Influence of structural damping and fluid compressibility on harmonic vibrations in concrete gravity dam

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Abstract

In this research, the coupled fluid-structure forced vibrations (harmonic load) of the Koyna gravity dam are studied. Using the finite element method (FEM), the influence of structural damping and fluid compressibility are studied for different reservoir dimensions of the dam. The numerical approach is done through the U-P formulation (structure displacement and pressure for fluid). Thus, the spectral response of structural displacements and of hydrodynamic pressures were investigated with different structural damping rates, both considering incompressible and compressible fluids. With analyses, the greater the effect of the structure's damping, the lower the displacement and the hydrodynamic pressure amplitudes. The structural damping has the same effect tendency in both incompressible and compressible fluids. Furthermore, for the incompressible fluid, the coupled modes are not influenced by the length of the reservoir, there are no acoustic modes identified and the mass modes are predominantly identified. With the compressible fluid, the analysis of the dominant modes showed that the fundamental mode is not altered by the length of the reservoir, but from the second mode onwards, each cavity geometry predominates in the vibration, and it is necessary to evaluate the frequency range of the structure and the fluid separately. Therefore, the harmonic numerical analysis of the present study contributes with innovative results of the Koyna dam and in the analysis of the effects involved in Fluid-Structure Interaction (FSI) simulations of other problems related to Dam-Reservoir Interaction (DRI).

Keywords: Finite Element Method, dam-reservoir interaction, fluid-structure interaction.

1. Introduction

Dams are generally large structures with a considerable variety of uses and purposes according to the needs of the region where each is implemented. In the field of dam engineering, it is essential that the minimum safety conditions are guaranteed, since the rupture of such structures can lead to immense economic and social catastrophes.

In the coupled dynamic analysis of dam-reservoir interaction (DRI), the presence of the liquid pressure distribution (hydrodynamic pressures) influences directly on the vibration modes of the structure and the various parameters of the structure influence the fluid response, producing a complex phenomenon of fluid-structure interaction (FSI).

The coupled dam-reservoir frequencies depend on the frequency range of the decoupled structure and the frequency range of the decoupled reservoir (fluid) domain. Thus, each frequency can produce dominant modes coupled with the additional mass structure (AM) in the incompressible regime, the dominant cavity modes (CM) in the compressible regime or mixed modes (MM). The hydrodynamic pressures are related to the effect of fluid compressibility, which depends on the behavior of the systems involved (structure and fluid).

When designing dams, the maximum height of impounded liquid (L_z) imposes the most unfavorable effects on the structure. Thus, the length of the reservoir (L_x), that should be adopted in simulations, is an important variable to study, since different lengths alter the frequency ranges of the fluid, and consequently, alter the fluid compressibility regime, which in turn changes the frequencies and coupled modes of the dam-reservoir problem.

In the studies related to DRI to evaluate the effect of hydrodynamic pressures and coupled modes, the classic study by Westergaard (1933) considered only the aspects of the inertial coupling of the liquid (additional mass), assuming the dam displacement as rigid-mobile. Then, in the studies of Chopra & Chakrabarti (1972) and Chopra (1978), the effect of fluid compressibility on DRI was investigated, emphasizing that these compressibility effects cannot be neglected and express a field of significant hydrodynamic pressure for design.

Later, with the advancement of the finite element method (FEM), both analytical and numerical studies on DRI were expanded, involving more complex situations, such as the studies of Chopra & Chakrabarti (1981), Hall & Chopra (1982) and in Ftima & Léger (2006). These studies addressed aspects related to foundation flexibility and fluid-structure dynamic interaction in dams.

Silva (2007) used a technique for the separation of variables and developed analytical solutions for the field of hydrodynamic pressures, considering the IFE in rigid-mobile and flexible dams, both in the incompressible regime and compressible regime. Ribeiro (2010) developed an analytical procedure for solving the frequencies and modes of the dam-reservoir coupled a system called the Pseudo-Coupled Method. Bouaanani & Perrault (2010) created a simplified analytical procedure to determine the natural frequencies and hydrodynamic pressure vibration modes of the dam-reservoir interaction and compared it with numerical solutions.

The problem of DRI through the finite element method is also evidenced in more recent research, such as the study of Pelecanos *et al.* (2016) that investigated the effects of dam-reservoir interaction on the dynamic response of concrete dams. The accelerations at the crest of the dam were studied under a harmonic acceleration load. In some cases of dams, the upstream reservoir significantly affected the accelerations of the structure. The analysis of the influence of the foundation and the reservoir on the dynamic response of dam-gravity is presented in the articles of Silveira (2018) and Silveira *et al.* (2021).

Other studies relevant to the DRI theme can still be mentioned, such the analytical-numerical and experimental study of dynamic fluid-structure interaction problems with application to concrete locks and dams in França Júnior (2022). Silveira *et al.* (2023) analyzed the state of stress in the characteristic of reservoir-induced earthquakes for a case study of Irapé in Minas Gerais. Ye *et al.* (2023) applied Computational Fluid Dynamics (CFD) to perform the numerical calculation of hydrodynamic pressures in dams excited by harmonic vibration. The dam vibration amplitude, the period variation and the reservoir water depth influenced the hydrodynamic pressures in dams.

Thus, regarding the studies found in literature, herein, the forced vibrations (harmonic load), decoupled and coupled fluid-structure, of the Koyna gravity dam, located in India, are presented.

The frequency response spectrums of the structural displacements and hydrodynamic pressures were investigated for different relationships $\Upsilon = L_x / L_z$ (length/height) of the reservoir and structural damping rates, considering incompressible and compressible fluid, using the finite element method and the ANSYS® software.

It is worth mentioning that this article is a continuation of the study presented in França Júnior *et al.* (2022), where the coupled fluid-structure analysis in free vibrations of the Koyna dam was carried out for the same $\Upsilon = L_x / L_z$ (length/height) ratios of the reservoir. At the time, the following were studied: the natural frequencies, structural vibration modes and hydrodynamic pressures. Therefore, the values obtained in the modal analysis carried out by França Júnior *et al.* (2022) are then compared with the response spectra and effects obtained in this study.

Therefore, this study contributes with advances in the analysis when compared to the research carried out in França Júnior *et al.* (2022), and in view of the bibliography cited, contributes with innovative results from the Koyna dam, specifically in the study of fluid compressibility (incompressible and compressible) and the dominant modes for different structure damping effects and reservoir lengths (far boundary).

2. Theoretical formulation for the Dam-Reservoir Interaction (DRI)

The fluid-structure interaction problem is analyzed using the U-P formulation, with displacement as the variable for the structure and pressure as the variable in the fluid domain. In discretization using FEM, the problem is idealized by simulation of the structural response using interpolating functions that are defined for each type of finite element. Thus, having the constitutive relationships, the physical properties of the fluid and structure's material, the interpolating functions allow the creation of the problem's mass, damping and stiffness matrices.

The U-P formulation unites the two equations for motion (of the structure and of the fluid). The matrices relating to the structure are derived from the classical dynamic equilibrium equation for continuous systems. In the fluid domain, the problem is solved using the Helmoltz's formulation (wave equation), which is the governing equation for the vibration problem of confined fluids (acoustic media, which considers the distribution and propagation of acoustic pressures.

Fluid-structure coupling is achieved by integrating the pressures at the fluid-structure interface, which consequently, transfers the fluid forces to the structure's equation of motion as an external force. With this, the fluid-structure (FS) coupling matrix is generated, which couples the effects. The complete U-P formulation can be found in França Júnior (2022), Pedroso (2003), and many others. In compact form the U-P formulation is given by:

$$\begin{bmatrix} [M_S] & [0] \\ \rho_f [FS]^T & [M_f] \end{bmatrix} \begin{Bmatrix} [\ddot{u}] \\ [\ddot{p}] \end{Bmatrix} + \begin{bmatrix} [C_S] & [0] \\ [0] & [C_f] \end{bmatrix} \begin{Bmatrix} [\dot{u}] \\ [\dot{p}] \end{Bmatrix} + \begin{bmatrix} [K_S] & [-FS] \\ [0] & [K_f] \end{bmatrix} \begin{Bmatrix} [u] \\ [p] \end{Bmatrix} = \begin{Bmatrix} [F_E] \\ [0] \end{Bmatrix} \quad (1)$$

Where ρ_f is the specific mass of the fluid, $[F_E]$ is an external force vector, $\{u\}$ is the structure displacement vector, $\{\dot{u}\}$ is the structure velocity vector, $\{\ddot{u}\}$ is the structure acceleration vector, $[M_S]$ is the structure mass matrix, $[K_S]$ is the structure stiffness matrix, $[C_S]$ is the structure damping matrix, $[p]$ is the pressure vector, $\{\dot{p}\}$ is the pressure velocity vector, $\{\ddot{p}\}$ is the pressure acceleration vector, $[M_f]$ is the fluid mass matrix, $[C_f]$ is the fluid damping matrix, $[K_f]$ is the fluid stiffness matrix and $[F_S]$ is the fluid-structure coupling matrix that correlates the nodal pressures at the fluid-structure interface with the nodal displacements of the structure. The matrices cited are expressed by:

$$[M_s] = \int_V \rho_s \cdot [N_u]^T \cdot [N_u] \cdot dV \quad (2)$$

$$[C_s] = \int_V [N_u]^T \mu_s \cdot [N_u] \cdot dV \quad (3)$$

$$[K_s] = \int_V [B_u]^T [D] \cdot [B_u] \cdot dV \quad (4)$$

$$[M_f] = \int_{\Omega f} \frac{1}{\rho_f c^2} \cdot [N_p]^T . [N_p] \, . \, d\Omega f \quad (5)$$

$$[C_f] = \int_{\Omega f} \frac{4\mu_f}{3\rho_f^2 c^2} \cdot [B_p]^T . [B_p] \, . \, d\Omega f \quad (6)$$

$$[K_f] = \int_{\Omega f} \frac{1}{\rho_f} \cdot [B_p]^T . [B_p] \, . \, d\Omega f \quad (7)$$

$$[FS]^T = \int_{\Gamma_{FSI}} [N_u]^T . \vec{n} . [N_p] \, . \, d\Gamma_{FSI} \quad (8)$$

Where $[B_u]$ is the matrix of the derivative of element shape functions, $[D]$ is the stress-strain elastic matrix, $[N_u]$ is the matrix of structural element shape functions, μ_s is a viscosity parameter of the structural material which imposes a constant viscous-type resistance on the material, dV is the volume differential, ρ_s is the specific mass of the structural material, the index T means transposed in the matrix, $d\Omega_f$ is the domain of the reservoir, $[N_p]$ is the matrix of fluid shape functions, $[B_p]$ is the matrix of derivatives of the fluid pressure shape functions, ρ_f is the specific mass of the fluid, μ_f is a viscosity parameter of the fluid, c is the wave propagation speed in an acoustic medium, Γ_{FSI} is the dam-reservoir interaction coupling surface.

Equation (1) is valid for the DRI problem in free vibrations or forced vibrations. In a system of undamped free vibrations, the terms of Equation (1) associated with external actions and structural damping are null, that is, $\{F_E\} = 0$ and $[C_S] = 0$. In this study, in the harmonic analysis, the vector external load is $\{F_E\} = \{P_0 \cdot \mathrm{sen}(f_\omega\ t)\}$, where P_0 is the amplitude of the harmonic load, f_ω is the excitation frequency and t is the time. The boundary conditions of the problem under study are shown in Figure 1.

3. Methodology and description of numerical models

The Koyna dam (Figure 1a), object of study in this research, is in the state of Maharashtra, India. According to Chopra (2020), the concrete of the Koyna dam has physical properties, such as: specific mass (ρ_s) equivalent to 2643 kg/m³, modulus of elasticity (E) of 31027 MPa, Poisson's ratio (ν) equal to 0.20. The modeling of the dam structure was performed according to a plane deformation state (Figure 1b) in the ANSYS® software, in which the PLANE183 finite element was used to discretize the structure. The boundary condition of the dam was clamped in the base; that is, a rigid foundation was assumed.

The rectangular reservoir (Figure 1c) was assumed to have a height (L_z) of 91.74 m and three different longitudinal lengths (L_x) of 91.74 m, 385 m and 642.18 m. The three distinct lengths reflect in three different length/height ratios ($\Upsilon = L_x / L_z$) of the reservoir, being: $\Upsilon = L_x / L_z = 1.0$; $\Upsilon = L_x / L_z = 4.2$ and $\Upsilon = L_x / L_z = 7.0$. The specific mass of the fluid corresponds to 1000 kg/m³ and for fluid considered compressible, the wave propagation velocity in the medium (c) is equal to 1440 m/s. For fluid considered incompressible, c tends to infinity ($c \rightarrow \infty$).

The FLUID29 element was used to discretize the fluid. The fluid boundary conditions are zero pressure (p = 0) at the free surface and at the far boundary of the finite end of the reservoir, as well as the rigid boundary condition ($\partial p/(\partial \vec{n})$=0), which is applied at the reservoir base (rigid foundation at the reservoir base). The fluid-structure condition is applied to the contact interface between the dam and the fluid (Figure 1c).

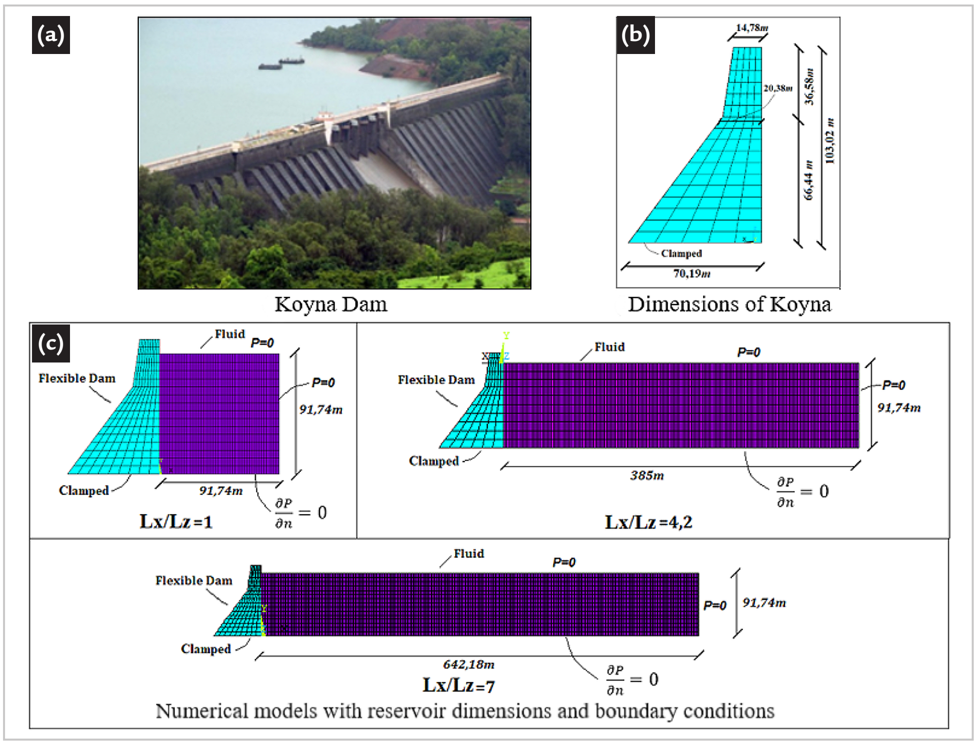

Figure 1 - Numerical models of the Koyna dam for different ratios Υ (L_x / L_z) studied in this research.

It is worth mentioning that this study continues the analysis carried out in França Júnior *et al.* (2022). At the time, the values of the natural frequencies and vibrations modes associated with the free vibrations uncoupled (vacuum) and coupled fluid-structure were studied by França Júnior *et al.* (2022) and the results validated based on the research of Chopra (2020). From the validated numerical model, this present study realized the harmonic analysis for the three different length/height ratios ($\Upsilon = L_x / L_z$) of the reservoir, where there is considered incompressible ($c \rightarrow \infty$) and compressible fluid (c = 1440 m/s), with different damping ratios (ξ=2%, ξ=4% and ξ=6%) for the structure. Thus, a total of 12 (twelve) different simulations were carried out in this study. The frequency spectra obtained express the influence of structural damping, the three different length/height ratios ($\Upsilon = L_x / L_z$) of the reservoir and fluid compressibility. Figure 2 shows the points of analysis, namely: place of application of the load (point A), place of obtaining the displacements of the structure (point B) and place of obtaining the hydrodynamic pressures in the fluid (point C and D).

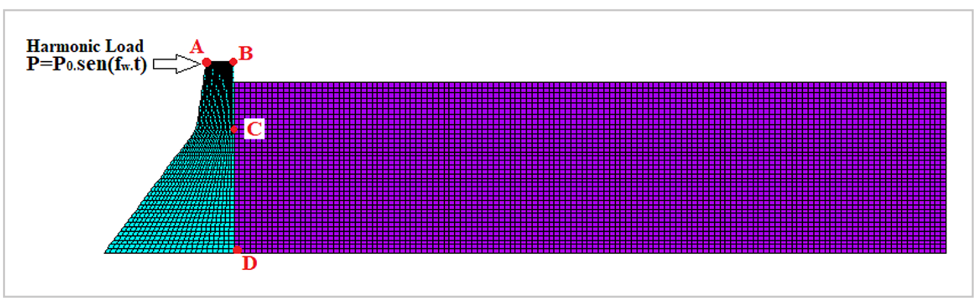

Figure 2 - Harmonic analysis points in the numerical models.

For this study, a point harmonic load was imposed on the left end of the dam crest in the same flexural direction of the vibration of the structure (point A – Figure 2) of the form $P = P_0$ sen(f_ω t) where the amplitude applied load the P0=10000N. The excitation frequency (f_ω) of the load was varied from 0 to 10 Hz. Furthermore, when the fluid is considered incompressible, c was considered infinite through a very high value.

In the first case, the influence of the structural damping and the compressibility of the fluid on the DRI was studied with relation to Υ=4.2, being analyzed assuming different damping rates (ξ) equal to 2%, 4% and 6%. The damping effect is small (subcritical damping) and the purpose of harmonic analysis is to analyze the transition between additional mass (AM) and cavity dominant (CD) modes.

In the second case, the influence of reservoir dimensions and fluid compressibility on DRI was studied. Thus, the frequency sweep was performed for different Υ ratios (Υ=1.0, Υ=4.2 and Υ=7.0) with fixed damping ratios (ξ) equal to 2%.

4. Results and discussions

4.1 Influence of structural damping and fluid compressibility on DRI

Through harmonic analysis, it was possible to obtain the frequency spectra with curves of displacement amplitudes (point B) and hydrodynamic pressures (point C and D) for different damping ratios as a function of this sweep in the applied excitation frequency. The results are shown in Figure 3, where the compressibility parameter ($\lambda = (f_\omega L_z)/c$) is presented. The compressibility parameter represents the ratio between the speed of the wavelength at the excited frequency and the speed of sound. The value of $\lambda=\pi/2$ expresses the singularity analyzed in the analytical solutions of the DRI problem obtained from the Acoustic Wave Equation analyzed in Pedroso (2003), Silva (2007), Chopra (2020), França Júnior (2022) and others. The parameter $\lambda=\pi/2$ expresses a proximity of the resonance in the coupled problem in relation to the frequency of the uncoupled acoustic fundamental mode.

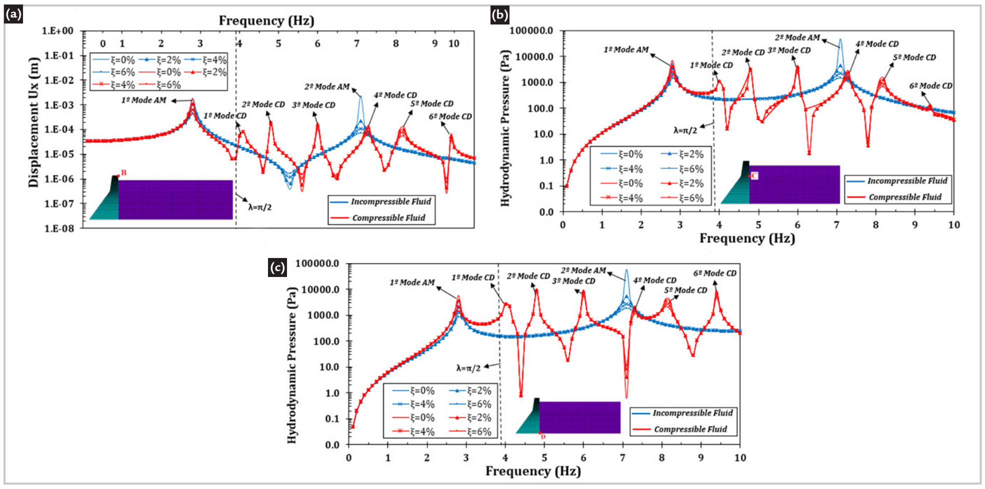

Figure 3 - Frequency spectrum for relationship Υ=4.2, being:
(a) structure displacement in B point, (b) hydrodynamic pressure in C point and (c) hydrodynamic pressure in D point.

In the fluid-structure coupled harmonic analysis (Figure 3), the frequency spectra with resonance referring to the natural frequencies and deformed modal related to the vibration modes studied by França Júnior *et al.* (2022) were obtained. This validates the model in harmonic analysis.

Based on the frequency spectra shown in Figure 3, it may be concluded that the peaks of the curves with displacement and pressure amplitudes occur for applied frequencies equal to the natural frequencies at which the coupled system is being excited. Furthermore, the fundamental mode of vibration (f_ω=2.8Hz) in the coupled phenomenon is an additional mass mode with incompressible behavior. After this frequency, in the compressible analysis, the pressure waves propagate in the cavity and the effect of the fluid's compressibility becomes predominant in the vibration phenomenon (cavity dominant modes CD). In incompressible fluid, the acoustic modes do not appear, with only the second additional mass mode occurring at the frequency of 7.2Hz.

In addition, the greater the effect of the structure's damping (ξ), the lower the displacement and hydrodynamic pressure amplitudes. Damping has the same tendency in both incompressible and compressible fluids. To emphasize what has been said, for the ratio Υ=4.2, the frequency spectra made it possible to identify the vibration modes from the modal analysis. Figure 4 shows the results obtained of the hydrodynamic pressure in the reservoir due to harmonic analysis for the ratio Υ=4.2 and ξ=2% with compressible fluid considered.

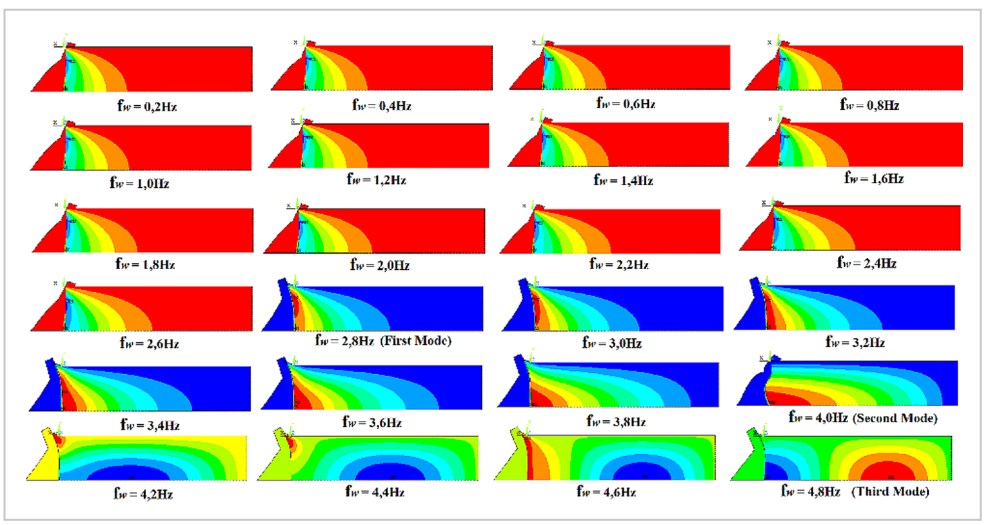

Figure 4 - Hydrodynamic pressure in the reservoir due
to harmonic analysis for the ratio Υ=4.2 and ξ=2% with compressible fluid considered.

In Figure 4, with the harmonic analysis, it is noted that in the fundamental mode in compressible analysis ($0 < f_\omega \leq 2.8$Hz), the structure predominates at vibration and moves the fluid close to it. Then, the dominant coupled mode is the additional mass mode (AM). The structure vibrates in the first mode and predominates over the acoustic cavity. This result is similar to the incompressible behavior due to the low frequencies. For the second coupled frequency ($f_\omega = 4.0$ Hz), the cavity vibrates in the first acoustic mode and predominates over the structure; that is, the structure follows the effect of the fluid. For the third coupled frequency ($f_\omega = 4.8$Hz) the cavity vibrates in the second acoustic mode and the structure also follows the effects of the reservoir. Then, as the excitation frequency increases, the cavity dominant modes are reached, and pressure waves propagate in the acoustic medium. Figure 5 shows the results obtained of the hydrodynamic pressure in the reservoir due to harmonic analysis for the ratio Υ=4.2 and ξ=2% with incompressible fluid considered.

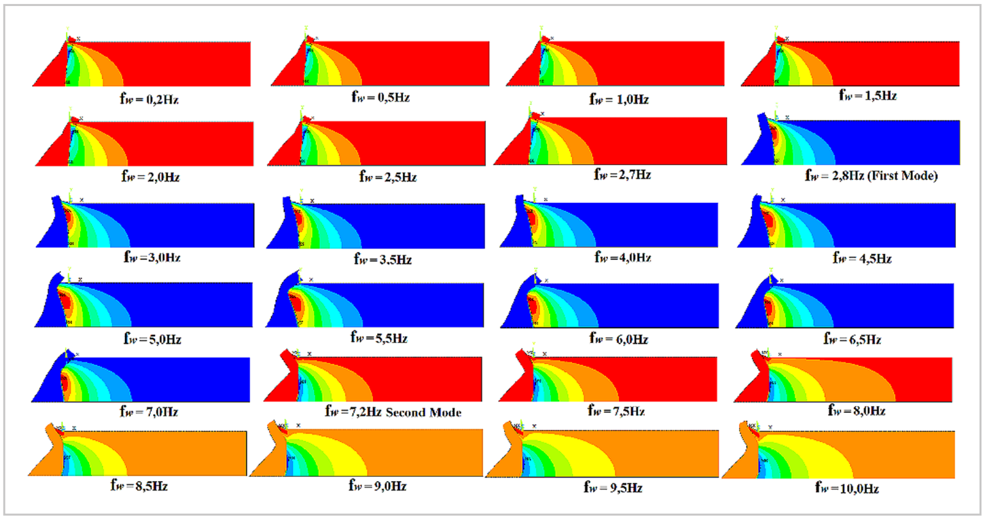

Figure 5 - Hydrodynamic pressure in the reservoir due to harmonic analysis for the ratio Υ=4.2 and ξ=2% with incompressible fluid considered.

In Figure 5, it is noted in the incompressible regime, the structure predominates at vibration and moves the fluid close to it. For the first (f_ω = 2.8 Hz) and second (f_ω = 7.2 Hz) coupled frequencies, the structure predominates over the fluid and vibrates in the first and second uncoupled mode, respectively. At both frequencies, the fluid follows the vibration mode of the structure. Acoustic modes are not found in the incompressible fluid simulation. The analyses in Figures 4 and 5 complement the effects found in Figure 3.

4.2 Influence of reservoir dimensions and fluid compressibility on DRI

Through harmonic analysis, it was possible to obtain the curves of displacement amplitudes (point B) and hydrodynamic pressures (point C and D) for different Υ ratios (Υ=1.0, Υ =4.2 and Υ =7.0) as a function of this sweep in the applied excitation frequency. The damping ratio (ξ) is fixed equal to 2%. The results are shown in Figure 6.

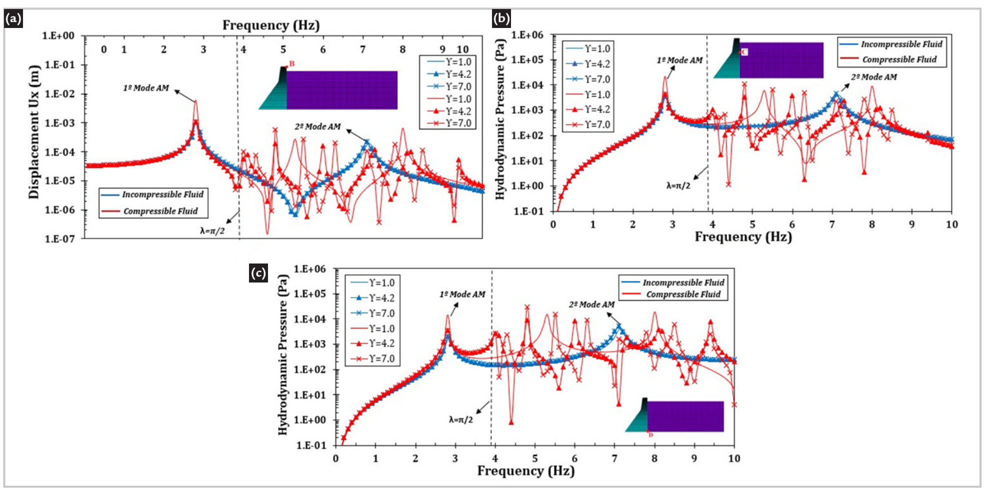

Figure 6 - Frequency spectrum for different Υ ratios and ξ=2%, being: (a) structure displacement in B point, (b) hydrodynamic pressure in C and (c) hydrodynamic pressure in D.

In Figure 6, it is possible to notice that the first fundamental mode of vibration is a well-defined mode for the different Υ ratios of the reservoir; that is, the fundamental mode (f_ω = 2.8 Hz) is of additional mass and is independent of the length of the acoustic cavity discretized in the numerical model. After the fundamental frequency, in the compressible analysis, the different pressure waves propagate in the cavity for each ratio ϒ and the effect of the compressibility of the fluid becomes predominant in the vibration phenomenon (dominant modes of the cavity - CD).

In the incompressible fluid, the acoustic modes do not exist, appearing only additional mass modes (f_{ω} = 2.8 Hz and f_{ω} = 7.2 Hz) at the studied frequencies. So, in the incompressible fluid, the ϒ ratio does not influence.

In Figure 7 and Figure 8, shows the results obtained of the normalized hydrodynamic pressure in the reservoir due to harmonic analysis for different the ratio ϒ and ξ=2%, with compressible and incompressible fluid considered, respectively. The analyses in Figures 7 and 8 complement the analyses in Figure 6.

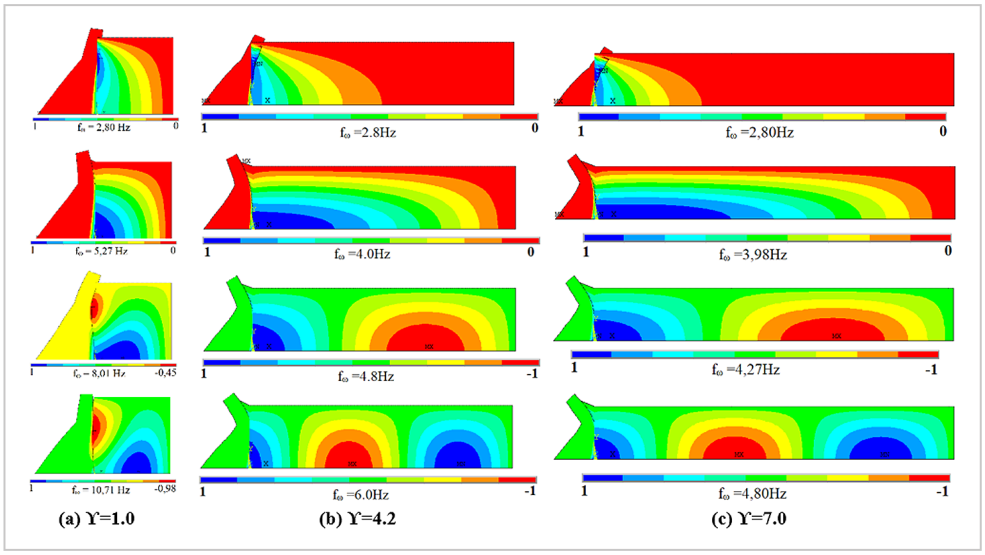

Figure 7 - Normalized hydrodynamic pressure in the reservoir due to harmonic analysis for different the ratio ϒ and ξ=2%, with compressible fluid considered.

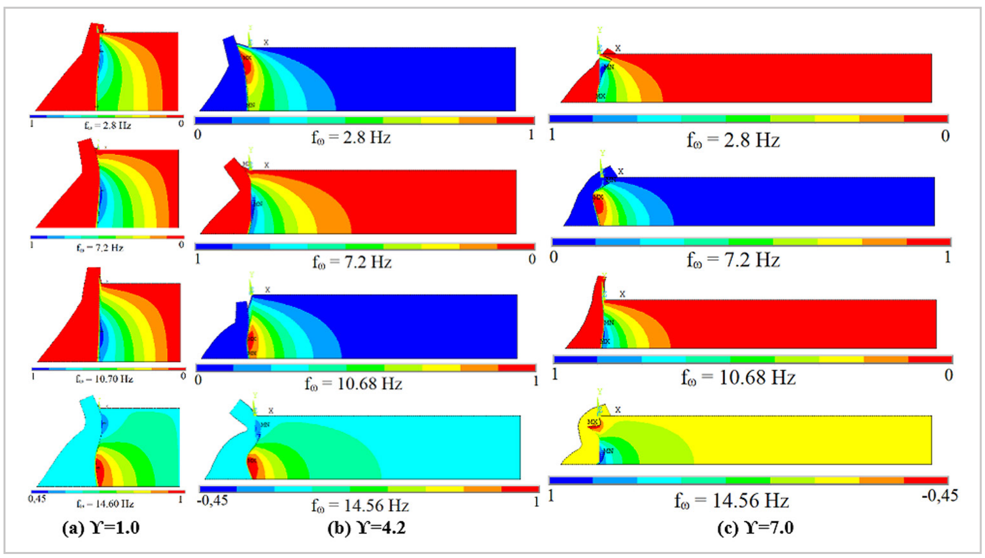

Figure 8 - Normalized hydrodynamic pressure in the reservoir due to harmonic analysis for different the ratio ϒ and ξ=2%, with incompressible fluid considered.

In Figure 7 and Figure 8, in both the compressible and incompressible regimes, the first additional mass mode remains similar for all of the reservoir dimensions. In the compressible regime (Figure 7), for all ϒ ratios, the first mode is an additional mass (dominant structure) with the same frequencies. All the other modes have the resonance governed by the reservoir in acoustic modes, and consequently, have frequencies of different values that depend on the size of the reservoir. Note that the compressible fourth deformed mode of the coupled dam for the ϒ=1 ratio is changed due to the CD transverse mode. In the incompressible regime (Figure 8), for all ϒ ratios, all modes have the same frequency values and, regardless of the length of the reservoir, behave at vibration in a manner governed by the structure.

5. Conclusions

This article showed the free and forced vibrations (harmonic load), uncoupled and coupled fluid-structure, of the Koyna gravity dam. After the different simulations presented herein, some important conclusions were reached and can be listed:

- The greater the effect of the structure's damping (ξ), the lower the displacement and hydrodynamic pressure amplitudes. The structural damping has the same effect tendency in both incompressible and compressible fluids in DRI problems.

- For the incompressible fluid, the analysis showed that the modes are not altered by the length of the reservoir. The cavity acoustic modes do not exist, appearing only additional mass modes at the studied frequencies. So, in the incompressible fluid the ϒ ratio does not influence.
- The analysis of the dominant modes with compressible fluid showed that the fundamental mode is not altered by the length of the reservoir, but from the second mode onwards, each cavity geometry predominates in the vibration, and it is necessary to evaluate each frequency range of the structure and the fluid separately.
- The effect of fluid compressibility on coupled vibrations changes as the cavity coupled with the dam is shorter or longer. In shorter cavities, the effect of compressibility is greater, i.e., pressure waves propagate at a much higher speed than the speed of sound in the acoustic environment.
- Finally, the authors recommend that in a dynamic analysis of a dam, all the parameters involved are analyzed in detail in simulations considering the incompressible and compressible fluid. In general, in DRI problem simulations, it is recommended that the reservoir discretization considers the longest longitudinal dimension L_x, that is, $\Upsilon > 1$. Both the additional mass effect and the acoustic dominant modes converge common effects in these cases.

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