, 1, 1
**
**------------------------------INITIAL STRESS----------------------------------
**Pre tension in ground
*include,input=grounddone.inp
**----------------------------STEP: GEOSTATIC---------------------------------
*STEP,name=GEOSTATIC
*GEOSTATIC
1.,1.
*CONTROLS, ANALYSIS=DISCONTINUOUS
*Dload
EL_FEM_GROUND, GRAV, 9.81,  0.,-1
** OUTPUT REQUESTS
*Output, field
*Element Output
S,PEEQ
*node output
U
**
*End Step
**----------------------------------GRAVITY---------------------------------------
*Step, name=Gravity,inc=10000
*Static
0.1, 1., 1e-12, 1.
*CONTROLS, ANALYSIS=DISCONTINUOUS
**
**Loads
*Dload
EL_FEM_DAM, GRAV, 9.81, 0., -1.
*Output, field
*Element Output
S,PEEQ
*node output
U,COORD
**
*node file
U,COORD
*El file
S
*End Step
**-------------HYDRO-, SAND- AND UPLIFTPRESSURE----------------
```

```
*Step, name=hydro-static,inc=1000000
*Static
0.05, 1., 1e-12, 1.
*CONTROLS, ANALYSIS=DISCONTINUOUS
**
** water upstream
*DLOAD
List of elements in Water upstream group
**
** Water downstream
*DLOAD
 List of elements in Water downstream group
**
** Sand upstream
*DLOAD
List of elements in Sand upstream group
**
**Reduced gravity simulating Uplift pressure
*Dload
EL_UPLIFT, GRAV, 4.0875, 0.,1.
**
**------------------------------------------------
**Reduced gravity in Watertube
*Dload
EL_WATERTUBE, GRAV, 2.2179, 0.,1.
**
**------------------------------------------------
**Reduced gravity in Turbine room
*Dload
EL_TURBINE_ROOM, GRAV, 3.27, 0.,1.
**
**------------------------------------------------
** OUTPUT REQUESTS
*Output, field
*Element Output
S,PEEQ
*node output
U,Coord
**
*node file
U,COORD
*El file
S
*End Step
**-------------------------------FINISHED-------------------------------------
```

6. MODELING PROCEDURE

When the type of dam and roughly the location for the dam has been decided, the next step is to use a dam from a previous, similar project and perform a stress and strain analysis on that structure. This model will most likely prove to have a lot of flaws and must therefore be improved. After these improvements another stress and strain analysis will be performed on the new model, after repeating this step a number of times, the dam may finally be constructed. (Armstrong, 1988)

7. FEM SOFTWARE

The following chapter contains the different software we have used during the entire FEM evaluation process. The way we describe them is the way we have used them, and since some of them are very versatile there is probably a lot of different ways of using the software.

First a model was drawn in CAD mechanical and then exported to MSC Patran. Patran creates an INP file which may be edited with UltraEdit and then read by Abaqus. The result interpreted as pictures from Abaqus were imported into Surfer to make more comprehensible pictures of the result.

7.1. CAD Mechanical

The mechanical version of the engineer's best friend, CAD, is necessary to be able to export the drawings to MSC Patran. CAD Mechanical is, as its name implies, as well as most CAD versions, software for making precise drawings. Either drawing in two or three dimensions, CAD provides a simple and very accurate tool for drawing constructions.

7.2. MSC Patran

Patran is software widely used for processing FEM models. It provides the user with the complete tools for modeling, meshing, applying different types of loads, both linear and non-linear, such as pretension, thermal and inertial loads among others and it calculates all input data to create an analytic model. (www.mscsoftware.com)

Patran provides a setup for a number of different programs for analyzing the implemented model e.g. Marc, Abaqus, MSC Nastran and ANSYS. Patran is designed to collaborate with other modeling programs like for example CAD Mechanical as mentioned above. This feature makes Patran very wieldy when it comes to importing or exporting a file into or out of the software. The modeling in Patran can be divided into groups similar to the different menu options in the program, the most frequently used are the following:

- Geometry
- Elements
- Loads/Boundary conditions
- Materials and properties

Geometry is where the drawing of the object is made, or often more convenient, import a drawing from CAD Mechanical or other software more suitable for drawing. Important to notice about the geometry part is that it just makes the creating of elements a lot easier. The calculations and results that we later could acquire from the model is not directly affected by anything created in this category.

Elements is the part of the program where the actual is model made, supported by the geometry mentioned above. The creating of the elements is essential to the results of the modeling and has to be done carefully. Since a model of a dam contains vast numbers of elements it is neither time nor cost effective to create them one by one, although it is possible. To assist the user in element creating there are a lot of meshing functions which create a chosen number, or density, of elements in the surface being be meshed. (www.mscsoftware.com)

Loads/Boundary conditions is where the model comes to life. In this menu the natural forces affecting the dam can be simulated and applied. The different water and sand pressures, gravity and also the boundary conditions used in the ground can be set here. (www.mscsoftware.com)

Materials and **properties** is where data such as elasticity modulus and density for different types of construction materials is put in. Usually we used an elastic model of the materials which was very simple to input, since it is only a constant value. Of course it is also possible to input an elasto-plastic model of the material behavior instead.

7.3. UltraEdit

UltraEdit is merely a program for reading and editing text files. The editing of the text files first occurred to us as complicated and time wasting, but later on has shown to be a very valuable, if not a necessary tool in completing the models. Since the text files may be 20 000 lines or more, it can seem like impossible to get a good overview. But in our text files the vast majority of the lines tend to be just listing of the nodes and elements created in Patran, the lines we want to edit is all at the same place in the end. With Ultraedit the editing in the text file is easy with just a little program experience required.

7.4. Abaqus

Abaqus is the software we use to view the models and the results, such as displacement or principal stress. Although models can be created and modified in Abaqus as well, we used the programs mentioned above for those tasks instead Abaqus gives a clear overview and makes it easy to analyze the complex variations of stresses and displacements in the dam as well as the foundation. With Abaqus we analyzed how the dams handled tensile and compressive stress, if there were any surfaces with a obvious risk for sliding and also what displacements that would occur in the dam and the foundation.

7.5. Golden Software Surfer

Surfer is a program used for extensive terrain modeling, surface analysis, gridding, 2D map generating and a lot of different 3D visualizations alternative. This program is easily worked and transforms images in a way decided by the user. The program itself is not unique, there are other programs with the same abilities, however Surfer creates presentable pictures in an easier way than other similar programs and that is the software's strength.

7.6. Microsoft Office Excel

Microsoft Office Excel is a part of the Microsoft Office package, it provides the user with functions for calculations, making tables and conducting diagrams.

8. LEARNING THE SOFTWARE

To begin with, when totally unfamiliar with the layout as well as the different features of the programs, we decided that the fastest and most logical way to learn to deal with future problems seemed to be starting enhancing our skills in Patran since that is where we were going to conduct the future dam models for our thesis. Our first move was to create the simplest model thinkable, with the least number of parameters, followed by a slightly less simple model with a few more features applied, followed by yet another one and so on.

When we had gotten so far as to be able to conduct simple models without analyzing or model construction problems we began to compare how the accuracy of the stresses and displacements ranged depending of the number and form of the elements in the model. It was here that Abaqus came to good use for us. To extend our understanding we also compared the results with the structural material mechanics which we are already familiar with.

To broaden our skill in working with the programs we applied different examples, still in a very simple level to try and learn as many different features as possible. We made cantilever and simply supported beams, applied loads that were evenly distributed and point loads, created "reinforced" beams with more than one material and attached the materials together. Both because we wanted to learn to model in different ways and because we wanted to get a full grip and understanding of the analysis that we knew needed to be done. Thus meaning working with both Patran and Abaqus simultaneously, just as we wanted.

Since we did our jobs with the beams line with the theoretical calculations we had done, we made some simple dam models combining all the knowledge we so far had acquired when using the program. It was only a simple model and after consulting with some of the Ph. D students at our office, we received useful pointers in how to improve the model further. Up until our first presentation the different forces we had applied on the dam was the gravity of the dam, the pressure created by the water upstream and downstream and the uplifting force because of water seepage into the dam. Our concern was that we also wanted to know how to create a pre-tension situation in the ground below the dam, something we learned later in the process and will be described when we present the learning process of the text file software, Ultraedit.

As mentioned our models grew more complex and because of that we started to use CAD mechanical to draw the models. Since we were familiar with that software we could spend more time learning the important features, in the other software, that we needed to conduct our dam model.

Abaqus gives an easy and structured view over displacements and plane strains and stresses. There is also possible to add different loads and pressures to surfaces and elements in the Abaqus program, which maybe a better choice than redo the model in Patran thus creating a completely new input text file.

As our models grew more and more complicated the text file in which information was transported in between Patran and Abaqus grew longer and longer, mainly because of the increasing number of nodes and elements in our model. At first glance, the text file, which were read in by Ultraedit, looked rather complicated and it seemed that in order to understand it we would have to gain knowledge of a completely new (to us) programming language. We thought that it would only be, as mentioned earlier, a time wasting process. The real time wasting process became abundantly clear to us when we had to include or exclude a load e.g. the pretension situation in the ground beneath the dam or the water uplift pressure inside the dam. These were easy to apply as addition to the already existing text file. Since Ultraedit only is a program for reading and editing text files it allows the user to do just that and through that affect the output results that we got in Abaqus without us having to change anything in the original model. Including or excluding anything we wanted and still doing it in such a way that made it easy to overview added a needed complement to finishing our model. However Ultraedit, does not do anything special it is just software for reading and editing text files.

At the presentation it was decided that we were going to receive data for yet another dam, thou under construction and despite being located in Myanmar is mainly a Chinese project. We were going to model and analyze the stresses and displacements due to Chinese standards of one section of the projected dam. This in addition to our original project, to conduct a model, in a static state, of the Chinese dam, Baozhusi Hydropower Station, situated in Sichuan.