

## Influence of damping and different interaction modelling on a high arch dam

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**Abstract.** Arch dams are designed as relatively thin structures compared to gravity concrete dams. Due to this fact these structures are to a higher extent susceptible to earthquake excitation. Possible local damage they could suffer e.g. by means of cracks, lead to nonlinear effects and to a redistribution of forces in the structure. They have substantial extra capacities to be overloaded until a more severe damage occurs. Especially in seismic active areas high dams need to be investigated carefully. The stresses in the structure could be increased by more than 100 percent due to a seismic event compared with normal static loading conditions. Investigations of the dynamic behaviour with numerical simulations are very helpful, though it is not easy to account for the inherent nonlinearities. A part of the nonlinear behaviour in dynamic simulations is modelled with damping to account for the energy dissipation. Damping factors or Damping-Matrices are not a material parameter, which could be tested in a laboratory. However, with different in situ methods it is possible to account for the hysteretic damping.

Viscous damping could be applied in numerical simulations by using so called Rayleigh-Damping. For concrete structures or especially dams the damping factor is accounted for with approx. 5 percent of the critical damping. Investigations of existing dam structures in the past showed that this factor could vary between 1 to 7 percent (or be even much higher), which leads to an increase or decrease of the stress level due to shaking.

Within this contribution the influence on stresses in the dam structure is investigated by applying different damping factors and being accelerated with a transient earthquake record. The arch dam, which is an idealized model itself, has a total height of 220 meters. The interaction with the water is accounted for by using added mass technique and for comparison reasons with a fully modelled reservoir too. The reservoir is discretized with so called "Acoustic Elements". This work shows the impact of varying damping factors and different interaction modelling for the dam and a reservoir on the stress level in the dam.

*Keywords: Damping, Arch Dam, Fluid Structure Interaction*

### 1 INTRODUCTION

Seismic interaction between dam and reservoir is an important aspect for stability calculations. An Earthquake excites the eigenfrequencies of the dam and thereby increases the loading on the structure significantly. So it could happen that the sliding stability is exceeded or local cracks in the dam structure could lead to a failure. Not only the accelerated mass of the dam itself, but also the mass of the water loading from the reservoir plays an important role in such scenarios. Numerical programs offer a wide range of modelling techniques for the dam – reservoir interaction. The easiest way to take the water mass into account is to use an added mass technique according to Westergaard or Zangar. Because of this rough estimation the results may be very conservative dependent on the geometry and dimensions of the structure. However, in almost all cases investigated, these results are conservative. A more appropriate way to model such behavior is to use, so called, Acoustic or Fluid Elements, which are based on Euler or Navier – Stokes equations for acoustic waves and fluid dynamics. A difficulty is that the volume of the water itself has to be generated and therefore different boundary conditions have to be defined. A higher level in detail requires more sophisticated constitutive models

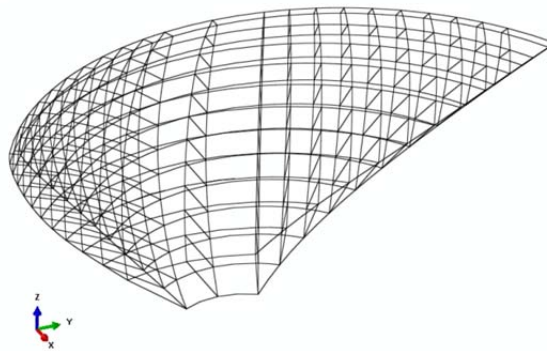
to take the occurring effects into account properly. This work shows the impact of the variation of damping factors and different kinds of interaction modelling for the dam and reservoir on the stress levels in the dam middle section.

## 2 FINITE ELEMENT MODELLING

The entire model and geometry is generated in Abaqus/CAE 6.11 EF2.

### 2.1 Arch Dam Model

The structure investigated is a double curved arch dam. It has been generated with the program “Arch Dam Design”, which was developed as part of the Master-Thesis by Manuel Pagitsch.

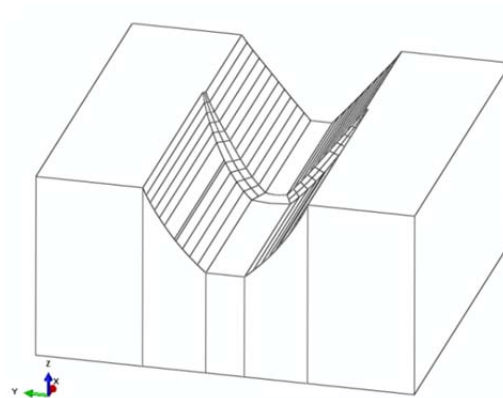


**Figure 1.** Arch Dam Geometry Grid

The arch dam has a total height of 220 meters, a crest length of 430 meters and a width at the base of 80 meters.

### 2.2 Foundation Model

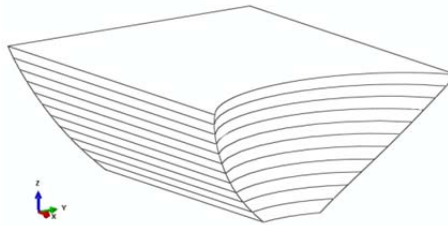
The underlying foundation is also chosen symmetric. The total height of the foundation is 500 meters and the dimensions in the horizontal plane are 1000x1000 meters. The distance between the lowest point of the dam foundation and the end of the model is discretized to be the height of dam structure itself, which is in this case 250m.



**Figure 2.** Foundation Geometry

## 2.3 Reservoir Model

For the use of Acoustic Elements for the Fluid Structure Interaction (FSI) it is necessary to model the reservoir. The model has a length of 460 meters, this is more than two times of the height of the dam, which is important in using such elements.

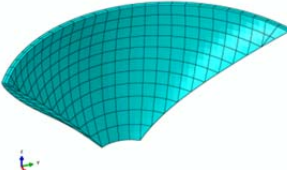
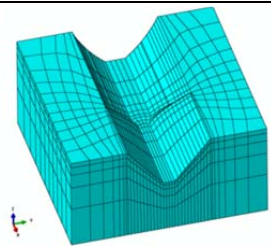
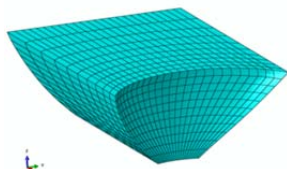


**Figure 3.** Reservoir Geometry

## 2.4 Finite Element Mesh Properties

According to the fact that numerical dynamic investigations could be very time consuming, the meshes of the models are chosen as coarse as possible, but still in a range, so that numerical loss of accuracy aren't too large and are not influencing the results significantly.

**Table 1.** Mesh Properties

Arch Dam	Number	Element Type (Abaqus/CAE)	
	312 quadratic hexahedral elements with reduced integration	C3D20R	
	44 quadratic wedge elements	C3D15	
Foundation	Number	Element Type (Abaqus/CAE)	
	2340 quadratic hexahedral elements with reduced integration	C3D20R	
Reservoir	Number	Element Type (Abaqus/CAE)	
	2640 quadratic hexahedral elements with reduced integration	C3D20R	
Total	5336 elements	Approx. 90000 DOF	

### 3 MATERIAL PROPERTIES

The material properties used, are left as simple as possible and defined for isotropic and homogenous conditions. The density of the rock mass in the foundation is set to zero.

**Table 2.** Material Properties

	Density [kg/m <sup>3</sup> ]	Poisson – Ratio [-]	Youngs/Bulk – Modulus [MPa]
Arch Dam	2400	0.167	27000
Foundation	0	0.2	25000
Reservoir	1000	-	2200

### 4 RESERVOIR MODELLING

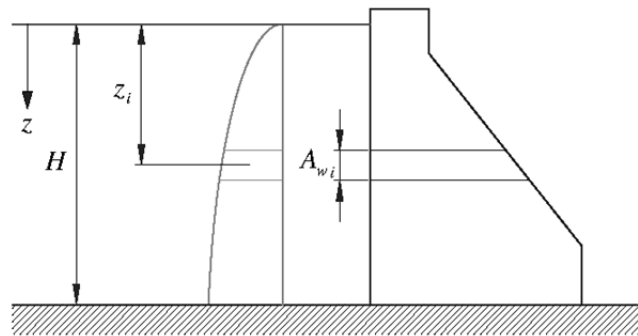
The first and easiest way to model the water is to treat it as an additional attached mass onto the upstream surface of the dam. The water mass is increasing with the depth of the reservoir. Two different ways to calculate the added water mass are used. For the application of these masses in the ABAQUS/CAE Model of the dam, a User Subroutine called UEL (User Element) was written. This subroutine calculates the mass for every node of an element surface, i.e. eight nodes for a quadratic formulation of a brick element and 6 nodes for a quadratic wedge element, and distributes it evenly. To define the element surface on which the mass is acting, a Python script was written, which extracts the nodes of the specific surfaces automatically and writes it back to input – file of the model.

Additionally to the added mass techniques by Westergaard und Zangar, the Fluid Structure Interaction is also modelled with so called Acoustic Elements.

#### 4.1 Added Mass according to Westergaard

According to the proceeding by Westergaard in 1933 “Water pressures on dams during earthquakes”, the water pressure is described as an added mass, acting on the upstream surface of the dam, the rest of the water is assumed to be inactive. He developed a parabolic shape of the mass as a function of the depth of the reservoir. Therefore the idealized two dimensional dam is assumed to be rigid and vertical. The reservoir is infinite in length and has a rectangular shape. The added water mass in a specific height of the dam surface can be calculated by

$$m_{wi} = \frac{7}{8} \cdot \rho \cdot \sqrt{H \cdot z_i} \cdot A_i \quad (1)$$



**Figure 4.** Westergaard Added Mass

## 4.2 Added Mass according to Zangar

In contrast to the Westergaard added mass approach, which has an analytical background, Zangar in 1952 published “Electric analog indicates effect of horizontal earthquake shocks on dams”. He described the hydrodynamic pressure experimentally for horizontal seismic excitations and varying slopes on the upstream surface of the dam.

The relationship between the added mass and the depth of the reservoir is

$$m_{zi} = C \cdot \rho \cdot H \cdot A_i \quad (2)$$

Where  $C$  is a coefficient, which is dependent on the depth of the reservoir and the slope of the upstream surface and  $C_m$  is the maximum value of  $C$  given by Figure 5.

$$C = \frac{C_m}{2} \left[ \frac{y}{h} \left( 2 - \frac{y}{h} \right) + \sqrt{\frac{y}{h} \left( 2 - \frac{y}{h} \right)} \right] \quad (3)$$

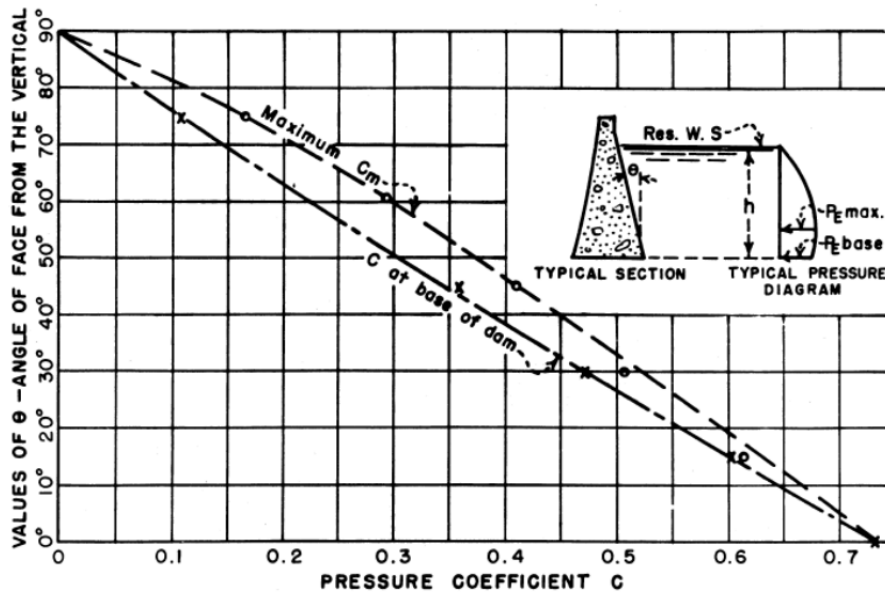


Figure 5: Relationship between the angle of the upstream surface and  $C_m$

## 4.3 Acoustic Elements

Acoustic Elements are special purpose elements - their only degree of freedom is pressure - so no deformation can happen. The acoustic medium equation is a combination of Newton's law of motion (conservation of momentum) and the continuity equation (Conservation of Mass). For fluid dynamics and the following assumptions:

- the fluid is compressible (density changes due to pressure variations)
- the fluid is inviscid (no viscous dissipation)
- the fluid is irrotational
- there is no mean flow of the fluid
- the mean density and pressure are uniform throughout the fluid
- no body forces
- homogeneous medium

The Equation of Motion for an acoustic medium can be written as

$$\rho \frac{\partial \mathbf{v}}{\partial t} + \nabla p(t) = 0 \quad (4)$$

and the continuity equation gives

$$\frac{\partial \rho(t)}{\partial t} + K \nabla \cdot \mathbf{v} = 0 \quad (5)$$

The constitutive law for an acoustic medium is defined as

$$K = c^2 \rho \quad (6)$$

with  $c$  as the wave speed of the medium and  $K$  as the Bulk Modulus.

Combining these three equations finally results in the linear acoustic wave equation

$$\frac{\partial^2 p(t)}{\partial t^2} - c^2 \nabla^2 p(t) = 0 \quad (7)$$

The boundary condition on the root of the reservoir model is set to non-reflecting, which means that that the pressure is completely absorbed (Lysmer and Kuhlemeyer boundary). On the upper surface the pressure head is set to zero.

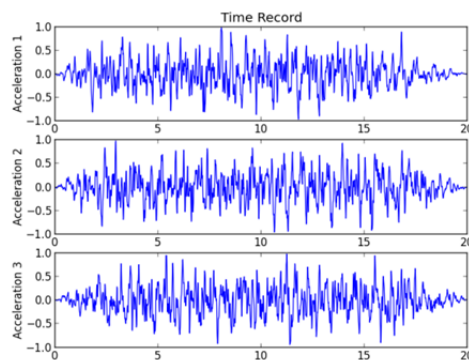
## 5 LOADINGS

### 5.1 Static Loads

The static loads have been defined in two steps, first, the gravity on the arch dam and second, the hydrostatic water pressure for full reservoir conditions (crest height).

### 5.2 Dynamic Loads

In the third step of the simulation, the seismic loading is applied. The accelerations are acting in all three directions X, Y and Z on the foundation boundaries in normal direction. The three orthogonal independent acceleration-time-history records have been generated according to the Austrian guidelines and are based on spectra. The maximum acceleration in each direction is set to 0.1g. For solving the equation of motion, implicit direct time integration according to Hilber-Hughes-Taylor is used.



**Figure 6:** Acceleration-Time-History Records

## 6 DAMPING

For all simulations Rayleigh-Damping is applied to the model. The stiffness- and mass-proportional damping factors are calculated for the first and fourth eigenfrequency of the dam-reservoir system. According to the fact that tests on existing dam structures showed that the critical damping factor can vary between 1% and 7%, the factors which are used are varied from 1% to 10%, in steps of 1 percent. For the damping of the rock mass, the simplification has been made, that the same Rayleigh-Damping factors are used as for the dam structure.

The mass-proportional factor for two specific eigenfrequencies and the critical damping is calculated with

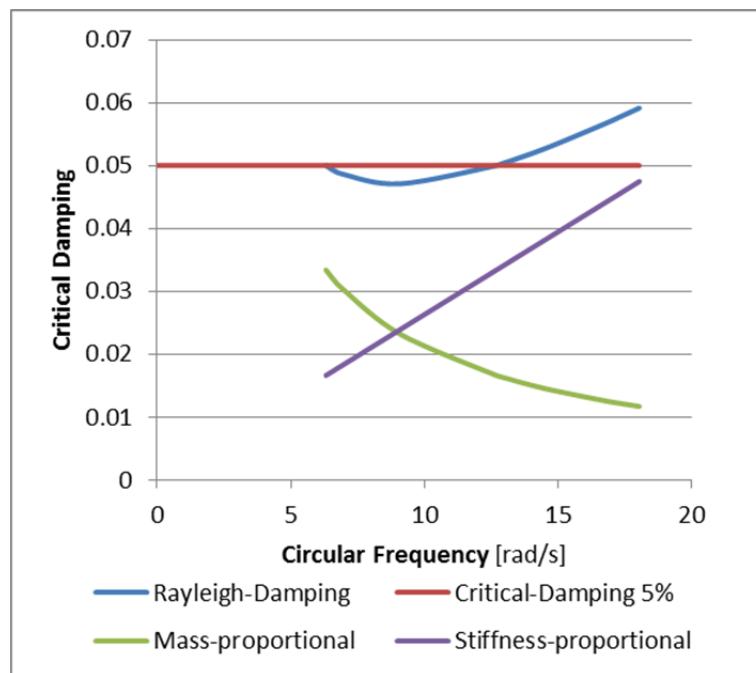
$$\alpha = \zeta \cdot \frac{2\omega_i\omega_j}{\omega_i + \omega_j} \tag{8}$$

and the stiffness-proportional damping with

$$\beta = \zeta \cdot \frac{2}{\omega_i + \omega_j} \tag{9}$$

**Table 3.** Mass- and stiffness-proportional damping factors

Critical Damp.	0.05	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.1
Mass-prop.	0.422	0.084	0.169	0.253	0.337	0.422	0.506	0.590	0.675	0.759	0.843
Stiffness-prop.	0.005	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009	0.011



**Figure 7.** Rayleigh-Damping for 5% critical-damping

## 7 RESULTS

### 7.1 Eigenfrequencies and Mode Shapes

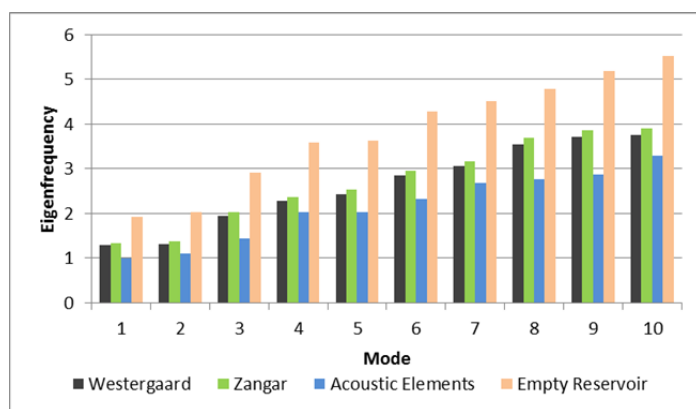
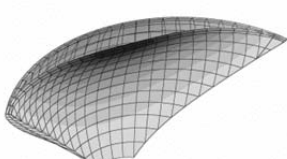
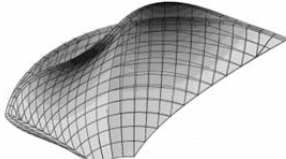
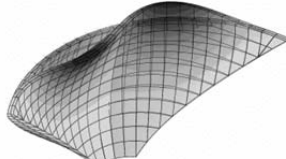
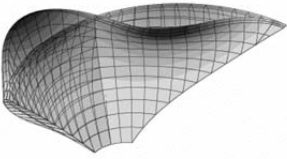
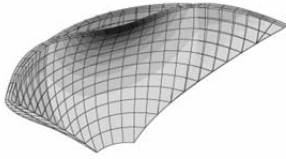
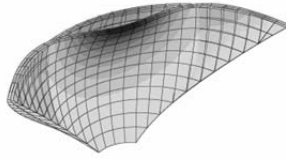
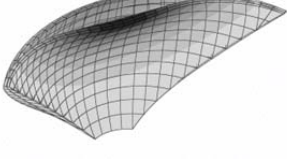
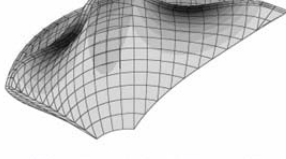
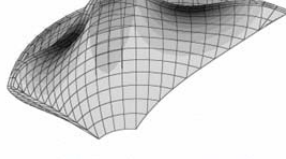





Figure 8. Eigenfrequency comparison

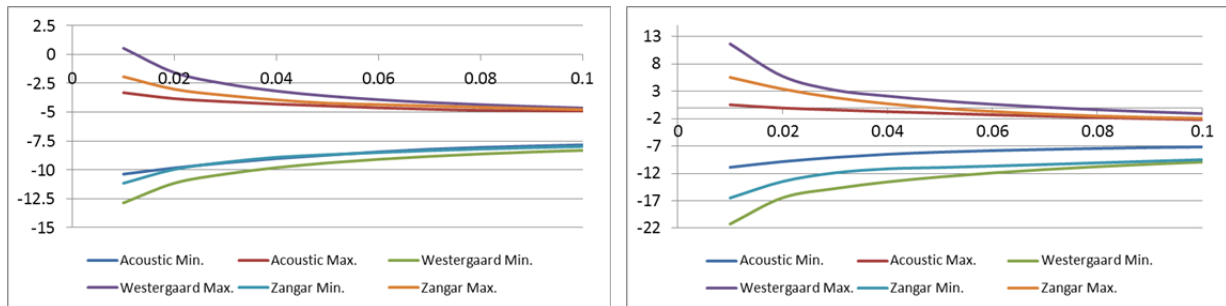
Table 4. Mode Shapes and Eigenfrequencies

Mode	Acoustic Elements	Westergaard	Zangar
1	 $f_1=1,01$ Hz	 $f_1=1,29$ Hz	 $f_1=1,33$ Hz
2	 $f_2=1,10$ Hz	 $f_2=1,31$ Hz	 $f_2=1,36$ Hz
3	 $f_3=1,44$ Hz	 $f_3=1,95$ Hz	 $f_3=2,02$ Hz
4	 $f_4=2,02$ Hz	 $f_4=2,28$ Hz	 $f_4=2,37$ Hz

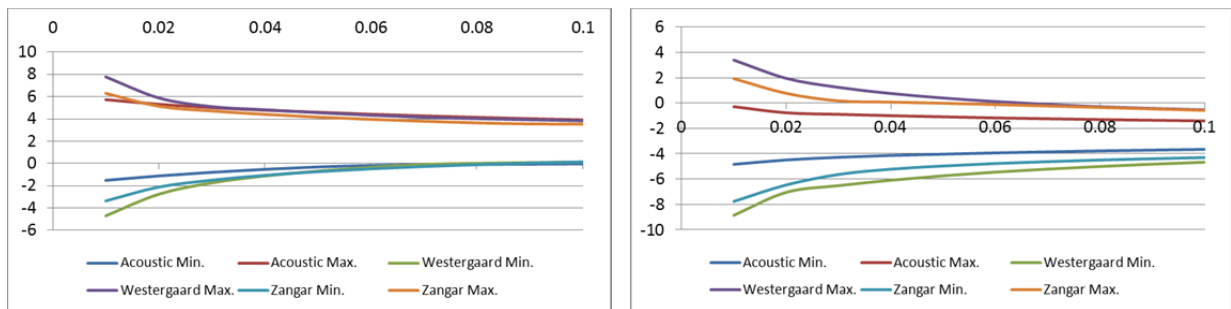


### 7.2 Stress Evaluation and Comparison

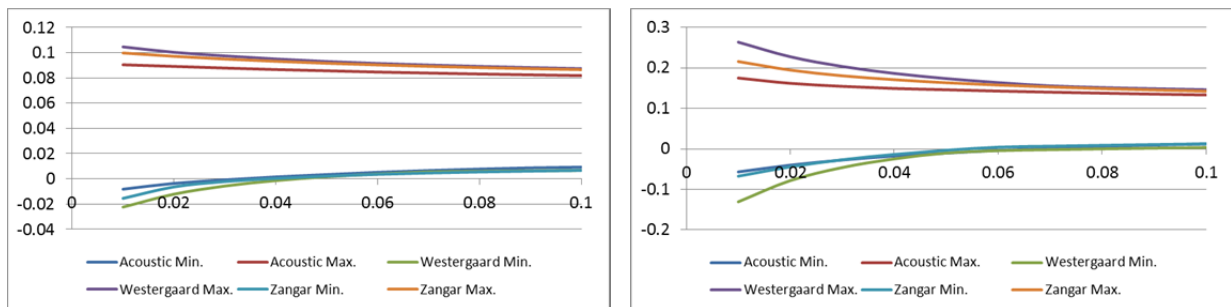
All stresses are evaluated in the main cross section of the dam (symmetric plane) for nodes on the upstream side. The following figures show the minimum/maximum stresses [MPa] or displacements [m] for two specific nodes for damping factors between 1% and 10% of the critical damping.



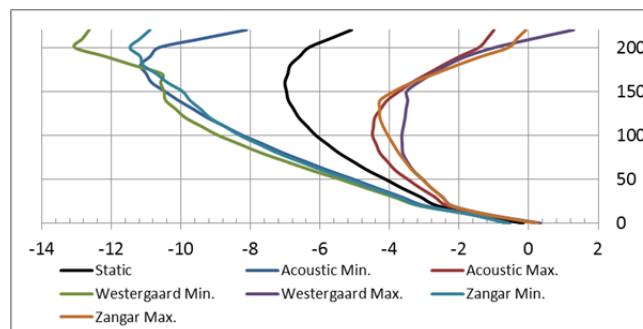
**Figure 9.** Hoop stress [MPa] comparison for nodes in a height of 110 meters (left) and 220 meters (right)



**Figure 10.** Vertical stress [MPa] comparison for nodes in a height of 0 meters (left) and 110 meters (right)



**Figure 11.** Displacement comparison for nodes in a height of 110 meters (left) and 220 meters (right)



**Figure 12.** Stress propagation along the height of the dam for 5% of the critical damping

## 8 CONCLUSIONS

Looking at the eigenfrequencies of the three different modelling techniques shows, that the empty reservoir, with less effective mass, has the highest eigenfrequency compared to the systems including the interaction. Important to mention is, that the acoustic elements show the lowest frequency, which could be interpreted as the system with the highest effective mass. But the stresses for this modelling technique are overall the lowest, so the damping effect is increased by these elements.

The stress development due to the variation of the critical damping factor decreases rapidly for factors between 1% and 3%. These curves are showing a more or less logarithmic behaviour and are converging to a specific stress level when the damping is increased, the same holds true for the displacements.

Finally, it can be concluded, that the added mass technique, for modelling such problems, should just be used for estimation purposes and dam structures not higher than 100 meters. The stress level could be overestimated by more than 100%, compared to the acoustic elements, especially in areas near the crest. Furthermore, the assumption of 5% damping for most of the problems is legit. A slight change of  $\pm 2\%$  doesn't influence the stresses/displacements significantly.

## REFERENCES

- Reynolds, D. (1981). *Engineering Principles in Acoustics*, Allyn and Bacon Inc., Boston: Allyn and Bacon Inc.
- Batchelor, G. K. (2000). *An introduction to Fluid Dynamics*. Cambridge: Cambridge University Press.
- Bathe, K. J. (2001). *Finite Element Methoden*. Berlin Heidelberg: Springer.
- Chopra, A. K. (2008). Earthquake analysis of arch dams: Factors to be considered. *The 14th World conference on earthquake engineering*. Beijing.
- Chopra, A. K. and Hall, J. F. (1982). Hydrodynamic effects in the dynamic response of concrete gravity dams. *Earthquake Engineering and Structural Dynamics*, 333-395.
- Dassault Systemes. (2011). *Abaqus 6.11-EF2 Documentation*. Dassault Systemes.
- Davidsson, P. (2004). Structure - Acoustic Analysis; Finite Element modelling and reduction methods. *Doctoral Thesis*. Lund, Sweden: Lund University.
- Feih, S. (2005). Development of a user element in ABAQUS for modelling of cohesive laws in composite structures. *Risø-R Report*. Roskilde, Denmark: Risø National Laboratory.
- Goldgruber, M., Feldbacher, R. and Zenz, G. (2012). Seismic stability of a rock wedge in the abutment of an arch dam. *Geomechanics and Tunneling* 5, No. 2, 186-194.
- Pagitsch, M. (2012). Arch Dam Design and Optimization. *Master Thesis*. TU Graz. Austria
- Scheulen, F. (2010). Numerical model validation for large concrete gravity dams. *United States Society on Dams Conference*.
- Tiliouine, B. and Seghir, A. (1998). Fluid-structure models for dynamic studies of dam-water systems. *Eleventh european conference on earthquake engineering*, (pp. 6-11). Paris.
- U.S. Army Corps of Engineers. (1995). *Engineering and Design, Gravity Dam Design, Engineer Manual 1110-2-2200*. Washington D.C.
- U.S. Army Corps of Engineers, Engineer Research and Development Center. (2000). *Evaluation and Comparison of Stability Analysis and Uplift Criteria for Concrete*. ERDC/ITL TR-00-1.
- Westergaard, H. M. (1933). Water pressure on dams during earthquakes. *Transactions, ASCE, Vol. 98*, 418-472.
- Zangar, C. N. and Haefeli, R. J. (1952). Electric analog indicates effect of horizontal earthquake shocks on dams. *Journal of the engineering mechanics division, Vol. 22, No. 4*.