A Concrete Arch Dam under Seismic Loading Conditions

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Abstract: A new regulation for the safety assessment of dams has just been developed in Italy and its approval process is still in progress. As a matter of fact the behaviour of dams under seismic loading conditions is deemed of actual interest due to the recent seismic events occurred. In earthquake analysis, some of the most challenging aspects dam engineers have to deal with are: the capability to take duly into account the dam-reservoir and foundation rock-reservoir interactions; a careful evaluation of the maximum displacements/stresses of the concrete structures; a proper choice of constitutive models. This paper shows how COMSOL Multiphysics can afford the safety assessment of a large concrete arch dam under dynamic excitation, taking into account the dam-reservoir and foundation rock-reservoir interactions as well.

Keywords: fluid-structure interaction, seismic analyses in time domain.

1. Introduction

The Committee on *Computational Aspects of Analysis and Design of Dams*, established by the International Commission of Large Dams (ICOLD), organizes almost every two years a Benchmark Workshop event with the aim to compare numerical results attained using different software and methodologies and to validated numerical data on the basis of experimental measurements as well as of the common engineering practice.

Bering in mind the recent earthquake events, this commission has proposed to evaluate in the last Benchmark Workshop held in Graz, Austria, the seismic behavior of a large concrete arch dam, taking into account the fluid-structure-foundation interaction (ref. Theme A, [1]).

In this paper the solution obtained using COMSOL Multiphysics is presented in details, outlining the main potentialities of the software in solving seismic analysis in time domain on a complex geometry.

2. The Finite Element model

The Formulators of Theme A, [1], provided a coarse mesh of the dam-reservoir-foundation system that has been slightly modified: the reservoir and the foundation rock domains have been extended towards the upstream direction to evaluate properly how the wave pressures move within the water basin (Figure 1).

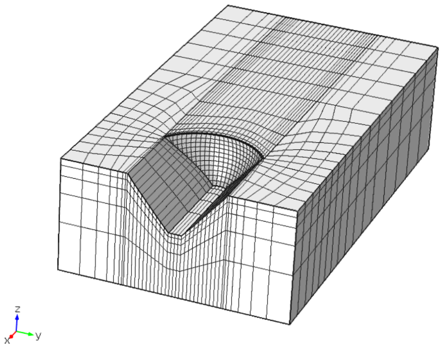

Figure 1. The coarse mesh of the dam-reservoir-foundation system.

The mesh of the modified geometrical model has been subdivided into groups of finite elements on the basis of the material parameters; in this way, the COMSOL command that allows importing a mesh recognizes automatically the domain of each group as shown in Figure 2.

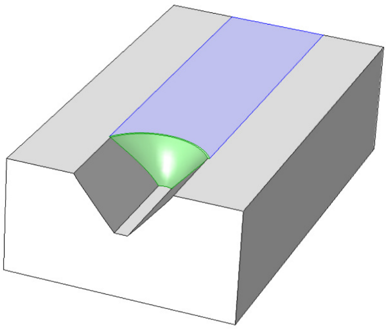

Figure 2. The geometrical model of the dam-reservoir-foundation system.

The model has three domains: the dam body, the reservoir and the foundations rock.

The displacement field of each finite element of the numerical model has been discretized with quadratic shape functions.

3. Material properties

Linear elastic constitutive models have been assigned to either the dam or the foundation rock. The physical-mechanical properties are summarized in Table 1.

Table 1: Concrete and rock properties

Domain	Density [kg/m^3]	Poisson ratio	Young modulus [MPa]
Dam	2400	0.167	27000
Foundation	0	0.200	25000

The Rayleight damping model has been taken into account to define the dam behavior during seismic loading conditions. Assuming a 5% structural damping ratio, the mass and stiffness damping parameters of the Rayleight formulation are $\alpha = 0.94$, and $\beta = 2.65E\text{-}03$.

The reservoir has been discretized by means of acoustic finite elements whose properties are reported in Table 2.

Table 2: Water properties

Domain	Density [kg/m^3]	Speed of sound in water [m/s]	Bulk modulus [MPa]
Reservoir	1000	1500	2200

4. Loading conditions

According to the formulation of Theme A, the following loading sequence has been simulated:

- Dead loads
- Hydrostatic water pressure with the maximum water level equal to the dam crest height (715 m a.s.l.)
- Seismic motions as provided by the Formulators in terms of accelerations along the three Cartesian directions (Figure 3).

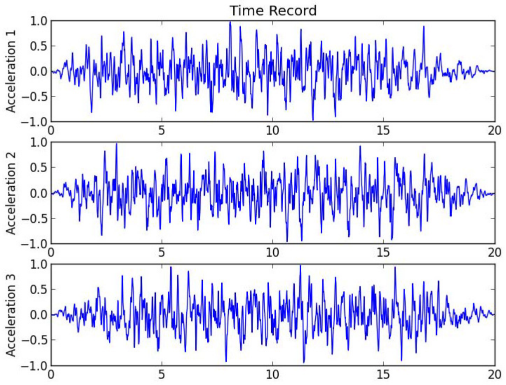

Figure 3. Time histories assigned to the foundation boundaries along the Cartesian directions.

5. Boundary conditions applied to the fluid domain

The fluid domain has been modeled by means of acoustic finite elements, assigning boundary conditions described hereafter.

- The dam-reservoir interface (refer to the COMSOL *acoustic-structure boundary* node, [2], and Figure 4) is governed by the following equations:

$$-n\cdot\left(-\frac{1}{\rho}(\nabla \mathrm{p} - q_d)\right) = -n\cdot u_{tt}$$

$$\sigma\cdot n = p\,n$$

where n is the normal to the interface, ρ the water density, p the fluid "acoustic" pressure, q_d the dipole source (null in the present case), u_{tt} the acceleration field of the structural domain at the fluid interface and σ the stresses tensor.

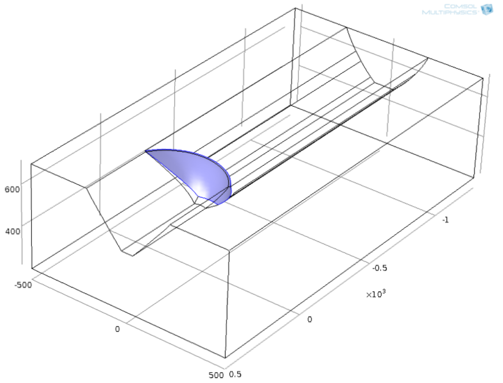

Figure 4. The dam-reservoir interface.

- The foundation-reservoir interface (refer to the COMSOL *impedance* node, [2], and Figure 5) is governed by the equation:

$$-n \cdot \left(-\frac{1}{\rho}(\nabla \mathrm{p} - q_d) \right) = \frac{1}{Z_i}\frac{\partial p}{\partial t}$$

where n is the normal to the interface, ρ the water density, p the fluid "acoustic" pressure, q_d the dipole source (null in the present case), Zi the acoustic input impedance assumed equal to:

$$Z_i = \rho/\mathrm{q}$$

being q a damping coefficient that characterizes the effects of absorption of the hydrodynamic pressure waves at the boundary, according to the equation [4]:

$$q = \frac{1}{c}\frac{1-\alpha}{1+\alpha}$$

α is the wave reflection coefficient that accounts for the behavior of the absorption of hydrodynamic pressure waves at the boundary, whereas c is the speed of sound in water. According to some literature case studies, α has been considered equal to 0.75, [5].

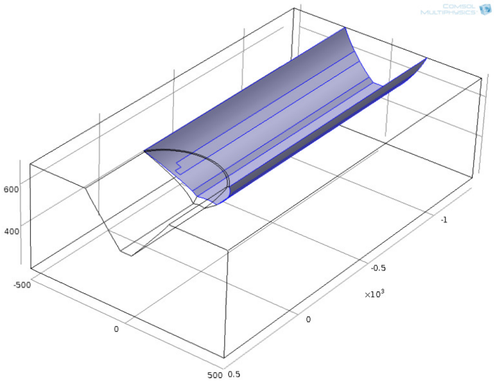

Figure 5. The foundation-reservoir interface.

- The upstream-reservoir surface (refer to the COMSOL *plane wave radiation* node, [2], and Figure 6) is governed by the equation:

$$-n \cdot \left(-\frac{1}{\rho}(\nabla p - q_d) \right) + \frac{1}{\rho}\left(\frac{1}{c}\frac{\partial p}{\partial t} \right) = Q_i$$

where n is the normal to the interface, ρ the water density, p the fluid "acoustic" pressure, q_d the dipole source (null in the present case), c is the speed of sound in water and Q_i the monopole source (null in the present case).

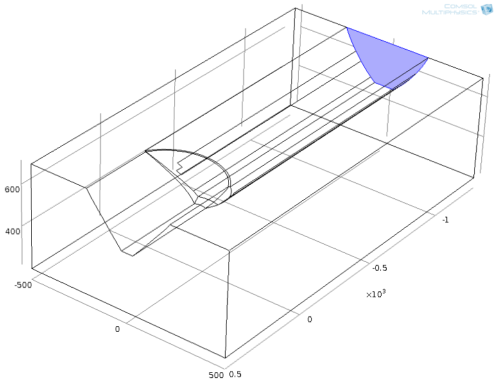

Figure 6. The upstream-reservoir surface.

- The free surface (refer to the COMSOL *sound soft boundary* node, [2], and Figure 7) is governed by the equation:

$$p = 0$$

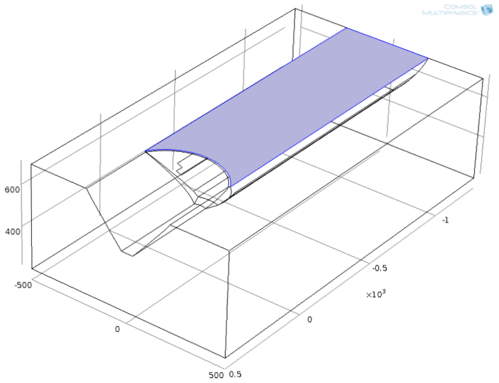

Figure 7. The free surface.

5. Seismic analysis in time domain

Seismic analyses in time domain are generally carried out considering a massless foundation and applying a spatially-uniform ground motion directly at the basement rock.

In this work, at first an ordinary differential equations problem has been solved, making reference to the foundation domain only, in order to compute the displacements associated to the earthquake motions. Then, these displacements have been applied to the bottom and lateral rock walls to calculate the dynamic response of the dam-reservoir-foundation system.

This procedure allows computing easily the relative displacements of the system; anyway, as an alternative, the same results could be attained applying directly the accelerations to the foundation boundaries.

6. Results

According to the requests of the Formulators of Theme A, the results of the seismic analysis are provided in terms of radial displacements [m], hoop and vertical stresses [MPa] on the upstream and downstream faces of three vertical sections of the dam. In Figure 8, for example, the maximum and minimum radial displacements in time on the upstream face of the main vertical section is shown, while in Figure 9 the contour of the radial displacements is reported on three vertical section of the dam at time 20s.

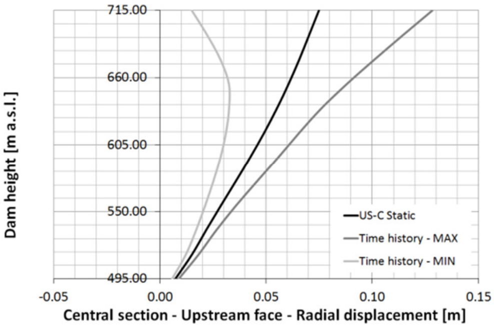

Figure 8. Radial displacements on the upstream face of the main vertical section.

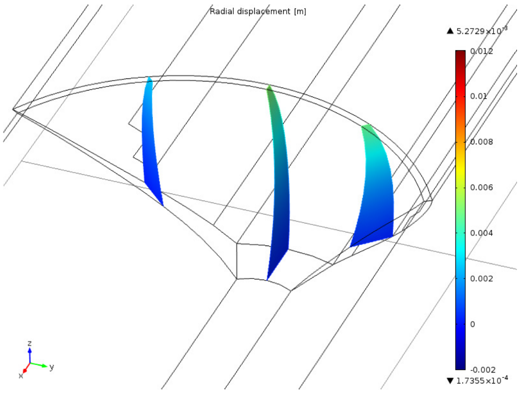

Figure 9. Radial displacements on three vertical sections at time 20s.

In Figure 10, the pressure field is visualized on the fluid domain on some section at time 9,65s, whereas in Figure 11 the same data are represented in terms of isosurface.

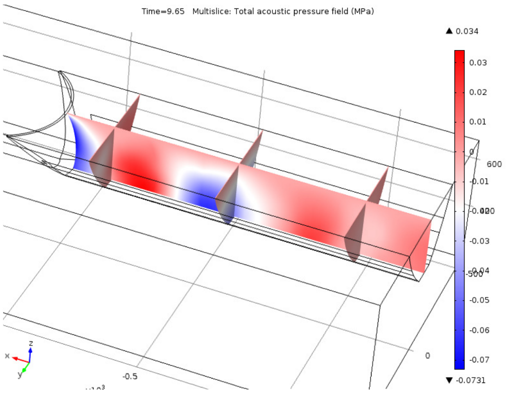

Figure 10. The pressure field in the fluid domain at time 9,65s.

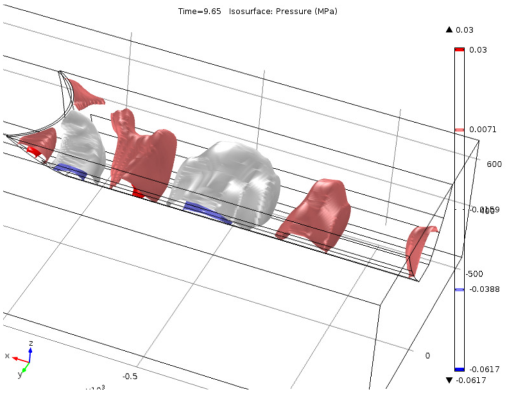

Figure 11. The isosurface of the pressure field in the fluid domain at time 9,65s.

It could be outlined that the extrapolation and visualization of any results data could be managed quite easily within COMSOL or making use of MATLAB scripts.

7. Conclusions

COMSOL Multiphysics has proved to be a practical software to compute seismic analyses in time domain. Anyway, this is just a preliminary application, and many future challenges are worthwhile to be afford and thorough; for instance, the main interest aspects are:

- the possibility to perform response spectrum analyses considering that in common practice

this type of analysis is usually adopted to evaluate the maximum displacements of the structure under exercise or ultimate strength limit conditions
- the use of contacts to simulate realistically the interaction between the dam and the foundation, and the construction joints as well
- the implementation of a constitutive model able to describe the complex behavior of concrete under any loading conditions. The Fenves law for instance could describe properly the damage elasto-plastic behavior of concrete also in case of cyclic loadings.

8. References

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9. Acknowledgements

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