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Seismic Response of Concrete Gravity Dams Considering Hydrodynamic Effects

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Abstract

This paper presents a dynamic analytical study to assess the effect of dam height as well as fluid compressibility on the gravity response of a concrete dam, considering the effects of hydrodynamic interaction. The analysis is carried out using the ADINA Finite Element software for empty and full reservoir conditions by considering several models. In the first model, the mass of fluid is taken into account by the concept of Westergaard added mass, in the second model; an acoustic fluid element is used to simulate the effect of water on the reservoir. The height of the dam is one of the main factors affecting the seismic response of gravity dams; because the change in height provides different responses depending on the natural periods, displacements and stresses obtained from static and dynamic analyses. The numerical results showed that the effect of interaction between the dam and the reservoir plays an important role in the precise estimation of the dynamic response of gravity dams. The hydrodynamic water pressure from the reservoir increases stresses in the dam body and horizontal displacements at the crest. The seismic response obtained by the incompressible water model (Westergaard) is compared with that of the compressible water model.

Keywords: added masses, dynamic analysis, Fluid-structure interaction, Finite Element Method, gravity dam, hydrodynamic

1 Introduction

Concrete gravity dams are very important structures that can be implemented in high-seismicity areas and whose security must be ensured. In this work, we intend to perform a seismic analysis to evaluate the linear response of concrete gravity dams considering different models.

The study of the behavior of dams under seismic loads is a key factor for the safety requirements of dams and to ensure this safety, a lot of research has been conducted to determine how dams behave under seismic loads. It is evident that the presence of fluid in the reservoir affects the response of dams under seismic excitation. Indeed, when the interaction of the reservoir is considered, the movement of the structure is influenced by the fluid flow

through the forces transmitted to the interface, and reciprocally, the movement of the structure influences the fluid flow through the displacements of the interface which drives the fluid in its movement. For this reason, the dynamic interaction between a fluid and a structure is an important concern in the field of safety evaluation of concrete dams. Earthquake-induced hydrodynamic pressures on the upstream face of a dam are important design factors.
The works of Westergaard and Zangar [1, 2] provided methods for simplified modeling of the dam-reservoir interaction. The most recent works allow more refined modeling of the dam-reservoir interaction.Various authors such as Tiliouine and Seghir [3], Bouaanani et all [4], Lotfi [5], Dey and Sawant [6], Mandal and Maity [7] taken into account the hydrodynamic interaction effects in the dynamic calculations by the Finite Element Method(FEM)in the time domain of reservoir-dam, foundation-structure and foundation-dam-reservoir systems.
Mohan Rao and Shaik [8] or Silveira and Pedroso [9] studied the influence of foundation and reservoir on the dynamic behavior of concrete gravity dams in terms of their parameters in terms of natural frequencies, periods, mode shapes, crest displacement, base reactions and, stress distributions. Ouzandja et al. [10], Ravindran and Jacob [11], Zeidan [12], Varughese and Nikithan [13] studied different dynamic modeling problems of a concrete gravity dam, with various field problems using the FEM. Salamone et al. [14] attempted to generate Finite Element results using various methods to determine the earthquake-induced hydrodynamic loads on the concrete arch dam. Millan et al. [15] studied the effects of reservoir geometry on the seismic response of gravity dams. For this purpose, a Boundary Element Method (BEM) model in the frequency domain was used to evaluate the influence of the reservoir geometry on the hydrodynamic dam response. Important conceptual conclusions about the dam-reservoir system behavior show that the reservoir shape influences the seismic response of the dam. Bayraktar et al [16] investigated the effect of reservoir length on the seismic performance of gravity dams to near and far-fault ground motions. Folsom Gravity dam is selected for a numerical example, and it is modeled considering four reservoir lengths and a foundation.
Dams of different heights of 100 m, 84 m, 60 m and 46 m were analyzed, and the results were obtained in terms of natural periods, stresses, and displacements at the crest of the dams for empty and full reservoir conditions.
The results obtained to allow a better understanding of the influence of different parameters considered on the seismic analysis of concrete gravity dams.

2 Fluid-Structure Interactions

The Finite Element Method (FEM) is a technique for obtaining a numerical solution to a specific problem, presented clearly, both in digital and graphic form; by defining the field problem, material properties, geometric properties, network model, boundary conditions, and element types. Usually, at this point, we will simplify the problem as much as possible to get fast and accurate results. Figure 1 Phases of the Finite Element.

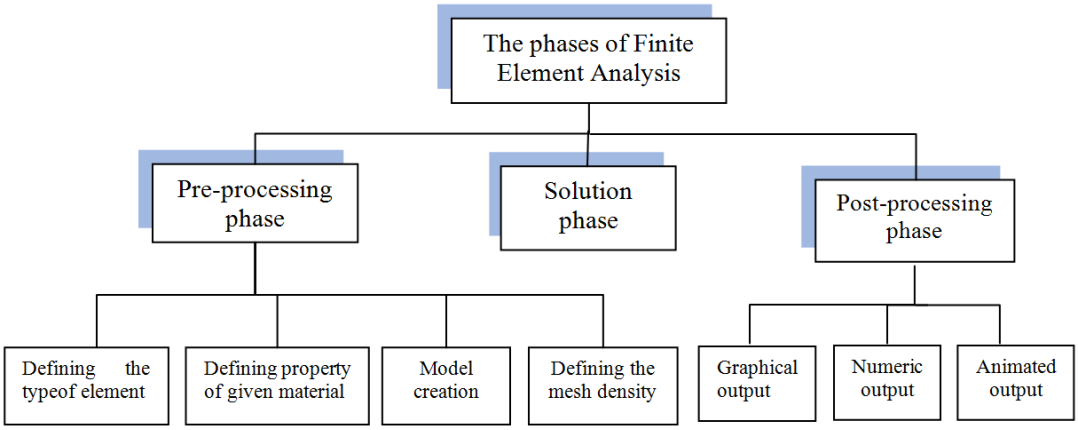


Figure 1: Phases of the Finite Element Analysis

2.1 Westergaard Method (Added Mass Method)

The generalized formula of Westergaard's theoretical solution to simulate the hydrodynamic pressure of reservoir water can be expressed using the added mass by Equation 1.

$$M_{ai} = 7/8\ \rho_w A_i \sqrt{H_i\left(H_i - Z_i\right)\lambda_i^T \lambda_i} \tag{1}$$

Where i is a node on the structural surface subjected to hydrodynamic pressure, ρ_w is the mass density of water, A_i is the effective area of i, H_i is the total water depth of the vertical surface at which i is located, Z_i is the height from i to the bottom of the structural surface subjected to hydrodynamic pressure, and λ_i is the normal vector of i,

$$\lambda_i = \{\lambda_{ix}, \lambda_{iy}, \lambda_{iz}\} \tag{2}$$

2.2 Potential-Based Fluid Formulation

We appreciate the comments, we have rewritten the sentence: “The assumptions made for the Potential-Based Fluid Elements in the program of Finite Element Analysis ADINA (Automatic Dynamic Incremental Nonlinear Analysis) are: inviscous, irrotational flow with no heat transfer; slightly compressible or almost incompressible flow; relatively small displacement of the fluid boundary; actual fluid flow with velocities below the sound speed or no actual fluid flow.”
The structure–fluid interaction is described as follows.

$$\begin{bmatrix} 0 & 0 \\ 0 & -M_{FF} \end{bmatrix} \begin{Bmatrix} \Delta\ddot{u} \\ \Delta\ddot{\Phi} \end{Bmatrix} + \begin{bmatrix} C_{UU} & C_{UF} \\ C_{FU} & -(C_{FF} + (C_{FF})_S) \end{bmatrix} \begin{Bmatrix} \Delta\dot{u} \\ \Delta\dot{\Phi} \end{Bmatrix} + \begin{bmatrix} K_{UU} & K_{UF} \\ K_{FU} & -(K_{FF} + (K_{FF})_S) \end{bmatrix} \begin{Bmatrix} \Delta u \\ \Delta\Phi \end{Bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} - \begin{bmatrix} F_U \\ F_F + (F_F)_S \end{bmatrix} \tag{3}$$

where Δu is the unknown displacement vector increment; $\Delta\Phi$ is the increment of the unknown potential vector; M_{FF} is the fluid element mass matrix; C_{UU}, C_{FU}, C_{UF}, C_{FF} are the damping matrices of the structure, the fluid caused by the structure, the structure caused by the fluid, and the fluid on the fluid-solid coupling interface, respectively; K_{UU} , K_{FU}, K_{UF}, K_{FF} are the stiffness matrices of the structure, the fluid caused by the structure, the structure caused by the fluid, and the fluid on the fluid-solid coupling interface, respectively; F_U, F_F,$(F_F)_S$ are the

fluid pressure on the structure boundary, the volume integral term, and the area integral term corresponding to the fluid continuity equation, respectively.
Equation 3 does not include any structural system matrices, and only gives the contribution of the potential-based Fluid Elements to the system matrices. The contribution of the structural term is added to Equation 3 to obtain the finite element equation of motion for fluid-structure interaction, as follows:

$$\begin{bmatrix} M_{SS} & 0 \\ 0 & -M_{FF} \end{bmatrix} \begin{Bmatrix} \Delta\ddot{u} \\ \Delta\ddot{\Phi} \end{Bmatrix} + \begin{bmatrix} C_{UU} + C_{SS} & C_{UF} \\ C_{FU} & -(C_{FF} + (C_{FF})_S) \end{bmatrix} \begin{Bmatrix} \Delta\dot{u} \\ \Delta\dot{\Phi} \end{Bmatrix} + \begin{bmatrix} K_{UU+}K_{SS} & K_{UF} \\ K_{FU} & -(K_{FF} + (K_{FF})_S) \end{bmatrix} \begin{Bmatrix} \Delta u \\ \Delta\Phi \end{Bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} - \begin{bmatrix} F_U \\ F_F + (F_F)_S \end{bmatrix} \tag{4}$$

In Equation 4, the structural element matrix of mass, damping, and stiffness, and the load vector, can be defined as:

$$M_{SS} = \int_{V_S} \rho s\, \bar{N}^T \bar{N} dV\ , C_{SS} = M_{SS}\alpha + \beta K_{SS}, K_{SS} = \int_{V_S} B^T DB\, dV\ ,$$

$$F_S = \int_{V_S} \bar{N}^T P dV + \int_S \bar{N}^T \bar{T} dS \tag{5}$$

where V_S is the solid region of the calculation; ρs is the density of the solid region; N is the nodal shape function of the solid region; α and β are the structural mass and stiffness matrix coefficients, respectively; B and D are the displacement-strain matrix and the elastic stiffness matrix of the solid region, respectively; P, T, and S are the physical force, surface force and boundary surface of the solid region, respectively.

2.3 Boundary Conditions

Reservoir Upstream Boundary

With the vibration of the dam, volumetric hydrodynamic pressure waves are created in the reservoir and propagate upstream. If the length of the reservoir is assumed to be infinity, then these waves would start to vanish. It should be noted that the length of the reservoir is assumed as a finite length, L, in numerical modeling. Hence, an artificial boundary is applied to simulate the effect of the infinite reservoir. This boundary is modeled based on the Sommerfeld boundary:

$$\partial p / \partial n\ (x, y, z) = -\ 1/\ C(\partial p / \partial t)\ (x, y, z) \tag{6}$$

The Bottom of the Reservoir

According to the rigidity of the reservoir bottom, by assuming the horizontal movement of the Earth, the pressure gradient is neglected:

$$\partial p / \partial n\ (x, y, z) = 0 \tag{7}$$

The Free Surface of the Reservoir

By neglecting the effects of surface waves, the governing boundary condition is as follows:

$$p(x, y, z) = 0 \tag{8}$$

Fluid-Structure Interface

In the common boundary between the reservoir and the dam body, an interaction between these two occurs which the result of inertia force is caused by the movement of the dam body. Hence, the applied pressure on the reservoir face caused by the inertial force is as follows:

$$\partial p / \partial n(x, y, z) = -\rho . \ddot{u}_n(x, y, z) \quad (9)$$

In which ρ is the density of the fluid and $\ddot{u}_n$ is the structure's acceleration vector in the direction normal to the common boundary of the fluid and structure.

3 Numerical Results and Discussion

The subject of this article is to present a dynamic computational model by the Finite Element Method for a concrete reservoir-gravity dam system taking into account the hydrodynamic interaction effects. Dams of different heights, 45 m, 60 m, 85 m, and 100 m shown in Figure 2 have been analyzed and the results obtained are compared in order to better understand the dynamic behavior of the concrete gravity dam for the performances analyzed by the Westergaard model (incompressible water)and the acoustic water model (compressible water). Concrete reservoir gravity dam systems are idealized as two-dimensional sections in the plane normal to the dam axis. The dam is assumed to be homogeneous, isotropic, and linearly elastic having a modulus of elasticity (E_d) equal to 24 e^6 kN/m^2, Poisson's ratio v of 0.2, density ρ of 2500 kg/m^3 and the critical damping percentage γ = 5%. The water in the tank is assumed to have a density equal to 1000 kg/m^3, and the modulus of compressibility of water K = 2.2 MPa. The dam is assumed to be fixed at the base and the reservoir length is taken as two times the depth.

The objective was to study the effect of the geometry of the dams on the frequencies, periods, stresses, and displacements of four concrete gravity dams. The dams taken into consideration are of variable height; they are named A1, A2, A3, and A4. The geometries of dams are presented in Table1.

Table 1: The geometry of dams

	Height of dam(m)	**Base width (m)**	**Top width(m)**	**Reservoir Height(m)**
Dam A1	100	80	14	95
Dam A2	84	67	12	80
Dam A3	60	48	8	57
Dam A4	46	37	6	44

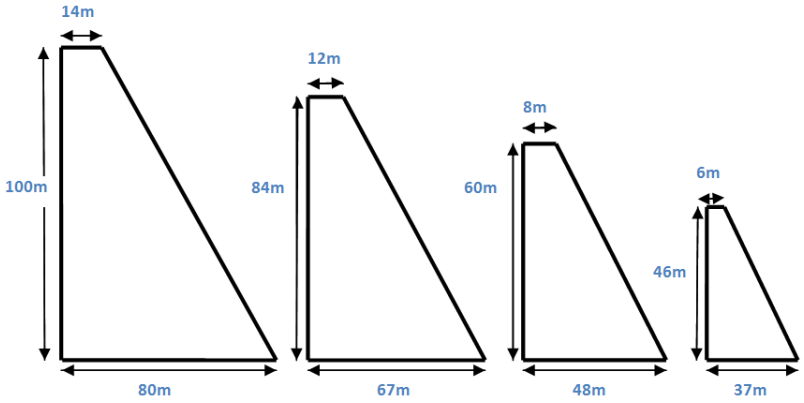


Figure2: Finite element idealization adopted for the four dams

3.1 Modal Analysis of Dam-Reservoir System

3.1.1 Effect of Dam Height on Periods

A modal analysis was performed on the selected family of concrete gravity dams; Figure 3 shows the typical form for the first two positions of each dam. The modal periods of the first six patterns of vibration of the dam reservoir system for different conditions of the dam length are listed in Table 2.

Table 2: First six natural periods of concrete gravity dams with empty reservoirs

Dam	A1	A2	A3	A4
1	0.268	0.226	0.160	0.120
2	0.106	0.090	0.064	0.049
3	0.098	0.082	0.058	0.044
4	0.057	0.048	0.034	0.026
5	0.043	0.036	0.025	0.020
6	0.038	0.032	0.023	0.017

It can be seen that the length of the dam has the main effect of prolonging the periods of vibration of the dam, especially for the highest dam whose values of the periods of vibration are doubled compared to the shortest dam. The period of the dam increases with an increase in height of the dams (for a constant ratio of bottom width to height).

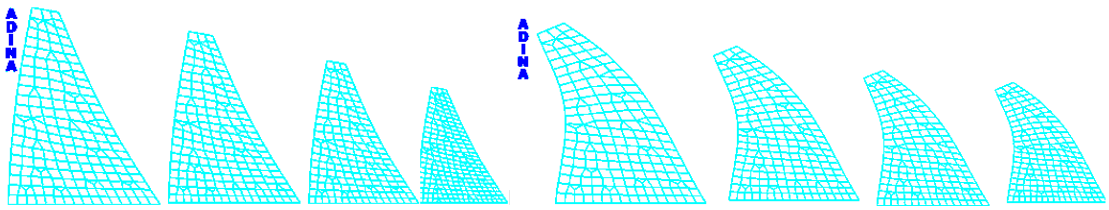


Figure 3: Modal distortions. Modes 1 of the empty dams, Modes 2 of the empty dams

3.1.2 Effect of Fluid Compressibility on Natural Periods

It can be seen in Table 3 below that the FEM using a compressible fluid provides values for periods greater than the Westergaard model of an incompressible fluid.

Table 3: First six natural periods of concrete gravity dams with a full reservoir

Dam	A1		A2		A3		A4	
Mode	Added mass	Acoustic fluid	Added mass	Acoustic fluid	Added mass	Acoustic fluid	Added mass	Acoustic fluid
1	0.33	0.37	0.28	0.31	0.19	0.22	0.15	0.17
2	0.14	0.21	0.12	0.17	0.08	0.12	0.06	0.10
3	0.11	0.15	0.09	0.12	0.06	0.09	0.05	0.07
4	0.07	0.11	0.06	0.09	0.04	0.07	0.03	0.05
5	0.06	0.10	0.05	0.08	0.03	0.06	0.02	0.05
6	0.05	0.09	0.04	0.08	0.03	0.05	0.02	0.04

The results clearly show that taking into account the compressibility of the water leads to an increase in the periods, especially for the longer dam. This can be explained by the increase in the mass of the coupled fluid-structure system which leads to a smaller frequency and therefore a larger period. It can be noticed that the FEM model using a compressible fluid provides larger period values than the Westergaard added mass model.

3.2 Static Analysis

A static analysis of the dam-reservoir system is first performed to assess its pre-seismic state. This analysis is carried out for the two models considering the self-weight of the dam and the hydrostatic pressure. The following figures show the vertical stresses obtained by static analysis on the empty and full dam.

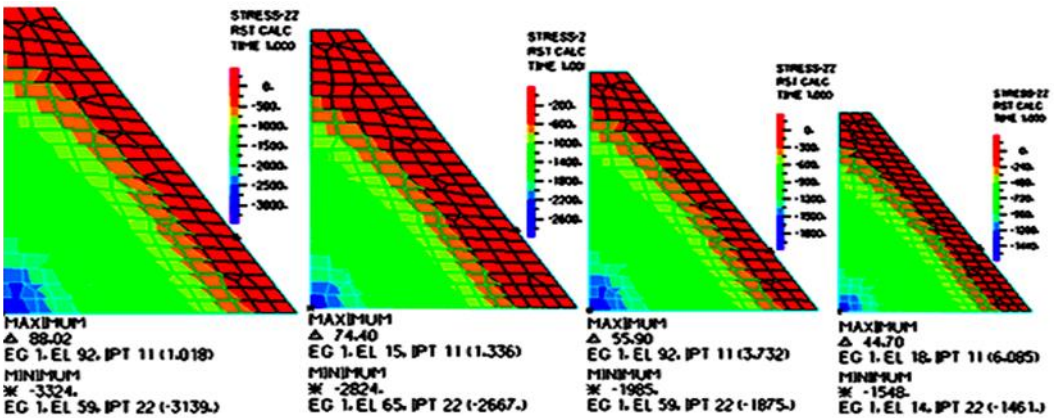


Figure 4: Vertical stresses distribution ZZ of empty dams

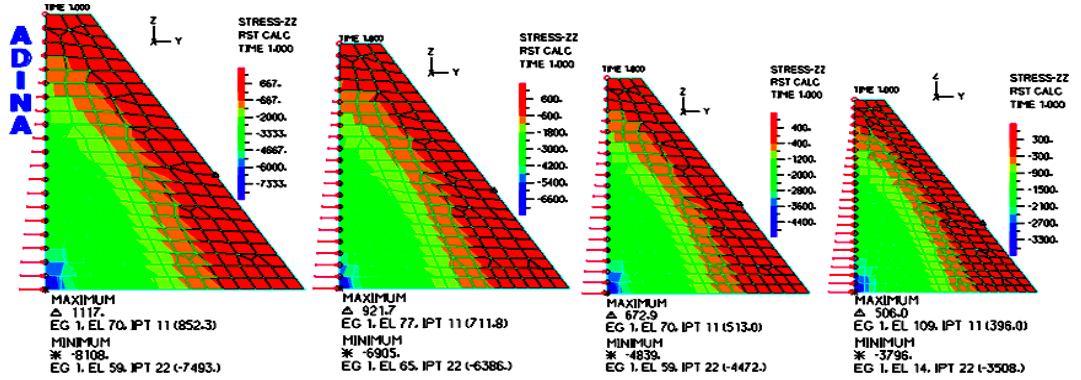


Figure 5: Vertical stresses distribution ZZ of full dams (added mass)

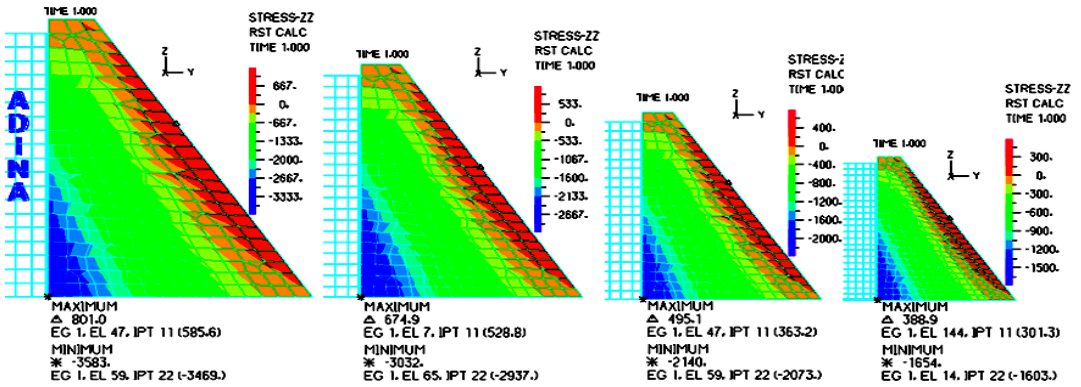


Figure 6: Vertical stresses distribution ZZ of full dams (acoustic fluid)

Figure 4 shows the vertical stress in the static state in the case of an empty reservoir (dam under its weight).The vertical stresses at the base are only the compressive stresses of four dams. Figures 5 and 6 show the vertical stress in the case of the filled reservoir (the hydrostatic state). The compressive stresses increase at the heel level of four dams under the influence of water pressure. The compressive stresses doubled in the case of the added mass with the presence of a tension in the dam toe. Pressures are proportional to the depth of the reservoir, so at the base of the dam, they will have maximum values. The stress distribution of the four dams is identical in all cases, directly proportional to the dam height and stress values.

3.3 Dynamic Analysis

The dynamic excitations considered in this study are represented by the accelerometric recordings of the horizontal component of the Loma Prieta replica from October 18, 1989 (Figure 7). The seismic response of the models is evaluated by analyses that display normal periods, displacements, and stresses. The different results obtained were compared. A summary of the main numerical results obtained is presented below to illustrate the studied effects of various factors on the dynamic response of a coupled system.

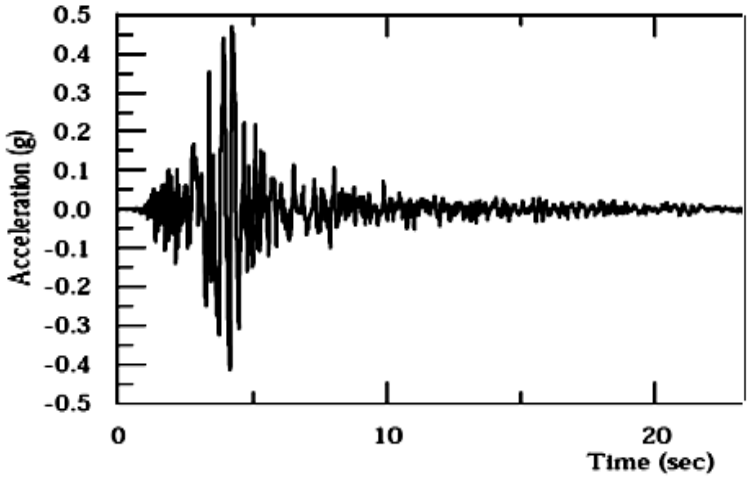


Figure 7: Loma Prieta Accelerogram

The stresses in the four empty dams and with the presence of water under the action of the accelerogram are shown in Figure 8.

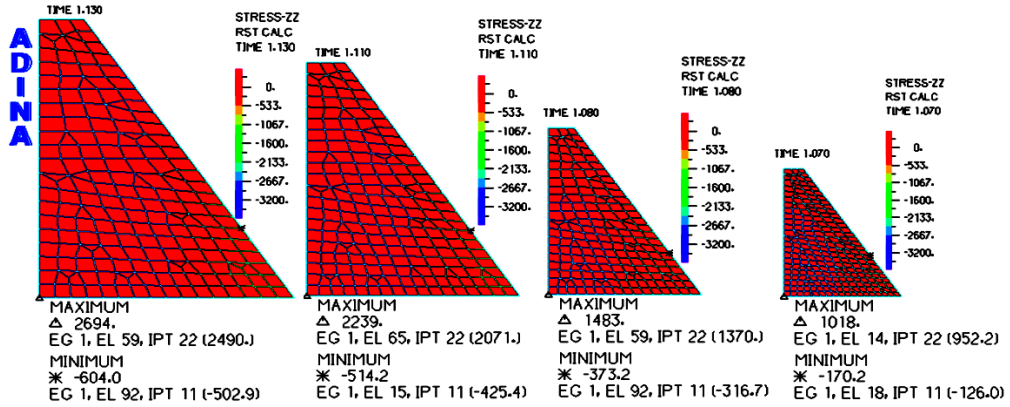


Figure 8: Vertical stresses distribution ZZ of empty dams

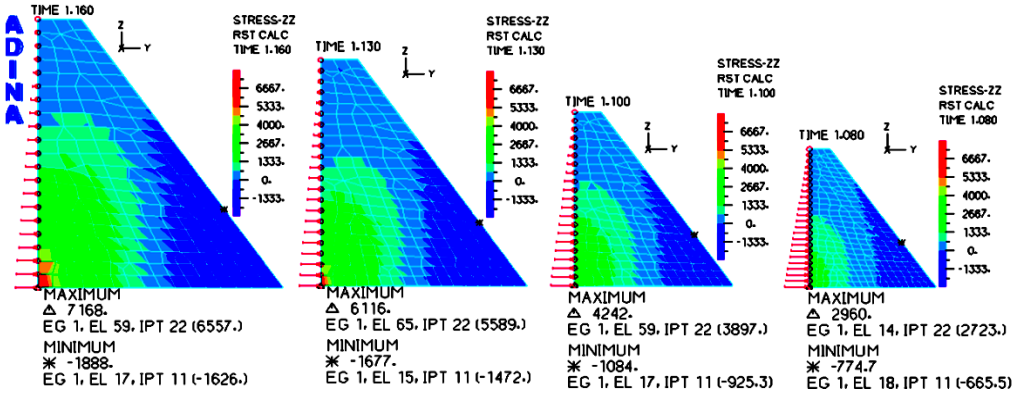


Figure 9: Vertical stresses distribution ZZ of full dams (added mass)

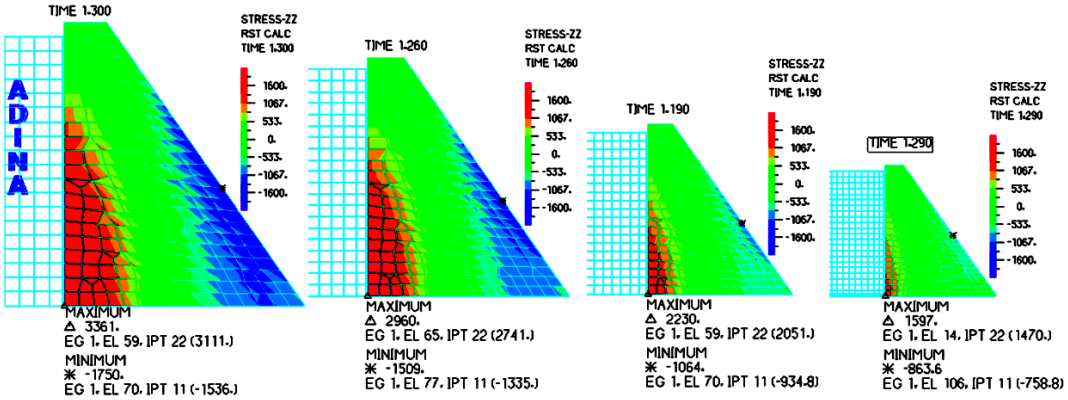


Figure 10: Vertical stresses distribution ZZ of full dams (acoustic fluid)

Vertical tensile stresses start downstream of the dam, then propagate towards the dam body and finally reach the upstream face. Therefore, there's a risk of concrete cracking in these areas because the tensile strength of concrete is low compared to the compressive strength. The stress profiles obtained for the four dams with compressible and incompressible fluids are similar but with different values, highlighting the influence of the height of the dam and the type of fluid in the reservoir. Vertical stress results given in Figures 8, 9, and 10 confirm that as the dam rises, vertical stresses at the dam's heel increase dramatically. Especially for dams with incompressible liquids, we observe unwanted tensile stresses in the heel. Comparisons of vertical stresses (mass added of Westergaard versus acoustic fluid) are shown in Figures 11 and 12."

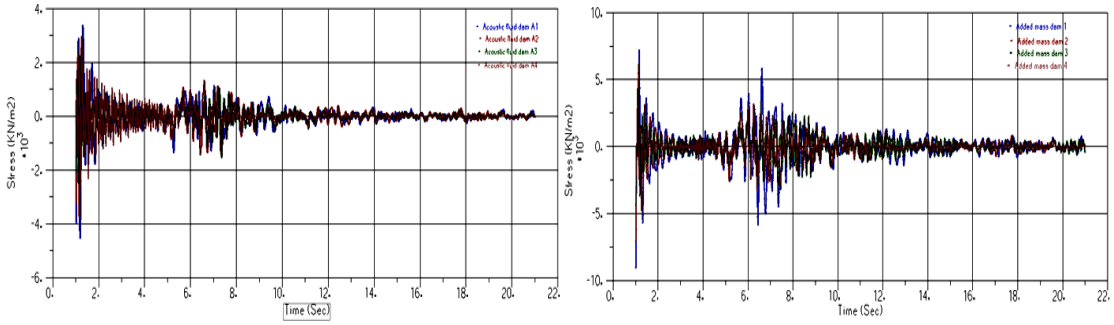
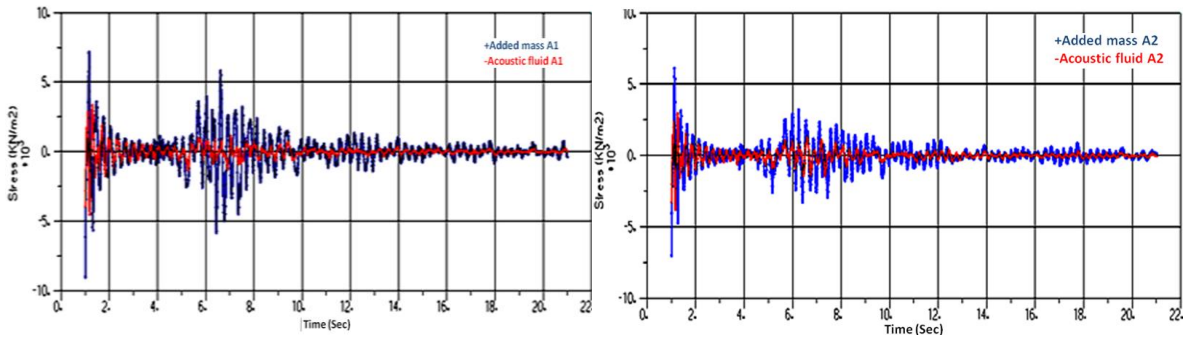


Figure11: Vertical Stresses at dam heel (acousticfluid –added masses) for A1-A4



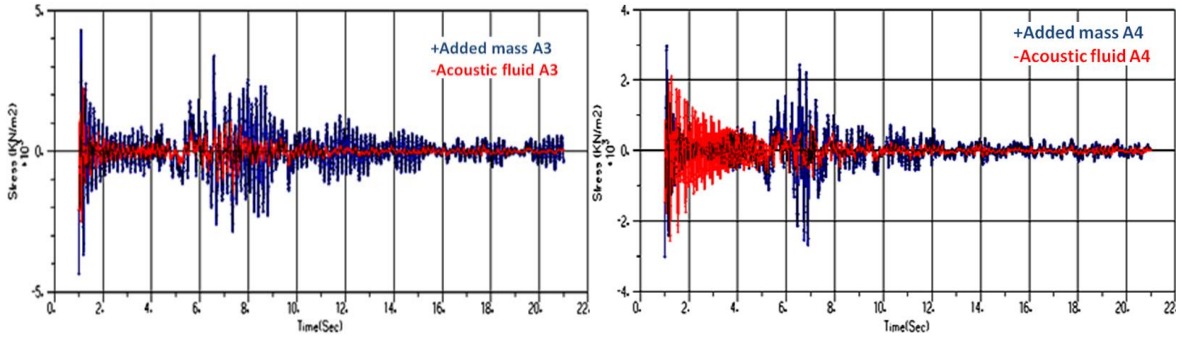


Figure 12: Vertical Stresses at dam heel (added masses vs. acoustic fluid) for A1-A4

The stresses were compared at the heel of the dams. We note that the response of the three highest dams in the first five seconds to the earthquake is the same; the earthquake is the same in the first five seconds, but with double, the values for the incompressible fluid compared to the compressible fluid. In contrast to the lowest dam, the stress values increase after the first to the fifth second in the compressible fluid. Regarding the effect of length on the stresses at the dams' heel for the two fluids, the frequency content is similar, but the vertical stresses increase as the dam height increases with appreciable values in the incompressible fluid. The amplifications and changes in the response of the dam due to the added mass are clearly visible.

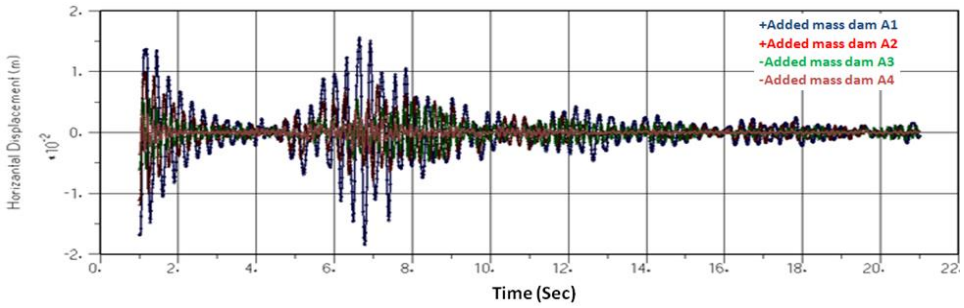


Figure 13: Crest horizontal displacements of full gravity dams (added masses)

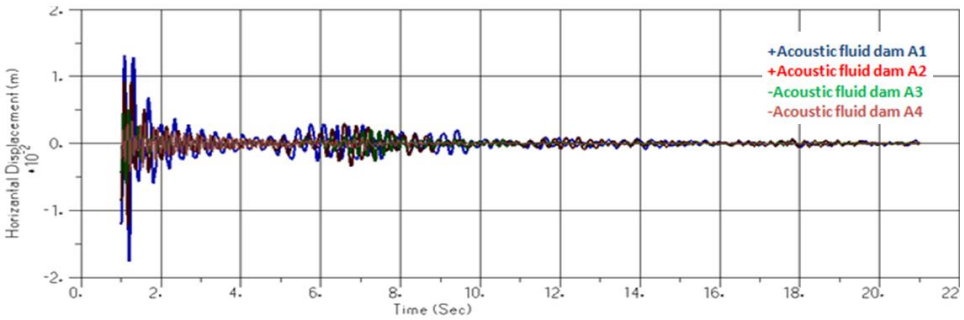


Figure 14: Crest horizontal displacements of full gravity dams (acoustic fluid)

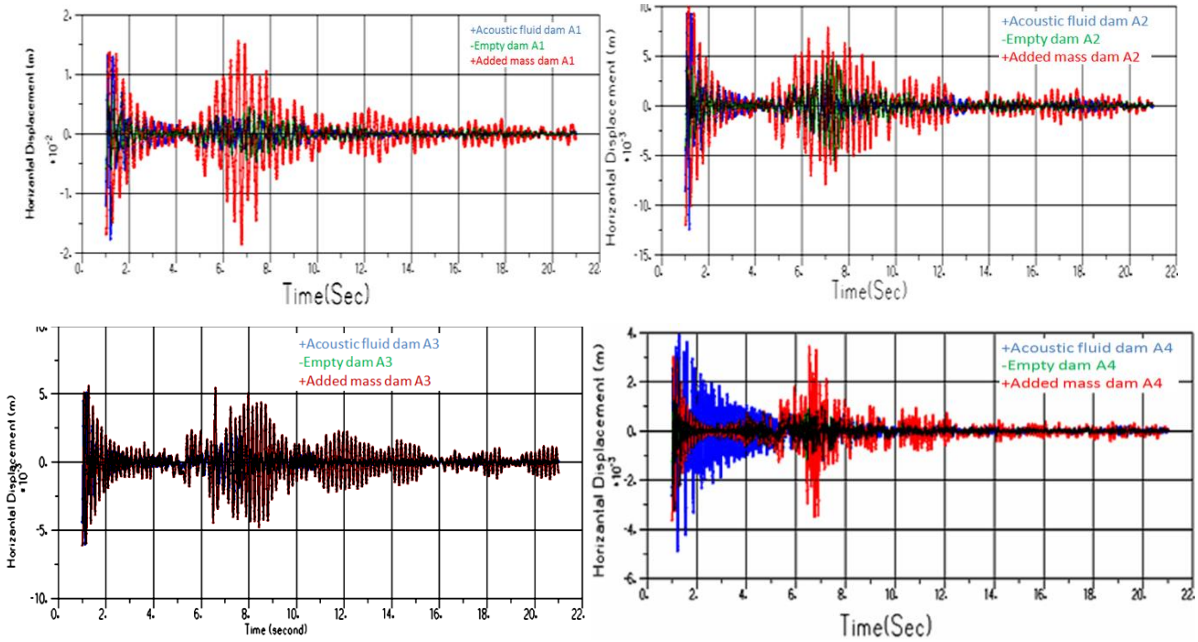


Figure 15: Crest horizontal displacements (added masses vs.acoustic fluid)

Figures13-15 show the time history of the horizontal displacement at the dam's crest (crest point) upstream of the empty and full reservoir cases. The maximum values of horizontal displacement noted at the dam's crest empty reservoir were 5.87, 5.44, 2.44 and 1.27mm for modelsA1, A2, A3, and A4, respectively. For the full reservoir, the horizontal displacements noted at this point were18.46, 11.96, 6.09 and 3.60mm respectively. Therefore, an increase of 68.2, 54.51, 59.93 and, 64.7%, respectively, is observed between the results of an empty and full reservoir (added masses). It is obvious that the horizontal displacements obtained from the full reservoir case are higher than the ones obtained from the empty reservoir case due to the effect of hydrostatic and hydrodynamic pressure of the reservoir water. The maximum values of horizontal displacement noted at this point are 17.76, 12.36, 6.02, and 4.85 mm for the full reservoir (acoustic fluid). Therefore, an increase of 66.94, 55.98, 59.46 and, 73.81%, respectively, is observed between the results of both cases (empty and full reservoir (acoustic fluid).So, the displacements of the crest in the horizontal direction due to the hydrodynamic effect of an incompressible fluid increases by 5% compared to the horizontal displacements of the crest dams of compressible fluid.

4 Conclusions

In this study, the effect of the hydrodynamic pressure of the reservoir on the response of concrete dams subjected to seismic excitations was studied. The results of the study were obtained in terms of displacement and, stresses. Based on the results, the following conclusions are drawn:

1. The natural period of the dam increases with an increase in height for a constant ratio of the bottom's width to height.
2. The time analysis with an "incompressible fluid" material model provides different results when the compressibility of the fluid is considered.

3. Crest displacement is maximum at the peak of the dam and increases with the height of the dam, hence proper measures should be taken while designing dams.
4. According to the analysis of the vertical stresses, the heel element has the most stress absorption compared to the other parts of the dam.
5. The displacement of the crest in the horizontal direction due to the hydrodynamic effect of an incompressible fluid increases by 5% compared to the horizontal displacement of the crest dams of compressible fluid.
6. Regarding the effect of fluid compression, it was found that for concrete gravity dams, the response of the structure in terms of displacement is not significantly affected; on the other hand, the vertical stresses are particularly amplified at depth.
7. The tensile strength under dynamic loading increases significantly in an incompressible fluid bed. The level of seismic cracking at the base of the dam is likely to be significant. A non-linear analysis is required.

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