SECOND EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING
AND SEISMOLOGY, ISTANBUL AUG. 25-29, 2014

INFLUENCE OF DAM-RESERVOIR INTERACTION FOR SEISMIC ANALYSIS OF ARCH DAMS

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ABSTRACT

Dynamic response of arch dams to earthquake ground motion is significantly affected by the interaction between the dam and the impounded water. There are several approaches to take into account this dynamic dam-water interaction. The purpose of this paper is to compare different modelling techniques with different levels of precision for an arch dam case. This work has been realized for the 2013 CIGB workshop about numerical analysis of dam (Diallo & Robbe, 2013).

This paper presents the results of the 3 approaches investigated and the fundamental hypotheses adopted for each them. The first approach is a generalized Westergaard added mass, the second approach is an incompressible finite-element added mass and the third approach is based on a sub-structuring method where the fluid is compressible. All investigations are carried out for an artificially generated symmetrical arch dam and simplified loading and boundary conditions. In general, Westergaard added mass yields higher compressive and tensile stresses, as well as higher radial displacement. The sub-structuring approach, where the compressibility of the water and the impedance of the foundation are taken into account, yields lower stresses.

INTRODUCTION

The objective of this paper is to present the seismic analysis of a 220 m high double curvature arch dam undertaken as part of the 12th CIGB benchmark about numerical analysis of dam. The results of the analysis are presented for the 3 approaches used to take into account dam-water interaction in accordance with the general assumptions made by the benchmark organizing committee. The analyses of the results focus on the impact of the hydrodynamic approach used on the computed stresses and displacements of the dam.

The following approaches are presented:

- Generalized Westergaard added mass
- Incompressible finite element added mass
- Sub-structuring method where water compressibility is taken into account.

For each approach, the fundamental hypotheses are presented and the physical justification is given.

Analyses are performed with *Code_Aster*, developed by EDF; it offers a full range of multiphysical analysis and modelling methods.

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DESCRIPTION OF ARCH DAM ANALYSIS – STATIC ANALYSIS

The application of the dead load should consider the manner in which the dam was constructed. Arch dams are often constructed as independent cantilever blocks separated by vertical joints. Since these joints are not capable of transferring dead load horizontally until they are grouted, dead loads should be applied to individual cantilever to simulate this condition. This may be accomplished by performing dead load analysis in two steps. First, dead loads are applied to even cantilevers (Set-1) and the stresses are extracted. In second analysis, the dead loads are applied to odd cantilevers (Set-2) separately and the stresses are extracted. The addition of the stresses obtained from the two steps is considered as the initial stress state of the dam and the displacement of the dam due to the dead load is not considered.

Water loads due to the hydrostatic pressures of the normal water level are external forces acting on the u/s face of the dam. The hydrostatic pressures are applied to the monolithic arch structure after the construction joints are grouted.

DESCRIPTION OF ARCH DAM ANALYSIS – DYNAMIC ANALYSIS

The methods used in this analysis are based on the modal superposition method. The modal analyses performed for the empty dam show that 90 percent of the mass of the dam is excited by a frequency range between 1.93 and 10 Hz. The maximum of the seismic is also in the same range (1-10 Hz). A significant amplification can therefore be expected.

The different approaches used to take into account the fluid-structure interaction are:

- Generalized Westergaard Added-mass
- Incompressible Finite-Element Added Mass – Potential Approach
- Compressible Water with Absorptive Reservoir Boundary- Sub-structuring Method

For first approach, the added-mass representation of dam-water interaction during earthquake ground shaking was first introduced by Westergaard (Westergaard, 1933). In his analysis of a rigid 2D gravity dam with a vertical upstream face, Westergaard showed that the hydrodynamic pressures exerted on the face of the dam due to the earthquake ground motion is equivalent to the inertia forces of a body of water attached to the dam and moving back and forth with the dam while the rest of reservoir water remains inactive.

A general form of the Westergaard added-mass concept which accounts for the 3D geometry (Kuo, 1982) can be applied to the earthquake analysis of arch dams.

The general formulation is based on the same parabolic pressure distribution with depth used by Westergaard, except that it makes use of the fact that the normal hydrodynamic pressure Pn at any point on the curved surface of the dam is proportional to the total normal acceleration, $\ddot{u}^t_n$:

$$P_n = a\ddot{u}^t_n \tag{1}$$

$$\alpha = \frac{7}{8}\rho_w\sqrt{H(H-Z)} \tag{2}$$

ρ_w: Density of water;
α: Westergaard pressure coefficient;
H: Water depth;
Z: Level of the point on the curved surface of the dam.

The normal pressure Pn at each point is then converted to an equivalent normal hydrodynamic force by multiplying by the tributary area associated with that point.

For the second approach, the added-mass representation of the impounded water can be obtained more accurately by a finite-element solution of the pressure wave equation, which fully accounts for the complex geometry of the dam and the reservoir. The impounded water represented by the wave equation is discretized using a finite element mesh of incompressible liquid elements. The solution is obtained by numerical procedures with the following boundary conditions:

$$\Delta P(x,y,z,t) = 0 \tag{3}$$

- The hydrodynamic pressures at the water – free surface are assumed to be zero, that is, the effects of surface waves are neglected.
- The reservoir bottom and sides, as well as a vertical plane at the upstream end of the reservoir model, are assumed to be rigid. For rigid boundaries the normal pressure gradients or the total normal accelerations are zero.
- The normal pressure gradients at the dam-water interface are proportional to the total normal accelerations of the fluid.

The computed pressures for the nodal points on the upstream face of the dam are then converted into equivalent nodal forces, from which an added-mass matrix representing the inertial effects of the incompressible water is obtained.

Finally, the sub-structuring method consists of dividing the complete system into three substructures: the structure, the water, and the foundation, each of which can be partially analysed independently of the others. The structure is represented by a 3D finite element, which permits modelling of a general geometry and linear elastic material properties. The water domain and the foundation region are represented by boundary elements.

The added mass representation of the impounded water described above ignores the effect of water compressibility and reservoir boundary absorption. However, the water compressibility and reservoir boundary absorption can significantly affect the hydrodynamic pressure and hence response of arch dams to earthquakes (Fok & Choppra, 1985).

Interaction of the dam with the foundation rock leads to an increase in vibration periods, primarily due to the flexibility of the foundation rock. Dam-foundation interaction also decreases the dam response if damping arising from material damping in the foundation rock and radiation damping associated with wave propagation away from the dam are considered in the analysis.

Procedures for earthquake response analysis of arch dams including dam-water interaction, water compressibility, reservoir boundary effects and dam-foundation interaction are developed by EDF (Code_Aster). In this procedure, the radiative damping and the hysteretic damping of the foundation are also considered. To represent the infinity domain, Green’s functions are used in the fluid domain and in the foundation domain.

In the fluid domain, the Helmholtz equation is discretized using boundary elements.

$$\Delta p + \frac{\omega^2}{c^2 w^2} p = 0 \tag{4}$$

The solution is obtained by numerical procedures with the following boundary conditions:

- The hydrodynamic pressures at the water – free surface are assumed to be zero, that is, the effects of surface waves are neglected.
- The normal pressure gradients at the dam-water interface are proportional to the total normal accelerations of the fluid.
- The normal pressure gradients at the foundation-water interface (reservoir boundary) are proportional to the total normal accelerations of the fluid.
- The hydrodynamic pressure wave impinging on the reservoir boundary is partly reflected into the water, and partly refracted (absorbed) into the boundary materials. The partial absorption at the reservoir boundary is approximately represented by a reflection coefficient known as “α”, which is the ratio of reflected to incident wave amplitude.

In the foundation domain, the Navier equation is also discretized using boundary elements. To take into account the infinity domain, Green functions are used.

$$div\sigma_f + f_f = \rho_f \frac{\partial^2 u}{\partial t^2} \tag{5}$$

The solution is obtained by numerical procedures with the following assumptions:

- The rock foundation is assumed homogeneous, isotropic and linear elastic.
- A value of 5% is considered for the modal damping.

RESULTS AND COMPARISON OF THE DIFFERENT APPROACHES – MODAL ANALYSIS

The interaction of an arch dam with the impounded water leads to a decrease in the dam vibration frequencies. This is because the dam cannot move without displacing the water in contact with it. The fact that water moves with the dam increases the total mass that is in motion. This added mass decreases the natural frequencies of the dam, which in turn affects the response spectrum ordinate and hence the effective earthquake inertia forces. The flexibility of the foundation rock also decreases vibration frequencies of the dam.

Table 1 gives the fundamental modes obtained by the 3 approaches investigated in this analysis. The results show that the Westergaard method gives the largest added-mass value, as evidenced by its decreasing the fundamental frequency the most. However, this does not automatically means that Westergaard approach gives the largest stresses, because the response of the dam also depends on the characteristics of the earthquake ground motion.

Table 1: fundamental frequency of the dam

	Empty reservoir	Full reservoir		
		Westergaard	Incompressible fluid elements	Compressible fluid element with 50% wave absorption
Fundamental frequency	1.93 Hz	1.29 Hz	1.57 Hz	1.49 Hz

RESULTS AND COMPARISON OF THE DIFFERENT APPROACHES – STRESSES AND DISPLACEMENTS

Under static loads, the maximum radial displacement reaches 8.32 cm at the top of the central cantilever. This displacement is only due to hydrostatic pressure acting on the u/s face of the dam.

The relatively symmetrical deformation of the arch dam leads to the compression of the lower portion of the d/s face of the dam and to tractions in the abutments on the u/s face of the dam. The maximum static principal stress (compression) reaches 9.32 MPa at lower portion in the abutments on the d/s face of the dam. The minimum static principal stress (tensile) also reaches 4.40 MPa at the lower portion of the u/s of the dam. This tensile stress could lead to the opening of the dam/foundation contact.

Figures 1 and 2 give the principal stress contours under static loads.

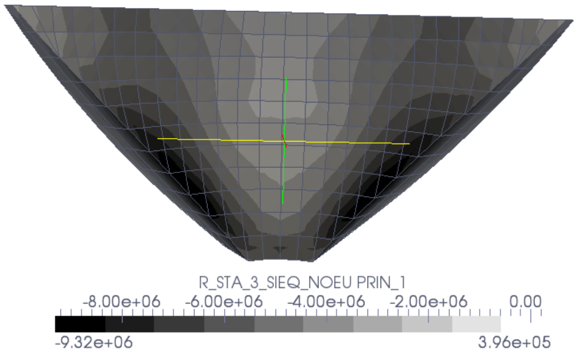

Figure 1: Principal stresses (compression) under static loads at d/s face

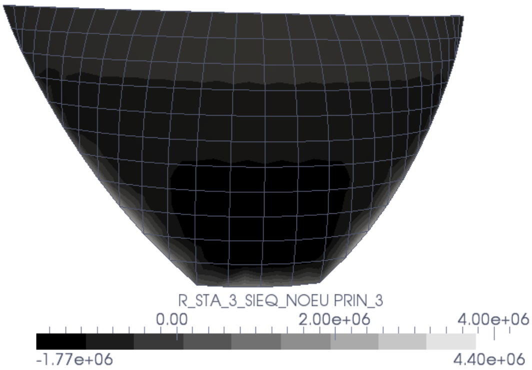

Figure 2: Principal stresses (tensile) under static loads at u/s face

During the ground motion, the maximum displacement of dynamic vibrations is about 6 cm with the respect to the initial displaced shape of the dam.

The maximum displacements of the central cantilever represented in fig.3 show that the Westergaard method yields higher radial displacements. The sub-structuring method, taking into account radiative damping, hysteric damping in the foundation and wave absorption at the reservoir boundary, yields lower displacements (20% of reduction).

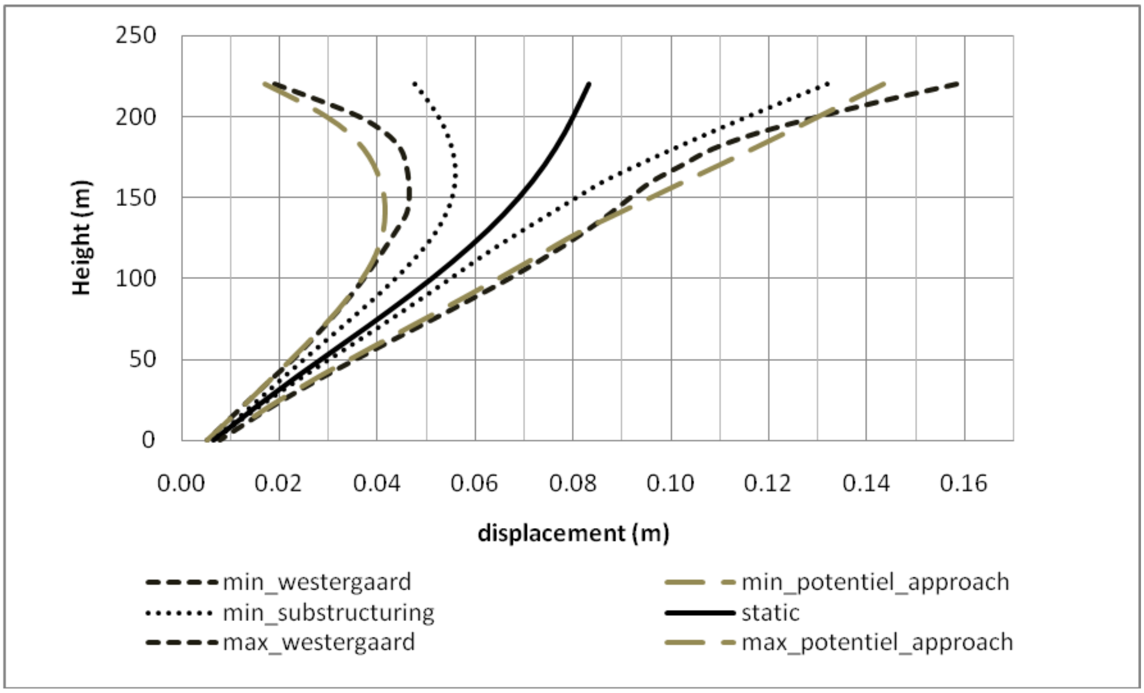

Figure 3: Maximum displacement of the central cantilever at the d/s face of the dam

In general, the Westergaard method yields higher compressive and tensile stresses. Indeed, the seismic tensile vertical stresses at the u/s face of the main cantilever vary from 2.4 MPa for the Westergaard method to 0.2 MPa for the substructuring method at a point at ¾ of the dam height (fig.4).

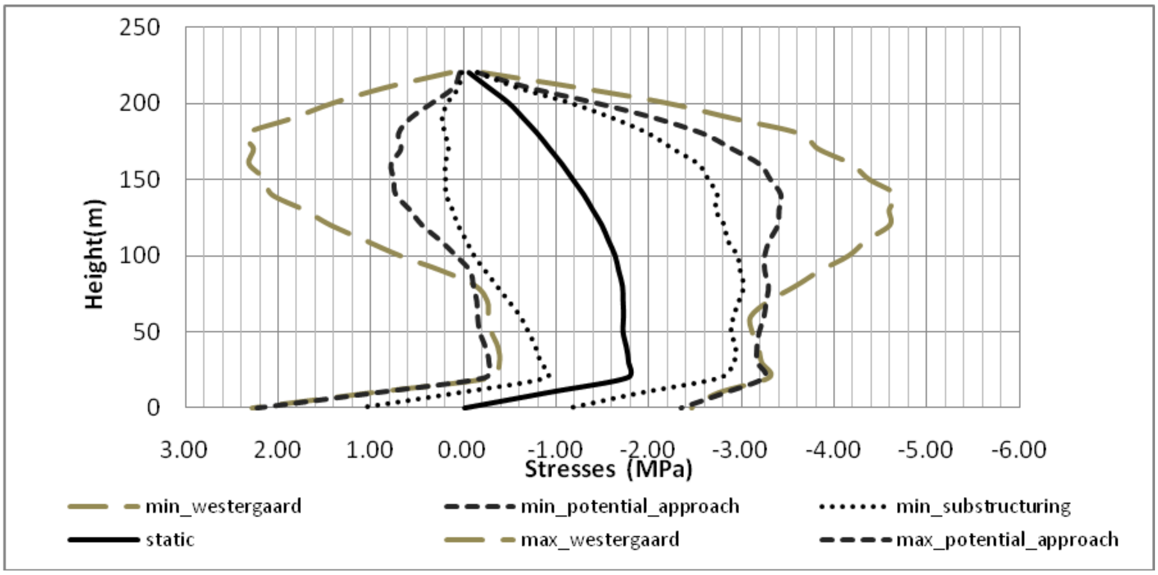

Figure 4: Vertical stresses at u/s face during the ground motion

Fig.5 gives maximum hoop stresses at the d/s face of the central cantilever during the earthquake. It shows a tensile stress varying from 2.2 MPa for Westergaard and potential approach to 1.6 MPa for Sub structuring method at the top part of the cantilever; this could lead to the opening of vertical joints.

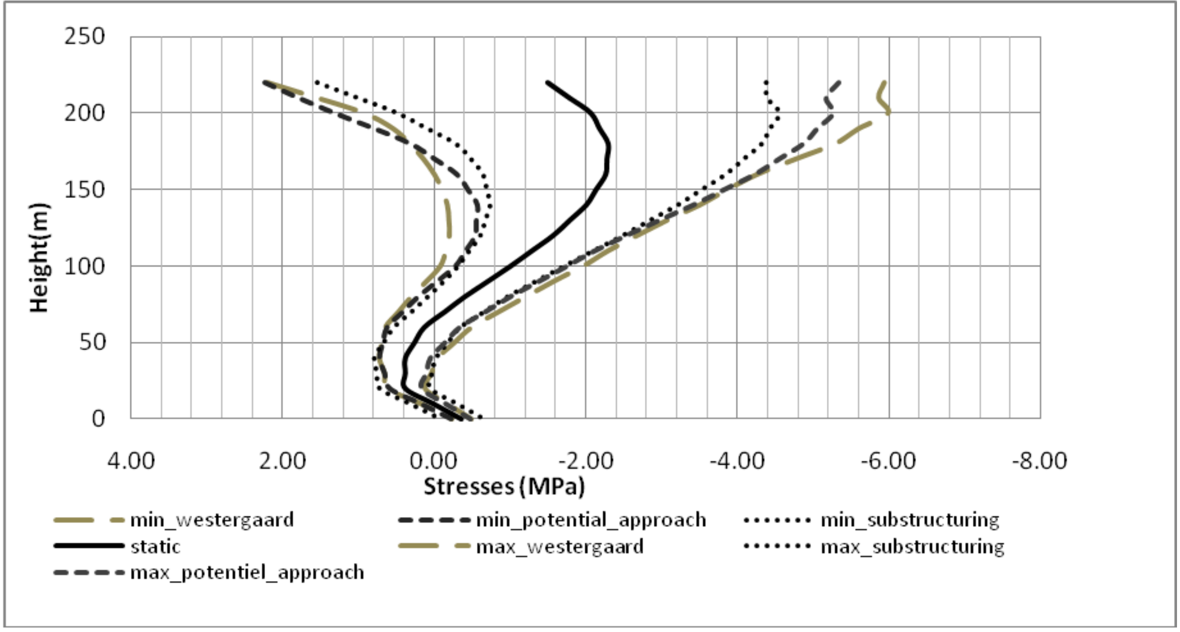

Figure 5: Hoop stresses at d/s face during the ground motion

For this dam, the ground motion increases the maximum principal stress observed at the lower portion of the abutments on the d/s face of the dam as well the minimum principal stress observed at the lower portion of u/s face of the dam.

For the 3 methods, the maximum stresses on the dam during the ground motion are in the same range of values (fig.6).

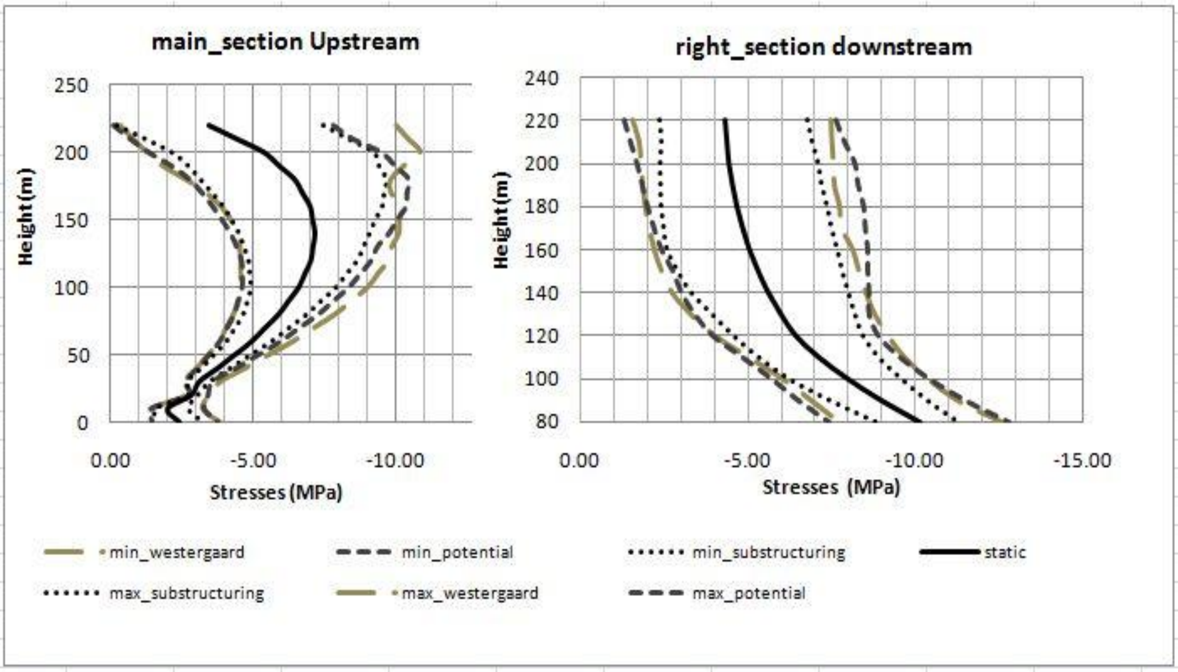

Figure 6: Maximum principal stresses at u/s face of central cantilever and d/s face of right section

Comparing the minimum stresses, fig.7 shows that the sub-structuring method increases slightly the tensile stress at the dam/foundation contact (2.84 MPa under static loads and 3.14 MPa during earthquake). However this amplification is very significant with added-mass methods, thus with Westergaard added mass, the tensile stress reaches 5.96 MPa during the earthquake and with the potential approach it is about 5.24 MPa. These tensile stresses could lead to the opening of the dam/foundation contact.

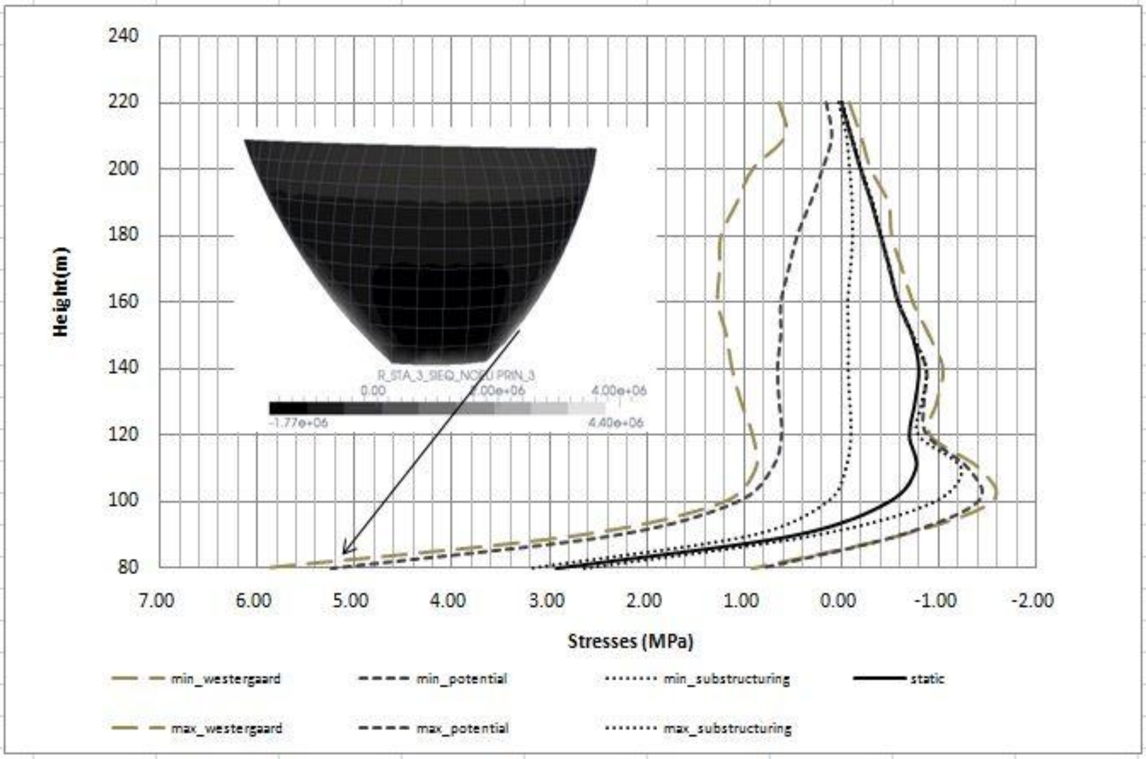

Figure 7: Minimum principal stresses (tension) at the u/s face of right section

From the engineer point of view, in this case, the 3 approaches investigated lead to the same conclusion, except regarding the tensile stress at the dam/foundation contact. For this point, the sub-structuring method reduces significantly the stresses (fig.7).

INFLUENCE OF RESERVOIR BOUNDARY ABSORPTION

A hydrodynamic pressure wave impinging on the reservoir boundary is partly reflected into the water, and partly refracted (absorbed) into the boundary materials. If the reservoir boundary materials are relatively soft, an important fraction of the reservoir water energy can be absorbed, leading to a major reduction in the dynamic response of the dam. Therefore, the values of the absorption ratio for the design and safety evaluation of dams subjected to earthquake loading should be measured or selected conservatively.

The purpose of this section is to show the effect of this absorption on the dynamic response of the dam by studying 3 cases of absorption (0%, 50% and 100% absorption).

As expected, wave absorption at the reservoir boundary reduces significantly the dynamic response of the dam. Fig.8 gives the radial spectrum at the crest of the dam and for fundamental frequency (f1=1.49 Hz), we observe that the correspondent pseudo acceleration varies from 1.93 g (total absorption) to 4.14 g (without absorption).

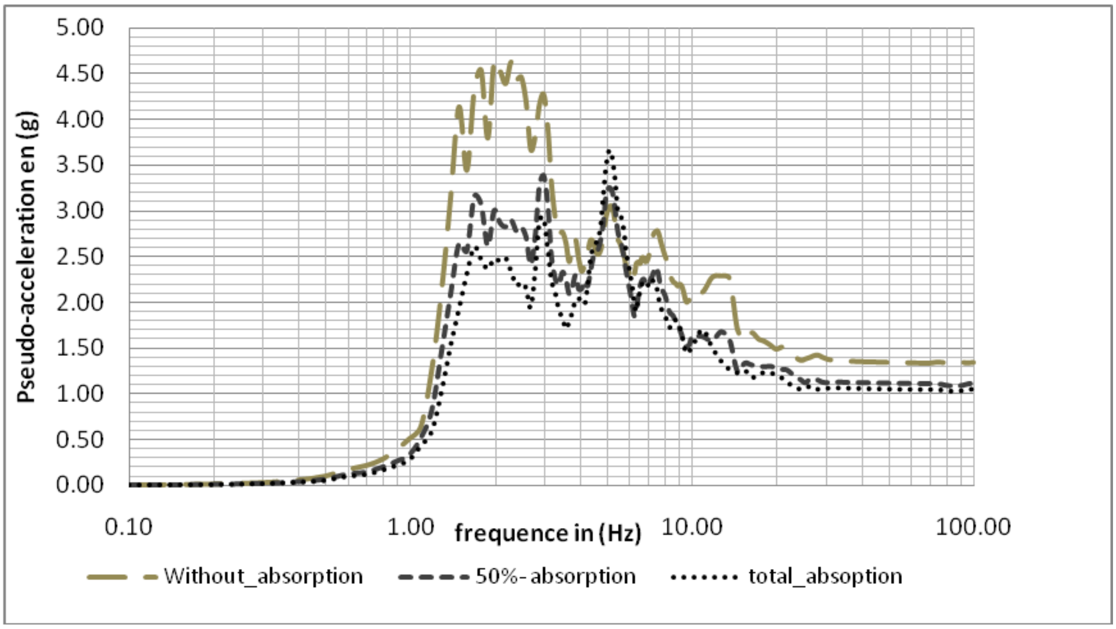

Figure 8: radial spectrum at the crest of the dam for 3 cases of absorption

Reservoir boundary absorption also decreases compressive and tensile stresses (fig.9), as well as the radial displacement (cf fig 10). In fig.9, maximum stress varies from 8.95 MPa ***(***total absorption***)*** to 11.26 MPa (without absorption) at ¾ dam height on the u/s face of the main section.

Fig.10 gives the radial displacement of the central cantilever for 3 cases of absorption: crest displacement varies from 11.4 cm (total absorption) to 15.9 cm (without absorption).

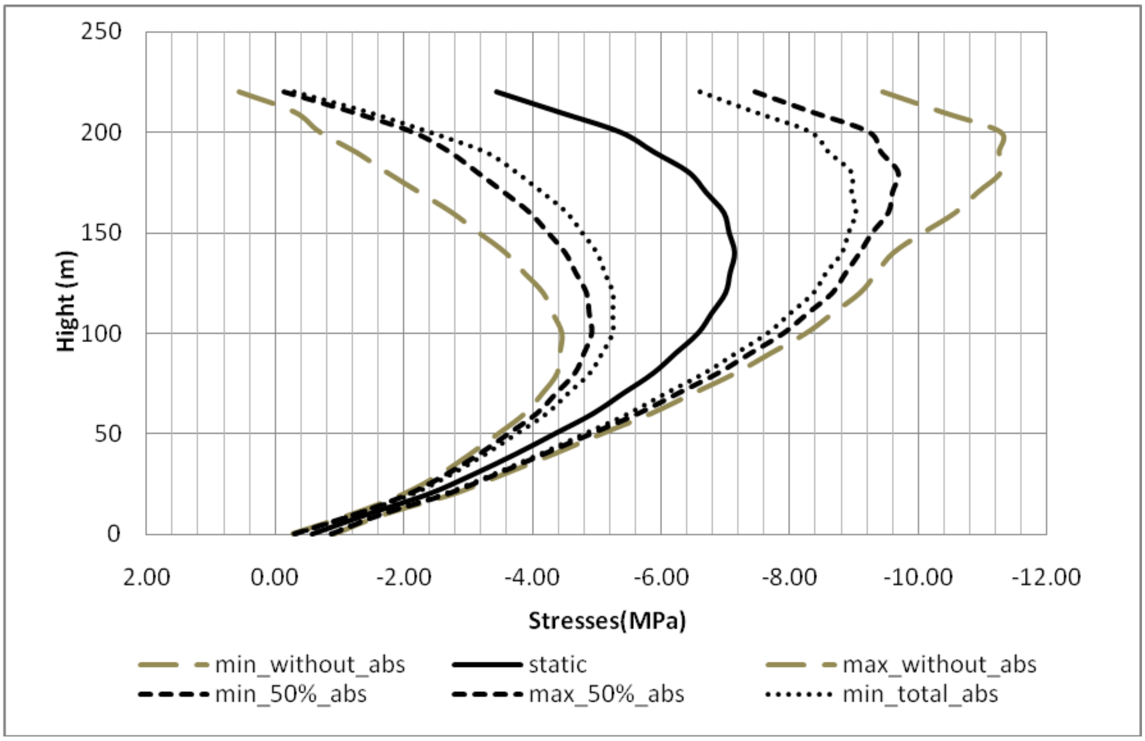

Figure 9: Hoop stress of the central cantilever for 3 cases of absorption

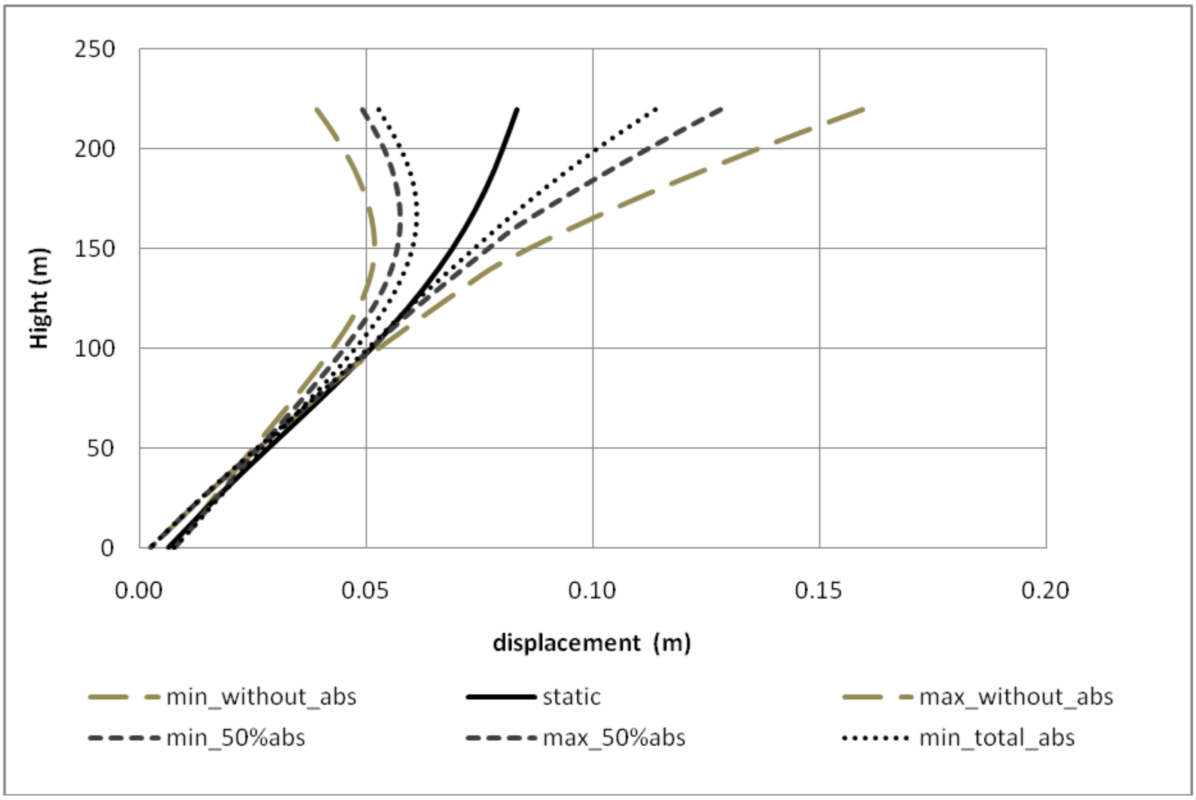

Figure 10: Radial displacement of central cantilever for 3 cases of absorption

CONCLUSION

The different approaches to hydrodynamic effect modelling investigated in the present study lead to similar behaviour regarding the structural response of the arch dam studied. Westergaard approach yields higher compressive and tensile stresses, as well as higher radial displacements. The sub-structuring method taking into account wave absorption at the reservoir boundary decreases significantly the dynamic response of the dam due to the increased damping of the coupled system.

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