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EFFECTS OF DAM-RESERVOIR-FOUNDATION INTERACTION ON MODAL BEHAVIOUR OF GRAVITY DAM

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Abstract —*Dams have played a vital role in regulating water flow to cater to the needs of irrigation, for human consumption for harnessing hydroelectric power, as well as control of floods. Some of the important aspects that may affect the response of gravity dams subjected to earthquakes have been recognized through the dam-reservoir-foundation interaction. Modal characteristics such as natural frequencies and mode shapes undergoes modifications due to these interaction. The influence of foundation flexibility on the dynamic response of gravity dam is also significant. Modal analysis is a simple way to find the various periods at which structure will naturally resonate. These periods of vibration are very important in earthquake engineering. The present study aims to determine the effects of dam-reservoir-foundation interaction on modal behaviour of gravity dam. The effect of foundation flexibility on the modal period is also studied. Relation between modal period, height and base width is also obtained. Modelling is done using ANSYS 16.2 computer program. The analytical results obtained from 2D finite element modal analysis of concrete gravity dam show that modal period of dam is functions of its overall height and also dam- reservoir-foundation interaction and foundation flexibility has a significant influence on the modal periods and mode shapes. So, its consideration is essential while designing the gravity dam for safety, reliability and quality*

Keywords*-modal period, foundation flexibility, gravity dam, mode shapes, natural frequency, reservoir*

I. INTRODUCTION

Dams form key structures for harnessing hydroelectric power, with all its advantages over other source of large energy generation, as well as control of floods. They have also played vital role in taming some of the largest rivers on earth, in many cases at point's upstream cities and populous and developed valleys. Their number, height, economic and social importance has increased exponentially over last decades, including their cost. A concrete gravity dam is defined as a structure, which is designed in such a way that its own weight resists the external forces. This type of structure is durable, and requires very little maintenance. The section of the gravity dam is approximately triangular in shape, with its apex at its top and maximum width at bottom. The upstream face is vertical or slightly inclined. The slope of the downstream face usually varies between 0.7: 1 to 0.8: 1. The two general concrete construction methods for concrete gravity dams are conventional placed mass concrete and RCC. Concrete gravity dams are preferred these days and mostly constructed. They can be constructed with ease on any dam site, where there exists a natural foundation strong enough to bear the enormous weight of the dam. Some of the important aspects that may affect the response of gravity dams subjected to earthquakes have been recognized through the dam-reservoir-foundation interaction. Dam-foundation and dam-reservoir interactions are two important aspects in the dynamic analysis of dams. When a dam and its foundation are subjected to an earthquake, it generates an acceleration field which depends on the shape of the dam and the various constituent materials. Depending on the stiffness of materials and their internal damping capacity, depending on the height and shape of dam in relation to the earthquake spectrum, the response of dam will be more or less strong. This response is also influenced by the characteristics of the foundation and the restraint; therefore, good consideration of dam- foundation interaction is essential. The dam-water interaction must be taken into account since the dam undergoes deformation, which influences the motion of water in the reservoir. The water that moves along the dam increases the total mass moved due to earthquake and affects inertial forces created due to earthquake action. The catastrophic consequences on life and property resulting from failure of large dams have lead 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. Structures cannot be declared safe only on the load withstanding capability but should be safe considering the structural dynamic aspect as well. Modal analysis is used to find the offending frequencies and move them by varying increasing the stiffness or mass to ensure the structure safe from the natural frequency problems. Generally, the dynamic behaviour of structures is characterized in terms of modal parameters (modal frequencies, modal damping and scaled mode shapes) and modal analysis is a branch of advance vibration analysis that deals with the identification of modal parameters. The influence of foundation flexibility on the dynamic response of massive concrete structures may be very significant. This may have a considerable effect on the dynamic performance of gravity monoliths subjected to seismic ground motion.

II. LITERATURE REVIEW

Rajib Sarkar *et al.* [1] conducted studies on the influence of reservoir and foundation on the nonlinear dynamic response of concrete gravity dam. The response of a dam subjected to dynamic loading is a combined effect of the interaction among dam, reservoir and foundation systems. The behaviour of dam structure under earthquake largely depends on the foundation and the reservoir. With a decrease in the foundation modulus, the displacements increase. R. Ayothiraman *et al.* [2] conducted studies on the combined effect of foundation reservoir interaction on the seismic response of concrete gravity dam. The significance of foundation flexibility on the seismic response of dam was investigated by comparing the response of dam with rigid and flexible foundations. The studies reveal that the dam with rigid foundation is relatively safe, but the dam with flexible foundation suffers moderate damage when the reservoir is empty and full. Brijesh Singh and Pankaj Agarwal [3] investigated the earthquake response of high concrete gravity dam reservoir foundation system to study the effect of foundation flexibility and reservoir on the response of high concrete dam under transient dynamic analysis. The parametric studies conducted on various models show that the response quantity of the dam in terms of displacement and stresses depends largely on the foundation modulus of elasticity and reservoir height. In case of flexible foundation significant changes in response is observed are compared to rigid foundation. Z. Heirany and M. Ghaemian [4] conducted study on the effect of dam reservoir foundation interaction on nonlinear behavior of concrete gravity dams. Results show that when the nonlinear analysis includes the dam foundation interaction and the foundation's mass, flexibility and radiation damping, the seismic response of concrete gravity dam will be reduced to a realistic level. Decreasing in ratio of foundation's modulus of elasticity to dam's modulus of elasticity (EF/ES) causes increasing in dam crest displacement. Sajith S Pai *et al.* [5] conducted a study on response of gravity dam under earthquake acceleration including the effect of the interaction among dam, reservoir and foundation and found the type of failure, the dam likely to suffer. The results show that foundation has a significant effect on the stress development of the dam and should be given dual consideration during the analysis of gravity dams. Response quantity reduces with the increase in width of the base. Bakenaz A. Zeidan [6] conducted seismic finite element analysis of dam reservoir foundation interaction. The effect of foundation flexibility has been obtained by considering various dam foundation rock interaction ratios i.e. modulus of elasticity of foundation to modulus of elasticity of dam. Results show that both foundation mass and flexibility have an outstanding impact on the behaviour of dams and is necessary to consider their impact while simulating seismic response of concrete gravity dams. Jiji Anna Varughese and Sreelakshmi Nikithan [7] conducted study on seismic behaviour of concrete gravity dams. Seismic response of gravity dams subjected to earthquake acceleration is evaluated in terms of peak displacement and stress. The study reveals that the dynamic response of dams is affected by the interaction of reservoir and foundation. Hence, it is necessary to consider both the dam-reservoir interaction and dam-foundation interaction for predicting the realistic behaviour of dams under earthquake forces. From the time-history results, it is also observed that maximum displacement occurs at the crest of dam and the higher values of stresses are obtained at the heel, neck, and the region opposite to neck of the dam on the upstream side. Majid Pasbani Khiavi [8] investigated seismic performance of concrete gravity dams using probabilistic analysis. The effect of the modulus of elasticity of concrete on seismic behavior of Koyna gravity dam in India is studied in the paper using probabilistic analysis. Numerical model based on the finite element method is used to analyse the base-case scenario involving the dam-reservoir-foundation interaction. The results show that the modulus of elasticity significantly affects seismic behaviour of concrete gravity dams.

III. MODELS USED FOR ANALYSIS

To study the relation between modal period, height and base width a family of concrete gravity dams have been selected with varying height and base width. The height and base width of the selected dams are given in Table 3.1.

Table 1. Dimensions of dams

Dam ID	Height (m)	Base width (m)	Top width (m)
Dam 1	100	180	10
Dam 2	125	225	10
Dam 3	150	270	10
Dam 4	175	320	10
Dam 5	150	180	10
Dam 6	150	135	10
Dam 7	200	360	10
Dam 8	50	90	10
Dam 9	250	450	10

The 2D cross-section of the dams was modelled using a commercially available finite element package, ANSYS 16.2 according to ANSYS user's manual. Following the work of other investigators, the non-overflow monolith of the dams is assumed to be in the plane stress condition. First order and plane stress elements have been used to model the dam body. The element type used is Solid Quad 4 node 182 PLANE182. The boundary condition is given fixed at the bottom of the dam. To study the effect of dam-reservoir-foundation interaction on modal behavior of gravity dam, two concrete gravity dams with 103m and 53.66m in height are selected. Water is treated as compressible fluid. The dam with height 103m is assumed to rest on a 350 × 140m foundation. The dam with height 53.66m is assumed to rest on a 188.2 × 73m foundation. The bottom of the foundation is assumed to be fixed and the foundation is considered to be in plane strain condition. First order and plane strain elements have been used for modelling the foundation. The element type used is PLANE182. The elastic modulus of foundation E_f, varies from 0.25, 0.5, 1, 2 times that of the dam E_d, to consider effects of foundation flexibility. The ratio is defined by:

$$B = E_f / E_d \quad (3.1)$$

The reservoir is assumed to be of length 140m and 73m for dams with height 103m and 53.66m respectively. First order acoustic elements have been used for the reservoir. The element type used is ANSYS Fluid 2D acoustic 29 (FLUID29). The properties of dam body considered are modulus of elasticity, E_d =31027MPa, mass density 2643 Kg/m^3, Poisson's ratio = 0.2. The properties of reservoir water are mass density = 1000 Kg/m^3, sonic velocity = 1440m/s, boundary admittance = 0.5. The properties of foundation are modulus of elasticity, E_d =62054MPa, mass density 3300 Kg/m^3, Poisson's ratio = 0.33. To study the modal response four cases are considered

1. Dam with fixed base, Empty Reservoir(M1)
2. Dam with fixed base, Full Reservoir(M2)
3. Dam with foundation, Empty Reservoir(M3)
4. Dam with foundation, Full Reservoir(M4)

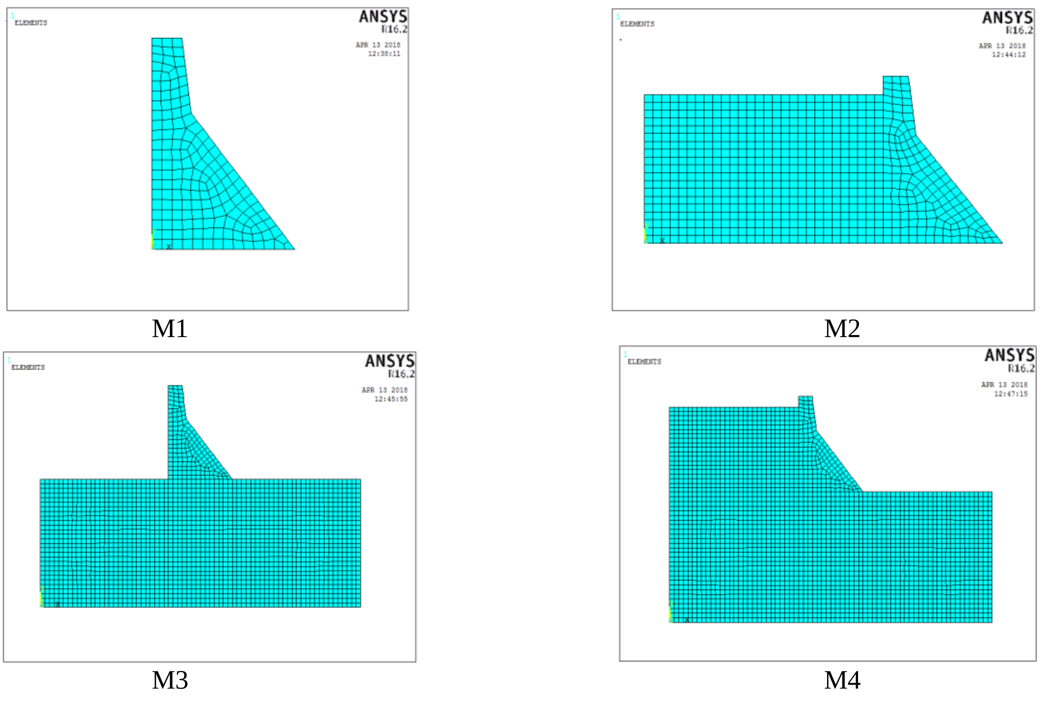

Figure1. FE Models

IV. RESULTS AND DISCUSSIONS

4.1. Relation between modal period, height and base width

Modal analysis was performed on the selected family of concrete gravity dams and modal periods were obtained. Figure 4.1 shows the relation between modal period and height. It can be seen that time period of dam increases with increase in height. Hence, it can be concluded that fundamental time period of dam is functions of its overall height. Structures become laterally flexible as their height increases. As a result, the natural period of structure increase with increase in height. However, the fundamental mode shape does not change significantly. Figure 4.2 shows the relation between modal period and base width. It can be clearly seen that the 1st mode period of the dam decreases with increase in base width. The rate of decreasing is decreasing with increase in the base width. But in case of 2nd, 3rd, 4th and 5th mode period; the base width was found to have no influence. From this it can be conclude that the 1st mode period depends on base width but other higher mode periods are independent of base width.

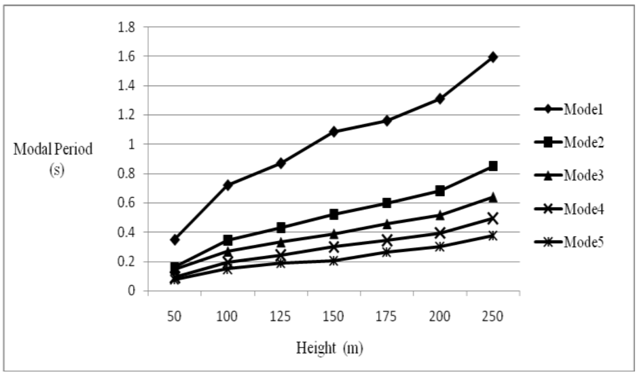

Figure 2. Modal Period v/s Height

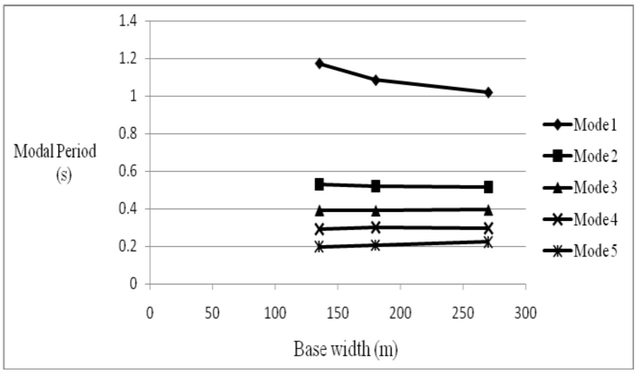

Figure 3. Modal period v/s Base width

4.2. Dam-reservoir interaction

Modal analysis was performed for the two concrete gravity dams in empty reservoir and full reservoir condition ,to study the effect of dam-reservoir-foundation interaction on modal behavior of gravity dam . Comparing M1 and M2 , it was found that model period increases with the reservoir modeling for both dams.

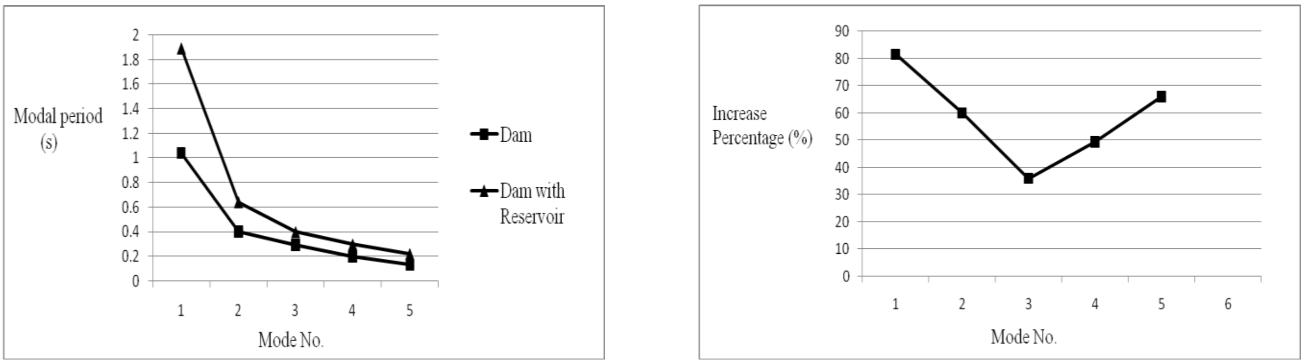

Figure 4. Effect of reservoir modeling (103m high dam)

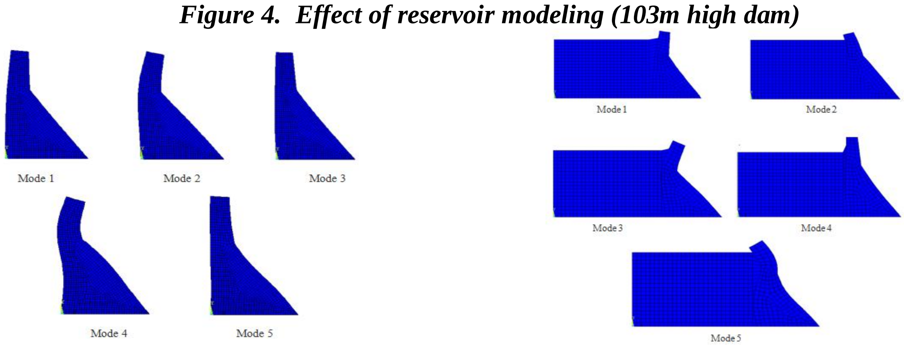

Figure 5. Mode shapes of M1 and M2(103m high dam)

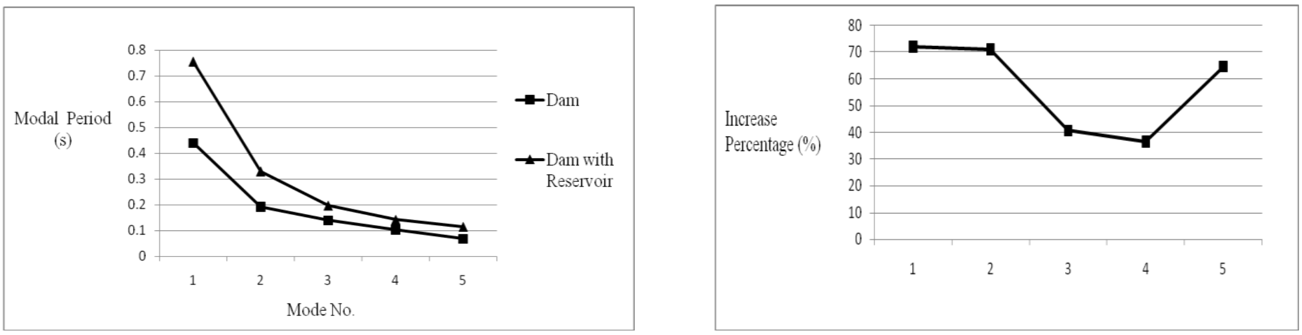

Figure 6. Effect of reservoir modeling (53.66m high dam)

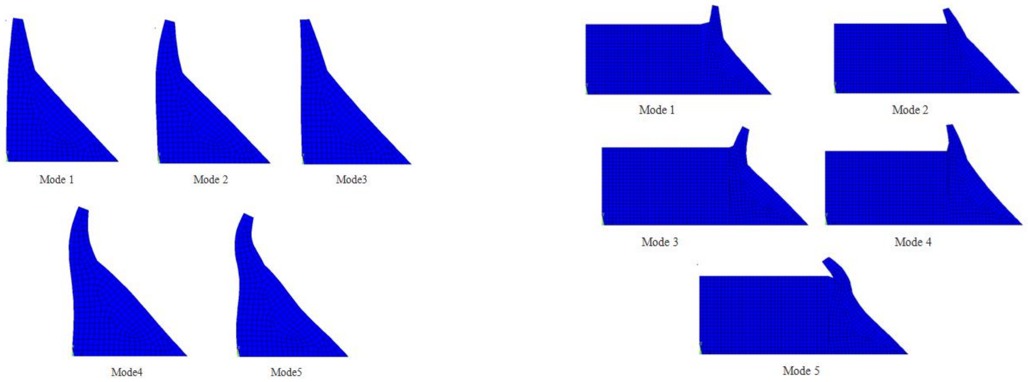

Figure 7. Mode shapes of M1 and M2(53.66m high dam)

On comparing the results it's clearly seen that the reservoir modelling changes modal shapes. For mode 2 the upstream of the dam has move towards the reservoir. Reservoir modelling increases the period of all modes, differently. The effect of reservoir increases the period of the 1st, 2nd, and 5th mode more than the 3rd and 4th mode.The reservoir modelling increases the modal periods of all modes upto 58% for 103m high dam and 57% for 53.66m high dam .The dam-water interaction must be taken into account since the dam undergoes deformation, which influences the motion of water in the reservoir. The interaction between the dam and water stored behind the dam leads to an increase in the period of vibrations of the dam. The water that moves along the dam increases the total mass moved due to earthquake. The added mass increases the natural vibrations period of the dam, and affects inertial forces created due to earthquake action.

4.3. Dam-foundation interaction

On comparing M1 and M3, it was found that modal period increases due to foundation modeling for both dams.

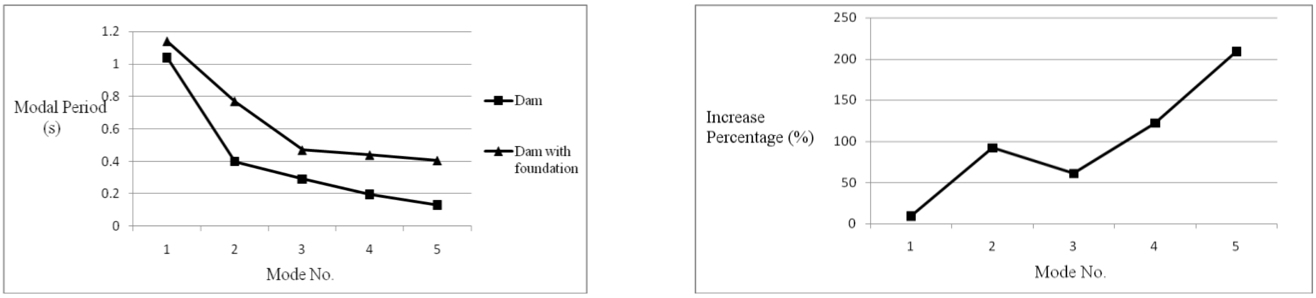

Figure 8. Effect of foundation modeling (103m high dam)

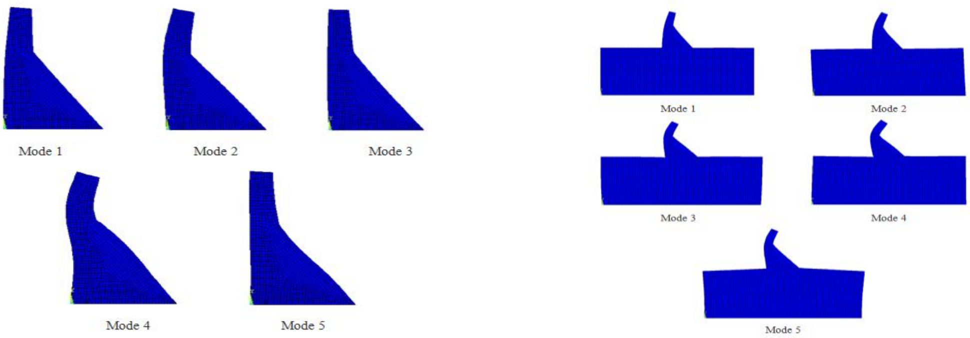

Figure 9. Mode shapes of M1 and M3(103m high dam)

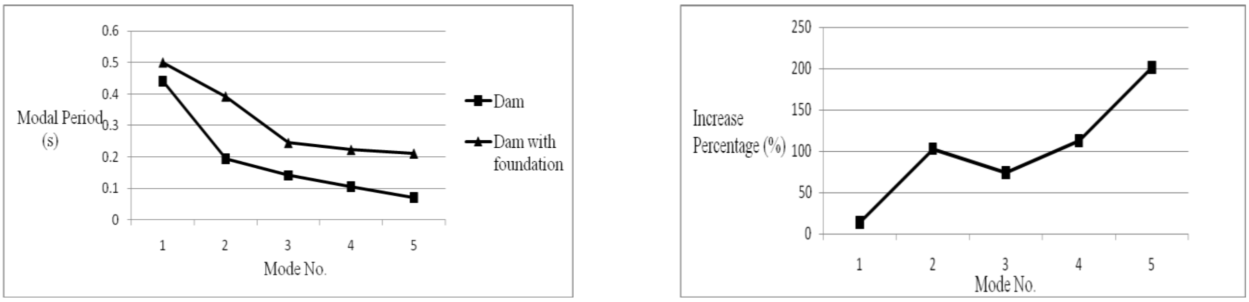

Figure 10. Effect of foundation modeling (53.66m high dam)

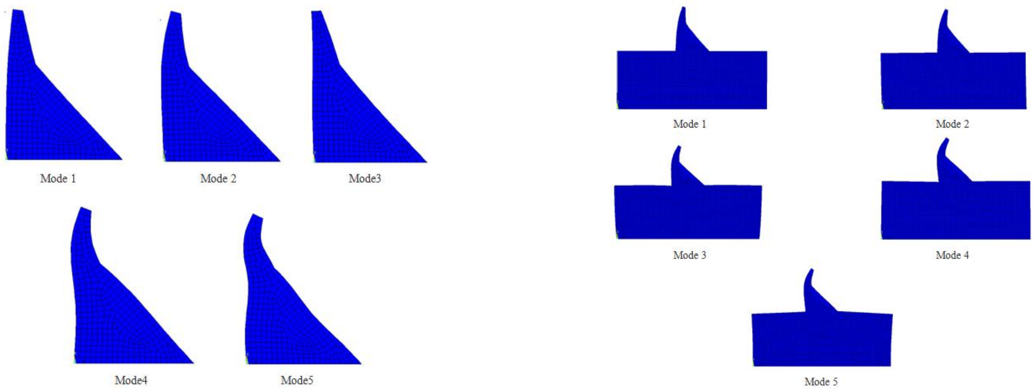

Figure 11. Mode shapes of M1 and M3(53.66m high dam)

The foundation modelling increases the modal periods of all modes up to 71% for 103m high dam and 76%for 53.66m high dam. In both dams the percentage increase is higher for 2nd and 5th mode as compared to that of 1st, 3rd, and 4th mode.

4.4. Dam-reservoir-foundation interaction

The reservoir and foundation are simultaneously modelled to evaluate modal behaviour of gravity dams .Modal analysis was performed. Results obtained were compared with that of M1. Simultaneous modeling of reservoir and foundation increases the modal period of both dams.

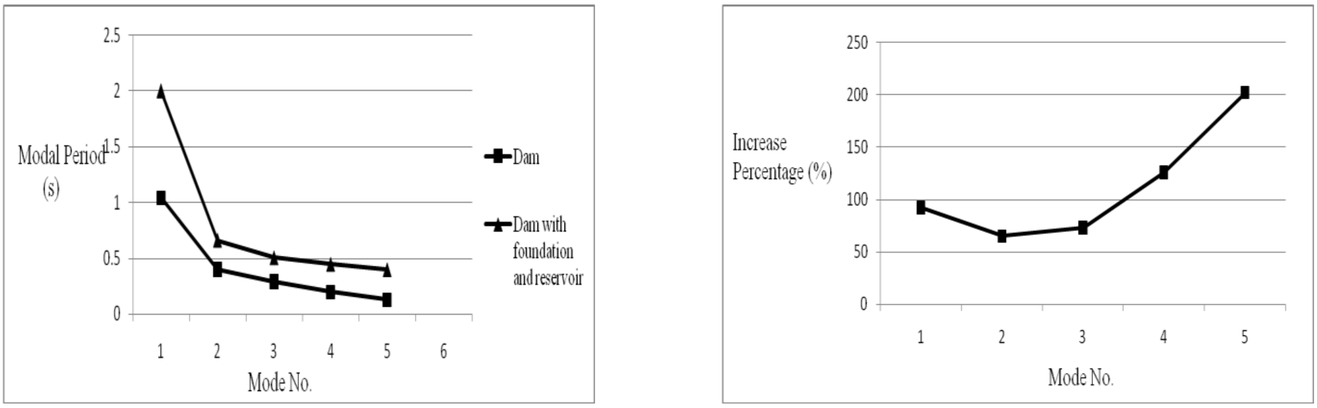

Figure 12. Effect of foundation and reservoir modeling (103m high dam)

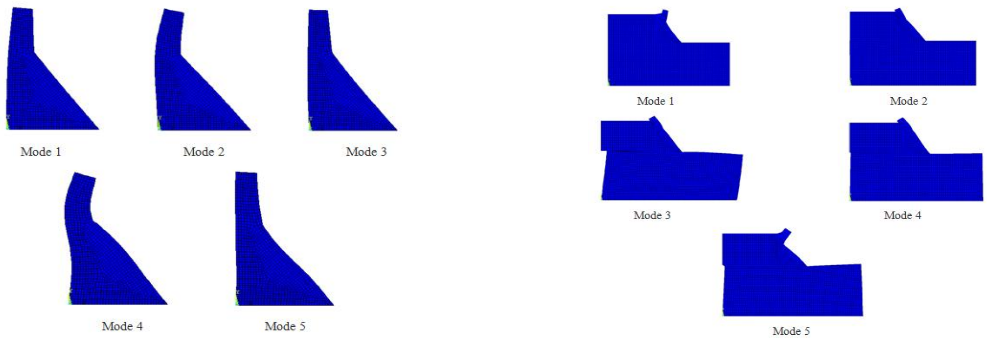

Figure 13. Mode shapes of M1 and M4(103m high dam)

Figure 14. Effect of foundation and reservoir modeling (53.66m high dam)

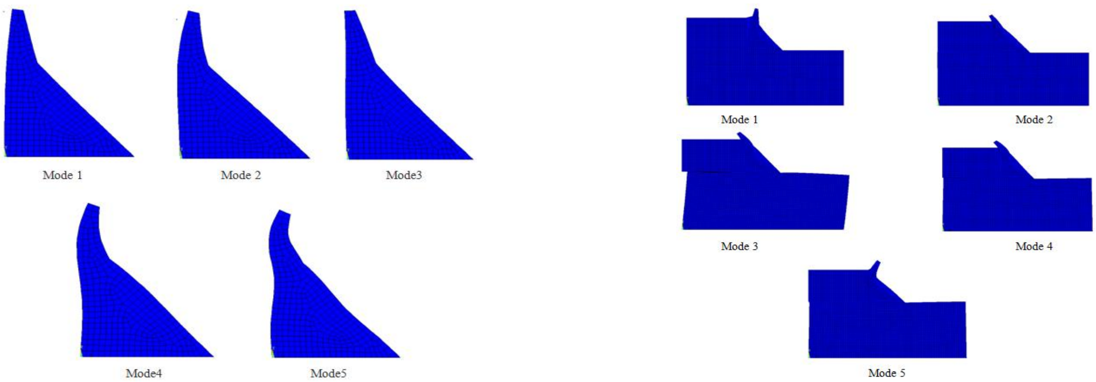

Figure15. Mode shapes of M1 and M4(53.66m high dam)

It was found that simultaneous modelling of reservoir and foundation increases the modal periods with respect to M1. The increase in the modal periods of all modes is up to 89% for 103m high dam and 94%for 53.66m high dam. Percentage increase is higher for 5th mode as compared to that of other modes.

4.5. Effect of foundation flexibility for 103m high dam in empty reservoir condition

Modal periods obtained for different values of B are compared with the modal periods of M1(Fixed dam base, Empty reservoir). It has been seen that the foundation modelling with dam causes to increase modal periods, regarding to increase in foundation flexibility. So it plays an important role in site selection. To show the increase in modal period with the increase in foundation flexibility a plot between modal period and mode no. is drawn for varying values of B for 103m high dam and compared with that of M1.

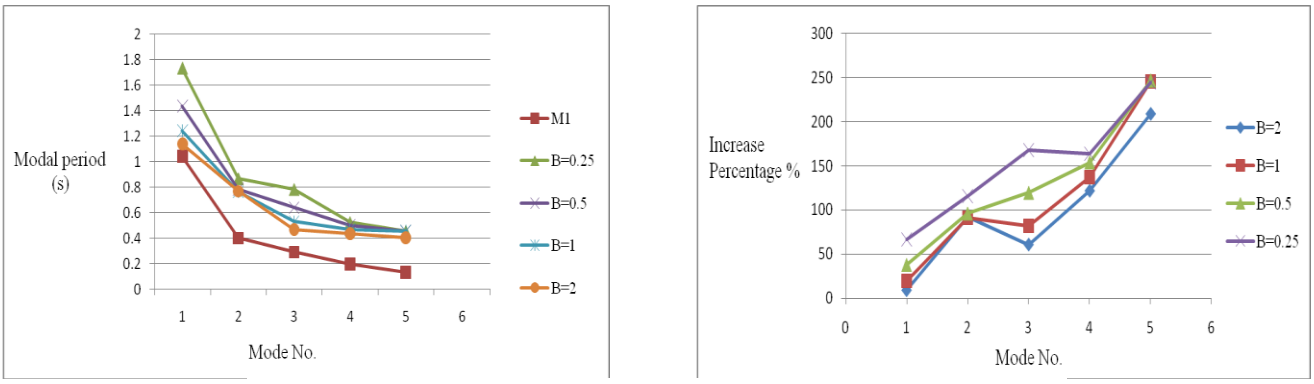

Figure 16. Effect of foundation flexibility, Empty reservoir (Height 103m)

The foundation modelling increases the modal periods of all modes. For B=2, 1, 0.5 and 0.25 the increase in modal period is up to 71%, 82%, 102% and 128% respectively for 103m high dam in empty reservoir condition. The increase in modal period is higher for B=0.25 and lower for B=2 when comparing with M1

4.6. Effect of foundation flexibility for 103m high dam in full reservoir condition

Modal analysis is performed on 103m high dam with foundation in full reservoir condition and modal periods are obtained. The foundation modulus is changed to study the effect of foundation flexibility on modal period.

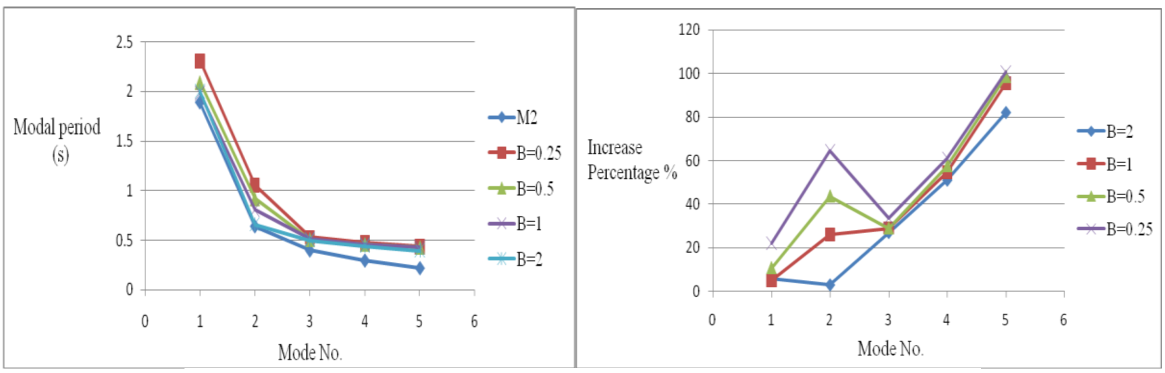

Figure 17. Effect of foundation flexibility, Full reservoir (Height 103m)

Modal periods obtained for different values of B are compared with the modal periods of M2(Fixed dam base, Full reservoir). It has been seen that simultaneous modelling of reservoir and foundation increases the modal period with respect to M2. Also the modal period increases with the increase in foundation flexibility. The foundation with B=0.25 has higher modal period as compared to that of B=0.5, 1, 2. For B=2, 1, 0.5 and 0.25 the increase in modal period is up to 33.7%, 42%, 48% and 56% respectively for 103m high dam in full reservoir condition. The percentage increase is higher for 5th mode. Hence it was found that foundation flexibility have a significant effect on modal period. It is seen that foundation modelling changes the modal shapes due to flexibility of foundation was introduced.

4.7. Effect of foundation flexibility for 53.66m high dam in empty reservoir condition

To study the influence of foundation flexibility on modal behaviour of dam, a dam with foundation is modelled in empty reservoir condition. Modal analysis was performed by changing the modulus of elasticity of foundation by 0.25, 0.5, 1, 2 times that of dam and modal periods are obtained. Modal periods obtained for different values of B are compared with the modal periods of M1 (Fixed dam base, Empty reservoir). It has been seen that the foundation modelling with dam cause to increase modal periods, regarding to increase in foundation flexibility.

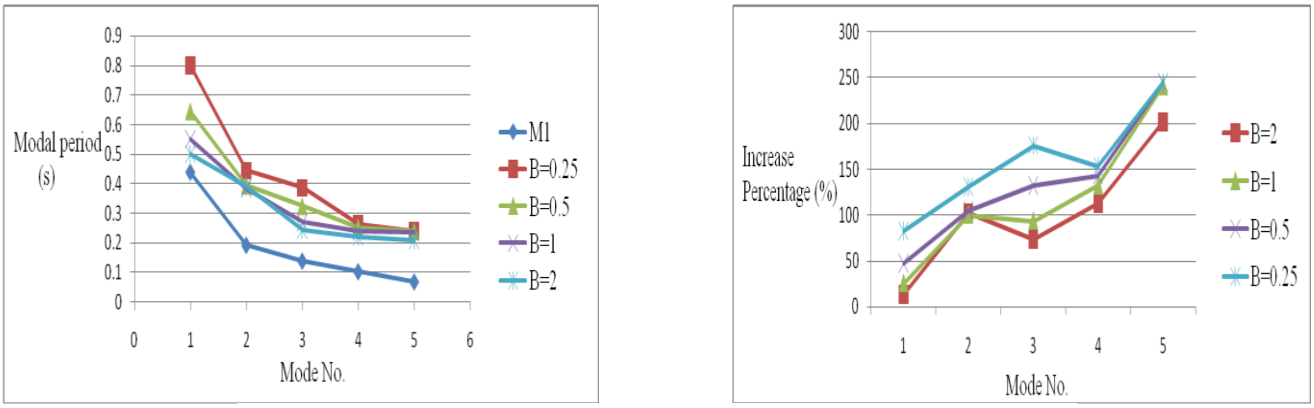

Figure18. Effect of foundation flexibility, Empty reservoir (Height 53.66m)

It is clearly seen from the above figures that the foundation modelling increases the modal periods of all modes. For B=2, 1, 0.5 and 0.25 the increase in modal period is up to 76%, 88%, 106% and 135% respectively for 53.66m high dam in empty reservoir condition. The modal period is higher in the case of B=0.25 and lower in the case of B=2. As the foundation flexibility increases the modal period increases. The percentage increase is higher for 5th mode and lower for 1st mode.

4.8. Effect of foundation flexibility for 53.66m high dam in full reservoir condition

Modal analysis was performed for 53.66m dam by simultaneously modelling foundation and the reservoir. To study the effect of foundation flexibility on modal period the modulus of elasticity of the foundation is varied and modal periods and mode shapes are obtained. Modal periods obtained for different values of B are compared with the modal periods of M2 (Fixed dam base, Full reservoir). It has been seen that simultaneous modelling of reservoir and foundation increases the modal period with respect to M2. Also the modal period increases with the increase in foundation flexibility. The foundation with B=0.25 has higher modal period as compared to that of B=0.5, 1, 2.

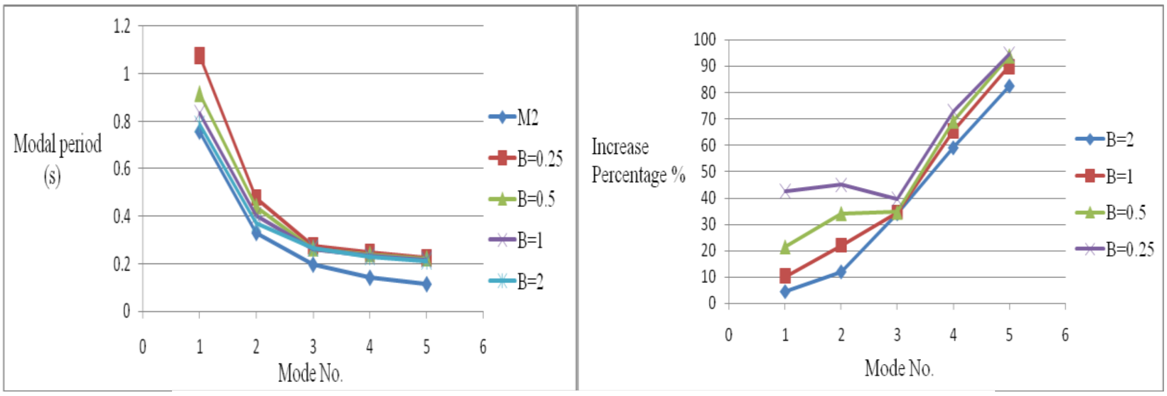

Figure 19. Effect of foundation flexibility, Full reservoir (Height 53.66m)

The simultaneous modelling of foundation and reservoir increases the modal periods of all modes. It is clearly seen that foundation flexibility has a significant effect on modal period. For B=2, 1, 0.5 and 0.25 the increase in modal period is up to 38%, 44%, 50.5% and 59% respectively for 53.66m high dam in full reservoir condition. The percentage increase is higher for 5th mode. On comparing the mode shapes, it is seen that foundation modelling changes the modal shapes due to flexibility of foundation was introduced.

V. CONCLUSIONS

Effects of dam-reservoir-foundation interaction and foundation flexibility on the modal behaviour of gravity dam were studied. Modal analysis was performed for reservoir empty and reservoir full condition. Relation between modal period, height and base width of dam was obtained by performing modal analysis on a family of concrete gravity dam.
Conclusion that obtained from the results is:

- Time period of dam is functions of its overall height. It increases with increase in height. However, the fundamental mode shape does not change significantly.
- Base width has no significant influence on the modal period. 1st mode period depends on base width but other higher mode periods are independent of base width.
- Reservoir modelling changes modal shapes and increases the period of the 1st, 2nd, and 5th mode more than the 3rd and 4th mode. The percentage increase in modal period is up to 58% for 103m high dam and 57% for 53.66m high dam.
- Foundation modelling increases the modal periods of all modes up to 71% for 103m high dam and 76%for 53.66m high dam. In both dams the percentage increase is higher for 2nd and 5th mode as compared to that of 1st, 3rd, and 4th mode.
- Simultaneous modelling of reservoir and foundation increases the modal periods The increase in the modal periods of all modes is up to 89% for 103m high dam and 94%for 53.66m high dam. Percentage increase is higher for 5th mode as compared to that of other modes.
- Modal period increases with the increase in foundation flexibility. For B=2, 1, 0.5 and 0.25 the increase in modal period is up to 71%, 82%, 102% and 128% respectively for empty reservoir condition and 33.7%, 42%, 48% and 56% respectively for full reservoir condition for 103m high dam.
- For 53.66m high dam with B=2, 1, 0.5 and 0.25, the increase in modal period is up to 76%, 88%, 106% and 135% respectively for empty reservoir condition and 38%, 44%, 50.5% and 59% respectively for full reservoir condition.

Thus dam-reservoir-foundation interaction and foundation flexibility has significant influence on the modal behaviour of gravity dam. Modal period is found to increase due to dam reservoir foundation interaction. Mode shapes was also changed due to these interactions. A gravity dam will be affected by long period waves of earthquake. Also it was found that changes in modulus of elasticity of foundation changes the modal period. Modal period increases with the increase in foundation flexibility. It plays an important role in site selection. So, consideration of these effects is essential while designing the structure for safety, reliability and quality.

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