Modal Response of Dam-Reservoir-Foundation Interaction

Hashem Shariatmadar[1], Adel Mirhaj[2]

1- Assistant Professor, Civil Engineering Dept., Eng. Faculty, Ferdowsi University of Mashhad
2- Structural Eng., Civil Engineering Dept., Eng. Faculty

shariatmadar@ferdowsi.um.ac.ir

Abstract

Vital and special structure such as dams, must have sufficient safety margin under conditions like when earthquake occurred as same as normal servicing time. Hydrodynamic pressures induced due to seismic forces and Fluid-Structure Interaction (FSI) are evaluated. The interaction of reservoir water-dam structure and foundation bed rock are modeled using the ANSYS computer program. The analytical results obtained from over twenty 2D finite element modal analysis of concrete gravity dam show that the accurate modeling of dam-reservoir-foundation and their interaction considerably affects the modal periods, mode shapes and modal hydrodynamic pressure distribution.

Keywords: Concrete Gravity Dam, Modal Analyze, Dam-Reservoir-Foundation Interaction, Hydrodynamic Pressure

1. INTRODUCTION

Today, use of water resources plays an important role to promote economical, 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. Iran on the base of technical potential of his experts has also been one of the famous pioneers in dam design and construction. 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 catastrophic consequences on life and property resulting from failure of large dams have led engineers to design and built these structures to resist strong ground motion with no or only minor damages. This has provided a strong impetus for wide researches, particularly in developing new methods of dynamic analysis for concrete gravity dams in seismic region.

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 [1] in 1933. Westergaard explained the physical behavior of dam-reservoir interaction for 2D coupled system [1]. Water compressibility and dam flexibility effects have been investigated by Chopra and Chakrabarti [2,3]. 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. Ghaemian and Ghobarah [4] have calculated nonlinear seismic response of concrete gravity dams including dam-reservoir interaction. It is found that proper modeling in dam-reservoir interaction is very important to predict exact crack pattern. Other numerical techniques using the displacement –based finite element method for dam-reservoir interaction problems in both time and frequency domains have been introduced by Chen and Taylor [5]. Fenves and Vargas [6] proposed a method for dam-reservoir interaction which is capable of developing symmetric matrices for the total equation of the system. Leger and Bhattacharjee [7] presented a methodology for the approximate representation of the dam-reservoir interaction. At the another study carried out by Lotfi [8], 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. 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. Generally, fluid-structure interaction effects may introduce substantial modifications in the modal characteristics such as resonant frequencies and vibration mode shapes, and cause a betting behavior in the response resulting in considerable amplification of hydrodynamic forces .

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 as same as hydrodynamic pressure distribution pattern. Furthermore, due to inherent simplicity of such analysis, it is necessary to investigate the effects of reservoir water compressibility and dam-reservoir-foundation interaction on modal behavior of gravity dams.

This paper 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.

3. Fluid-Structure Interactions

During an 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 adulatory 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 hydrodynamic pressure generated 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 hydrodynamic 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.

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:

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

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

Where [M], [C] and [K] are mass, damping and stiffness matrices of the structure, and [G], [C’] and [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. {Üg} is the ground acceleration and ρ is the density of the fluid. The dot represents the time derivative [4].

The hydrodynamic pressure distribution in the reservoir is governed by the pressure wave equation assuming the water is linearly compressible and neglecting its viscosity, 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 governed by the equation:

$$\frac{\partial P(x,y,t)}{\partial n} = -\rho_w a_n(x,y,t) \tag{4}$$

Where ρ_w is the density of water and an(x,y,t) is the component of acceleration on the boundary along the direction of the inward normal n.

4. State of Problem and Modeling Method

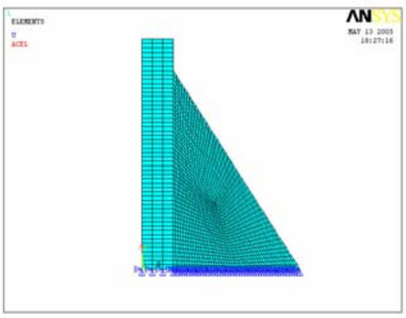
The main objective of this study is to investigate the effects of dam-reservoir-foundation interaction on modal behavior of gravity dams. For this purpose, two concrete gravity dams with 50m and 150m in height are selected which their dimensions are determined to satisfy stability and overturning control regarding to engineering guidelines [9].

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. Hence, 2-D finite element models are created using ANSYS program. Water is also treated as compressible fluid. For simplicity, no absorption is considered at reservoir bottom.

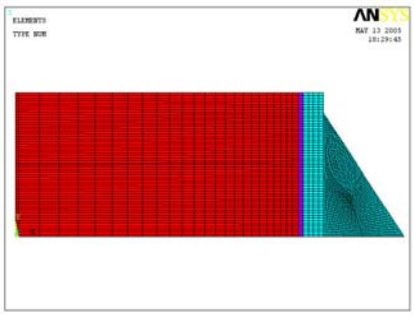
In order to determine modal hydrodynamic pressure on the dam, under the assumption of infinite reservoir, Sharan truncation boundary condition was applied at a distance L=10H from the dam, which reduced to L=2H after primary analysis so change in hydrodynamic pressure can be neglected. Boundary admittance at truncated far-end of reservoir is taken 1 to prevent wave reflection.

PLANE42 element was used to model dam body and foundation bed rock. To model water of reservoir, FLUID29 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 used taking into account the coupling of acoustic pressure and structural motion at the interface.

To investigate the modal behavior, four different cases as shown in Figure 1 are taken as followings:
Fixed-base dam, Empty reservoir (M1).
Fixed-base dam, Full reservoir (M2).
Rock-base dam, Empty reservoir (M3).
Rock-base dam, Full reservoir (M4).

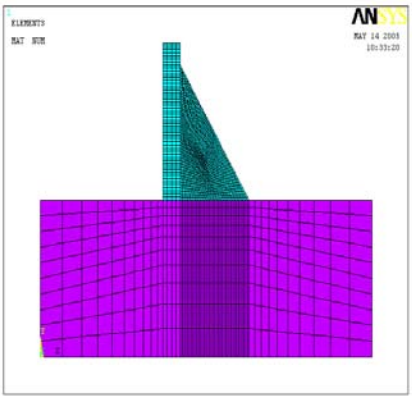


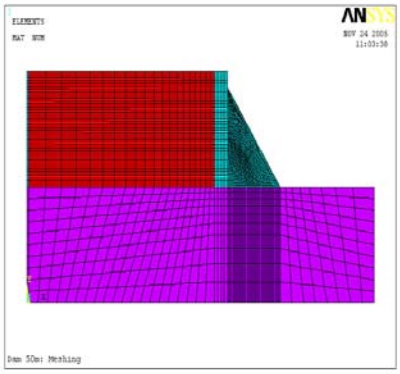
M1



M2

Figure 1. Finite element modeling of dam-reservoir-foundation





M3 M4

Figure 1 (continued). Finite element modeling of dam-reservoir-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. This ratio is defined by :

$$B = E_f / E_{st}$$

5. Results of Modal Analysis

Modal analyses are carried out for dams, and modal periods and shapes, hydrodynamic pressure pattern are obtained for five first vibration modes. Figure 2 shows modal shapes of (M1) only for 4 first modes.

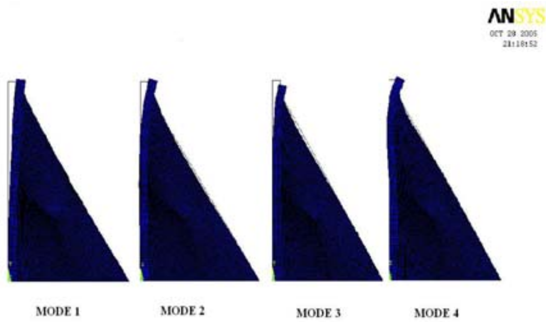


Figure 2: Modal shapes of M1

5.1 Effects of Reservoir Modeling

Modal shapes for M2 are shown in Figure 3. Comparing Figure 3 and 2, it's clearly seen that the reservoir modeling changes modal shapes, especially for mode 2. In this mode, the upstream of the dam has moves toward the reservoir.

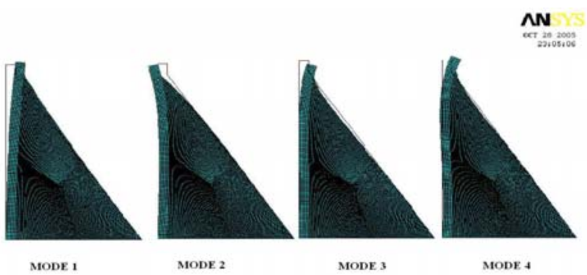
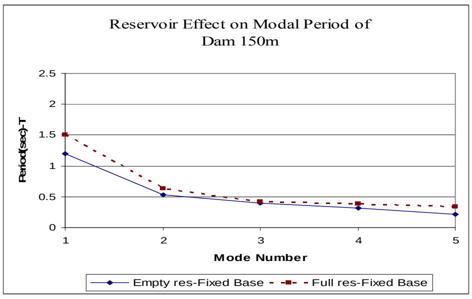


Figure 3: Modal shapes of M2

Diagrams in Figure 4, show the period of first five modes of dams for M1 and M2. As shown, reservoir modeling increases the period of all modes, differently. The effect of reservoir increases the period of the 5th and 1st modes more than the 3rd mode. Increasing percent of modal periods due to reservoir modeling has been shown in Figure 5.



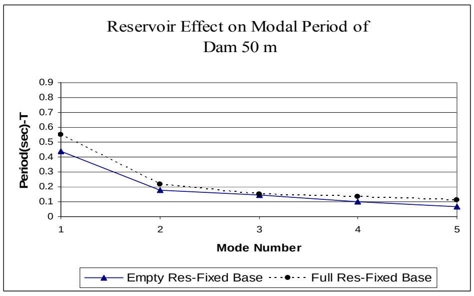


Figure 4: Effect of reservoir on modal periods

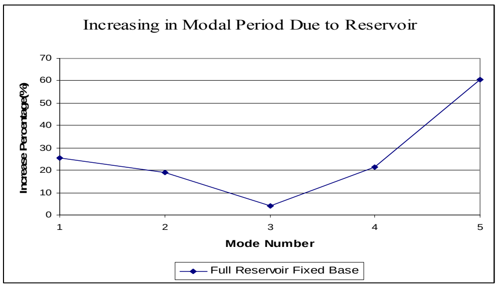
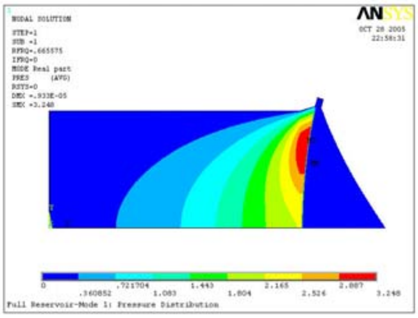
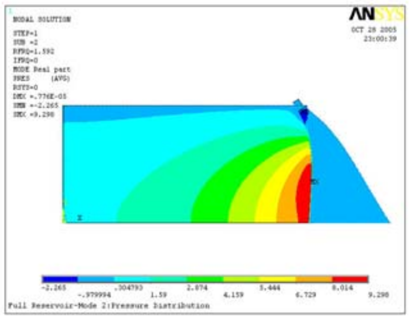
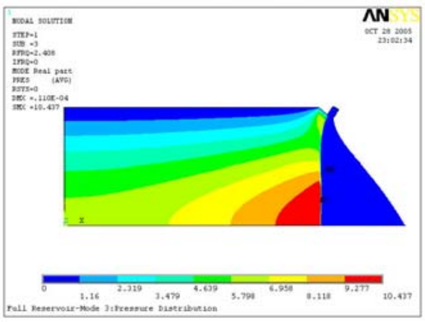


Figure 5: increasing percent due to reservoir

Modal hydrodynamic pressure distribution patterns are displayed in Figure 6. As seen, it depends on deformation of coupled dam-reservoir system. Moreover, maximum hydrodynamic pressure increases with respect to mode number.


Mode1


Mode 2


Mode3

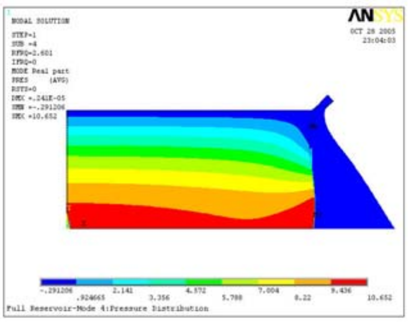

Mode 4

Figure 6: Modal hydrodynamic distribution.

5.2 Effects of Foundation Bed Rock Modeling

Modal analyses are performed including foundation bed rock region and modal deformation of first four modes has been displayed in figure 8. Comparing Figures 7 and 2, it is seen that the bed rock modeling changes modal shape due to flexibility of bed rock was introduced.

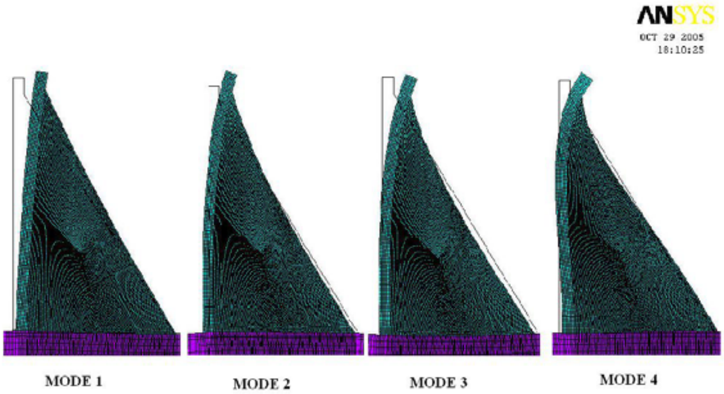


Figure 7: Modal shapes of M3

Diagrams of Figure 8 illustrate the effects of bed rock flexibility on modal period. M1 corresponds to fixed-base dam model. It has been seen 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 Figure 9 for all value of “B”. Only 3rd and first vibration modes have been greatly influenced by bed rock flexibility, respectively.

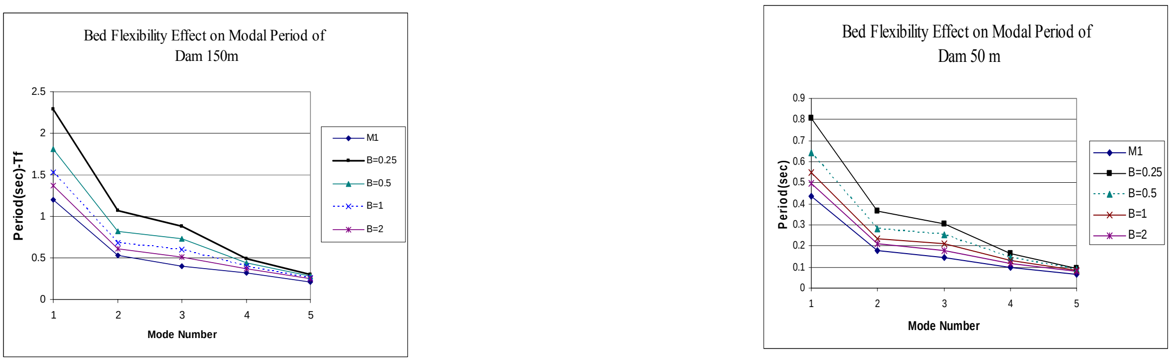


Figure 8. Effect of foundation on modal period

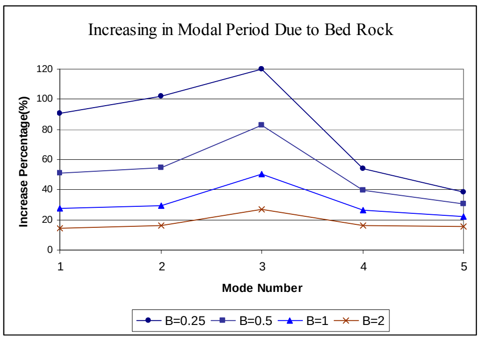


Figure 9. Increasing percent due to foundation.

5.3 Effects of Reservoir and Foundation Modeling

In this step, reservoir and bed rock are simultaneously modeled to evaluated modal behavior of gravity dams including modal periods, and hydrodynamic pressure distribution patterns. Period of each mode are shown in Figure 10. It can be observed that the bed rock modeling increases periods with respect to M2. Effect of bed rock flexibility is openly seen. Figure 11 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.

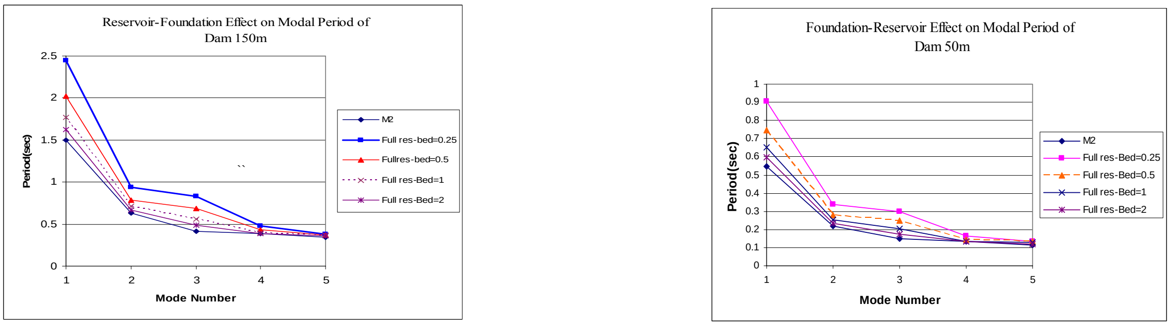


Figure 10. Effect of reservoir and foundation on modal periods

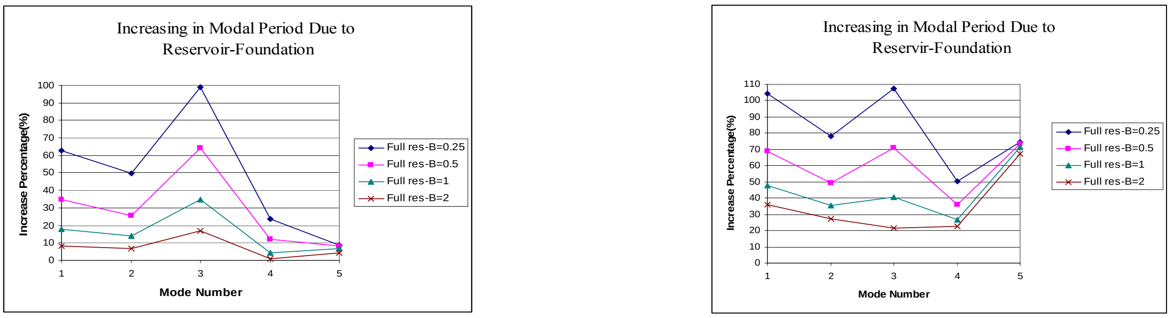


Figure 11. Increasing percent with respect to M2 (left) and M1 (right)

Modal hydrodynamic pressure distribution patterns are shown in Figure 12 for B=0.5. Comparing Figure 12 and 6, it's found that the simultaneous modeling of reservoir and bed rock, changes hydrodynamic pressure distribution patterns as same as modal shapes especially for the 3rd and 4th modes.

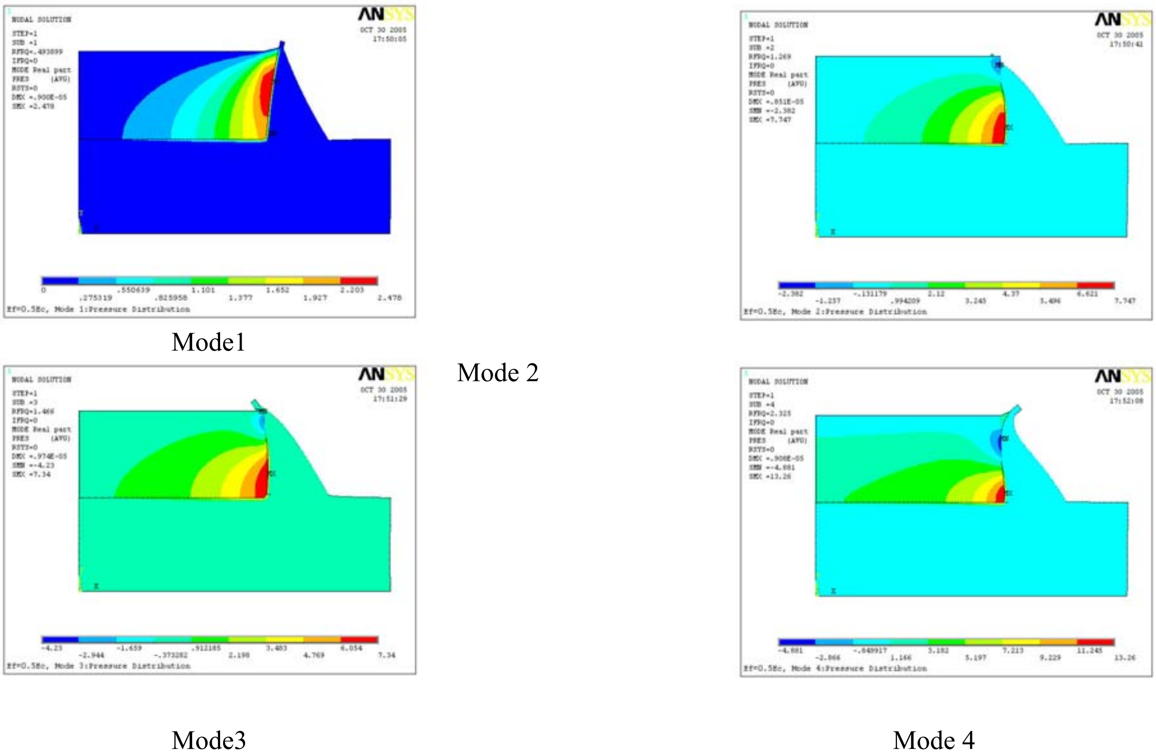
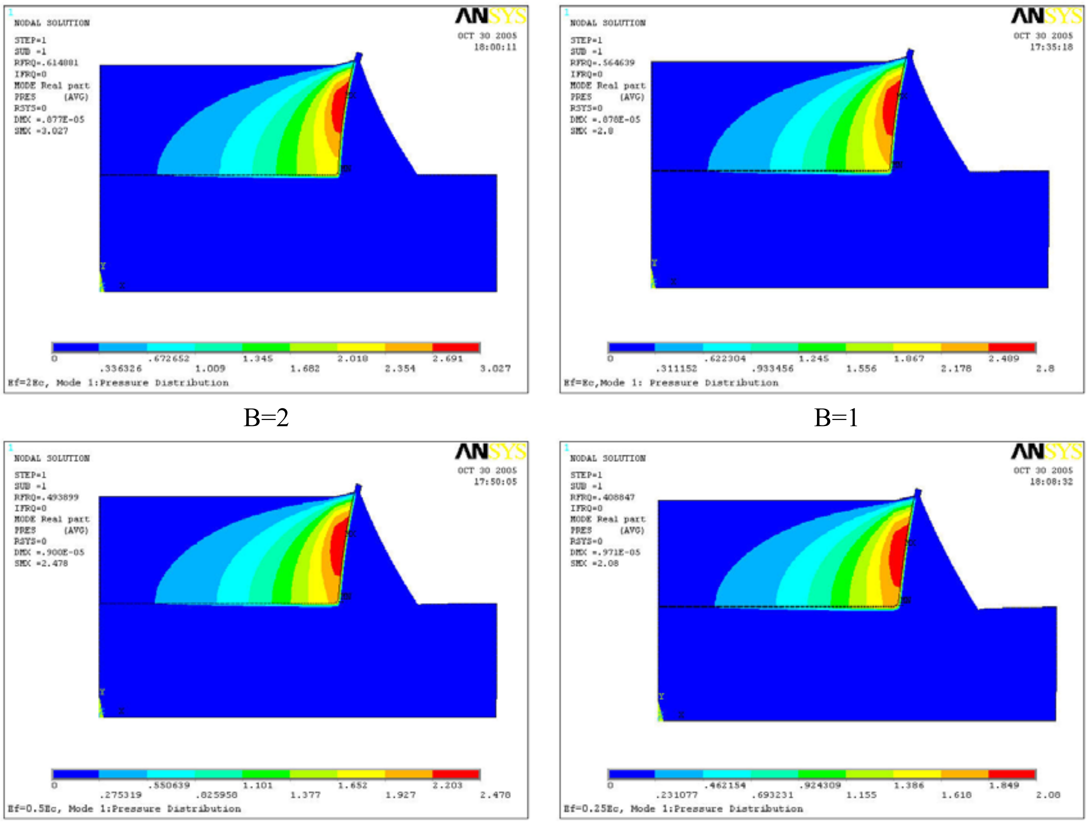


Figure 12: Hydrodynamic pressure (M4) for B=0.5

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 Figure 13, intends to develop to the base when bed rock flexibility increases.



B=2 B=1

B=0.5 B=0.25

Figure 13: Effect of bed rock flexibility on hydrodynamic pressure distribution

5. Conclusion

1) Foundation bed rock modeling increases modal periods about 80%.
2) Reservoir modeling changes modal shapes and increases the period of all modes up to 30%.
3) Reservoir-dam-foundation interaction increase modal period, 30% to 100% for different “B” values.
4) Hydrodynamic pressure reduced by foundation bed rock modeling for all value of “B”.
5) Simultaneous modeling of reservoir and bed rock changes hydrodynamic pressure distribution patterns.

6. References

1. Westergaard,H., Water pressure on dams during earthquakes, Trans. of ASCE.98,1933.
2. Chakrabarti,P. & Chopra,A., Earthquake response of gravity dams including reservoir interaction effects,Earthquake Eng. Research Center, Rep72-6, Berkley, 1972.
3. Chopra,A. & Chakrabarti.P, Dynamic of gravity dams. Significance of compressibility of water and 3D effects, Earthquake Engineering & Structure Dynamic, 2, 1973.
4. Ghaemian,M. & Ghobarah.A, Nonlinear seismic response of concrete gravity dam with dam-reservoir interaction, International journal of Engineering Structure,21, pp.306-315, 1999.
5. Chen,H.C.& Taylor,R.L., Vibration analysis of fluid-solid systems using a finite element displacement formulation, International journal of Numerical Method Eng, 29, pp.683-698,1990.
6. Fenves,G. & Vargas-Loli,M., Nonlinear dynamic analysis of fluid-structure systems, International journal of Engineering Mechanics, ASCE, 2(114), pp.219-240,1988.
7. Leger.P, Bhattacharjee.SS., Reduced frequency independent models for seismic analysis of concrete gravity dam, International Journal of Comput&Struc,6(44), pp.1381-1387,199).
8. Lotfi.V., Seismic analysis of concrete gravity dams by decoupled modal approach in time domain, EJSE, 3, pp.102-116, 2003.