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Evaluation of Seismic Performance of Concrete Gravity Dams Under Soil-structure-reservoir Interaction Exposed to Vertical Component of Near-field Earthquakes During Impounding (Case study: Pine Flat Dam)

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ABSTRACT

Given the current water crisis in the world and the fact that dams are superstructures for water conservation in agricultural and domestic uses, the seismic performance of Pine Flat Dam is evaluated under the soil-structure-reservoir interaction exposed to vertical component of near-field earthquakes in this study. Hence the dam is modeled in the plane strain space under the foundation-structure-fluid interaction using Abaqus finite element software in order to consider the effects of foundation flexibility and hydrodynamic forces. The reservoir is modeled in 3 full, half-full and empty conditions and the results are assessed and presented for each condition. The results of analysis show that when the dam is in use and the entire volume of reservoir is filled with water and the conditions of near-field earthquakes are predominated, more displacement is applied to the dam, which may make it enter the nonlinear region.

Key words: Water crisis, Concrete dam, Effect of vertical component, Soil-structure-reservoir interaction, Near-field fault.

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1. INTRODUCTION

Water supply has been always in the forefront of human's mind as the most crucial need for living (1). Today this need has also appeared in the policies of different nations around the world, so that geopolitical experts predict many wars to achieve water supplies (2). Meanwhile, the Middle East is one of the main centers of the crisis, facing a severe water scarcity (3). Moreover, dams are among the most important structures in today's industrial life, which are constructed for a variety of purposes, e.g. hydroelectric power generation, water storage for agricultural and industrial uses, flood control and drinking water supply. According to the reports of Iranian Bulletin of Water Research, the average annual rainfall is about 252 mm in Iran, which equals about one-fourth of the average rainfall in the world and one-third of the average rainfall in Asia. Therefore, Iran is known as a dry region in the world. On the other hand, Iran is one of the countries exposed to numerous severe earthquakes. Since most dams are constructed in high seismic risk areas in Iran, it is of particular importance to achieve adequate safety of dams against earthquakes (4). Numerous studies were carried out for seismic assessment of the dams under a variety of accelerograms. The occurrence, type and direction of seismic waves and frequency content are all factors which play an essential role in the dynamic response of dams (5-9). In the studies, different mechanisms were considered for support conditions and its impact on seismic performance of concrete dams; the main incompetence of these models was due to the dramatic difference between the motions in lower soil layers and the reality (10). In a modeling in China, the allowable stress under seismic stimulation and elastic modulus were increased by 30% for a damping ratio of 0.05 and it was concluded that the foundation flexibility changes the motion frequencies and dam-foundation movement modes (11). The dynamic analysis of dam and reservoir was conducted considering the effects of energy absorption at the end boundary of the reservoir and it was found that a great part of energy is absorbed by water and the construction cost is reduced significantly if water is supposed incompressible (12). Another study was carried out about the Morrow Point Dam and the effect of reservoir-foundation rock-dam interaction on the linear and nonlinear response of the arch dam was examined. The results showed that when the reservoir is empty and the foundation is considered rigid, the maximum frequency response is received from the model (13). It is so useful to investigate the nonlinear analyses of behavior response of dam structure. The most absolute method for the seismic analysis of dams in accordance with dam-reservoir-foundation interaction was done considering the nonlinear behavior of materials (14-17). In 2013, another research was conducted on Pine Flat Dam through the NSAG-DRI program. In this research, six near-field earthquake records were used for both mass and massless foundation states. The results demonstrated that the probability of surface crack limitation is almost the same for both models with and without foundation (13). In this study, the effects of vertical component of near-field accelerograms is assessed for three empty, half-full and full reservoir conditions under the soil-structure-reservoir interaction.

2. MATERIALS AND METHODS

Concrete dams are an important part of superstructures in each country. The safety of these structures is so important due to detrimental consequences of their destruction and damage. Gravity dams are concrete hydraulic structures which maintain their stability and water stored in the reservoirs by resisting the applied forces often through the geometric shape, weight and strength of concrete. Pine Flat Dam is selected as a case study to investigate the behavior of gravity dams under dynamic loads. Located on the Kings River in California State, this dam consists of 36 monoliths 15 m in width and 1 monolith 12 m in width and forms the Pine Flat reservoir. The crest of the dam is 550 m long and its highest monolith is 122 m in height. The dam section is illustrated in the figure below. The width of the dam is 97 m at the base level and about 10 m at the crest level. The upstream face of the dam is not vertical and has a slope of 5% from the base to the level of 102 m. The dam is employed primarily for flood control and secondarily for irrigation and recreational uses. The Abaqus software is utilized for numerical simulation of the dam. This software can simulate the seismic analysis accurately through its explicit and implicit dynamical solver code and there is a variety of fluid simulation methods and nonlinear behavioral models of materials in the database of this software, whose specifications can be easily used for modeling purposes. Figure 1 shows the picture and geometric conditions of this dam.

Figure 1. Geometric conditions of Pine Flat Dam (2)

3. MODELING

The plane strain 4-node element with reduced integration (CPE4R) is used for the modeling of foundation, the two-dimensional plane strain 4-node linear element (CPE4) is used for the modeling of dam and the acoustic plane strain 4-node element with reduced integration (AC2D4R) is used for the modeling of reservoir behind the dam.

4. VALIDATION OF NUMERICAL MODEL

The model used by Chopra and Fenves is employed to validate the modeling method in this study (18). They used the S69E component of Taft earthquake accelerogram in their study. When the dam-reservoir-foundation system is numerically simulated via Abaqus software (19) and this earthquake is applied, the horizontal displacement time history at the dam crest is derived from the Abaqus and compared to the results of Chopra and Fenves. It is observed that the extrema of both charts are the same and the maximum displacements are 1.45 and 1.39 inches, respectively, with a difference less than 5%. Therefore, the modeling method can be reliably utilized for numerical studies in this research (Figure 2).

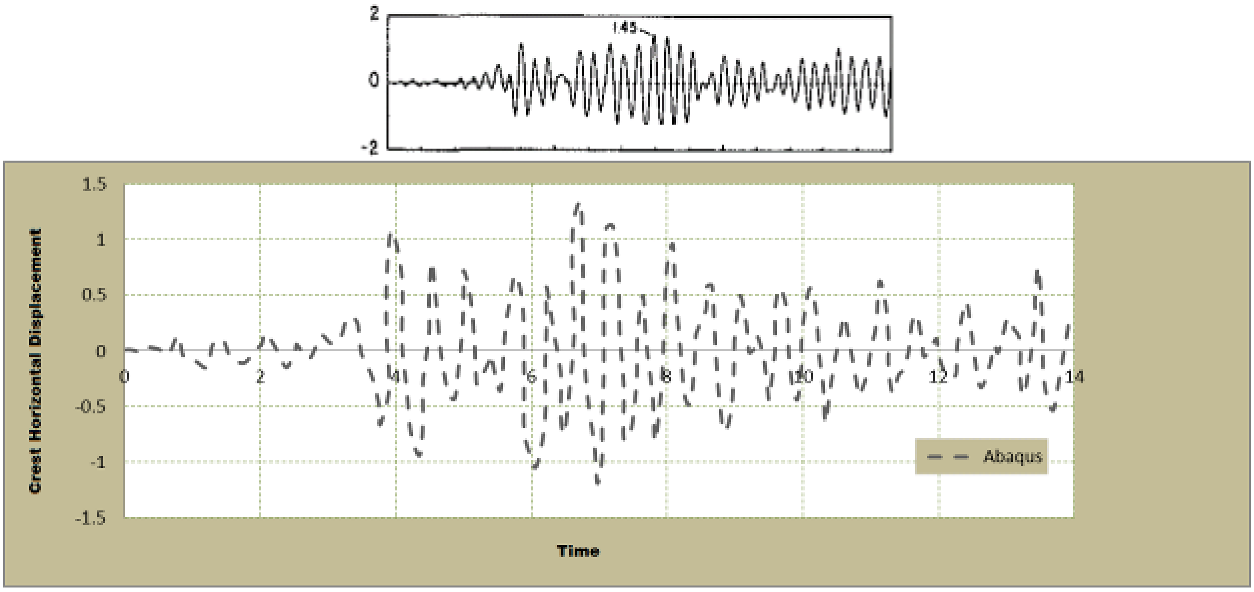

Figure 2. Comparison of numerical results of validation model and results of studies by Chopra and Fenves (18)

5. BOUNDARY CONDITIONS

There is the roller boundary condition in lateral edges of the foundation. The acoustic boundary condition is also used at the left end of reservoir to prevent the return of seismic waves. The physical properties of inter-surface contacts are determined via the interaction environment of the software. The contact condition between the dam sides and the bed of the valley is considered rough with node-to-node contact (tie), so that any displacement in the bed of the valley is transferred to the dam. The contact conditions between the reservoir water and dam and between the reservoir water and sides of the valley are considered with the tie without friction.

6. MATERIAL PROPERTIES

The International System of Units (SI) is used to define materials in this study. The units used in this system are given in the Table 1:

Table 1. Units used by Abaqus software

Variable	Stress	Time	Mass	Length
Unit	Pascal (N/mm^2)	Second	Kilogram	Meter

Hence the model outputs are also presented accordingly. Table 2 represents the numerical properties of materials used for each section.

Table 2. Material properties

Water	Foundation	Dam	Unit	Parameter
2070	24000	27580	(MPa)	Elastic modulus (E)
-	0.25	0.2	-	Poisson ratio (v)
1000	2500	2400	(Kg/m^3)	Density (ρ)
		3	(MPa)	Tensile strength of concrete (σ_{t0})
		0.00023	-	Ultimate tensile strain

The equations proposed by the ASCE and Rashid et al are used to calculate other mechanical properties of concrete and stress-strain curves (20).

7. INTRODUCTION OF APPLIED ACCELEROGRAMS

In dynamic analysis, an important part of modeling is to select and apply the earthquake spectra to the model. Six different earthquakes of different natures are chosen to create different natural conditions and applied to the foundation-dam interaction boundary in terms of spectral acceleration. The spectral acceleration, velocity and displacement caused by earthquake are then presented, which are calculated using the SeismoSignal software. Entire accelerations are scaled up to a maximum value of 0.15g using the software, according to the dynamic analysis of dams by the USBR.

The accelerograms used for this study are as follows:

1. Loma Prieta: The earthquake measuring 9.9 on the Richter scale occurred in 1988 in northern California (21).
2. Friuli: The earthquake measuring 6.5 on the Richter scale occurred in 1976 in northern Italy (22).
3. Hollister: The earthquake measuring 6.8 on the Richter scale occurred in 1989 in San Francisco (23).
4. Imperial Valley: The earthquake measuring 6.4 on the Richter occurred in 1979 in the southern Mex-

ico City (24).

5. Kobe: The earthquake measuring 6.8 on the Richter occurred in June 1995 within 20 km from Kobe, Japan (25).
6. Landers: The earthquake occurred in 1992 in Landers, California. This earthquake has been the most severe earthquake in California for the last 40 years (26).

8. DISCUSSION AND CONCLUSION

8.1. Assessment of dam response under vertical component of near-field earthquakes

Figures Figure 3, Figure 4Figure 5, Figure 6Figure 7Figure 8 demonstrate the displacements of the dam crest under seismic stimuli of near-field earthquakes for the full reservoir condition, considering the vertical component of earthquake for the full reservoir condition. According to the results, a maximum displacement of 8.1 cm is reported for the Loma Prieta earthquake, when the earthquake acceleration reaches its peak. The negative sign indicates that the direction of dam movements is towards the upstream. In the Friuli earthquake, a maximum displacement of 2.2 cm occurs at the third second for this condition.

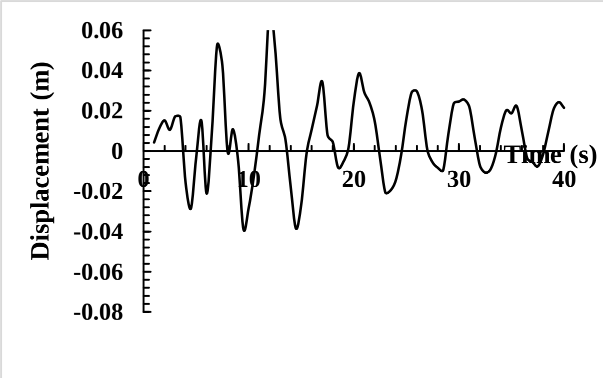

Figure 3. Displacement-time history of dam crest for model Kobe-N_v-1

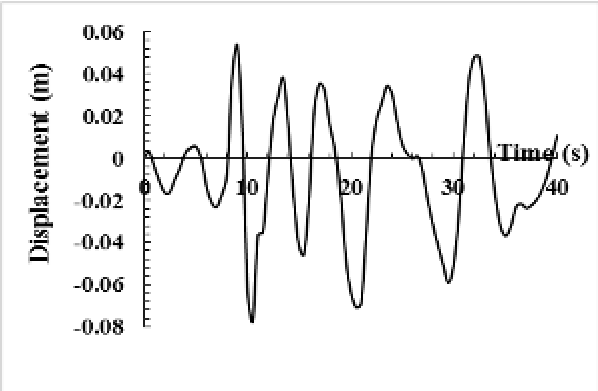

Figure 4. Displacement-time history of dam crest for model Imperial Valley-N_v-1

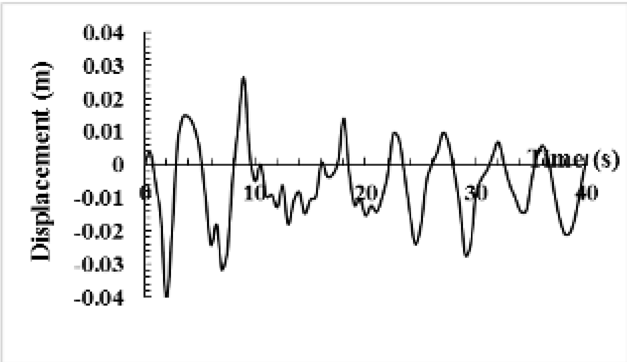

Figure 5. Displacement-time history of dam crest for model Hollister-N_v-1

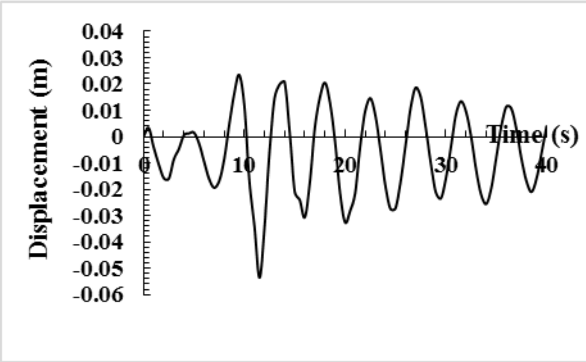

Figure 6. Displacement-time history of dam crest for model Landers-N_v-1

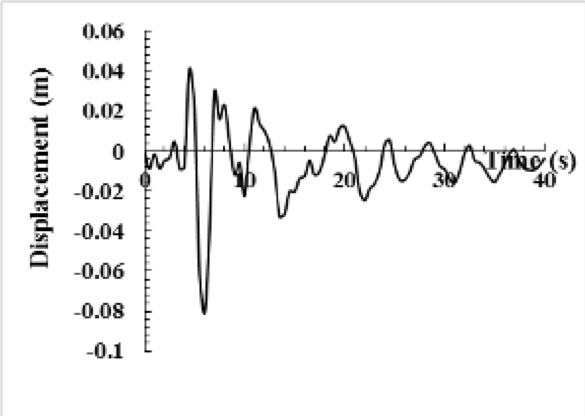

Figure 7. Displacement-time history of dam crest for model Loma Prieta-N_v-1

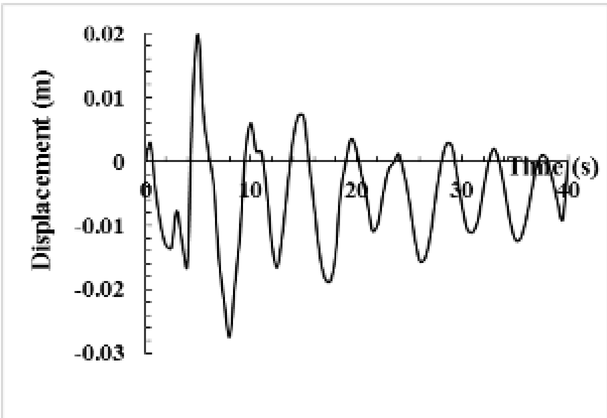

Figure 8. Displacement-time history of dam crest for model Friuli-N_v-1

According to Figures Figure 9, Figure 10, Figure 11, Figure 12, Figure 13Figure 14, it is observed that in the Imperial Valley and Loma Prieta earthquakes, the maximum displacement of the dam under vertical component of near-field stimuli is low at the beginning moments and then rises significantly and the maximum displacement is seen for these two accelerograms. Small displacements are observed in other parts of the range. According to the charts and occurred displacements, it should be noted that the Kobe and Landers earthquakes may also cause damage to the dam and must not be ignored. In general, however, the maximum displacements are reduced dramatically compared to the displacements for the full reservoir condition.

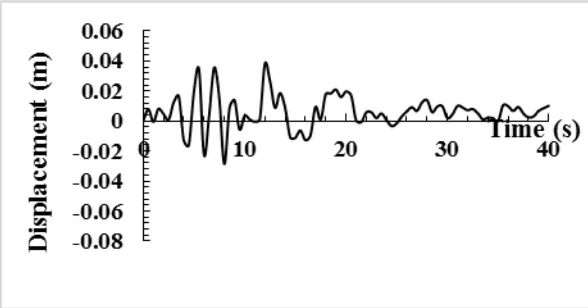

Figure 9. Displacement-time history of dam crest for model Kobe-N_v-2

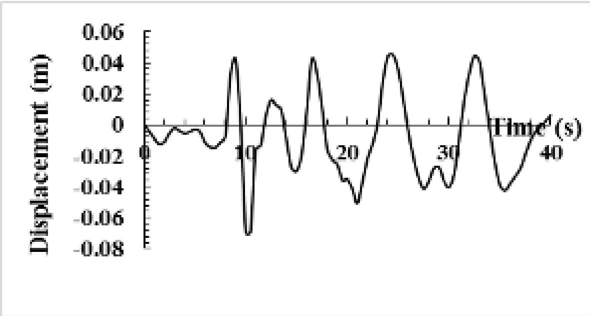

Figure 10. Displacement-time history of dam crest for model Imperial Valley-N_v-2

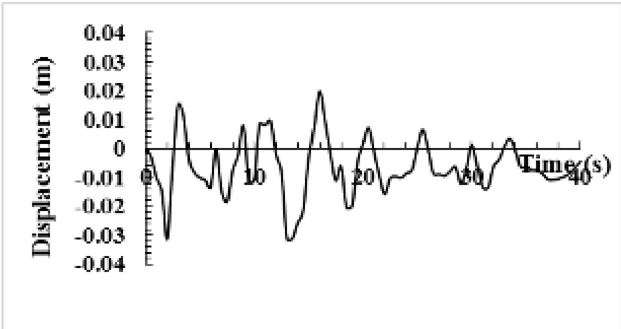

Figure 11. Displacement-time history of dam crest for model Hollister-N_v-2

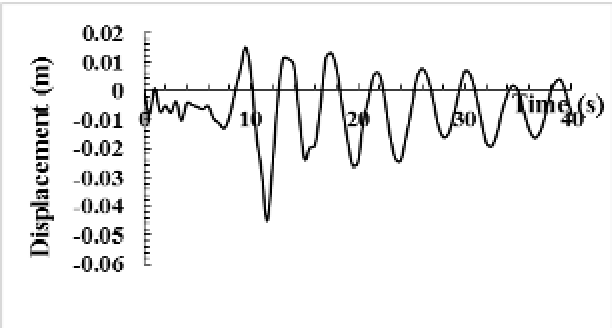

Figure 12. Displacement-time history of dam crest for model Landers-N_v-2

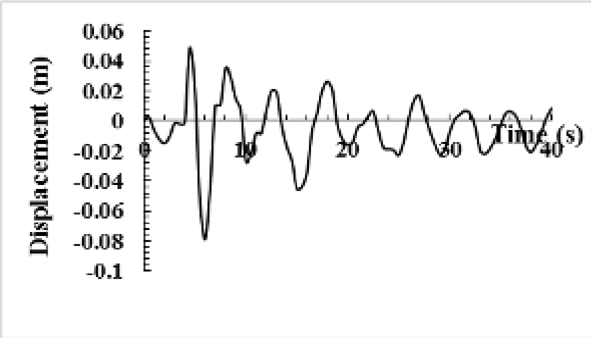

Figure 13. Displacement-time history of dam crest for model Loma Prieta-N_v-2

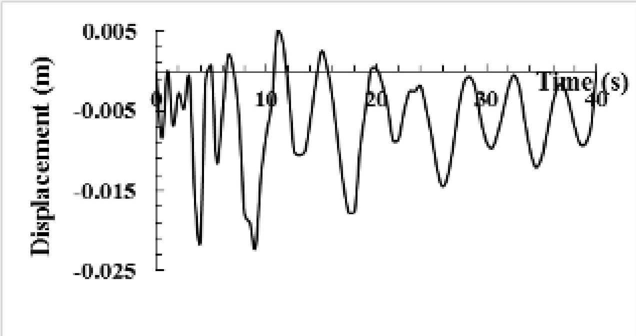

Figure 14. Displacement-time history of dam crest for model Friuli-N_v-2

When the vertical component of near-field earthquakes is applied for the empty reservoir condition, the displacements decrease, so that the maximum displacements of the dam crest are roughly the same for the Kobe and Landers earthquakes and the minimum displacement of the dam crest is reported about 2 cm. As expected according to the frequency content of accelerograms and the results, the maximum displacement of the dam with an empty reservoir is reported about 6 cm for the Imperial Valley and Loma Prieta earthquakes (Figure 15, Figure 16, Figure 17, Figure 18, Figure 19Figure 20).

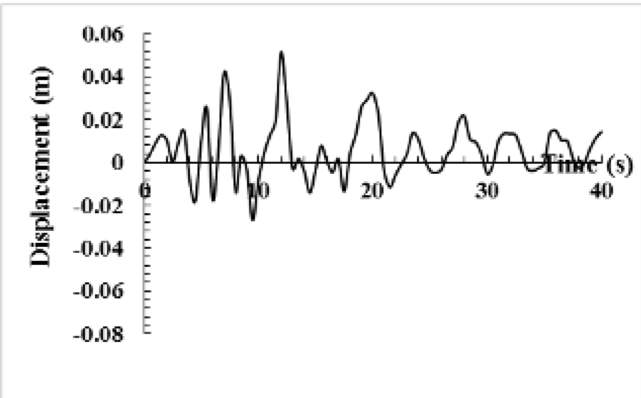

Figure 15. Displacement-time history of dam crest for model Kobe-N_v-3

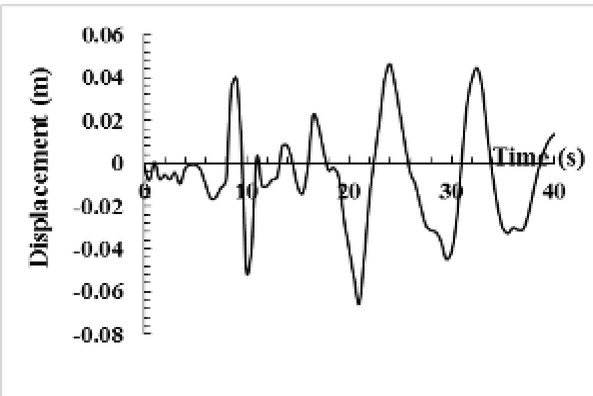

Figure 16. Displacement-time history of dam crest for model Imperial Valley-N_v-3

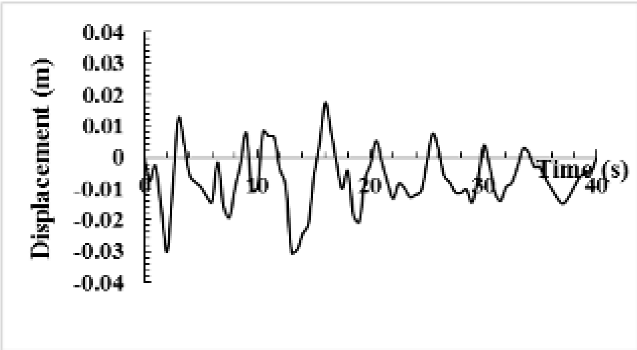

Figure 17. Displacement-time history of dam crest for model Hollister-N_v-3

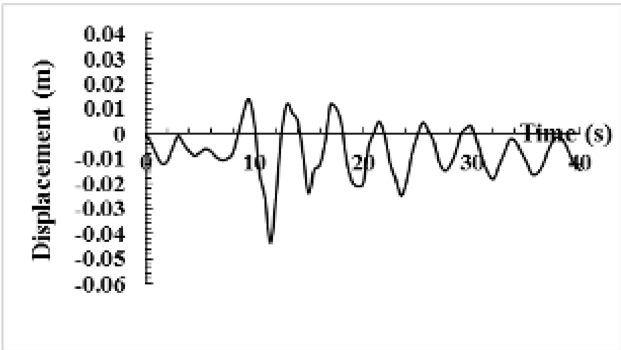

Figure 18. Displacement-time history of dam crest for model Landers-N_v-3

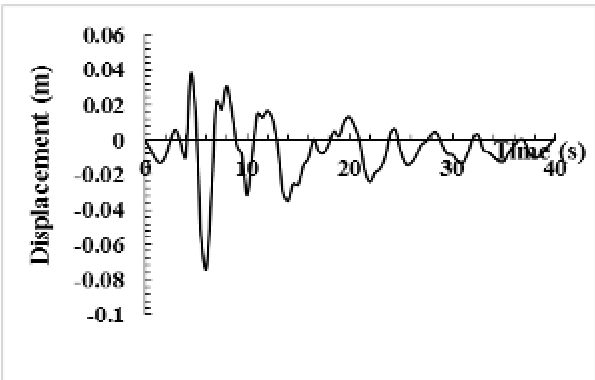

Figure 19. Displacement-time history of dam crest for model Loma Prieta-N_v-3

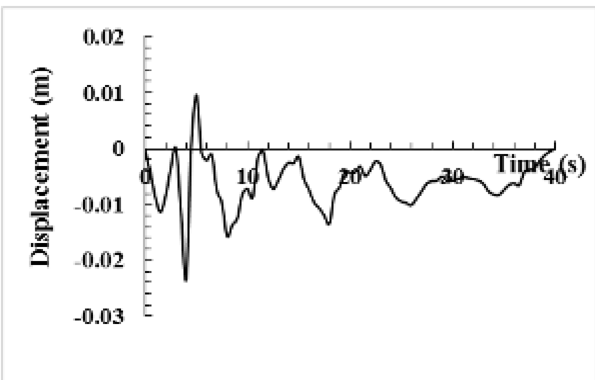

Figure 20. Displacement-time history of dam crest for model Friuli-N_v-3

Aimed to achieve a comprehensive response of behavior of the structure in the face of different earthquakes under various circumstances, whole maximum displacements occurred during different earthquakes and conditions are collected and presented in a chart. Figure 21 shows the absolute maximum displacements under the vertical component of near-fault earthquakes for the full reservoir conditions. As seen, the maximum displacement is for the Imperial and Loma Prieta earthquakes, occurred according to the frequency content of these two accelerograms. It must be noted that the displacement is due to the reservoir-bed-dam interaction and should be applied according to the accurate calculation of effects of each accelerogram; therefore, the force applied by the earthquake should be dissipated to avoid structural failure.

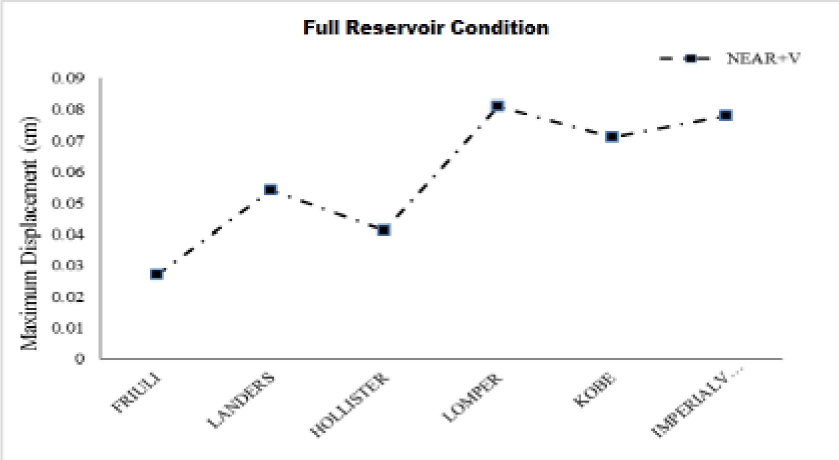

Figure 21. Comparison of maximum displacement of dam crest under vertical component of near-field earthquakes for full reservoir condition

In the full reservoir condition, it is observed that the minimum crest displacement occurs for the Friuli earthquake and the maximum crest displacement happens for the Loma prieta earthquake. Given the effect of vertical component of earthquakes, the maximum displacements for the Loma prieta, Imperial Valley, Kobe and Landers earthquakes are significant; so that the increase of displacements is reported over 50%, indicating the effect of vertical component in most of the studied earthquakes. The maximum displacement of the dam is not significant for the Friuli and Hollister earthquakes due to the frequency nature of the increase. Similarly, the maximum displacements of the dam crest for the half-full reservoir condition are shown in the chart of Figure 22. In the half-full reservoir condition, a maximum displacement of 7.7 cm is determined for the near-field earthquake in regard to the vertical component of Loma Prieta earthquake. As the vertical component of near-field earthquakes is applied, the maximum displacements increase.

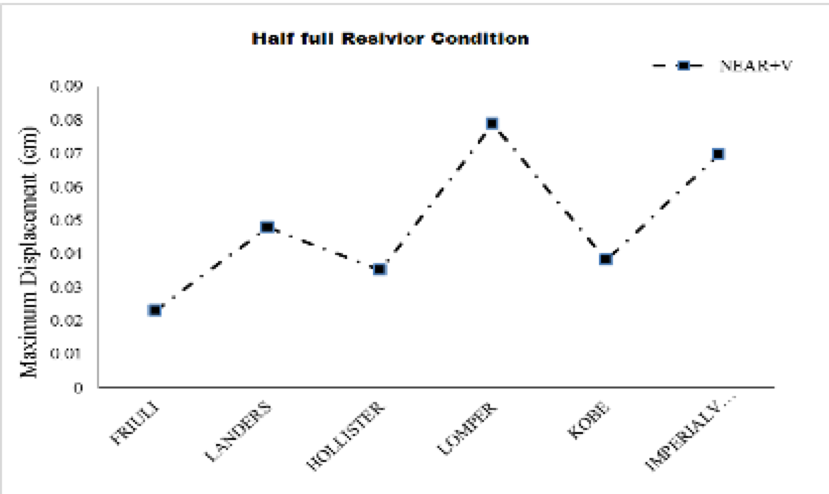

Figure 22. Comparison of maximum displacement of dam crest under vertical component of near-field earthquakes for half-full reservoir condition

According to the results of analysis of the dam for the empty reservoir condition, i.e. before impounding (Figure 23), the displacements decrease considerably and the hydrostatic pressure of the dam reservoir can be explained by the fact that increased and decreased displacements are observed for the full and empty reservoir conditions, respectively (Figure 23).

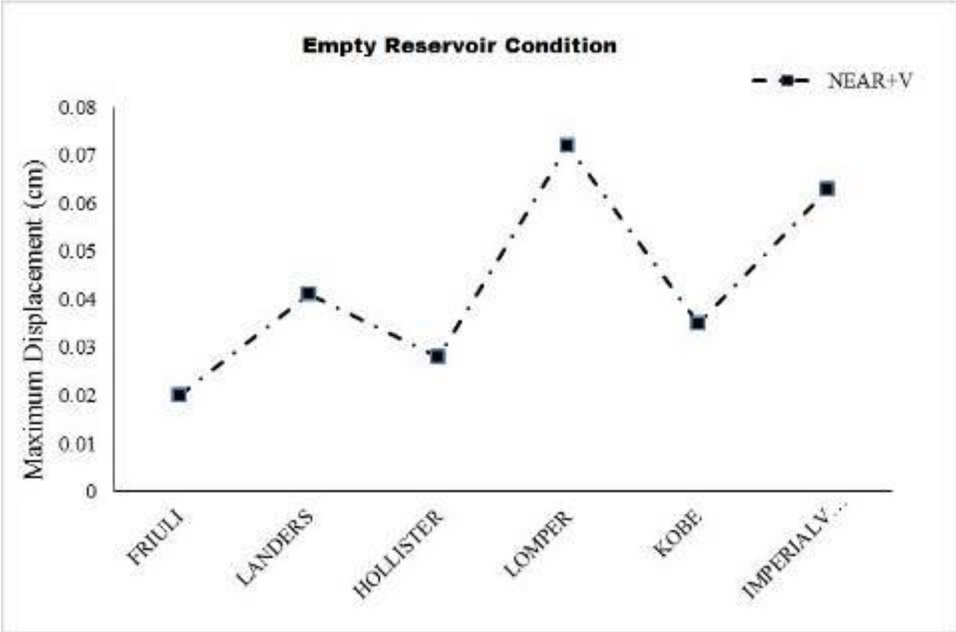

Figure 23. Comparison of maximum displacement of dam crest under vertical component of near-field earthquakes for empty reservoir condition

As seen in Figure 24, all charts derived from different reservoir conditions are presented and, obviously, the displacements increase as the level of impoundment rises in the reservoir. However, the increase of displacements is not significant for some accelerograms, but dramatic differences are observed for the KOBE earthquake due to the current frequency content. Generally, the increase of water level in the dam reservoir enhances the displacements; since just the hydrodynamic force is considered for the loading of reservoir, it can be concluded that the increase in the volume of water in the reservoir enhances the hydrostatic force applied to the dam by the reservoir and eventually results in the increased displacement of the dam crest.

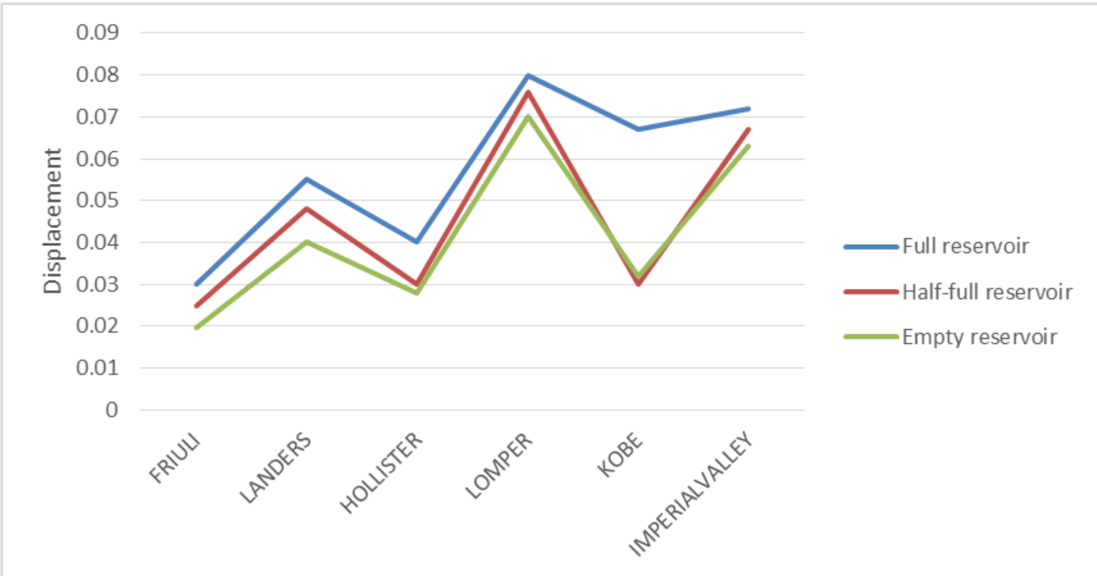

Figure 24. Comparison of maximum displacement of dam crest in different reservoir conditions

9. RESULTS

- The numerical simulation method used in the study can simulate the dam-reservoir-foundation behavior with proper accuracy and this method can be employed to model the dam-foundation-reservoir interaction in future studies.
- When the dam is in use and the whole volume of reservoir is filled with water and the conditions of vertical component of near-field earthquakes are predominated, more displacement is applied to the dam and may cause the dam materials to enter the nonlinear region.
- When the vertical component of near-field earthquakes is applied, the maximum displacements for the half-full reservoir condition increase and necessary measures should be taken to avoid dam

failure and fracture.

- For the empty reservoir condition, the maximum displacements decrease under the vertical component of near-field earthquakes.

Generally, as the level of impoundment declines, the effect of vertical component and the field of seismic stimuli are felt for a less number of accelerograms.

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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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