Journal of Multidisciplinary Engineering Science Studies (JMESS)
ISSN: 2912-1309
Vol. 2 Issue 1, January - 2016

The effect of substrate stiffness on seismic response of double-curvature arch dams using the finite element model

Mortaza Ali Ghorbani
Faculty of Engineering
University of Mohaghegh Ardabili
Ardabil, Iran
gorbani@uma.ac.ir

***Abstract*—In this study, the dynamic analysis of double-curvature arch dam to examine the effect of foundation stiffness on seismic response is discussed. Ansys software was used for analysis and interaction effect of dam, reservoir and foundation is included in the model. Three-dimensional modeling has been done due to the geometry and behavior of the double-curvature arch dams, and analysis was done using the Newmark method as time history. As a case study, seismic analysis of double-curvature Morrow Point dam is considered, and horizontal and vertical components of El Centro earthquake acceleration is applied to the model. Using the model, the complete analysis can be done with respect to general conditions, such as the slope of the dam upstream and the bottom of the reservoir and non-linear behavior for insulation materials can be considered. The results of the analysis of the impact of the foundation stiffness which is directly related to the modulus of elasticity, is shown clearly.**

Keywords—earthquake; interaction; Ansys; foundation stiffness; double- curvature arch dam

I. INTRODUCTION

The issue of structure and fluid interaction is one of the most extensive discussion related to fluid behavior, which is interesting from the point of view of engineering, and research have been done on it. The issues related to structure and fluid interaction is arisen when there is relative motion between the two systems. One of the most important issues in the debate over fluid -structure interaction is the interaction between the dam-reservoir in an earthquake. The interaction between a dam and water stored behind the dam leads to increase the period of vibrations at the dam. The reason for this is that the dam can't move without spatial variability of water tangent to it. The water which 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 the earthquake. Also, it could increase the mortality pressure during absorbing pressure waves on the borders of the reservoir and emission to the upstream side of the dam. These effects lead to different seismic response between situations related to the dam compared to empty tank.

Studies on modeling the effects of interactions on issues related to seismic analysis of dams have a long history. The first study in this area was conducted by Westergaard in 1933 [1]. He has considered interaction effects in the form of a two-dimensional dam-reservoir model which is affected by the vibration caused by the horizontal movement of the Earth. He assumed that the dam is a rigid body with a semi-limited reservoir with fixed depth. He extracted pressure distribution of the fluid at the contact of the dam and reservoir using methods of analysis. He found that, the interaction force is due to proportional to acceleration of seismic ground motion, and may be approximated by a parabolic distribution of mass on the dam height. This method is known as added mass approximation. Because of the added mass, specific frequencies of seismic response of a dam for the reservoir-dam system is clearly less than the empty dam system. Westergaard added mass approximation due to simplicity is one of the most practical models for analysis of dams in engineering operations, but this approximation does not consider the amortization of the release, and is only source of energy dissipation due to structural damping of the dam. Chopra in 1967 has examines the effects of fluid compressibility on the force due to the fluid-structure interaction [2]. His physical model was similar to the Westergaard model. He concluded that, if we ignore the effects of compressibility, significant errors in analysis will appear. In most studies, the assumption of incompressible water is used, because considering such assumption makes very simple dam and reservoir system modeling taking into account the effects of interaction. Waves move with an unlimited speed in the incompressible water, so that the interaction forces are proportional to the acceleration applied to the fluid. Therefore, in these circumstances, it is not necessary to solve complex integrations.

In some studies, the forces of interaction during seismic ground motion are considered as an external force on the dam, and dam response is not involved in the calculation of interaction forces, because the dam is assumed to be rigid. Chopra in 1968 has studied the impact of flexibility of the dam on interaction forces with dam modeling as a system including Mass, damper and spring [3, 4]. He indicated that the natural frequencies of the dam coupled system and reservoir are different from uncoupled systems. He found that, if the ratio of first frequency of dam to the first frequency of the reservoir is larger than two, you can disregard the effect of compressible water. He concluded that, when considering the effects of the interaction of the dam and reservoir, dam response compared to situation in which the interaction effect is ignored, is significantly increased.

For very complex geometries, hydrodynamic wave equation can only be solved numerically with considering suitable discrete model for the reservoir. Profile of unlimited reservoir must be displayed by selecting an appropriate numerical model on a cut boundary, so calculations must be done based on the absence of reflected waves from the distant boundary.

Dam reservoir usually is considered as a series of limited elements to achieve a relatively accurate result in the calculation of hydrodynamic pressure on the dam with irregular reservoir. For the first time, Zienkiewicz in 1965 showed formulation of finite elements to display the response of a submerged structure assuming incompressible water [5]. Zienkiewicz in 1978 tested formulation of finite elements for solving pressure wave equation with unlimited reservoir range [6]. He showed that, Sommerfeld distant boundary condition is suitable for quite long reservoir model and it can be used as a boundary condition in the place which domain is interrupted in the discrete finite element model related to the fluid domain. Some formulations of hydrodynamic pressure are expressed as sentences and dependent on the frequency, which has good behavior in the frequency domain. This process is shown at the computer program EACD-3D by Chopra et al in 1986 for seismic analysis of arch dam. Hydrodynamic pressure in the reservoir is generated by upstream acceleration and vertical acceleration at the bottom of the reservoir. The most appropriate method for dynamic analysis is analysis in the time domain which used to overcome the limitations of the response spectrum method to calculate the time-dependent response and better representation of the structure - soil and structure - fluid interactions. Earthquake inputs for analysis in the field of time are usually in the form of acceleration time history that is very accurate compared to a lot of seismic ground motion parameters such as duration and frequency. Time history analysis is the only suitable method for estimating the damage criterion. In this method, the response in the time domain is calculated using step by step numerical integration. Due to these reasons, in this study, a complete analysis is done using Ansys software in the time domain, and the effects of absorbing foundation will be discussed and investigated.

II. The Governing Equations

To obtain the governing equations related to fluid inside the reservoir, it is assumed that fluid is non-rotating, non-viscous and has a small displacement. In this case, the acoustic wave equation is as follows:

$$\frac{1}{C^2}\frac{\partial^2 P}{\partial t^2} - \nabla^2 P = 0 \quad (1)$$

Where, C is the velocity of sound waves in the fluid, P is the pressure of acoustic and t is time. The governing equation on the dam in the form of a matrix is shown as follows:

$$M\ddot{u} + Cu \dot{+} Ku = M\ddot{u}_g + F^{pr} \quad (2)$$

Where, M is mass matrix, C: damping matrix, K: stiffness matrix, u: displacement vector, F^{pr} hydrodynamic pressure applied from the reservoir on the dam at the point of contact between the dam and the reservoir and $\ddot{u}_g$:earthquake acceleration. Sommerfeld boundary conditions are used to express tank reservoir boundary behavior and Rayleigh method is used to express damping.

III. Model Analysis

The Ansys software is used for seismic analysis of the double-curvature arch concrete dam. The software is capable for seismic analysis with regard to the irregular geometry of domains and tank-foundation interaction. For this purpose, the appropriate elements are anticipated which display compressible behavior of fluid. Also, for analysis, appropriate absorbent boundaries have been cut off at the away boundary and defined in the bottom of the reservoir, and the Somerfeld boundary condition is used for the mentioned boundary. the Newmark method is used for numerical integration, the parameters β = 0.25 and γ = 0.5 and the time step Δt = 0.02 are selected for it. To analyze the dynamics, Morrow Point Dam is considered as a case study. Morrow Point Dam is a 468-foot-tall (143 m) concrete double-arch dam on the Gunnison River located in Colorado, the first dam of its type built by the U.S. Bureau of Reclamation. Located in the upper Black Canyon of the Gunnison, it creates Morrow Point Reservoir, and is within the National Park Service-operated Curecanti National Recreation Area. The dam is between the Blue Mesa Dam (upstream) and the Crystal Dam (downstream). Geometry of the desired model is shown in Figure 1:

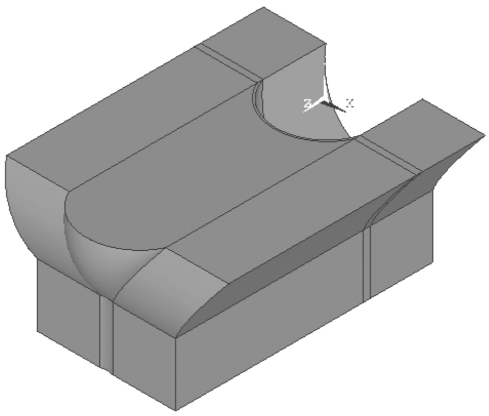

Fig. 1. *Geometry of the Model*

EL Centro earthquake is selected for seismic analysis, components. Figures 2 to 4 show acceleration of El Centro earthquake that occurred in 1940.

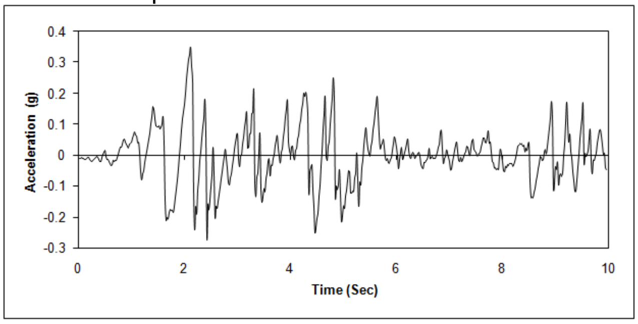

Fig. 2. *The north-south component of El Centro earthquake*

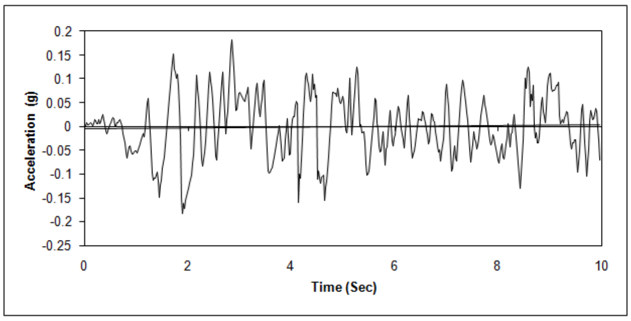

Fig. 3. *The East-West component El Centro earthquake*

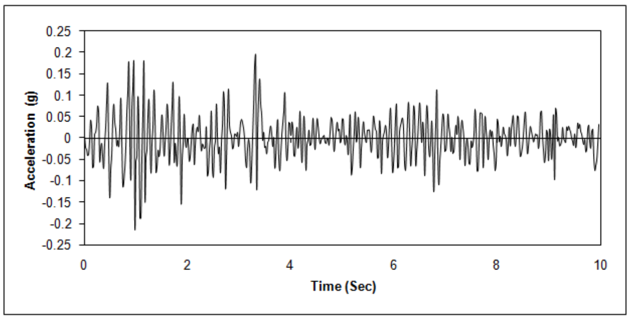

Fig. 4. *Vertical component of the El Centro earthquake*

After modeling and dynamic analysis, the results are extracted related to responses of shift, tensions arose in the dam body and there hydrodynamic pressure in the reservoir. Given that the main goal of this paper is to examine the effect of the foundation stiffness on seismic response of the double-curvature arch dam, the desired model is analyzed for both modes of flexible and rigid foundation, and the results obtained are provided as time history by applying horizontal and vertical acceleration for vice-EL Centro earthquake. For the flexible foundation, elastic modulus is intended equal to 22 GPa. Figures 5 and 6 show the results of the horizontal shift of the midpoint of the dam crest at along the reservoir for two modes.

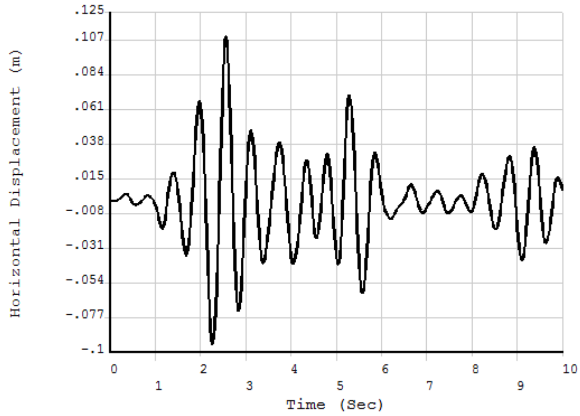

Fig. 5. *Time history of the horizontal shift of the dam crest for flexible foundation*

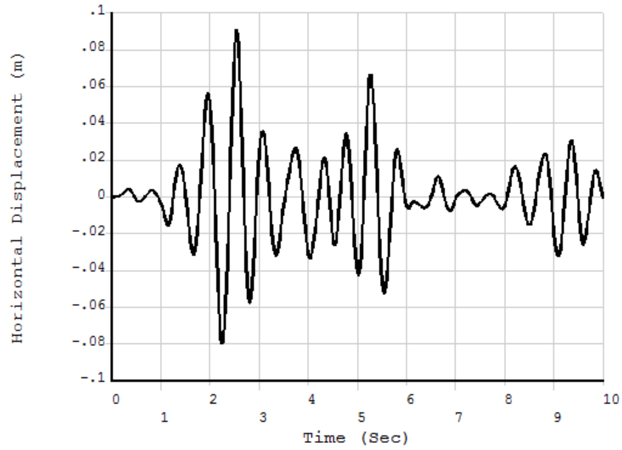

Fig. 6. *Time history of the horizontal shift of the dam crest for rigid foundation*

By comparing the curves, reduced the horizontal shift of the crown can be seen when the rigid foundation is considered. Also, to check the tension caused on the dam body, the results of the time history response of the maximum and minimum principal stresses at the critical point are drawn for both modes of the foundation, and are shown as curves 7 to 10. According to the results, you can see the effect of foundation stiffness on the seismic response of the double- curvature arch dam. As the results show, when the foundation is considered to be rigid, responses to stress also are reduced.

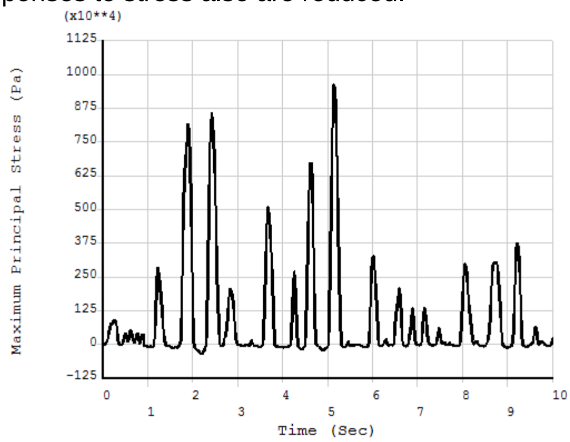

Fig. 7. *Time history of the maximum principal stress for flexible foundation*

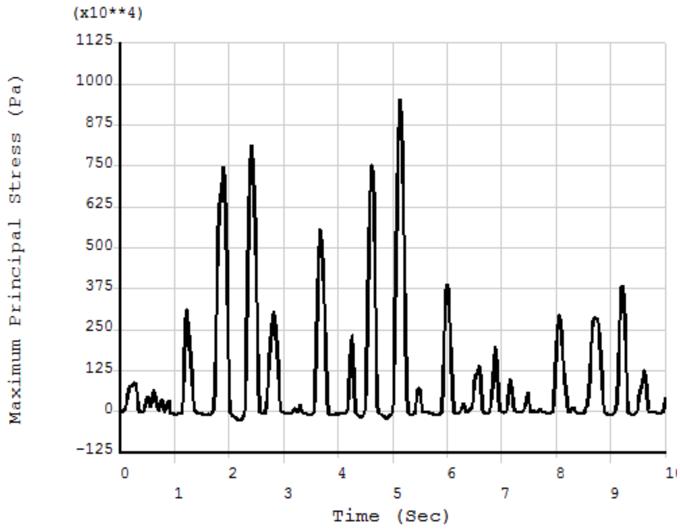

Fig. 8. *Time history of the maximum principal stress for rigid foundation*

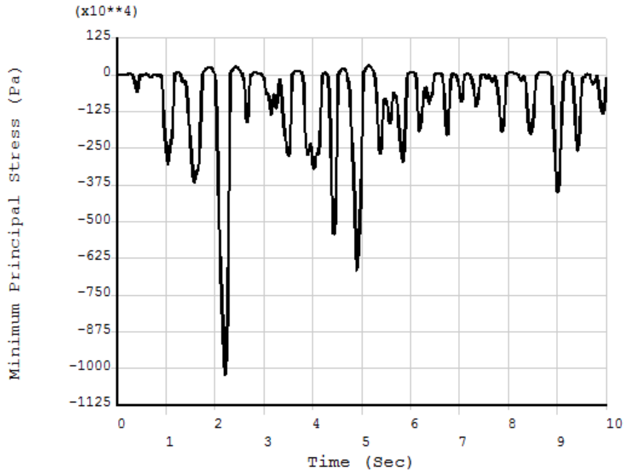

Fig. 9. *Time history of the minimum principal stress for flexible foundation*

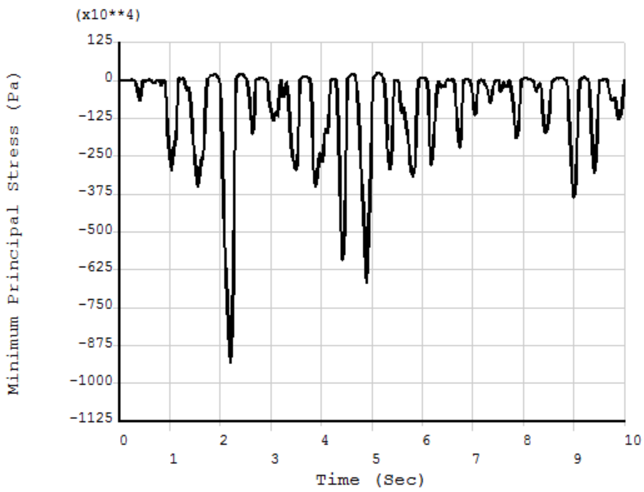

Fig. 10. *Time history of the minimum principal stress for rigid foundation*

To investigate the effect of foundation on hydrodynamic pressure generated in the reservoir, according to the absorption properties of the flexible foundation and the full reflecting property of rigid foundation, the results of hydrodynamic pressure generated at the dam heel have been compared.

Figures 11 and 12, show the time histories response of hydrodynamic pressure for both modes.

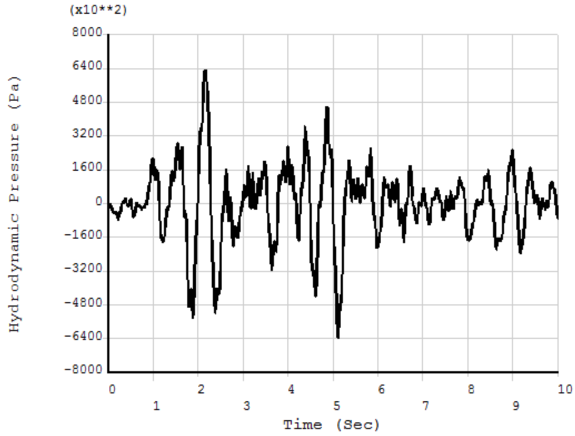

Fig. 11. *Time history of the hydrodynamic pressure generated by the dam heel for flexible foundation*

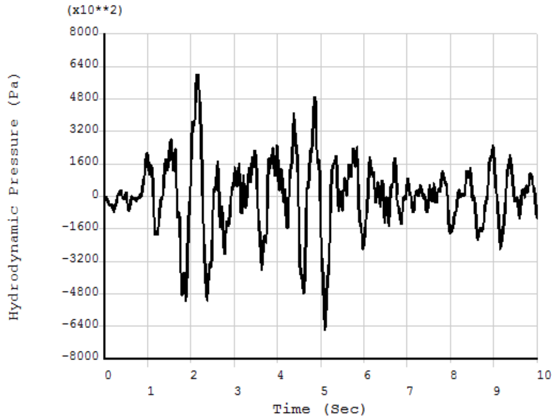

Fig. 12. *Time history of the hydrodynamic pressure generated by the dam heel for rigid foundation*

As the figures show, about the response of hydrodynamic pressure can't be said with certainty that Does foundation stiffness reduces the hydrodynamic pressure in the reservoir or not. The reason can be searched in the nature of the foundation in the absorption of hydrodynamic pressure generated in the reservoir. Rigid foundation, on the one hand due to lower transmission earthquake in the dam body reduces the dam displacement and hydrodynamic pressure caused by vibration in the reservoir, and on the other hand, due to complete reflection of the hydrodynamic pressure absorption leads to remain it as maximum value. However, in flexible foundation, an amount of hydrodynamic pressure generated is absorbed by the foundation. Therefore we can say that, absorption or hydrodynamic pressure waves' generation is dependent on the seismic loading and foundation specifications. In the end, for better examination of the effect of rigid foundation in reducing the displacement and stress, numerical values of the responses are presented in table. Table 1 shows numerical values of maximum responses on maximum horizontal shift and main stresses for both models of foundations.

TABLE I. THE NUMERICAL VALUED OF THE MAXIMUM HORIZONTAL DISPLACEMENT, MAIN TENSILE AND COMPRESSIVE STRESS FOR DIFFERENT CONDITIONS OF THE FOUNDATION

Dam response	Rigid foundation	Flexible foundation	Percent
The horizontal displacement of dam crest (m)	0.0908	0.709	16.7
The main tensile stress (MPa)	9.51	9.61	1.04
The main compressive stress (MPa)	9.31	10.23	9.0

Table 1 clearly indicates that when considering the foundation as rigid, shift to be reduced by 17%, and the tensions generated on the dam body by about 9%. The reason is less vibration transmitted to the dam body due to earthquake. Therefore it can be concluded that, to obtain reliable analysis and detailed design of two double-curvature arch dam, it is necessary that the effects of foundation in the analysis must be considered which this issue has been little noticed in previous studies.

IV. CONCLUSION

In this study, Morrow Point Dam was analyzed as a case study using the finite element model developed by Ansys software to demonstrate the importance of double-curvature arch dam modeling with reservoir and foundation. For seismic analysis, horizontal and vertical components of El Centro earthquake were imposed on the model. After analyzing the model, the results were extracted related to the horizontal shift and the main stress of the dam and the hydrodynamic pressure generated in the reservoir. The model was analyzed for different modes of foundation to assess the effect of the foundation stiffness. According to the results of the model, it can be concluded that the use of rigid foundation reduces the response of horizontal shift and the stresses generated on the dam body. Therefore, accurate modeling of the foundation should be considered for the detailed design of dams. Finally, it should be noted that, by the proposed model, we can examine the effect of other parameters such as the slope of the bottom of the reservoir and the slope of the upstream face of dam on the seismic response of two double-curvature arch dam.

REFERENCES

[1] H. M. Westergaard, "Water pressure on dams during earthquake,", Transactions, ASCE, vol. 98. 1933, pp. 418-433.

[2] A. K. Chopra, "Hydrodynamic pressure on dams during earthquakes,", Journal of engineering mechanics division, vol. 93. 1967, pp. 205-223.

[3] A. K. Chopra, "Earthquake behavior of reservoir-dam systems," Journal of engineering mechanics division, vol. 94. 1968, pp. 1475-1500.

[4] A. K. Chopra, "Earthquake response of concrete gravity dams," Journal of engineering mechanics division, vol. 96. 1970, pp. 443-454.

[5] O.C. Zienkiewicz, B. Iron, and B. Nath, "Natural frequencies of complex free or submerged structures by the finite element method," Symp. Vibration Civ. Engng, Butterworths, London, 1965.

[6] O.C. Zienkiewicz and P. Bettess, "Dynamic fluid-structure interaction: Numerical modeling of the coupled problem," John wiley, New york, 1978, pp. 185-193.

[7] G. Fenves and A. K. Chopra, "Effect of reservoir bottom absorption and dam-water-founation rock interaction on frequency response functions for concrete gravity dams," Earthquake engineering and structural dynamics, vol.13. 1985, pp.13-31.