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Dam-reservoir-foundation interaction effects on the modal characteristic of concrete gravity dams

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Abstract. Concrete hydraulic structures such as: Dams, Intake Towers, Piers and dock are usually recognized as" Vital and Special Structures" that must have sufficient safety margin at critical conditions like when earthquake occurred as same as normal servicing time. Hence, to evaluate hydrodynamic pressures generated due to seismic forces and Fluid-Structure Interaction (FSI); introduction to fluid-structure domains and interaction between them are inevitable. For this purpose, first step is exact modeling of water-structure and their interaction conditions. In this paper, the basic equation involved the water-structure-foundation interaction and the effective factors are explained briefly for concrete hydraulic structure types. The finite element modeling of two concrete gravity dams with 5 m, 150 m height, reservoir water and foundation bed rock is idealized and then the effects of fluid domain and bed rock have been investigated on modal characteristic of dams. The analytical results obtained from numerical studies and modal analysis show that the accurate modeling of dam-reservoir-foundation and their interaction considerably affects the modal periods, mode shapes and modal hydrodynamic pressure distribution. The results show that the foundation bed rock modeling increases modal periods about 80%, where reservoir modeling changes modal shapes and increases the period of all modes up to 30%. Reservoir-dam-foundation interaction increases modal period from 30% to 100% for different cases.

Keywords: dam-reservoir interaction; modal analysis; concrete hydraulic structure; gravity dam.

1. Introduction

Today, use of water resources plays an important role to promote economical and agricultural developments in each country. Aquifer saving, directing of ground water flow in order to percolation and especially "Dam construction" are of the new methods for this purpose. Concrete hydraulic structures such as : dams, intake towers, piers and etc have been accounted of "Special structures", which not only in normal servicing conditions should have a proper margin of safety, but also in critical conditions like as major earthquake, local and global failures must be prevented.

The dramatic consequences on life and property resulting from failure of large dams have led engineer to consider that these structures should withstand strong ground motion with no or only

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minor damage. This has provided a strong impetus for wide researches particularly for the development of new methods of dynamic analysis in seismic studies of concrete gravity dams.

Today, dynamic analysis of dam-reservoir systems is an important subject in civil engineering practice. It is based on dynamic interaction between a fluid and a structure as same as other engineering problems like as offshore and submerged structure, storage tanks. The main concern in fluid domain is the propagation of a pressure wave that interacts to face of structures. Extensive work has been done during the last decades, and many numerical procedures including the interaction between several domains with different properties, concrete dam, foundation rock, water, and the bottom sediments have been developed by using finite element method, boundary element method and also combination of both. The interaction can drastically change the dynamic characteristics of the structure and consequently its response to transient, cyclic, and stochastic excitation. Modal Analysis is the first economic and simple step to evaluate inherent dynamic characteristic of coupled dam-reservoir systems. Hence, this article presents a series of parametric study with a complete 2-D finite element model of a gravity dam including a mass-less foundation and a compressible reservoir to indicate some effective parameters. It must be noted that 2D modeling in such problems is not comprehensive study and so using 3D modeling approach for dam-reservoir-foundation systems would be result in better and more exact responses.

2. Literatures review

The evaluation of the important hydrodynamic forces that develop on the upstream face of a large dam during severe transient excitations has been the subject of numerous studies, starting with Westergaard's classical work in 1933 (Westergaard 1933). In his paper entitled "Water pressure on dam during earthquake", physical behavior of dam-reservoir interaction had been clearly explained for 2D coupled system. Chopra and Chakrabarti investigated the effects of water compressibility and dam flexibility on the response of concrete dams (Chopra and Chakrabarti 1972, 1973).

Housner suggested analytical formulations for distribution of hydrodynamic pressure on liquid tank and concrete guide channels (Housner 1954). In the aforesaid study, forces exerted by impulsive water on walls was replaced by the same equal force due to a constrained lumped mass with spring at a specific height. Fenves and Vargas (1988) proposed a method for dam-reservoir interaction which is capable of developing symmetric matrices for the total equation of the system. Generally, fluid-structure interaction effects may introduce substantial modifications in the modal characteristics such as resonant frequencies and vibration mode shapes, and cause a impact behavior in the response resulting in considerable amplification of hydrodynamic forces (Oconnor and Boot 1988). Recently, some researches develop innovative approach to calculate natural frequencies and mode shape of dams which based on results and data obtained from in situ test. In this solution strategy that called "Inverse Method", the calculated resonance frequency replaces the measured resonance which has been obtained practically throughout the in situ testing and the hydrodynamic pressure of the reservoir is calculated using the boundary element method (Nasserzare and Lei and Eskandari 2000). Other numerical techniques using the displacement-based finite element method in both time and frequency domains (Chen and Taylor 1990, Basu and Chopra 2003, 2004) and pressure-based transformation at the fluid domain (Park *et al.* 2001), for the fluid-structure interaction (FSI) problems have been introduced. A methodology was generally presented for the approximate representation of the fluid-structure interaction (Baaijens 2001) and also dam-reservoir interaction (Leger and Bhattacharjee 1990). Weber investigated the effects of water compressibility and ratio of harmonic excitation frequency to reservoir cut off frequency on hydrodynamic pressure distribution (Weber 1997). Considering compressible and incompressible water, it's found that the hydrodynamic pressure distribution pattern depends on the level of water compressibility and the ratio of harmonic excitation frequency to reservoir cut off frequency. Ghaemian and Ghobarah have calculated nonlinear seismic response of concrete gravity dams including dam-reservoir interaction (Ghaemian and Ghobarah 1999). It is found that proper modeling in dam-reservoir interaction is very important to predict exact crack pattern. Also smeared crack approach (Mirzabozorg and Ghaemian 2005) and some seismic fracture analysis (Calayir and Karaton 2005) are implemented to assess the nonlinear behavior of concrete gravity dam subjected to three-dimentional loading. In the another study carried out by Lotfi, decoupled modal approach in time domain was proposed using the mode shapes obtained from symmetric part of sub matrices of eigen value equations of dam-reservoir system (Lotfi 2003). In spite of the fact that a considerable amount of research has been directed towards the modeling of the dynamic response of large dams, only a limited well-documented correlation studies using experimental data obtained from forced-vibration tests are available (Proulx and Paultre 1997).

Although modal analysis doesn't lonely suffices to determine seismic response of coupled dam-reservoir-foundation system, it can be used to assess resonant frequency and modal shape the same as hydrodynamic pressure distribution pattern. Furthermore, due to inherent simplicity of such analysis, regarding to computational ability of existing PC and softwares; it may be more effective way to investigate the effects of reservoir water compressibility and foundation stiffness modeling on modal behavior of gravity dams. Specially, in the combination of such analysis with advance numerical methods for example: artificial neural networks, finite and boundary element in frequency domain, modal characteristic, eigen value, resonance frequency and other dynamic parameters of gravity dams are approximated (Karimi 2009). At the similar study, with the aid of FE-BE method, the influence of the reservoir geometry on the hydrodynamic dam response are investigated in frequency domain (Milan *et al.* 2007). The results obtained from this study show that the reservoir shape influences the seismic response of the dam, making it necessary to account for 3D effects in order to obtain accurate results. In particular, the 3D pressure and displacement responses can be substantially larger than those computed with the 2D model. The responses of four different types of dam including dam-reservoir-foundation interaction to the near-fault ground motion are investigated. The behavior of reservoir is taken into account by using Lagrangian approach. The displacements and principal stresses obtained from the four different dam types subjected to these near-fault strong-ground motions are compared with each other. It is seen from the results that near-fault ground motions have different impacts on the dam types (Bayraktar *et al.* 2008). The shaking table tests were conducted on two small-scale models to examine the earthquake-induced damage of a concrete gravity dam, which has been designed for the peak ground acceleration of the maximum credible earthquake of 0.42 g (Phansri *et al.* 2010). This study deals with the numerical simulation of shaking table tests for two small scale dam models. The plastic damage constitutive model is used to simulate the crack/damage behavior of the bentonite-concrete mixture material. The numerical results of the maximum failure acceleration and the crack/damage propagation are compared with experimental results. Numerical results of Model 1 showed similar crack/damage propagation pattern with experimental results, while for Model 2 the similar pattern was obtained by considering the modulus of elasticity of the first and second natural frequencies. The crack/damage initiated at the changing point in the downstream side and then propagated toward the upstream side. Crack/damage accumulation occurred in the neck area at acceleration amplitudes of around 0.55 g~0.60 g and 0.65 g~0.675 g for Model 1 and Model 2, respectively.

3. Fluid-structure interactions

During the earthquake, a gravity dam enters a forced-vibration state, which induces vibrating movements of the upstream face with respect to the static at-rest position. These relative displacements of the dam-reservoir interface disrupt the state of tension- prior to the earthquake motion- in the fluid mass, and subsequently induce pressure waves. This undulatory system, which develops temporarily in the fluid of reservoir, entails pressure wave propagation and reflection processes at solid boundary of the reservoir and at its free surface.

As a notice of seismic response of the coupled fluid-structure system, only the wave reflection at the dam upstream face is of interest. The immediate result of wave reflection is the hydrodynamic pressure, due to the elastic deformation of the dam. The generated hydrodynamic pressure in this manner can only be introduced in the analysis by considering water compressibility in the reservoir.

3.1 Effective parameters

Generally, dam-reservoir interaction depends on the following factors;

1. The length of the reservoir;
2. The shape of the valley cross-section in the axis of the dam;
3. The degree of compressibility of the ground motion outlining the reservoir;
4. The inclination of the upstream face of the dam;
5. The earthquake direction of travel with respect to the dam axis;
6. The horizontal or vertical component of excitation;
7. The shape of the oscillation of the coupled dam-reservoir system

On the other hand, during the seismic excitation inertia effects may arise in the water mass against the upstream face of the dam. An immediate consequence of such effects is the hydrodynamic pressure due to the rigid displacement of the dam with respect to the water.

The total hydrodynamic pressure is in excess to the hydrostatic pressure. Referring to the total hydroynamic pressure during the earthquake against the upstream face, it has been shown that during the initial earthquake phases, the hydrodynamic pressure is higher at the upper part of the dam because of the prevailing effect of water compressibility. If the dominating period of earthquake is long, the increase of the hydrodynamic pressure is negligible. Under the same condition, however, earthquake can also generate overall oscillation of the fluid mass, because of the inertia forces developed in the fluid body. This effect appears at the free surface as long waves called seich (Priscu and Popovici 1985).

3.2 Governing equations

The dam-reservoir interaction is represented by two coupled differential equations of the second order. The equations of the structure and the reservoir can be written in the form

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{f_1\} - [M]\{\ddot{u}_{gh}\} - [M]\{\ddot{u}_{gv}\} + [Q]\cdot\{P_h(t)\} \tag{1}$$

$$[G]\{\ddot{P}_h\} + [C']\{\dot{P}_h\}[K']\{P_h\} = \{f_2\} - \rho\cdot[Q]^T\{\ddot{u}\} \tag{2}$$

Where $[M]$, $[C]$ and $[K]$ are mass, damping and stiffness matrices of the structure, and $[G]$, $[C']$, $[K']$ are matrices representing mass, damping and stiffness of the reservoir, respectively. $[Q]$ is the coupling matrices and $\{f_1\}$ is the vector of body force and hydrostatic force. $\{f_2\}$ is the component of the force due to acceleration at the boundaries of dam-reservoir and reservoir-foundation. $\{P\}$ and $\{U\}$ are the vector of pressure and displacement. $\{\ddot{u}_g\}$ is the ground acceleration and ρ is the density of the fluid. The dot represents the time derivative (Ghaemian and Ghobarah 1999).

The hydrodynamic pressure distribution in the reservoir is governed by the pressure wave equation assuming the water is linearly compressible and neglecting its viscosity, where the small amplitude irrotational motion of water is governed by two-dimensional wave equation

$$\nabla^2 P(x,y,t) = \frac{1}{C^2}\ddot{P}(x,y,t) \tag{3}$$

where $P(x, y, t)$ is the hydrodynamic pressure in excess of hydrostatic, C is the velocity of pressure wave in the water and x and y are the coordinate axes.

For the earthquake excitation, the condition at the boundaries of the dam-reservoir, reservoir-foundation and the reservoir-far-end shown in Fig. 1 are governed by the following equations

$$S1 = \left.\frac{\partial p(x,y,t)}{\partial x}\right|_{x=0} = -\rho_w \phi \ddot{U}_g \tag{4}$$

where ρ_w is the density of water and $\ddot{U}_g$ is the component of acceleration at the structure's free edge. $\phi(y)$ is the shape function of the dam.

$$S2 = \left.\frac{\partial p(x,y,t)}{\partial y}\right|_{y=0} = 0 \tag{5}$$

$$S3 = p(x,y,t)|_{x\to\infty} = 0 \tag{6}$$

$$S4 = p(x,y,t)|_{y=H} = 0 \tag{7}$$

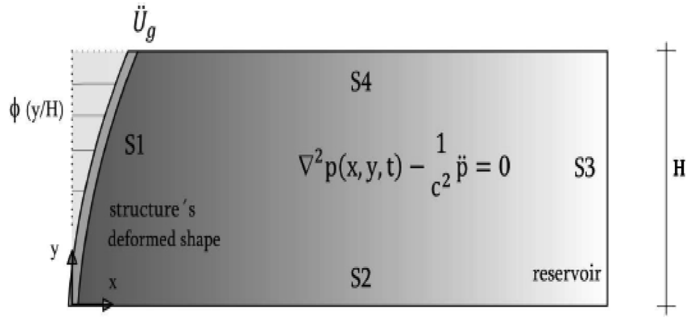


Fig. 1 Dam-reservoir domain representation with boundary conditions

4. State of problem and modeling method

The main objective of this study is to investigate finite element modeling effects of reservoir and foundation including dam-reservoir-foundation interaction on modal behavior of gravity dams. For this purpose, two concrete gravity dams with 50^m and 150^m in height are selected which their dimensions are determined to satisfy stability and overturning control regarding to engineering guidelines (EM 1110-2-2200 1965). Characteristic of geometry of the dam are shown in Table 1 and Fig. 2.

The "Plane strain" state is governing on the each cross-section of dams, because of the longitudinal length is very greater than other two dimensions (EM 1110-2-6051 2003). Hence, 2-D finite element models are created. Compressive strength, unit weight and Poisson's ratio of the concrete are taken as $f_c' = 250\ \text{kg/cm}^2, 2400\ \text{kg/cm}^3$, and 0.2 respectively. Static modulus of elasticity is taken as $(E_c)_s = 15800\sqrt{f_c'} = 249820\ \text{kg/cm}^2$. Unit weight of the water of the reservoir and the velocity of wave propagation is taken as $\rho_w = 1030\ \text{kg/m}^3$ and $V_w = 1440\ \text{m/sec}$, respectively. Water is also treated as compressible invisid fluid. For simplicity, no absorption is considered at reservoir bottom.

Neglecting the free surface wave, the boundary condition at the free surface is written as

$$p(x, h, t)| = 0 \tag{8}$$

where h is the height of the reservoir.

In order to determine modal hydrodynamic pressure on the dam, under the assumption of infinite reservoir, Sharan truncation boundary condition was applied at a distance $L = 10\text{H}$ from the dam,

Table 1 The geometry of the dams under investigation

No	B (m)	H (m)	h (m)	L (m)
1	100	150	10	7
2	35	50	7	7

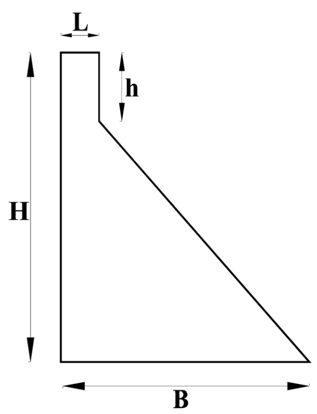


Fig. 2 Characteristic geometry parameters for dams

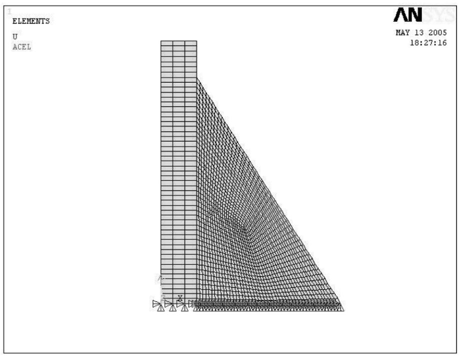
which reduced to $L = 2H$ after primary analysis in which the change in hydrodynamic pressure can be neglected (Sharan 1986). Boundary admittance at truncated far-end of reservoir is taken 1 to prevent wave reflection.

"PLANE 42" element was used to model dam body and foundation bed rock as suggested by related manual (EM 1110-2-6051 2003). This 2-D plane element is used to model solids, is defined by 4 nodes having two degree of freedom of translation in *x*, *y* direction. Shape function of this element is bilinear and the element has also nonlinear capability such as: plasticity, creep and strain softening. To model water of reservoir, "FLUID 29" element was used. This four nodes, 2-D element, which is used for modeling fluid medium and fluid-structure interface in interaction problems, are in two type: "Structure present" and "Structure absent". For "structure present" elements, each node has three degree of freedom: translation in the *x*, *y* directions and pressure. The translation, however, are applicable only at nodes that are on the interface. The governing equation, 2-D wave equation, has been discretized taking into account the coupling of acoustic pressure and structural motion at the interface.

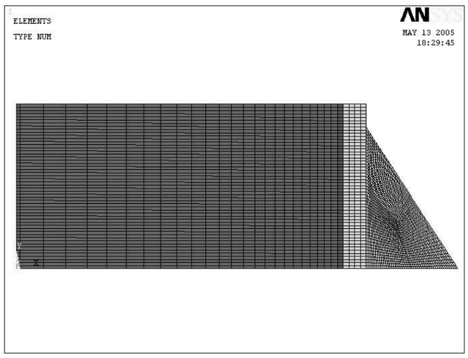
To investigate modal behavior, four cases are considered as followings:

1) Fixed-base dam, Empty reservoir (M1). 2) Fixed-base dam, Full reservoir (M2).

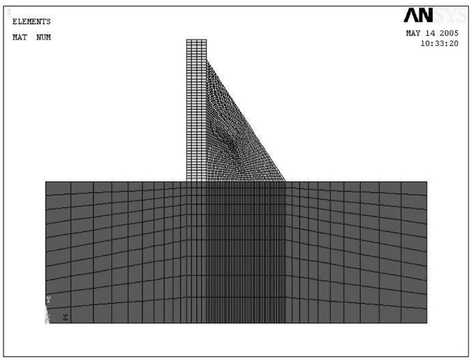
3) Rock-base dam, Empty reservoir (M3). 4) Rock-base dam, Full reservoir (M4).



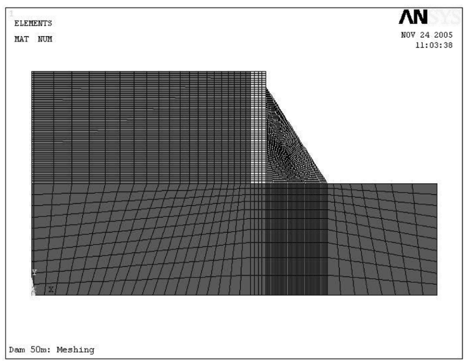
M2



M1



M4



M3

Fig. 3 Finite Element idealization for dam-reservoir-foundation model

Foundation bed rock was extended from upstream and downstream of dam equal to (B) and has a (H) in depth. All degree's of freedom at base of foundation bed rock and just vertical translation for circumferential nodes were constrained. The elastic modulus of foundation rock, E_f, varies from 0.25, 0.5, 1 and 2 times that of the dam, E_{st}, to consider effects of foundation flexibility, so $B = E_f/E_{st}$.

Four finite element models developed as shown in Fig. 3. The idealization meshes were created for the dams, as well as reservoir and foundation.

5. Results of modal analysis

Modal analyses are carried out, and the modal periods, mode shapes, hydrodynamic pressure distribution pattern are obtained for five first vibration modes. Fig. 4 shows modal shapes of (M1) only for 4 first modes.

5.1 Effects of reservoir modeling

Modal shapes of (M2) are shown in Fig. 5. Comparing Figs. 4 and 5, it is clearly seen that the reservoir modeling changes modal shapes, especially for mode 2. In this mode, dam has been inversed to the reservoir.

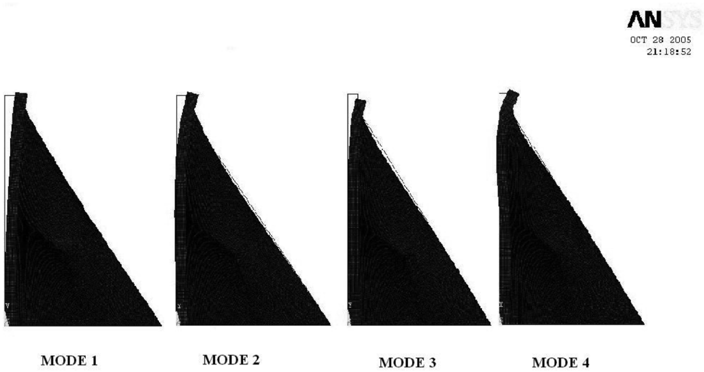


Fig. 4 Modal shapes of M1

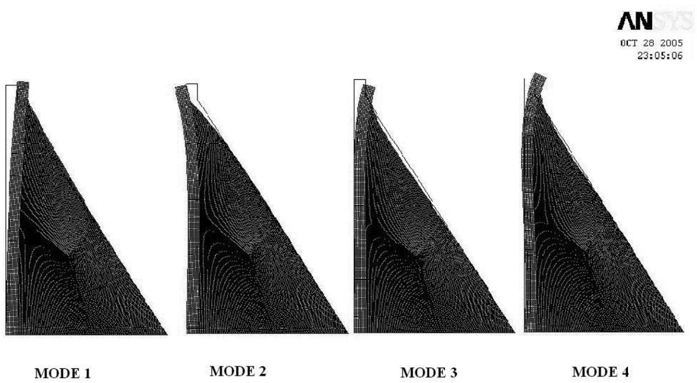


Fig. 5 Modal shapes of M2

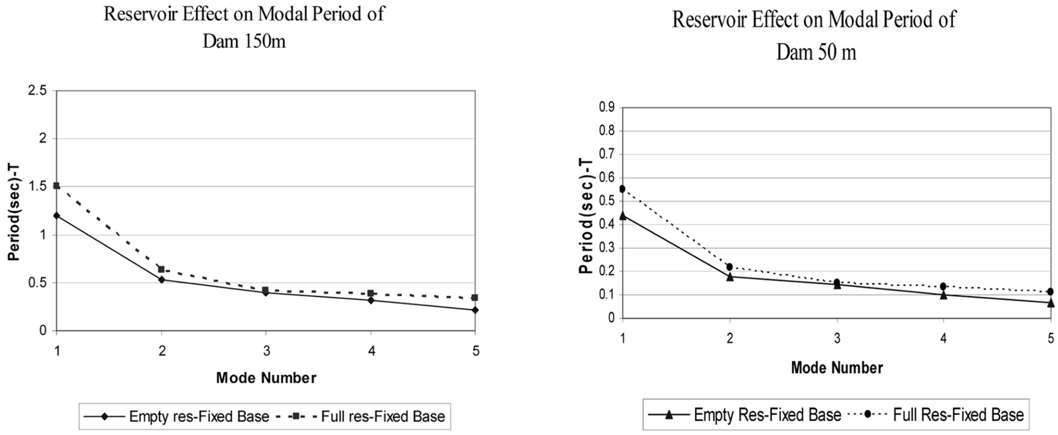


Fig. 6 Effect of reservoir on modal periods

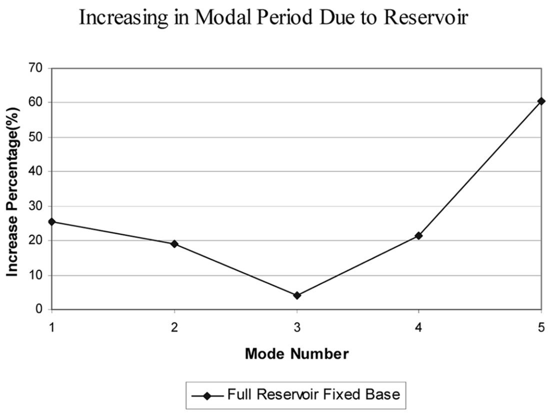


Fig. 7 Increasing percent due to reservoir

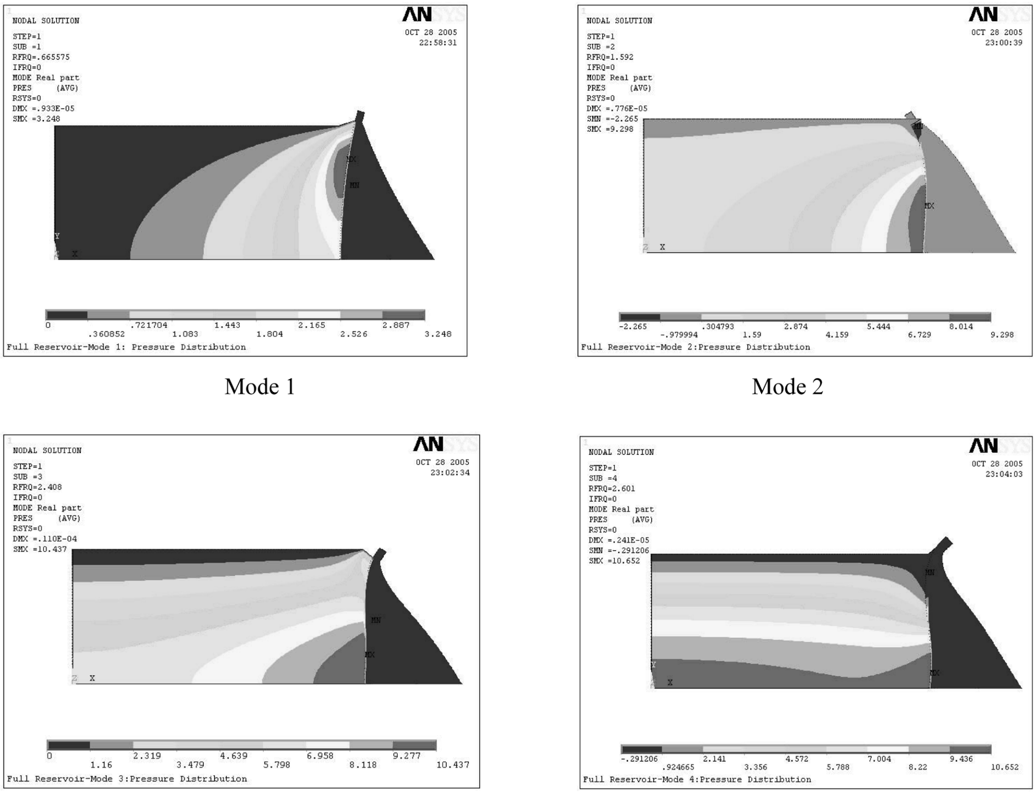
Diagrams in Fig. 6, show the period of first five modes of dams for M1 and M2. In these diagrams, horizontal axis represents mode number, and vertical axis represents the value of period. The results show that reservoir modeling increases period of all modes, as shown in Fig. 6. Reservoir increases period of 5^{th} and first mode, respectively rather than 3^{rd} mode. Fig. 7 shows the increasing percent of modal periods due to reservoir effects.

Modal hydrodynamic pressure distribution patterns are displayed in Fig. 8. As can be seen, it depends on deformation of coupled dam-reservoir system. Moreover, maximum hydrodynamic pressure increases with respect to mode number.

5.2 Effects of foundation bed rock modeling

Modal analyses have been performed including foundation bed rock region and modal deformation of the first four modes has been displayed in Fig. 9. Comparing Figs. 8 and 3, indicates that the bed rock modeling changes modal shape due to flexibility of the bed rock.

Diagrams in Fig. 10 illustrate the effects of bed rock flexibility on modal period. M1 corresponds



Mode 1 Mode 2

Mode 3 Mode 4

Fig. 8 Modal hydrodynamic distribution

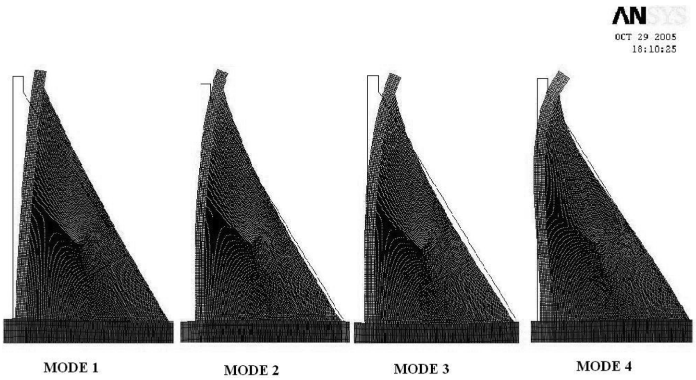


Fig. 9 Modal shapes of M3

to fixed-base dam model. It shows that foundation bed rock modeling with dam causes to increase modal periods, regarding to bed rock flexibility increasing. So it plays an important role in site selection! Increasing percent of modal periods due to bed rock modeling has been displayed in Fig. 11 for all value of "B". Only 3rd and first vibration modes have been greatly influenced by bed rock flexibility, respectively.

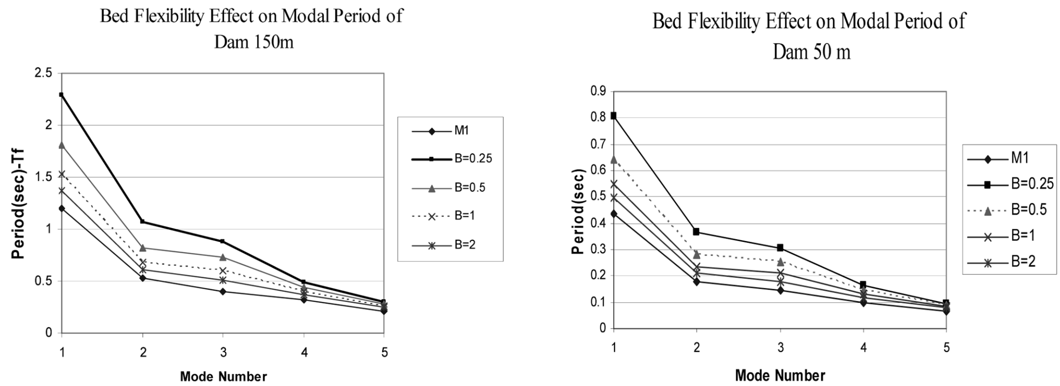


Fig. 10 Effect of foundation on modal period

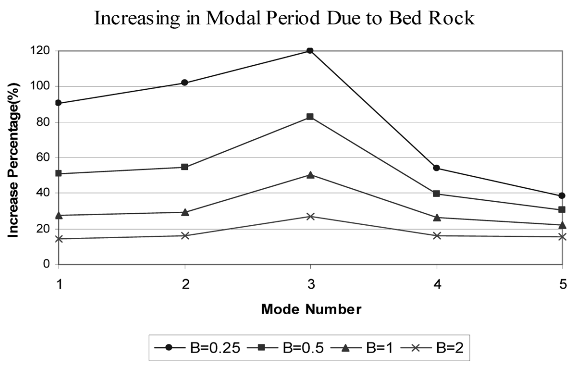


Fig. 11 Increasing percent of modal period due to foundation

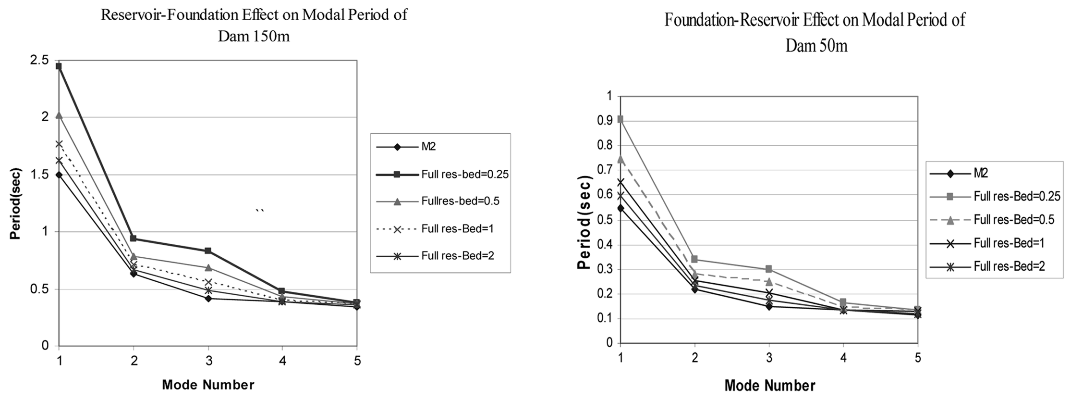


Fig. 12 Effect of reservoir and foundation on modal periods

5.3 Effects of reservoir and foundation modeling

In this step, reservoir and bed rock are simultaneously modeled to investigate the modal behavior of gravity dams, modal periods and hydrodynamic pressure distribution patterns. Period of each mode is shown in Fig. 12. M2 corresponds to fixed-base dam with full reservoir the same as other

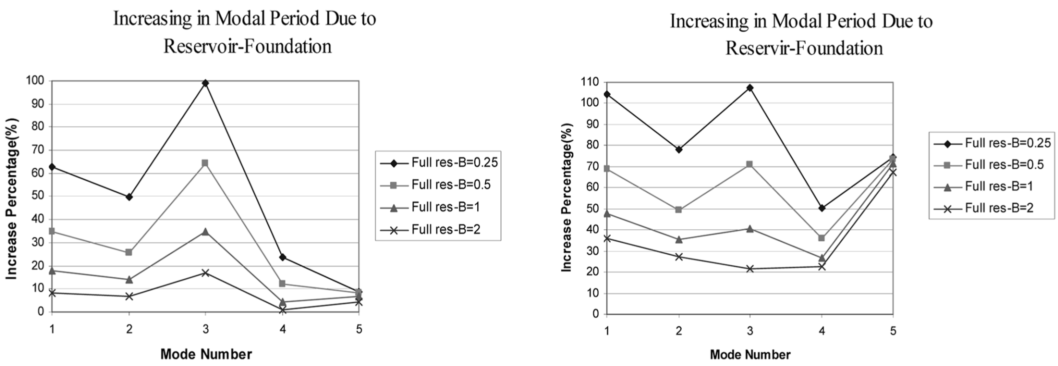
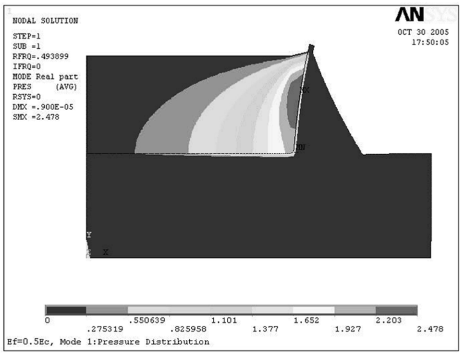
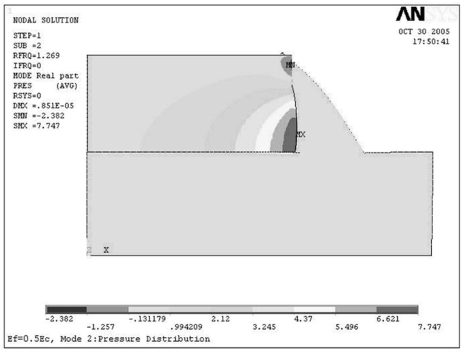


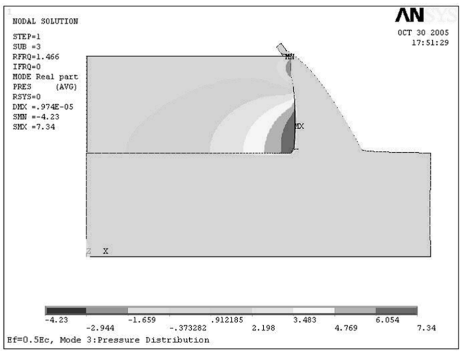
Fig. 13 Increasing percent of modal period with respect to M2 (left) and M1 (right)



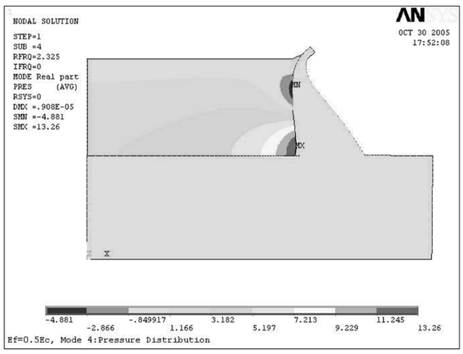
Mode 1



Mode 2



Mode 3



Mode 4

Fig. 14 Hydrodynamic pressure (M4) for $B = 0.5$

curves represent M4 corresponding to rock-base with full reservoir. It can be observed that the bed rock modeling increases periods with respect to M2. Effect of bed rock flexibility is clear. Fig. 13 displays increasing percent in modal periods with respect to M2. Period of 3rd mode increases considerably due to bed rock modeling. When comparison is made with respect to M1, however, not only 3rd mode, but also first and 5th modes have great increase in period.

Modal hydrodynamic pressure distribution patterns are shown in Fig. 14 for $B = 0.5$. Comparing

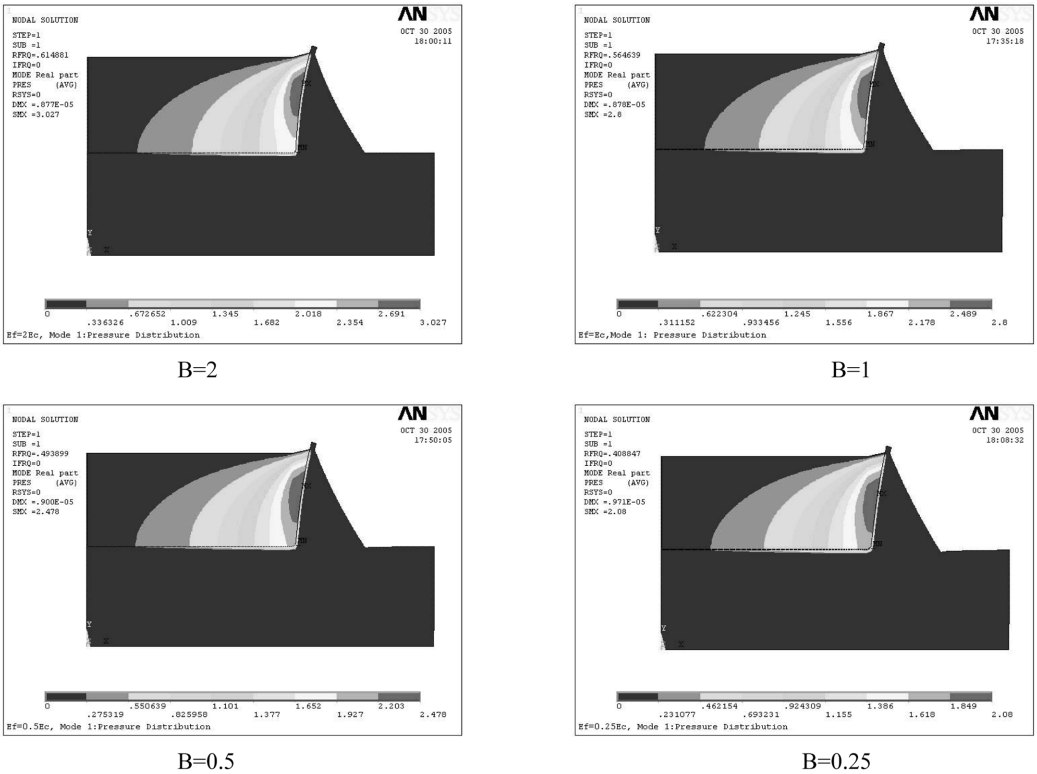


Fig. 15 Effect of bed rock flexibility on hydrodynamic pressure distribution

Fig. 14 and Fig. 8, it is found that the simultaneous modeling of reservoir and bed rock, changes hydrodynamic pressure distribution patterns similar to that for modal shapes especially for 3rd and 4th modes.

Generally, hydrodynamic pressure reduced by foundation bed rock modeling for all value of "B" rather than that of full reservoir with fixed base dam. The value of hydrodynamic pressure has been influenced by the level of flexibility, so it decreases by increase in base flexibility. Furthermore, restricted area of maximum hydrodynamic pressure at the first mode, as shown in Fig. 15, intends to develop to the base when bed rock flexibility increases.

6. Conclusions

Many modal analyses of concrete gravity dams which include dam-reservoir-foundation interaction were conducted to investigate the different effects of each reservoir and foundation bed rock. In the case of typical studied dams, it is found that the reservoir and foundation modeling can be effective in all modal characteristic of dam responses. The foundation bed rock modeling shifts the system period. Results show that including the effects of foundation increases modal periods about 80%. The reservoir water was included in the modeling to study the effect of reservoir pounding on modal responses. It is seen that the reservoir modeling changes modal shapes and increases the period of all modes up to 30%. The simultaneous modeling of the both water and bead rock in reservoir-dam-foundation interaction increases the modal period, 30% to 100% and reduces the hydrodynamic pressure for different bed rock extension from upstream and downstream of dam (B values). Moreover, the interaction changes hydrodynamic pressure distribution patterns.

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