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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

In light of the global water crisis and dams' role as water conservation superstructures for agricultural and domestic uses, this research assesses Pine Flat Dam's seismic performance when subjected to the vertical component of near-field earthquakes. In order to account for the impacts of foundation flexibility and hydrodynamic forces, the dam is modeled in the plane strain space under the foundation-structure-fluid interaction using Abaqus finite element software. The reservoir is simulated at three different levels of filling: full, half-full, and empty. The research shows that when the dam is operational, the full reservoir volume is filled with water, and near-field earthquake conditions prevail, greater displacement is applied to the dam, which might cause it to enter the nonlinear area..

**Key words:** There is a water shortage, Wall of cement, Impact of the vertical dimension, Interaction between soil, construction, and stor age Localized rupture.

## 1. INTRODUCTION

(1) Water has traditionally been considered by humans to be one of the most essential elements in maintaining life. As a result, geopolitical specialists now expect numerous battles to attain water supplies (2), a necessity that has also surfaced in the policies of many states throughout the world. Moreover, the Middle East is one of the epicenters of the issue, since it is experiencing a serious lack of water (3). Dams, which are built for several reasons including generating hydroelectric power, storing water for agricultural and commercial applications, preventing flooding, and providing a safe water supply, are among the most significant buildings in modern industrial life. According to the Iranian Bulletin of Water Research, Iran receives roughly one-fourth of the global average annual rainfall and one-third of the Asian average yearly rainfall. That's why Iran is commonly thought of as a desert. Iran, however, is one of the countries vulnerable to frequent, devastating earthquakes. Since most dams in Iran are built in high seismic risk zones, achieving proper safety of dams against earthquakes (4) is of utmost significance. Dam seismic evaluation under different accelerograms has been the subject of several research. Dams' dynamic responses are heavily influenced by seismic wave occurrence, nature, direction, and frequency content (5-9). Support conditions and their effects on the seismic performance of concrete dams were examined in the research, with a variety of processes being considered. The major ineptitude of these models was due to the significant discrepancy between the movements in the lower soil layers and the reality (10). Based on computer simulations conducted in China, it was determined that the foundation's pliability modifies the motion frequencies and the modes of movement of the dam (11). This was achieved by increasing the allowed stress under seismic stimulation and the elastic modulus by 30% for a damping ratio of 0.05. The reservoir and dam were subjected to a dynamic analysis that took into account the

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Since water is assumed to be incompressible, the cost of construction is drastically reduced (13) when studying the effects of energy absorption at the reservoir's end boundary. The impact of reservoir-foundation rock-dam interaction on the linear and nonlinear response of the arch dam at Morrow Point was investigated in a separate research. According to the findings, the maximum frequency response from the model is acquired when the reservoir is empty and the foundation is assumed to be rigid (13). Nonlinear assessments of dam behavior response are quite helpful. Nonlinear material behavior was taken into account in the most comprehensive approach to date (14) to seismic analysis of dams in accordance with dam-reservoir-foundation interaction. The NSAG-DRI initiative funded more investigation of Pine Flat Dam in 2013. Six near-field earthquake data were employed in this study, two for the mass foundation and four for the massless foundation. The outcomes showed that models with and without a foundation have almost the same probability of surface fracture limitation (13). This research evaluates the influence of the reservoir's vertical component on near-field acceleration profiles in three different soil-structure-reservoir interaction scenarios: empty, half-filled,

Andfull.

## MATERIALS AND METHODS

Concrete dams play a crucial role in the infrastructure of any nation. The ramifications of its destruction or damage make ensuring their security a top priority. Dams built using gravity keep the water behind them secure in reservoirs by using the material's weight, density, and geometry to counteract external forces. For this study, we will use Pine Flat Dam as a case study to examine how gravity dams respond to dynamic stresses. With its 36 monoliths measuring 15 m in diameter and its single monolith measuring 12 m in width, this dam creates the Pine Flat reservoir on the Kings River in California. The dam has a 550-meter long crest and a 122-meter tall monolith. The image below depicts a part of the dam. The dam is 97 meters wide at its foundation and just around 10 meters wide at its highest point. From its base to its level at 102 m, the dam's upstream face has a slope of 5%. The dam is used primarily for flood control, with irrigation and recreation as secondary purposes. For the purpose of numerical modeling, the dam is modeled in the Abaqus program. The software's database contains a wide range of fluid simulation methods and nonlinear behavioral models of materials, whose specifications can be easily used for modeling, and the software's explicit and implicit dynamical solver code can accurately simulate seismic analysis. See Figure 1 for a visual representation of the geometric parameters of this dam.

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

## 2. MODELING

The foundation is modeled using the plane strain 4-node element with reduced integration (CPE4R), the dam is modeled using the two-dimensional plane strain 4-node linear element (CPE4), and the reservoir is modeled using the acoustic plane strain 4-node element with reduced integration (AC2D4R).

## 3. VALIDATION OF NUMERICAL MODEL

Chopra and Fenves's (18) model is utilized to validate the modeling approach in this research. The Taft earthquake accelerogram was used, namely the S69E component. The horizontal displacement time history at the dam crest is produced from the Abaqus simulation and compared to the results of Chopra and Fenves when the dam-reservoir-foundation system is numerically modelled using Abaqus software (19) and this earthquake is applied. Maximum displacements of 1.45 and 1.39 inches are observed, with a difference of less than 5% between the two charts' extremes. As a result, the modeling approach can be reliably utilized for numerical studies in this research (Figure 2).

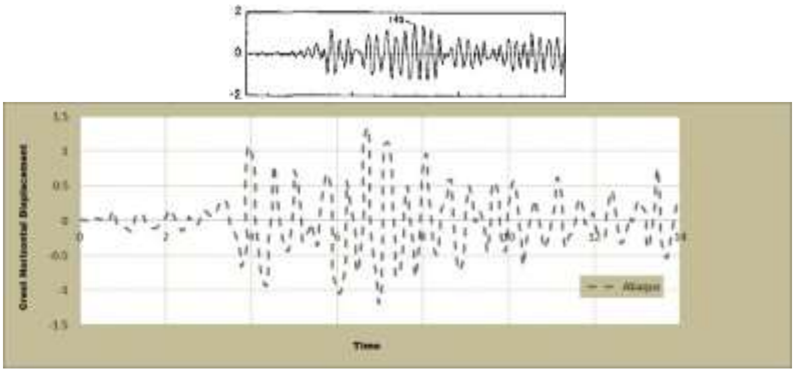

**Figure 2. Comparison of numerical results of validation model and results of studies by Chopra and Fenves (18)**

## 4. BOUNDARY CONDITIONS

The roller boundary condition is present in the corner radii of the base. At the reservoir's left end, the acoustic boundary condition is also employed to block the re-entry of seismic waves. The software's interaction environment establishes the physical characteristics of inter-surface connections. Any movement in the valley floor is transmitted to the dam because the contact state between the dam's sides and the valley floor is assumed to be rough with node-to-node contact (tie). With the tie without friction, we evaluate the contact conditions between the reservoir water and the dam and between the reservoir water and the sides of the valley.

## 5. 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 ($\sigma_{t0}$) |
|  |  | 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).

## 6. INTRODUCTION OF APPLIED ACCELERO- GRAMS

Modeling the selection and use of seismic spectra is a crucial aspect of dynamic analysis. The spectral acceleration of the boundary between the foundation and the dam is varied by applying six separate earthquakes of varying intensities and types. After that, the SeismoSignal software-calculated spectrum acceleration, velocity, and displacement- ment due to the earthquake are shown. Full accelerationerations 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:

First, in 1988, in northern California, a magnitude 9.9 earthquake occurred, named Loma Prieta (21).
Friuli, northern Italy, was hit by a quake measuring 6.5 on the Rich- ter scale in 1976 (22).
Hollister: In 1989, San Francisco had a magnitude 6.8 earthquake (23).

Imperial Valley, where a 6.4-magnitude quake hit in 1979, located south of Mexico City (24).
5. Kobe: In June of 1995, a magnitude 6.8 earthquake struck within 20 kilometers of Ko- be, Japan (25).
The Landers, California, earthquake hit in 1992. The last 40 years (26) have not seen a more devastating earthquake in California than this one.

## 7. DISCUSSION AND CONCLUSION

### *7.1. Assessment of dam response under vertical component of near-field earthquakes*

Figures Figure 3, Figure 4Figure 5, Figure 6Photo 7Dam crest displacements due to near-field earthquakes are shown in Figure 8 when the vertical component of earthquakes is taken into account for the full reservoir state. The data show that during the peak of the Loma Prieta earthquake's acceleration, there was a maximum displacement of 8.1 centimeters. Dam movements are upstream, as indicated by the negative sign. The largest displacement of 2.2 cm happens in the third second during the Friuli earthquake under these conditions.

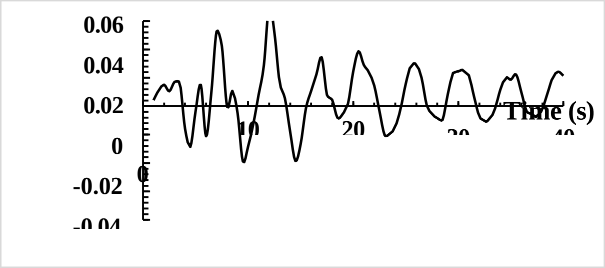

Figure 3. Displacement-time history of dam crest for model Kobe-$N_v$-1

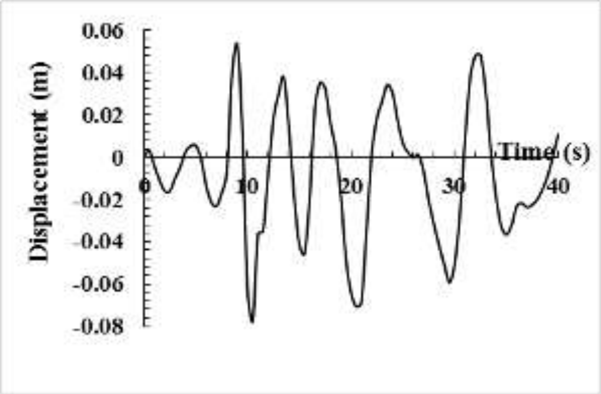

Figure 4. Displacement-time history of dam crest for model Imperial Valley-$N_v$-1

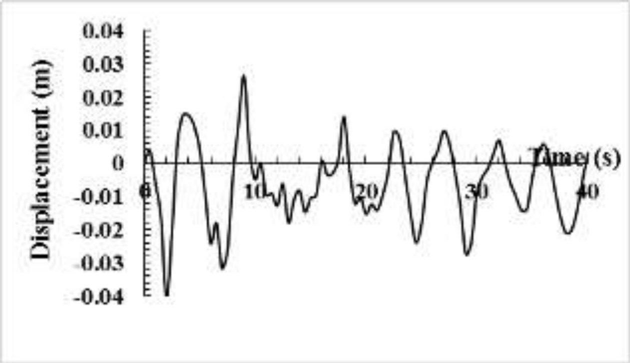

Figure 5. Displacement-time history of dam crest for model Holl

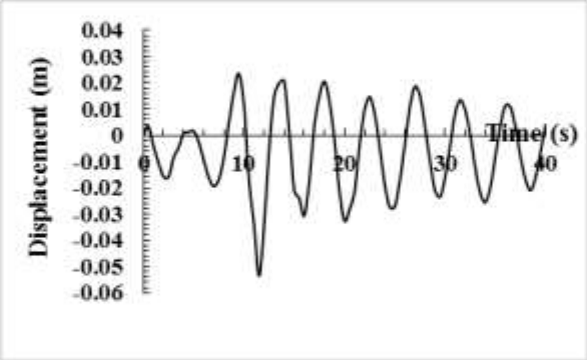

Figure 6. Displacement-time history of dam crest for model Landers-$N_v$-1

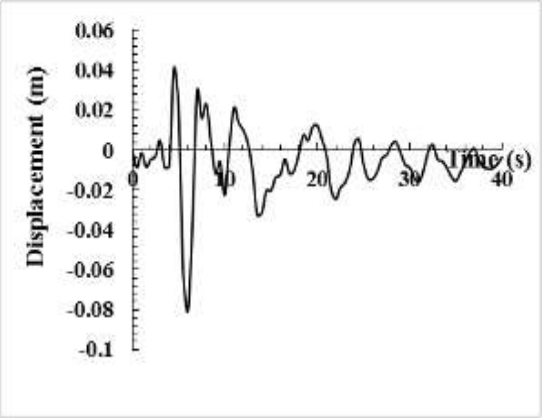

Figure 7. Displacement-time history of dam crest for model Loma Prieta-$N_v$-1

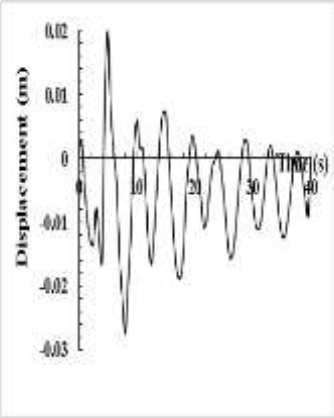

Figure 8. Displacement-time history of dam crest for model Friuli-$N_v$-1

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 dis- placement 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 com- pared to the displacements for the full reservoir condition.

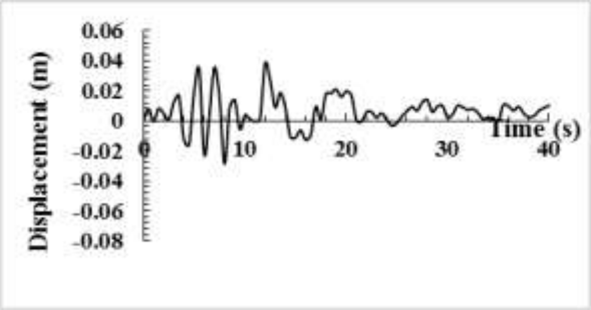

**Figure 9. Displacement-time history of dam crest for model Kobe-$N_v$-2**

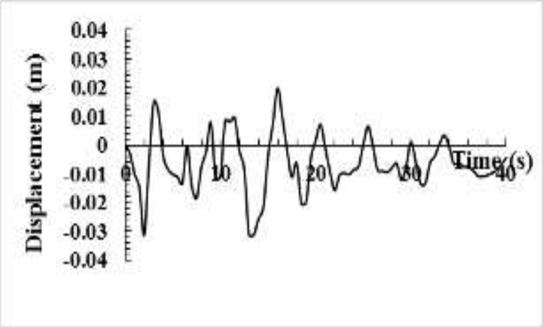

**Figure 11. Displacement-time history of dam crest for model Hollister-$N_v$-2**

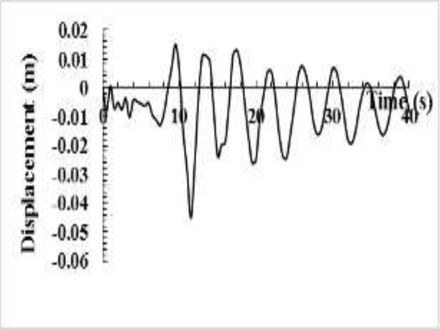

**Figure 12. Displacement-time history of dam crest**

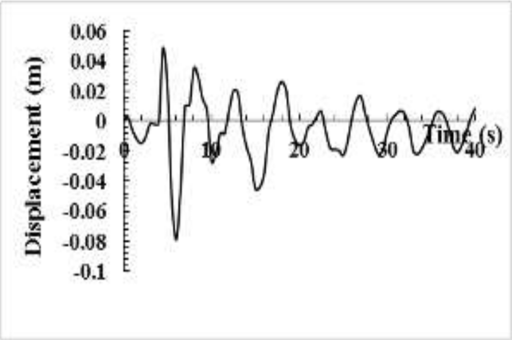

**Figure 13. Displacement-time history of dam crest for model Loma Prieta-$N_v$-2**

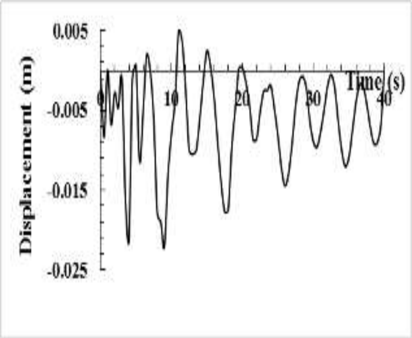

**Figure 14. Displacement-time history of dam crest for model Friuli-$N_v$-2**

The maximum displacements of the dam crest are about the same for the Kobe and Landers earthquakes, and the minimum displacement of the dam crest is reported to be around 2 cm when the vertical component of near-field earthquakes is applied for the empty reservoir condition. Figures 15, 16, 17, 18, 19, and 20 show that, consistent with the frequency content of accelerograms and the findings, the greatest displacement of the dam with an empty reser- voir is stated to be roughly 6 cm during the Imperial Valley and Loma Prieta earthquakes.

Whole maximum displacements oc- curred during different earthquakes and conditions are collected and shown in a chart with the goal of achieving a full response of behavior of the structure in the face of different earthquakes under var- ious situations. Maximum absolute displacements for full reservoir conditions during near-fault earthquakes with a vertical component are displayed in Fig. 21. These two accelerograms show that the greatest displacement, as seen, resulted from the Imperial and Loma Prieta earthquakes. It is important to remember that the reservoir-bed-dam interaction causes the displacement, and that the force exerted by the earthquake must be dissipated according to the precise computation of the consequences of each accelerogram.

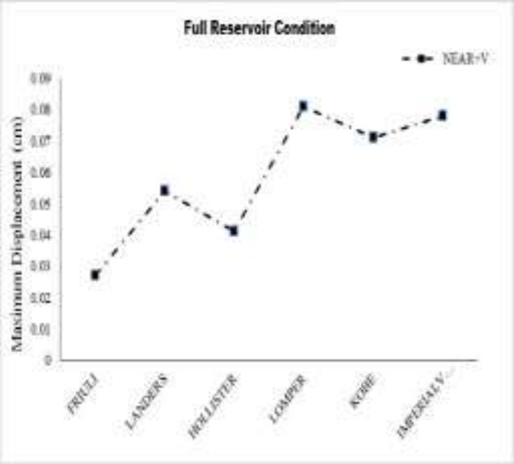

**Figure 21. Comparison of maximum displacement of dam crest under vertical component of near-field earthquakes for full reservoir condition**

Crest displacement is shown to be minimal for the Friuli earthquake under full reservoir conditions and maximal for the Lo- ma prieta earthquake under the same conditions. Maximum displacements for the Loma prieta, Imperial Valley, Kobe, and Landers earthquakes are noteworthy, given the effect of the vertical component; so much so that the increase of displacements is reported to be greater than 50%. For the Friuli and Hollister earthquakes, the maximum dam displacement is not noteworthy because of the frequency of the rise. Figure 22 displays a similar pattern, this time for the greatest displacements of the dam crest under a situation of a half-full reservoir. For the Loma Prieta earthquake's vertical component, a maximum displacement of 7.7 cm is determined in the half-full reser- voir condition. Maximum displacements get larger when the vertical component of near-field earthquakes is added

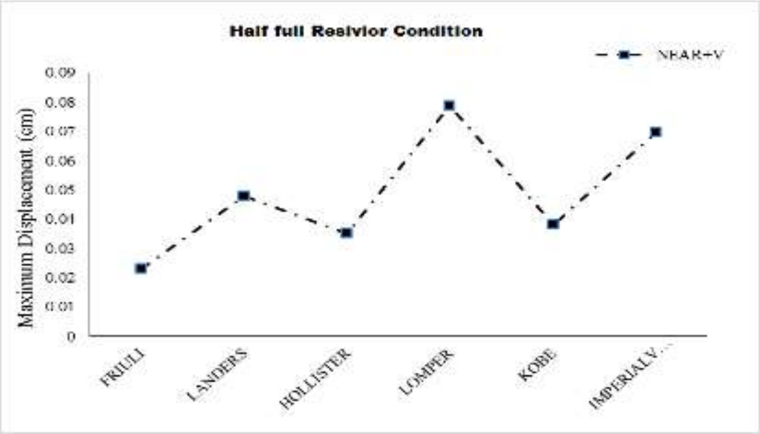

**Figure 22. Comparison of maximum displacement of dam crest under vertical component of near-field earthquakes for half-full reservoir condition**

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 hy- drostatic 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, re- spectively (Figure 23).

Figure 24 displays all charts resulting from various reservoir circumstances; as the reservoir's impoundment level rises, the resulting dis- placements make intuitive sense. with certain accelerograms, the rise in displacements is not noticeable, but with the KOBE earthquake, huge discrepancies may be seen because of the present frequency content. Since only the hydrodynamic force is considered for the loading of the reservoir, it can be concluded that an increase in the volume of water in the reservoir increases the hydro- static force applied to the dam by the reservoir, leading to an increased displacement of the dam crest.

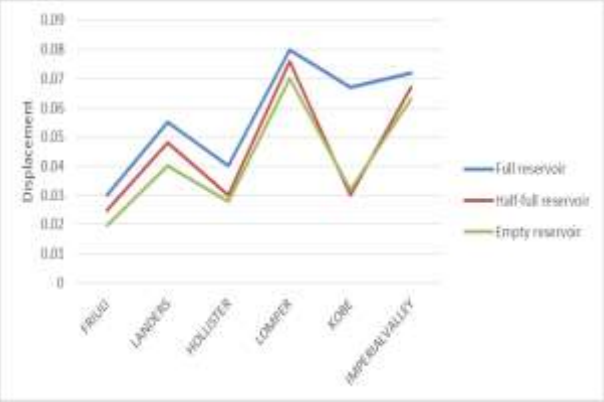

**Figure 24. Comparison of maximum displacement of dam crest in different reservoir conditions**

## 8. RESULTS

- The study's numerical simulation approach may be utilized to model the interaction between dam foundations and reservoirs in future research since it accurately simulates the behavior of the dam, reservoir, and foundation.

More displacement is imparted to the dam and may cause the dam materials to reach the nonlinear zone when the dam is in use and the whole volume of the reservoir is filled with water and under the conditions of vertical component of near-field earthquakes.

Dam collapse and fracture can be prevented by taking precautions when the vertical component of near-field earthquakes is applied, which increases the maximum displacements for the half-full reservoir state.

- Under the vertical component of near-field earthquakes, maximum displacements decrease for the empty reservoir state.

As the impoundment level drops, fewer accelerograms will register the influence of the vertical component and the field of seismic stimuli.

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