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A Preliminary Dynamic Study on Vibrations Free of the Influence of Upstream Reservoir Boundary Condition in the Concrete Gravity Dam

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Abstract-The effect of fluid-structure interaction can play a key role in dam designs, increasing its relevance in dynamic analyzes: seismic or reservoir-induced vibrations (induced earthquakes). In general, the reservoir dam coupled problem (IBR) involves a complex problem that consists in studying the dynamic behavior of two interconnected systems that interact simultaneously. If there are well-defined boundary conditions such as at the structure-reservoir or reservoir-foundation interface, for the simplest assumptions - flexible structure, compressible fluid and rigid foundation, the problem of distant surface and free surface wave dissipation effects presents difficulties. of representation and modeling, which influence the frequency-coupled fluid structure evaluations, so important in understanding the behavior of the systems involved. Thus, the objective of this work is to study the changes in the natural frequencies of the coupled system in free vibrations, caused by the influence of different distant boundary conditions imposed on the reservoir: zero pressure, rigid wall, and non-return condition. of the waves (Sommerfield condition). The adopted methodology comprises in a comparative study between the analytical formulations related to each type of boundary condition with the results obtained by numerical tools via ANSYS software. For this study, a dam with typical dimensions of Brazilian structures was analyzed considering the concrete with homogeneous and isotropic properties, and the set within a linear analysis.

Keywords- *Concrete Gravity Dam, Dynamic Analysis, ANSYS*

I. INTRODUCTION

Dams are of great economic and social importance to society, by providing the main resource for energy production, food and to smooth losses due to long droughts periods in certain places. However, these structures have a high risk as a result of their possible rupture, which can lead to deaths, as well as the destruction of local fauna and flora. It is therefore important to have the maximum knowledge about these structures, the place of installation and their history, so that allows a high level of assurance to both designers and society about the safety of the structure.

In Brazil, the constant concern of designers mainly involves the problems related to static evaluations and their relations with the stability of the structural system. However, this structures requires the evaluation of possible consequences caused by the dynamic actions, since it should no longer be Considering Brazil a seismic activity free country, a fact evidenced by the advances in the country's seismological area, and the reservoir filling can trigger earthquakes near the dam region and its structural elements by induced seismicity.

Given the above, it should be emphasized that the evaluation of the fluid-structure interaction in concrete gravity dams is constituted by a coupled system that involves two medias (dam and reservoir), in which the understanding of the boundary conditions is imperative for solution of the problem involved. Another highlight is related to the fact that these medias must be evaluated in a coupled and uncoupled form, since the domain of a certain media in the uncoupled form may be related to the coupled system.

Another highlight pointed by Silveira [1] mentions the importance of studying the effects of fluid-structure interaction (IFE), since for the study of seismic or fluid-induced vibrations in dams in which the movement of the structure inevitably causes a fluid movement, which remains in contact with the structure walls, as a result, the fluid-structure assembly constitutes a coupled system for which it is often impossible to consider responses and excitations separately.

Moreover, dynamic dam evaluation is a complex problem because it involves elements and formulations related to the coupling between the media that require a high level of knowledge for their understanding, for example: fluid-structure interaction. These notes have been studied by many international researchers, as well as by the Fluid-Structure group (FSDG) of the University of Brasilia (UnB) that stands out in the various studies on static and / or dynamic analyzes on concrete gravity dams and related structures under various aspects of IFE and which have also contributed in some way to this work, such as the work done by França Júnior et al [2-3], Pedroso [4], Mendes [5], Lopez [6], Mendes et al. [7], Silveira and Pedroso [8-9].

II. THEORETICAL FORMULATION

The dam-reservoir resting fluid coupling model is governed by two-dimensional wave equation:

$$\nabla^2 p = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} \tag{1}$$

Where c is the wave velocity, p is the hydrodynamic acoustic pressure and t is the time. This mathematical problem described by equation [1] with the respective boundary conditions presented in Figure [1], leads the equation of the dam - reservoir coupled system. By assessing the non-return condition of the wave on surface 3, the general fluid-structure equation for these problems is presented in equation [2].

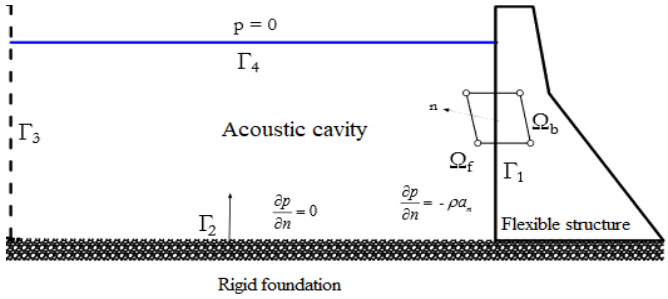


Figure 1. Fluid-structure interaction system and their boundary conditions

Equation [2] involves terms of the structural motion, fluid motion and coupling, where [M], [K] and [C] represent, respectively, the mass, stiffness and damping matrices, and the indices b and f refer to the dam and the fluid, respectively. The matrices [U] and [P] characterize, respectively, the displacement of the structure and the pressure in the fluid, and the term [Q] represents the coupling matrix between the fluid and the structure.

$$\begin{bmatrix} M_b & 0 \\ \rho Q^T & M_f \end{bmatrix}\begin{Bmatrix} \ddot{U}_b \\ \ddot{P}_f \end{Bmatrix} + \begin{bmatrix} C_b & 0 \\ 0 & C_f \end{bmatrix}\begin{Bmatrix} \dot{U}_b \\ \dot{P}_f \end{Bmatrix} + \begin{bmatrix} K_b & -Q \\ 0 & K_f \end{bmatrix}\begin{Bmatrix} U_b \\ P_f \end{Bmatrix} = \begin{Bmatrix} -M_b \ddot{U}_b \\ 0 \end{Bmatrix} \tag{2}$$

This work, however, will implement the three boundary conditions facing the longitudinal surface of the reservoir, evaluating the difference between the results and presenting the main difficulties in their implementation, as well as the efficiency of each one.

III. PARAMETERS AND MODEL DEFINITION

To obtain the dynamic response, the modal analysis was performed in which the natural frequencies and their respective modal deformations were determined with the aid of the numerical tools ANSYS. In the structure modeling, the following physical properties were used for dam concrete: specific mass 2400 kg / m3, Young 25GPa modulus, Poisson's ratio 0.25. Physical properties of water are: sound velocity 1440 m/s and specific mass 1000 kg/m^3.

For the modeling of the systems in the ANSYS software, the finite element element Plane 183 was used for the structure (plane deformation state). This element has 8 nodes with two degrees of freedom each node, which features a high convergence element. Many analyzes use a similar element, Plane 182, but have 4 nodes with 2 degrees of freedom each node. These two elements are presented below in Figure 2.

which have already been evaluated in other reports, and validated Plane 183's best convergence capacity relative to Plane 182

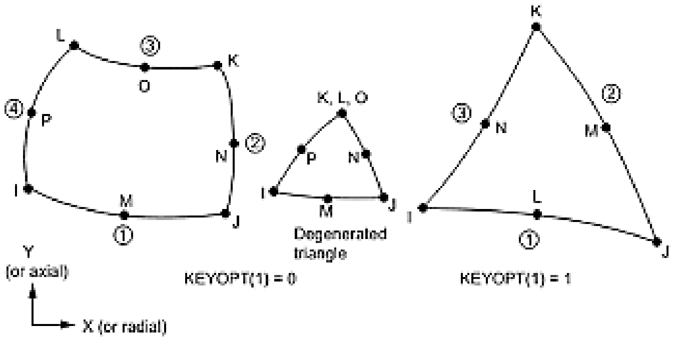


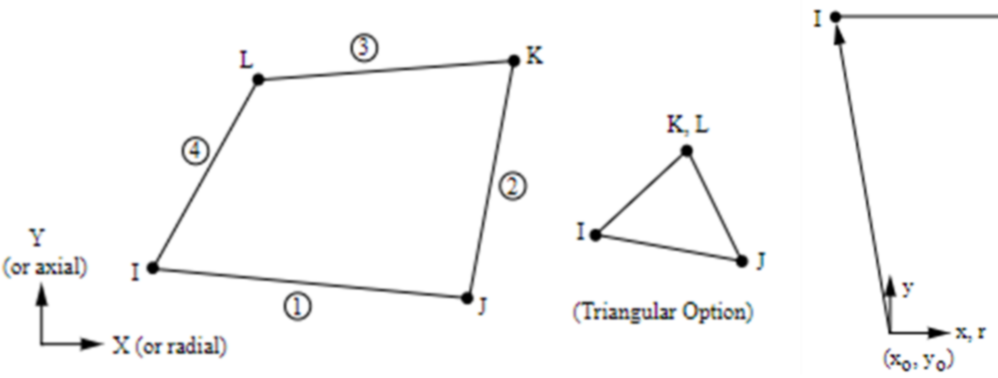
Figure 2. Plane Element ANSYS (Library ANSYS)

For the reservoir, the acoustic element FLUID29 was used, and at the far edge of the reservoir, the FLUID 129 element was used for the case that had the condition of absorption of waves in the contour (no return of the wave - Sommerfield condition). These two elements are presented in Figure 3.

Developing the FLUID129 in more detail, this element was developed as a complement to FLUID29, and is intended to simulate the absorbing effects of a fluid domain extending to infinity beyond the limit of the FLUID29 finite element domain. It performs a second order absorbent limit condition, so that an output pressure wave that reaches the model boundary is "absorbed" with minimal reflections back into the fluid domain and can be used to model the limit of the 2-D fluid regions (flat or axisymmetric) and as such is a line element; It has two nodes with a degree of freedom of pressure per node. In addition, FLUID129 can be used in transient, harmonic and modal analysis. Typical applications include structural acoustics, noise control, underwater acoustics, etc.

The case studies analyzed in this paper are oriented towards the analysis of a typical 2 D profile of Brazilian dams, in accordance with the conditions, and physical constants prescribed in this section.

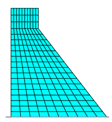
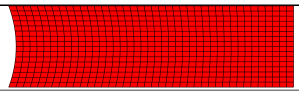
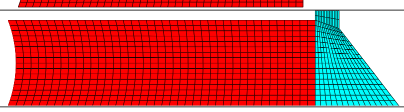
Table 1 illustrates the plan of the simulations performed in this work for the modal dynamic analyzes performed with the coupled and uncoupled systems. The simulations include the influence of the boundary condition to the far boundary of the reservoir (zero pressure, rigid wall and non-return wave or absorbent element condition - Sommerfield condition)



(a) (b)

Figure 3. Fluid 29 Element (a) and Fluid129 Element – Library ANSYS

TABLE I. DAM-RESERVOIR SYSTEM ANALYZES MODEL

	System	Sketch	Reservoir boundary
Case (Dynamics Analysis)	Dam		---
	Reservoir		Zero pressure Rigid
	DRF		Zero pressure Sommerfield Rigid

IV. RESULTS

According to the methodology adopted and presented in Table 1, this analysis was a function of the evaluation of the decoupled dam and reservoir systems, as well as the coupled dam-reservoir system. Thus, the results were subdivided into three topics in order to understand and relate the modal deformations of the decoupled system to the coupled one, since they interrelate and the dominant medium of the system can be determined.

A. Uncoupled System: Dam

In this case, the values of the natural frequencies and their modal deformations were determined by considering a rigid foundation. The natural frequencies of the structure are shown in Table 2 and their respective modal deformations is in Figs 4.

TABLE II. LOWEST NATURAL FREQUENCIES FOR RIGID DAM (HZ)

Mode	ANSYS
1	4,69
2	11,54
3	12,43
4	20,88

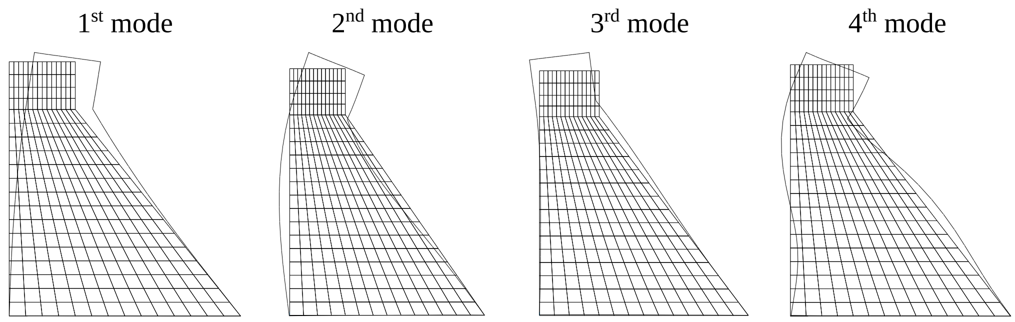


Figure 4. Strucure modal deformations – ANSYS

From these results it can be verified that the first, second and fourth modes are represented mainly by the bending modes; while the third mode resembles a tension mode.

It can also be verified that both numerical results were very similar, which suggests accuracy for the simulation. Moreover, in other internal studies, the evaluation of modeling convergence was validated by comparison with results from other renowned authors.

B. *Uncoupled system: Reservoir*

In the study of free vibrations for the uncoupled reservoir, the condition of zero pressure at the far boundary was used and the natural frequency results were compared with the analytical expression, which represents a closed-open acoustic cavity in the x and y directions. The analytical solution is given by equation 3, for i and j = 1, 2, 3 ..., where c is the velocity of sound in the fluid, L is the length of the reservoir and H is its height.

$$f_{anal.}^{i,j} = \frac{1}{2\pi}\sqrt{(\pi c)^2\left(\frac{(2i-1)^2}{4L^2}+\frac{(2j-1)^2}{4H^2}\right)} \qquad (3)$$

Table 2 presents the results obtained analytically and numerically using the ANSYS software.

TABLE III. RESERVOIR NATURAL FREQUENCIES (HZ)

Mode	ANSYS	Analytical
1	5,20	5,22
2	6,69	6,72
3	8,95	9,01
4	11,52	11,63

Figure 5 show the first four modal deformations for the decoupled reservoir and their respective numerical natural frequencies by ANSYS software and the analytical ones. It is observed that the difference between the frequencies are negligible.

C. *Coupled System: Dam-reservoir*

Then, the coupled dam-reservoir system was evaluated, in which three conditions were studied: rigid wall, zero pressure and no wave return or Sommerfield condition to the far surface of the reservoir.

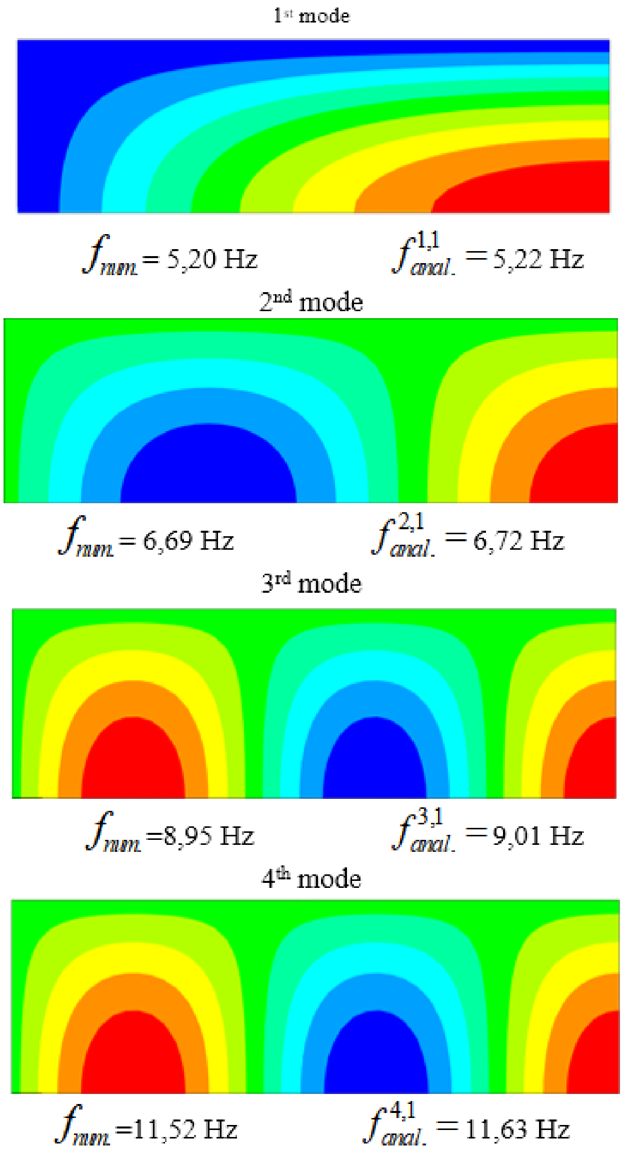


Figure 5. Reservoir and deformations - ANSYS

In order to study the influence of each boundary condition, it was decided to evaluate the first 4 modes of the coupled system, however only the first four modal deformations were compared with the deformed ones of the dam and reservoir decoupled cases.

Thus, it is possible to evaluate the dominant medium of the coupled system, which can be the dam or the additional mass mode of the cavity or mixed in which there is influence of both media.

By initially evaluating the far condition, it was observed that when using both rigid wall and Sommerfield the results are very similar, whereas for zero pressure case there is a slight divergence in some modes compared to the other two cases, as noted by results presented in Table 4.

TABLE IV. NATURAL FREQUENCIES FOR THE DAM-RESERVOIR COUPLED SYSTEM FOR DIFFERENT BOUNDARY CONDITIONS IN THE DISTANT RESERVOIR REGION

Frequencies (Hz)			
Mode	Rigid wall E_c = 500 GPa	Zero pressure	Sommerfield
1°	4.1702	4.1736	4.1712
2°	5.0865	5.3624	5.2692
3°	5.8897	6.7230	6.2601
4°	7.7336	8.8783	8.1253

According to the results presented in Table 4 and compared to the results in Table 2 it was observed that there is a reduction in frequencies with the inclusion of the reservoir in relation to the previous case. Next, the first 4 modal deformations were presented for the studied cases, evaluated in Figures 6, 7 and 8.

V. CONCLUSION

This work presents a dynamic study of the dam-reservoir interaction behavior in terms of free vibrations. For this, finite element models were developed at the ANSYS environment, using APDL language. After performing the simulations presented in this work, some important conclusions were reached, namely:

- In the study of free vibrations, the dam-reservoir (DR) systems were evaluated in the coupled and uncoupled mode for the dam and the reservoir. For these cases, the influence of decoupled modes in relation to the coupled system was observed. Furthermore, it has been observed that the first mode is dam controlled (additional mass), unlike the other higher modes that are controlled by the reservoir;
- Another highlight is the comparison between the far boundary conditions in the reservoir, the zero pressure, rigid wall and Sommerfield condition for rigid foundation. By considering these cases the results were similar, which ensure the simpler condition (zero pressure) and mainly rigid wall similarly reproduces the results for a modal analysis with the most realistic non-return or Sommerfield condition.
- Finally, the authors recommend that for a dynamic dam analysis, all parameters involved should be analyzed in a consistent manner to the conditions present in the dam-reservoir system. With respect to the reservoir, simplified models of additional mass, zero pressure and rigid wall at far boundaries can be considered, particularly in preliminary design steps.

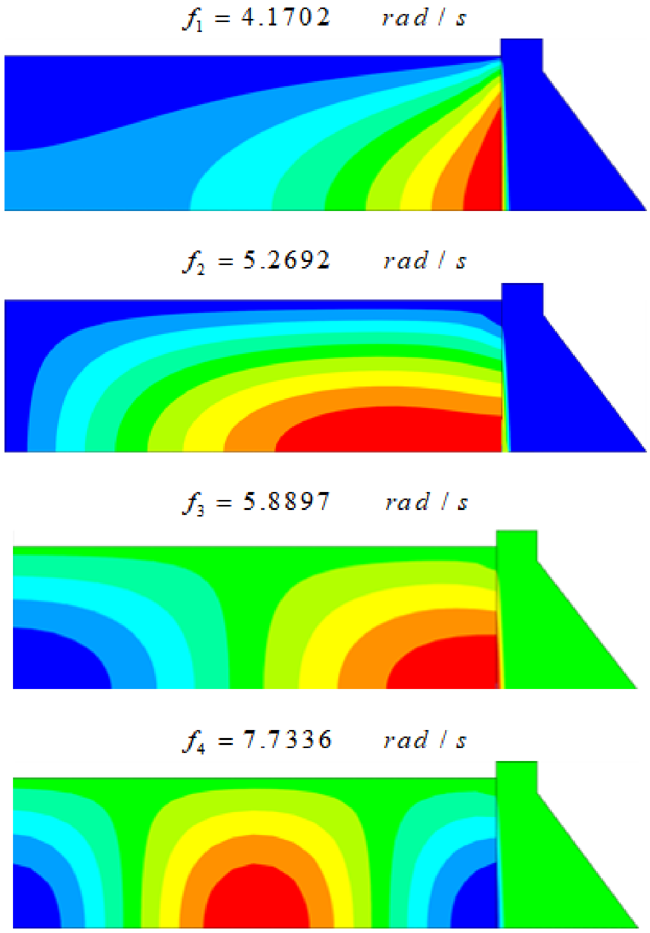


Figure 6. Modal deformation for the dam-reservoir coupled system considering the rigid wall at the far end of the reservoir

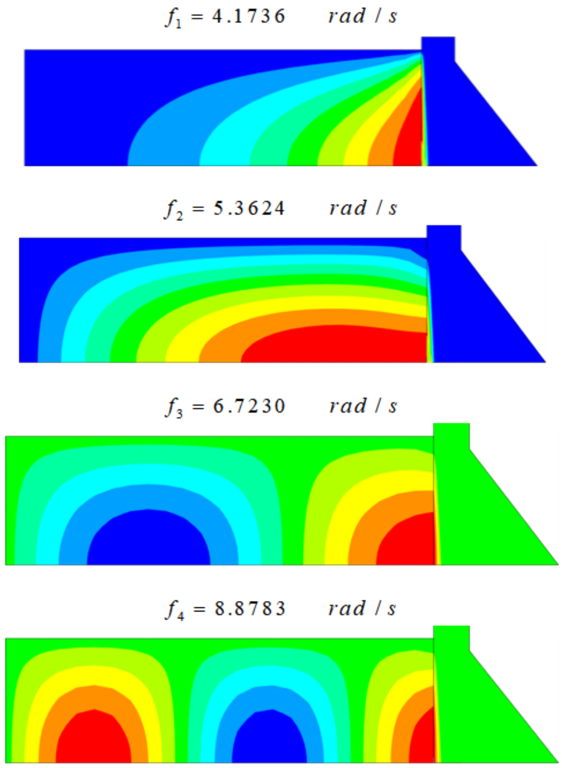


Figure 7. Modal deformations for the dam-reservoir coupled system considering the zero pressure at the far end of the reservoir.

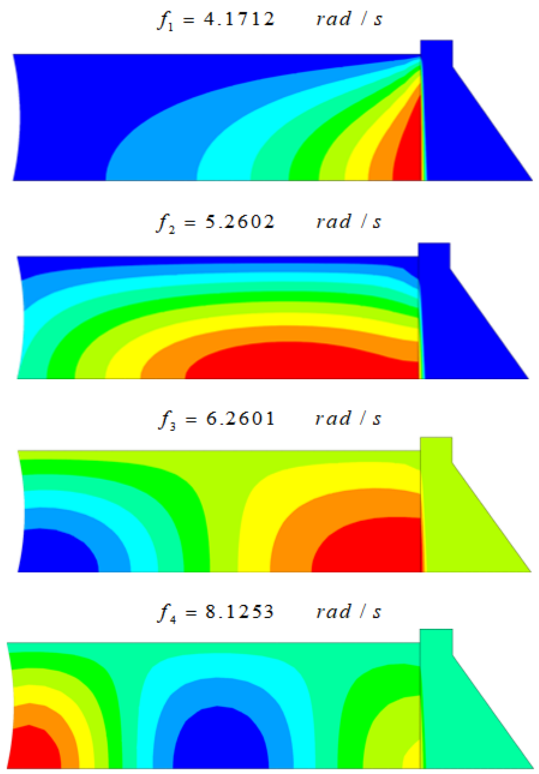


Figure 8. Modal deformations for the dam-reservoir coupled system considering the Sommerfield condition for the reservoir far

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