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Investigation into the Effect of Bed Stiffness on Seismic Performance of Concrete Gravity Dam Under far- and near- field Earthquakes

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ABSTRACT

Today hydraulic reservoir structures are one of the most significant structures over the world and, on the other hand, have become of great importance because of current droughts, particularly in the Middle East. Concrete dams are noteworthy superstructures amongst these structures and their construction and maintenance involve intensive research. In this study, the effect of bed stiffness on a concrete gravity dam is examined under far- and near-fault ground motions. This study is conducted through the numerical modeling of Pine Flat concrete dam as a case study via Abaqus software, the import of 6 far- and near-field accelerograms and the investigation into the effect of 3 stiffness ratios. The results indicate that the stiffness ratio of 1 has a more reasonable effect, for which the response of structure is more logical and appropriate.

Keywords: **Concrete gravity dam, stiffness ratio, dam behavior, Pine Flat, far- and near-fault**

1. INTRODUCTION

Given the obvious water crisis around the world that many countries are faced with, especially in the Middle East, the protection of water resources is so important. Since dams are one of the hugest water resources employed for many purposes, such as power generation and agriculture, the protection of these superstructures is of great importance. In a study on the Xialuodu Dam in China in 1988, where the modeling was conducted by 30% increase in allowable stress under seismic stimulation, 30% increase in dynamic elastic modulus and a damping ratio of 0.05, it was concluded that the flexibility of foundation cause changes in motion frequencies and dam-foundation movement modes. The seismic energy is also dissipated in an infinite medium of foundation, which is 1.5 times the height of the dam [1].In 2007, a dynamic analysis of the dam and reservoir was carried out in regard to the effects of energy absorption on the boundaries of reservoir. They considered water as an incompressible material to accomplish the modeling in relatively actual conditions and properly notice the impact of energy absorption by water during earthquakes. They then concluded that when water is considered incompressible, a large part of energy is absorbed by water and the construction cost is reduced dramatically [2]. In 2009, Iranian researchers performed a case study on Marrow Point Dam to examine the effect of water-structure interaction using the Westergaard added mass model with a viscous damping ratio of 0.05. They also considered the fluid incompressible to model the reservoir. The results of their research suggested that conventional models of concrete dams are less compatible with reality, e.g. Mohr-Coulomb and Drucker-Prager models, and it is better to utilize specific behavior models for concrete dams with plasticity models, e.g. Willam-Warnke model [3]. In another study in 2013, the impact of elastic modulus on the behavior of concrete gravity dam during crack propagation was evaluated considering the water-dam-foundation interaction through a nonlinear finite element method. They utilized the crack propagation behavior model to define the properties of concrete materials in their research. In this model, the physical properties of system included the elastic modulus, tensile strength and specific failure energy, which were considered to make the dynamic response of the dam closer to the actual value. As the dimensionless ratio of E_f/E_d decreases, the energy dissipation of structure increases and the crack depth declines [4]. In 2015, the nonlinear behavior of dam body materials was simulated before and after crack initiation via Abaqus in regard to the dam-reservoir-foundation system. They used 20 earthquake records in their research where the accelerograms were modified and both vertical and horizontal components of the seismic acceleration were simulated. The results demonstrate that both reservoir-modeling methods have different advantages and disadvantages. Generally, however, there is no considerable difference in the responses of the dam [5]. In a study in Canada, the seismic vulnerability of concrete, earth and rockfill gravity dams was addressed by extracting the fragility curves. Given that the characteristics of design codes, construction techniques and seismic conditions in western Canada resemble those in California, they applied the collapse criterion developed in the ATC-13 report for buildings in California [6]. Wang et al (2017) investigated the seismic cracking behavior of Guandi Concrete Dam in a high seismic zone in China, based on which it is possible to calculate the collapse probability of these structures under different seismic intensities using failure curves [7]. It is also observed that the variables, e.g. frequency contents, far- and near-field accelerograms and crack propagation were assessed by most previous studies in regard to the effect of field of earthquakes on the seismic performance of dams [8-11]. In this study, the dam-foundation-reservoir interaction is simulated for more accurate evaluation in order to consider the impact of hydraulic forces of reservoir and foundation stiffness and measure the effect of conditions on the behavior of concrete gravity dam.

2. MATERIALS AND METHODS

Pine Flat dam is investigated as a case study to assess the behavior of gravity dams under dynamic loads. Located on the Kings River in the California State, this dam forms the Pine Flat reservoir and is made of 36 monoliths 15 m in width and a monolith 12 m in width. The dam crest is 550 m in length and its tallest monolith is 122 m in height. A cross-section of the dam is displayed in the figure below. The dam is 97 m wide at the base level and about 10 m wide at the crest level. The upstream side of the dam is not vertical and has a slope of 5% from the base to the level of 102 m. The dam is primarily used for flood control and secondarily for irrigation and recreation. The Abaqus software is employed for the numerical simulation of this dam. This software can use explicit/implicit dynamic solver code to simulate the seismic analysis precisely. In the database of this software, there are a variety of methods for fluid simulation and nonlinear behavior models of materials, which can be employed simply for modeling purposes [12]. Figure 1 illustrates the image and geometrical conditions of the dam.

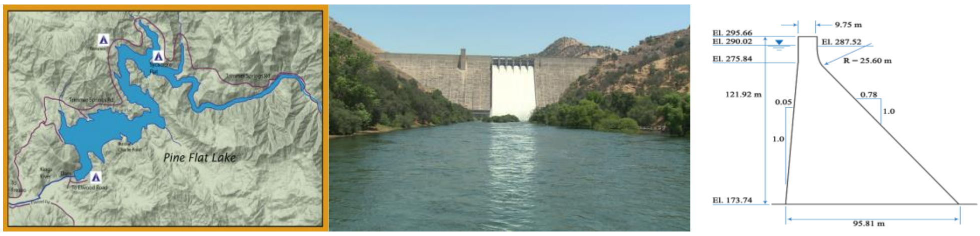

Figure 1. Geometrical conditions of Pine Flat Dam [13]

Modeling

In the case study of this research, the 4-node plane strain element with reduced integration, the 4-node linear 2D plane element (CPE4) and the 4-node acoustic plane strain element with reduced integration (AC2D4R) are used to model the foundation, dam and reservoir, respective.

Validation and Numerical Model

The model utilized by Fenves and Chopra is investigated to validate the modeling method in this study [14]. In their study, they applied the S69E component of Taft earthquake accelerogram. When the numerical simulation of dam-reservoir-foundation system is done via the Abaqus software and this earthquake is applied, the horizontal displacement time history diagram for the dam crest is derived from the Abaqus software and compared to the results of Chopra and Fenves. It is observed that the maxima and minima of both diagrams are the same and the maximum displacements are 1.45 and 1.39 inches, respectively, which have a difference of less than 5%. Therefore, the modeling method can be certainly employed for numerical studies in this research (Fig. 2).

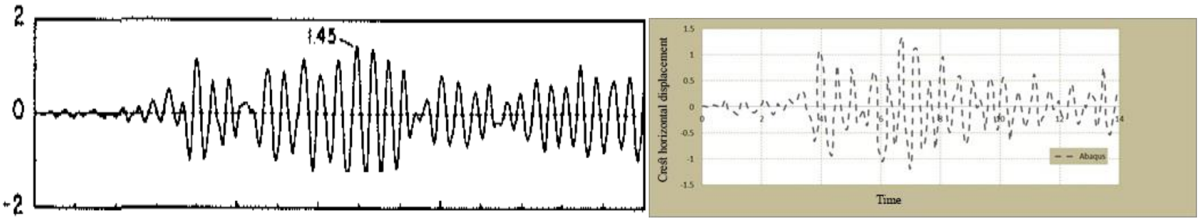

Figure 2. Comparison of results of numerical modeling validation and study by Fenves and Chopra **[14]**

Boundary Condition

In this study, the roller boundary condition is used for the lateral edges of foundation and the acoustic boundary condition is applied for the left end edge of reservoir to avoid the reflection of waves. In the interaction medium, the interface between the dam body and the foundation is considered rough node by node in order to transfer all forces applied on the foundation to the dam. The interface between the water, dam body and sides of the valley are considered without friction [13].

Material Properties

The SI units are applied to define the materials in this study. The units used in the system are given in Table1

Table 1. Units used by Abaqus software **[15]**

Variable	Stress	Time	Mass	Length
Unit	Paskal (N/mm2)	Second	Kilogram	Meter

Hence the model outputs are represented accordingly. Table 2 shows the numerical specifications of materials used for each section.

Table 2. Specifications of Materials

Parameter	Unit	Dam body	Foundation	Water
Elastic modulus (E)	(MPa)	27580	24000	2070
Poisson’s ratio (ν)	-	0.2	0.25	-
Density (ρ)	(Kg/m3)	2400	2500	1000
Tensile strength of concrete (σt0)	(MPa)	3		
Ultimate tensile strain	-	0.00023		

The equation proposed by the ASCE, as well as the equations presented by Rashid et al. are used to calculate other mechanical properties of concrete and stress-strain diagram [16].

Introduction of Applied Accelerograms

In the dynamic analysis, an important part of modeling is to choose and apply the earthquake spectra to the model. Six earthquakes of different natures are selected and applied to the foundation-dam body interaction boundaries as acceleration spectra in order to create a variety of natural conditions. Then, the ground displacement, velocity and acceleration spectra are presented during earthquake, obtained using the SeismoSignal software. All accelerations are scaled to the peak acceleration of 0.15g using the software, in accordance with the USBR code for dynamic analysis of dams.

The accelerograms applied in this study are as follows:

1. Loma Prieta: This earthquake measuring 6.9 on the Richter scale occurred in 1988 in northern California [17].
2. Friuli: This earthquake measuring 6.5 on the Richter scale occurred in 1976 in northern Italy [18].
3. Hollister: This earthquake measuring 6.8 on the Richter scale occurred in 1989 in San Francisco [19].
4. Imperial Valley: This earthquake measuring 6.4 on the Richter occurred in 1979 in Mexico City [20].
5. Kobe: This earthquake occurred in 1995 near Kobe in Japan, measuring 6.9 on the Richter [21].
6. Landers: This earthquake has been the biggest earthquake in California for the last 40 years, which happened in 1992 in Landers [22].

3. DISCUSSION AND RESULTS

Evaluation of dam response under near-field accelerograms

In this study, three bed-to-dam stiffness ratios of 0.5, 1 and 2 are used to evaluate the effect of bed stiffness on the behavior of concrete dams. The numerical studies of six accelerograms are assessed for both far- and near-fault states and 32 numerical models are totally compared and evaluated. Then, the dam crest displacement time history diagrams are presented for the full reservoir conditions (Fig. 3-14). It must be noted that the bed-to-dam stiffness ratio of 1 was used for the full reservoir conditions in previous sections; hence just the diagrams for stiffness ratios of 2 and 0.5 are collected in this section. The diagrams for the stiffness ratio of 2 under near-field earthquakes show that the maximum dam crest displacement is reported for the Imperial Valley accelerogram, which equals 8.1 cm, and the minimum value occurs for the Friuli accelerogram. It is observed that the dam crest displacement is more than that for the stiffness ratio of 1; therefore, the seismic response of the dam becomes more critical as the stiffness ratio increases.

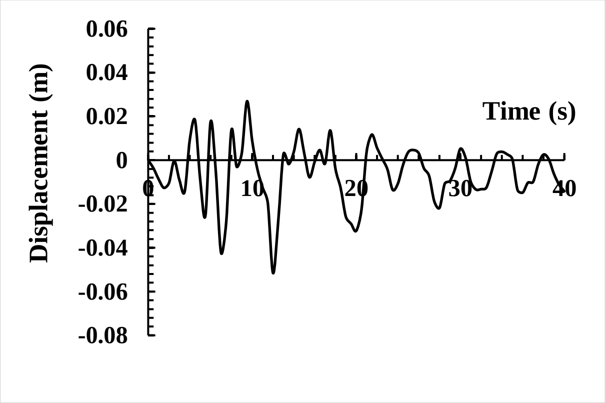

Figure 3. Dam crest displacement time history of Kobe-N-1 model for stiffness ration of 2

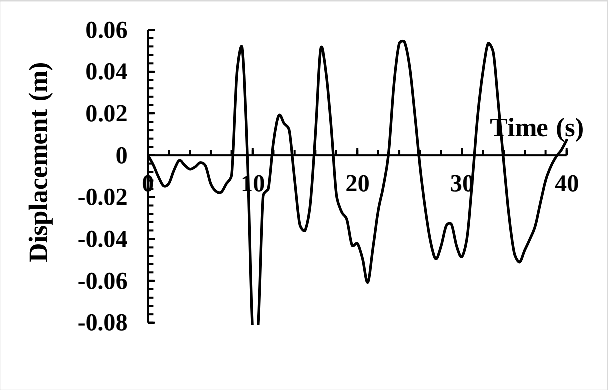

Figure 4. Dam crest displacement time history of Impe rial Valley-N-1 model for stiffness ration of 2

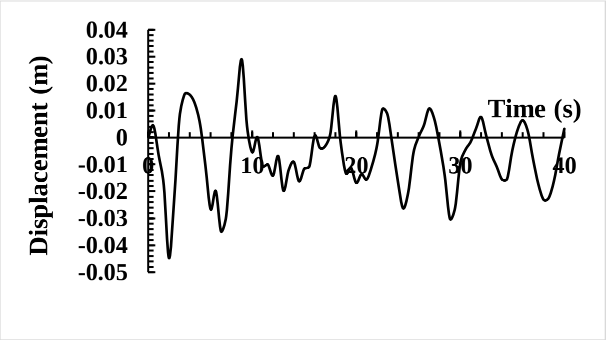

Figure 5. Dam crest displacement time history of Hollister-N-1 model for stiffness ration of 2

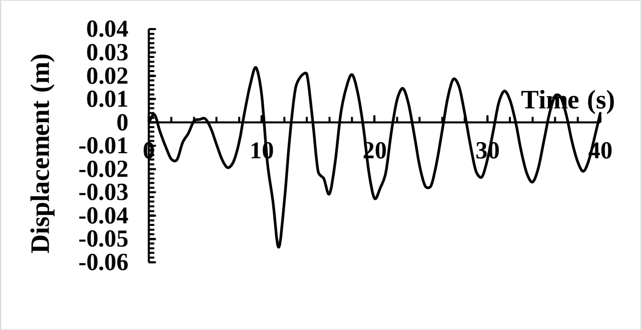

Figure 6. Dam crest displacement time history of Landers-N-1 model for stiffness ration of 2

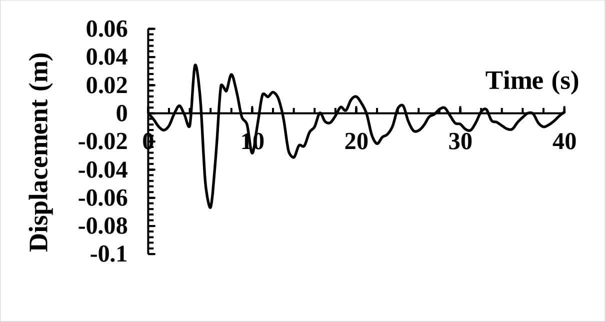

Figure 7. Dam crest displacement time history of Loma Prieta-N-1 model for stiffness ration of 2

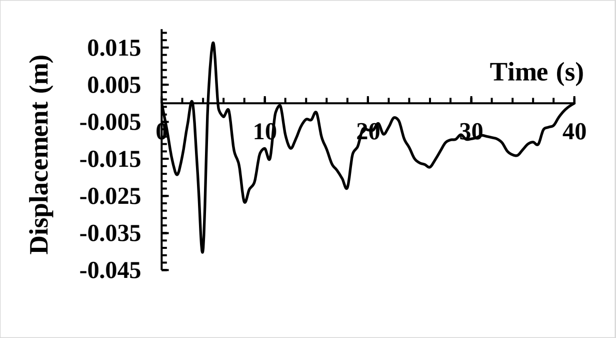

Figure 8. Dam crest displacement time history of Friuli-N-1 model for stiffness ration of 2

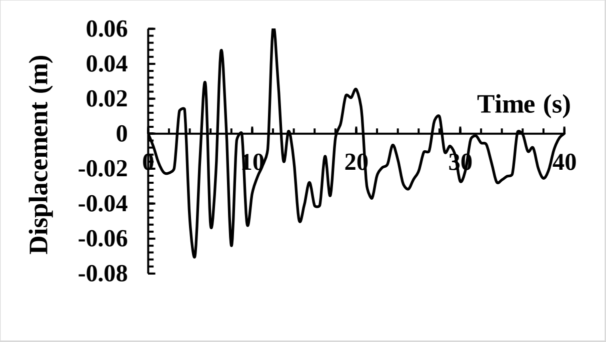

Figure 9. Dam crest displacement time history of K obe-N-1 model for stiffness ration of 0.5

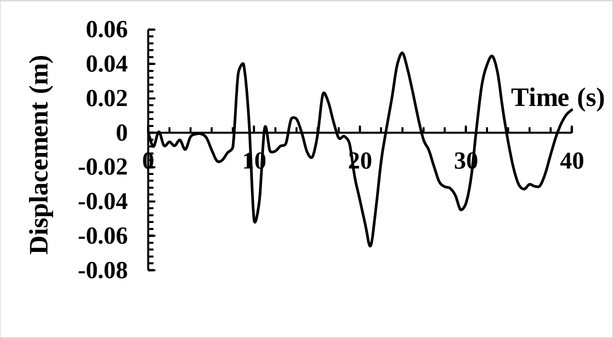

Figure 10. Dam crest displacement time history of Imperial Valley-N-1 model for stiffness ration of 0.5

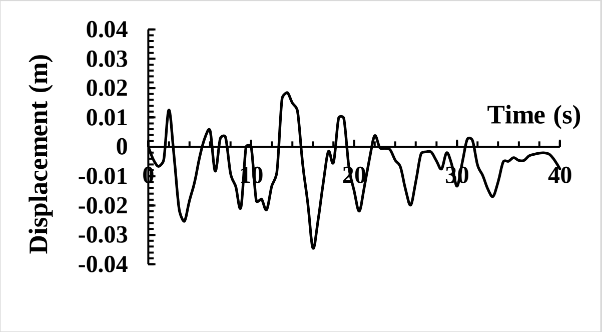

Figure 11. Dam crest displacement time history of Hollister-N-1 model for stiffness ration of 0.5

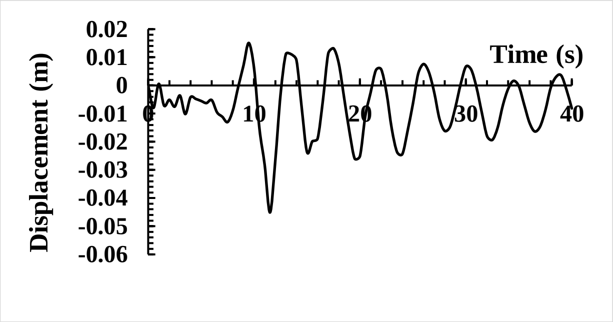

Figure 12. Dam crest displacement time history of Landers-N-1 model for stiffness ration of 0.5

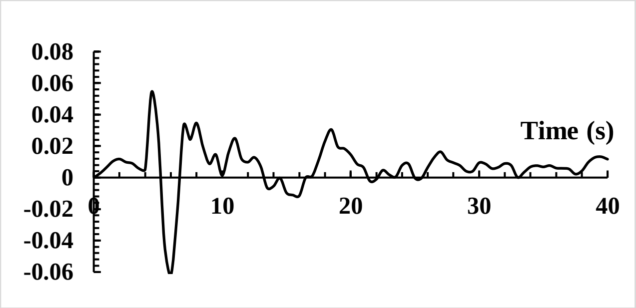

Figure 13. Dam crest displacement time history of Loma Prieta-N-1 model for stiffness ration of 0.5

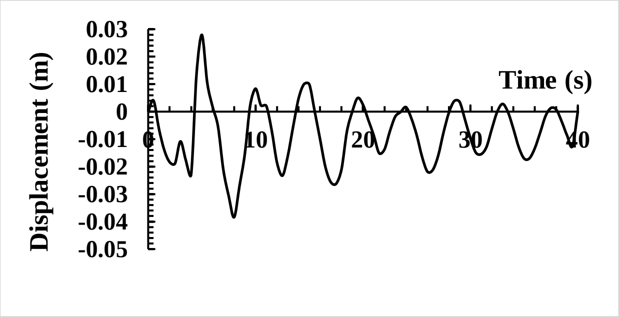

Figure 14. Dam crest displacement time history of Friuli-N-1 model for stiffness ration of 0.5

Evaleation of Dam Response Under Far-Field Accelerograms

In this study, six accelerograms are used for three stiffness ratios of 0.5, 1 and 2 in order to evaluate the effect of bed stiffness on the seismic performance of concrete dams under far-field earthquakes. In the diagrams for stiffness ratio of 2 (Fig. 15-26), it is observed that the minimum dam crest displacement occurs for the Landers accelerogram, with about 7 cm for the Imperial Valley accelerogram, 5.6 cm for the Kobe accelerogram and 5.4 cm for the Landers accelerogram. For the stiffness ratio of 0.5, it is observed that the maximum dam crest displacement of 6.1 cm occurs under the Imperial Valley earthquake and the minimum value of 4.12 cm is reported for the Landers accelerogram. The observations suggest that the seismic performance of the dam varies dramatically as the stiffness ratio changes slightly.

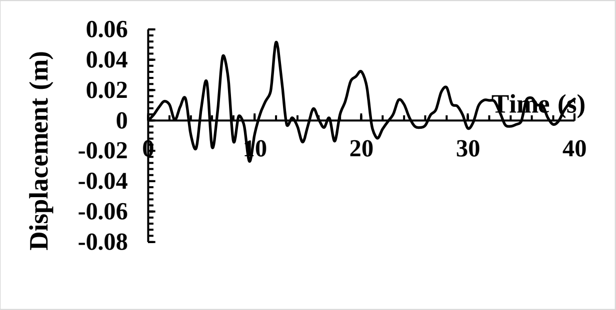

Figure 15. Dam crest displacement time history of Kobe-F-1 model for stiffness ration of 2

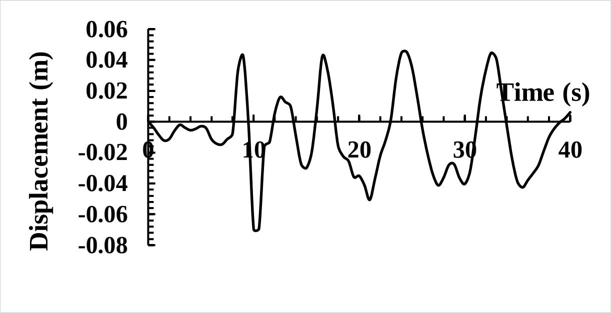

Figure 16. Dam crest displacement time history of Imperial Valley-F-1 model for stiffness ration of 2

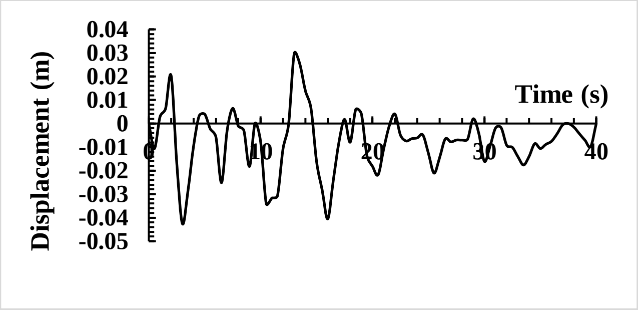

Figure 17. Dam crest displacement time history of Hollister-F-1 model for stiffness ration of 2

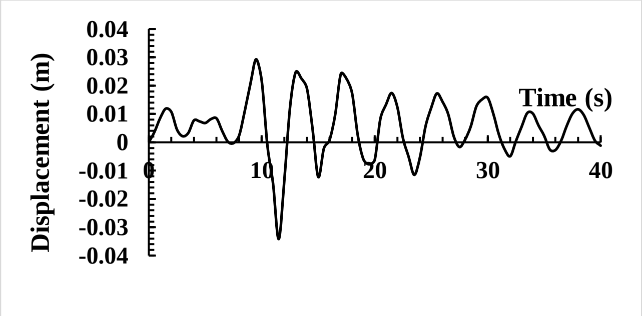

Figure 18. Dam crest displacement time histo ry of Landers-F-1 model for stiffness ration of 2

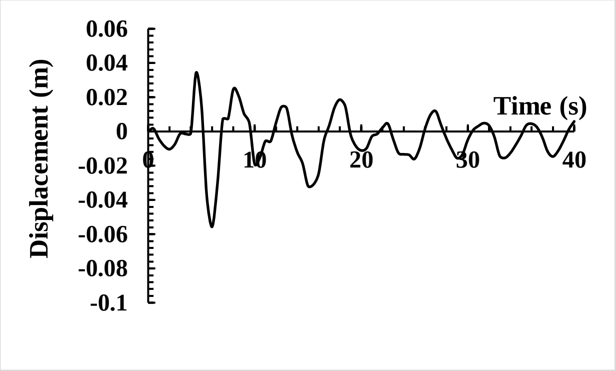

Figure 19. Dam crest displacement time history of Loma Prieta-F-1 model for stiffness ration of 2

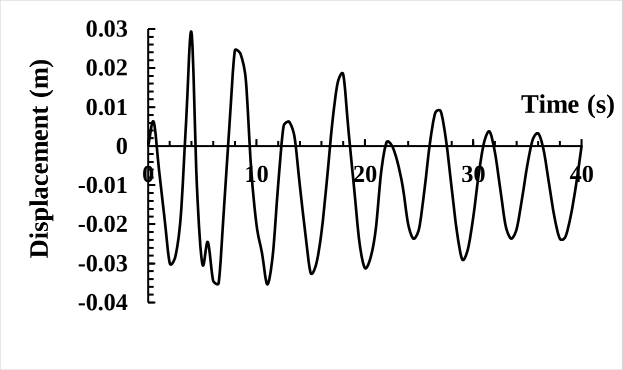

Figure 20. Dam crest displacement time history of Friuli-F-1 model for stiffness ration of 2

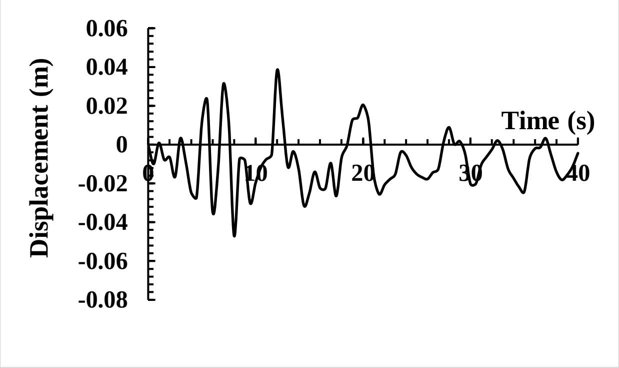

Figure 21. Dam crest displacement time history of Kobe-F-1 model for stiffness ration of 0.5

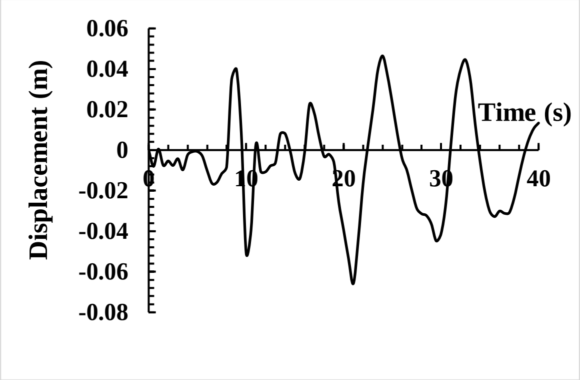

Figure 22. Dam crest displacement time history of Im perial Valley-F-1 model for stiffness ration of 0.5

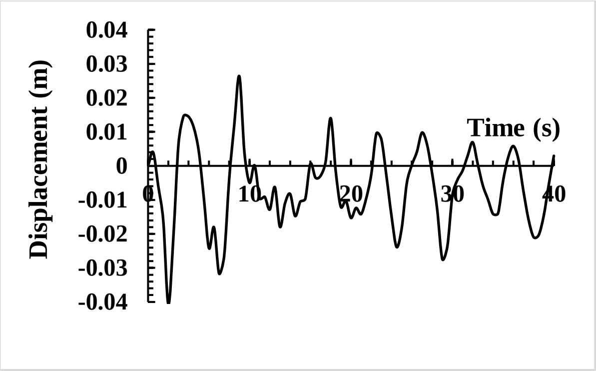

Figure 23. Dam crest displacement time history of Hollister-F-1 model for stiffness ration of 0.5

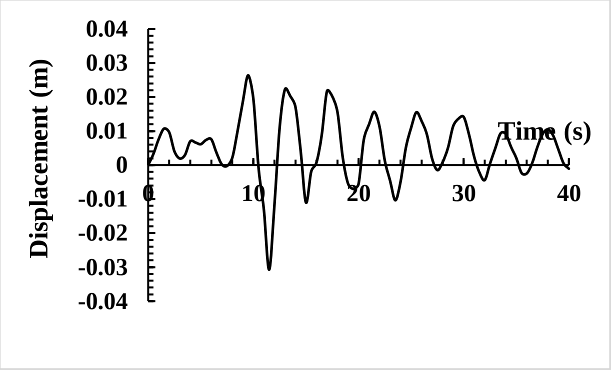

Figure 24. Dam crest displacement time history of Landers-F-1 model for stiffness ration of 0.5

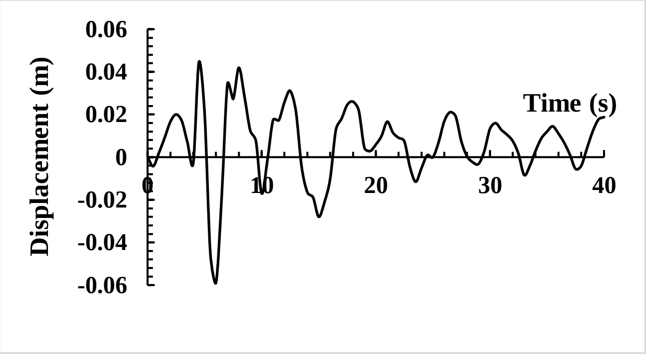

Figure 25. Dam crest displacement time history of Loma Prieta-F-1 model for stiffness ration of 0.5

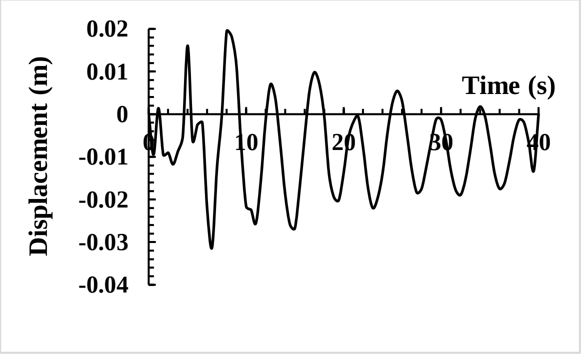

Figure 26. Dam crest displacement time history of Friuli-F-1 model for stiffness ration of 0.5

In Figure 27, the maximum dam crest displacements are collected in form of a graph for better evaluation of the effect of bed stiffness on seismic behavior. According to the results, the seismic response of the dam for both stiffness ratios of 0.5 and 2 is more critical than the equivalent stiffness ratio of 1 in all 6 accelerograms. It is observed that the dam crest displacement under all accelerograms (except the Kobe earthquake accelerogram) for stiffness ratio of 2 is higher than that for stiffness ratio of 0.5.

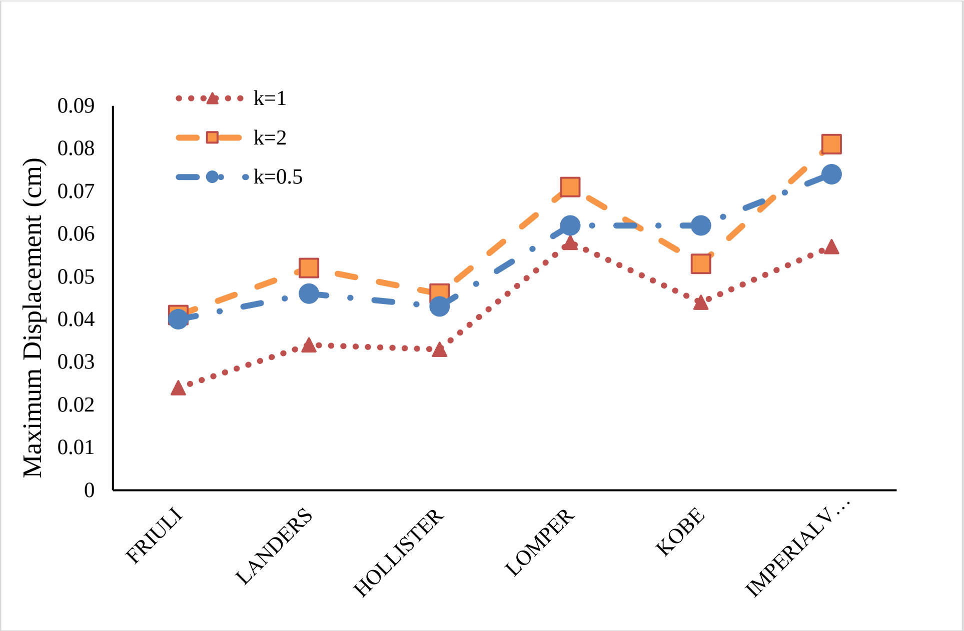

Figure 27. Comparison of maximum dam crest displacements for various stiffness ratios under near-field ground motions

The maximum dam crest displacements for various stiffness ratios under far-field ground motions are displayed in the graph below (Fig. 28). It is observed that the seismic response of the dam for both stiffness ratios of 0.5 and 2 under far-field ground motions is more critical than the equivalent stiffness ratio of 1. According to the results, the increase in the dam crest displacements for various stiffness ratios follows no specific trend; for example, the dam crest displacements under Friuli, Hollister and Kobe accelerograms for stiffness ratio of 2 are higher than those for stiffness ratio of 0.5. But the inverse is true for Landers, Loma Prieta and Imperial Valley earthquakes. As a practical result based on the studies, it is found that lower seismic responses are obtained for the same bed-to-dam stiffness ratios. For initial studies to select a site for a dam, it is thus recommended to choose the site with the same stiffness ratio as the dam; because in this site, the reinforced concrete dam experiences less displacement and, consequently, lower stresses under the same conditions and a safer and more economic dam design is achieved.

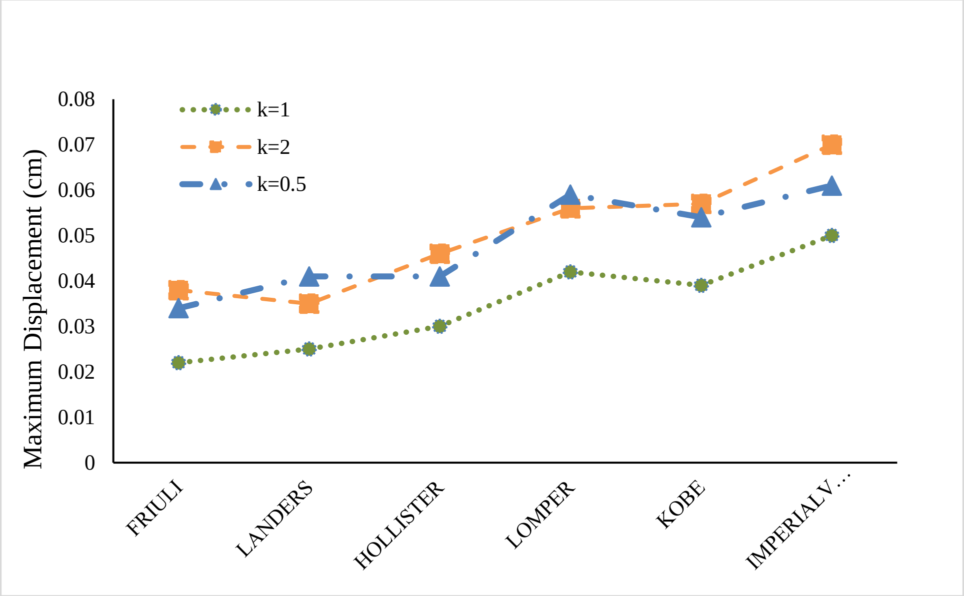

Figure 28. Comparison of maximum dam crest displacements for various stiffness ratios under far-field ground motions

4. CONCLUSION

According to the investigations, it is observed that the different states of bed stiffness have a significant effect on the behavior of a concrete gravity dam and the response of the structure is more favorable for equivalent stiffness ratio of 1 in all accelerograms under both far- and near-field earthquakes. It is also found that the accelerogram with the same frequency content as the Imperial Valley earthquake has a significant effect on the dam crest displacement and considerably affects the structure. For stiffness ratios of 0.5 and 2, it is eventually observed that these stiffness ratios lead to high responses for all accelerograms and can cause failure in the structure; among these cases, the earthquake with same frequency content as Imperial Valley earthquake poses the maximum effect upon the structure for stiffness ratios of 0.5 and 2 and causes the maximum displacement in the dam crest. Consequently, a bed with stiffness ratio of 1 is the most appropriate site for the construction of a concrete gravity dam; this stiffness ratio is more suitable for both far- and near-fault ground motions.

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AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

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