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The Seismic Response of Dams: A Numerical Investigation of the Effect of Shear Stiffness and Height of Embankment Dam Foundation

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ABSTRACT

The type and height of foundations of embankment dams are among the factors affecting their seismic responses. The kinds and heights of these foundations and the other conditions play fundamental roles in transmitting, attenuating, or amplifying the seismic waves. Considering 6 different types of shear stiffness and 7 different heights for Mashkid Olia dam foundation, the effect of shear stiffness and height of the foundation on the seismic behavior of the dam through the equivalent linear method were investigated. It was indicated the undeniable effect of conditions and height of foundation on the seismic behavior of the embankment dam.

1. Introduction

Embankment dams are among the main hydraulic structures whose failure can lead to irreparable damage; therefore, all essential controls and sensitivities should be investigated to design these hydraulic structures. Controlling dam stability during and after earthquakes is one of these instances [1]. Severe earthquakes cause increased stress and deformation of the dam and its ancillary structures. In some cases, the deformations and stresses may exceed the permitted levels, leading to full or partial damage to the dam. Accordingly, measuring and recording severe earthquakes at the dam site and the reaction of the dam to the earthquake are of great importance [2].

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Specialists have recently sought to achieve more appropriate methods for seismic analysis and design of embankment

dams. These efforts have led to the development of various methods, including quasi-static analysis and permanent quasi-dynamic and dynamic displacement, paving the way for predicting the behavior of embankment dams under various loading conditions. Methods such as dynamic analysis predict the behavior of the dam more accurately, but employing such methods necessitates more cost and time. In contrast, simpler methods such as quasi-static analysis and permanent displacement analysis (quasi-dynamic analysis) require less time and are more economic. However, the performance of each of these analytical methods is identified when their results are consistent with the response of embankment dams [3].

Changes in the geometric characteristics of the foundation, including the foundation height and its geotechnical properties such as shear stiffness, the angle of internal friction (φ), and the adhesion of the foundation materials play important roles in the stability of embankment on the foundation against earthquake forces. The study conducted by Chopra and Perumalswami (1971), in which the foundation is modelled using an elastic half-space, is one of the first studies examining the effect of foundation on the seismic response of dams [4]. Following that, Dakoulas (1993) and Dakoulas and Hsu (1995) studied the impact of valley shape on the seismic response of the dam, using analytical methods. They indicated that the amplitude of the seismic response of the dam is affected by the impedance between the dam and the site [5, 6]. Applying neural network, Tsompanakis et al. (2009) evaluated the dynamic response of the sample embankment through the finite element method. Considering the non-linear behavior of embankment materials, they found that the zoom module would decrease along with the increase in the maximum seismic acceleration and the admittance of materials to the non-linear part [7].

2. Materials and Methods

We performed the numerical analysis, using the software package of Geostudio (the 2007 version) which is capable of simultaneous analysis of water flow and soil deformation by linear and non-linear behavioral models for soil and rock. In this software, the numerical solution method is the finite element method that is highly consistent with non-linear behaviors and time-dependent analyses. The key stages of applying the above-mentioned software are as follows: creating the network, applying the boundary and initial conditions, selecting the behavioral model of the materials, assigning the parameters of the materials to different parts of the network, and finally solving the network.

Different stages of the analysis and the software employed are as follows:

A – The static analysis to determine the initial stresses in the dam foundation and wall by Sigma/w and Seep/w software (from the software package of Geostudio)

B – The dynamic response analysis and the determination of the history of stresses, strains, and horizontal acceleration at the dam foundation and wall via Quake/w software (from the software package of Geostudio)

For the static analysis, the elasto plastic behavioral model was used for wall materials. Moreover, for the dynamic analysis of Mashkid dam, the equivalent linear elastic method and the linear elastic method were employed for wall materials and foundation materials, respectively.

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2.1.Mashkid Olia Dam

Mashkid Olia reservoir dam is constructed at a 50-km distance from Saravan, Iran with the aim of storing surface flows optimally by exploiting the natural potential of the Mashkid river to supply Saravan and its agriculture with drinking water as well as to restrain the floodwater of Mashkid basin. The height and the crest length of the dam are 24 and 895 meters, respectively [2].

2.1.1. Cross-Section Geometry for Analysis

The critical cross-section is extracted based on the layout and the sections presented in the technical drawings of the dam wall. The height of the dam and the depth of the alluvial foundation are maximal in this section (Figure 1).

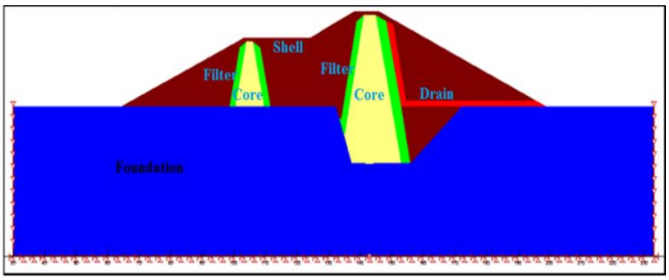


Fig.1.Critical section of the Mashkid dam [2]

2.1.2. Physical Properties of Materials

The properties of core and shell materials are determined based on the results of laboratory experiments on fine-grained and coarse-grained construction materials (Table 1).

Table 1. Physical properties of the Mashkid dam material [2]

Materials type	Saturated unit weight (KN/m^3)	Angle of internal friction (degree)	Adhesion (KPa)	Poisson's ratio
Core	*21*	*18*	*20*	*0.32*
Filter	*21.5*	*36*	*0*	*0.25*
Drain	*21.5*	*38*	*0*	*0.26*
Shell	*22*	*42*	*0*	*0.27*
Foundation	*23*	*35*	*0*	*0.3*

2.1.3. Dynamic Properties of Materials

In this study, the dynamic analyses are performed, using the equivalent linear method. Three basic parameters are usually defined in these analyses:

- The maximum shear stiffness of materials as a function of comprehensive stress

- The decrease in shear stiffness along with the increase in shear strain

- The increase in attenuation along with the increase in shear strain

All the above-mentioned parameters are obtained from the dynamic tests.

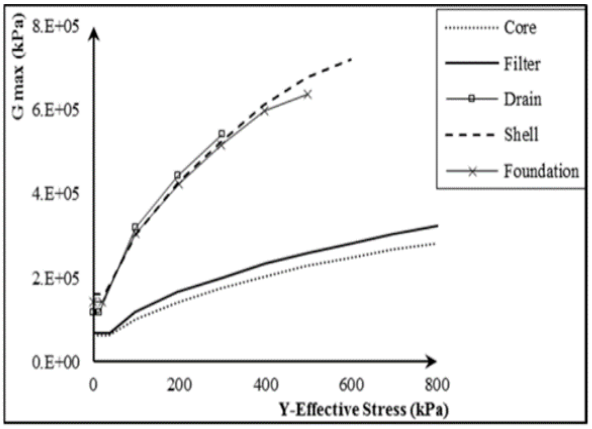


Fig.2. Shear stiffness changes versus effective stress for various materials[2]

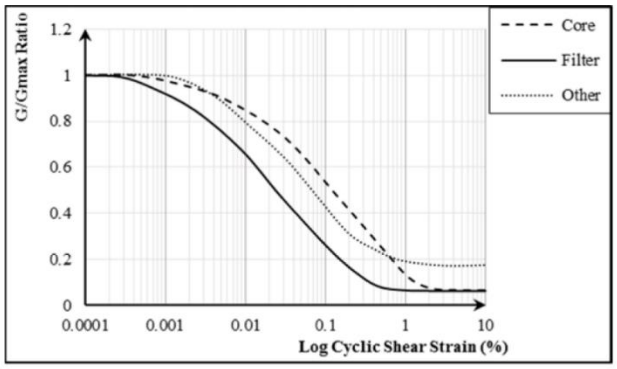


Fig.3.G/Gmax changes versus shear strain for various materials[2]

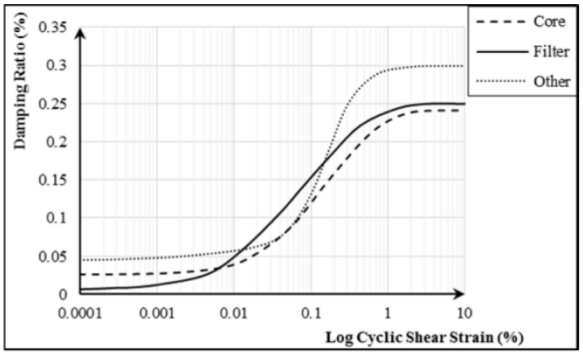


Fig.4. The attenuation changes versus shear strain for various materials.

3. Results and discussions

In the present study, two Northridge and Elcentro earthquakes are utilized for the dam dynamic analysis. The accelerogram of each earthquake is presented in what follows (Figures 5 and 6).

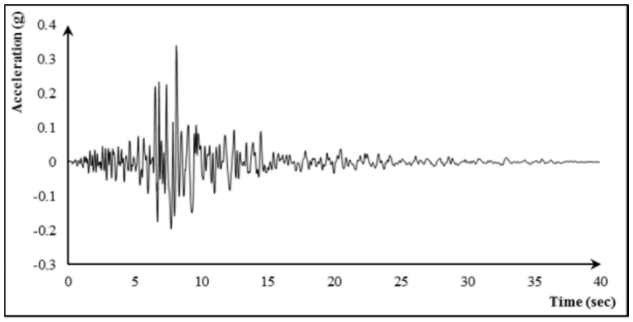


Fig.5. Accelerogram of the northridge earthquake

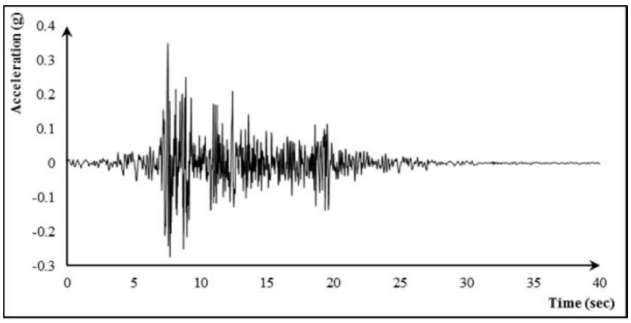


Fig.6. Accelerogram of the El Centro earthquake

3.1.Numerical data of Accelerograms

The information available in seismic databases is raw and should consequently be modified and coordinated by Seismo Signal software before utilization. This modification includes the determination of the zero line based on the zero displacement at the end of the earthquake displacement mapping. In other words, if the history of acceleration or velocity obtained directly from the accelerogram is used in a dynamic analysis, its displacement and velocity should be controlled at the end of the earthquake time to prevent the measuring system from an admissible displacement or velocity due to the error. In case of such errors, these time histories should be modified before the analysis. Indeed, the baseline modification is the input spectrum modification so that the history of velocity or displacement obtained at the end of the earthquake is brought to zero during the modification [1].

To modify data, all mappings should be coordinated, since this leads to the possibility of comparing the effect of earthquake on different structures and their review discussion. There are different methods for coordinating the earthquakes. In the present study, the PGA method is applied to coordinate the information, and the two accelerograms are coordinated at 0/3 g.

3.2. The Effect of Shear Stiffness of Embankment Dam Foundation on Wall Dynamic Response

The shear stiffness of soil is the most important soil property in a dynamic analysis. It depends on the effective stress and increases along with the increase in the effective stress. In the Geostudio software, shear stiffness is determined based on the soil type (coarse-grained and fine-grained). According to Seed & Idriss [8 & 9] and Hardin & Vincent [10], the Geostudio software uses equations (1) and (2) to calculate the shear stiffness for coarse-grained and fine-grained soils, respectively.

$$G_{max} = k_{2max}\sqrt{\sigma'_m} \quad \text{Used for Shell, Drain and Foundation} \quad (1)$$

In equation (1), σ'_m and k_{2max} are the mean effective stress and the factor dependent on the type and density of

$$G_{max} = 625\left(\frac{1}{0.3+0.7e^2}\right)(OCR)^k\sqrt{p_a\sigma'_m} \quad \text{Used for Core} \quad (2)$$

materials, respectively. These coefficients vary between 80-180 and 30-75 for gravel samples tested and sand, respectively.

In equation (2), e is void ratio, OCR is over consolidation ratio, p_a is atmospheric pressure, σ'_m is mean effective stress, and k is a factor dependent on the soil pastiness [9].

In this study, 6 different kinds of stiffness are used for the foundation in order to investigate the effect of the shear stiffness of the foundation on the dynamic behavior of the embankment dam. According to equation (1), 6 different values are considered for the k_{2max} parameter in a reasonable range which a dam may face in different sites. These values are equal to 30, 50, 80, 100, 150, and 180. By inserting each of these numbers in equation (1), 6 different functions of shear stiffness are obtained in terms of the effective stress. The curves obtained for each of these functions are presented in Figure 7.

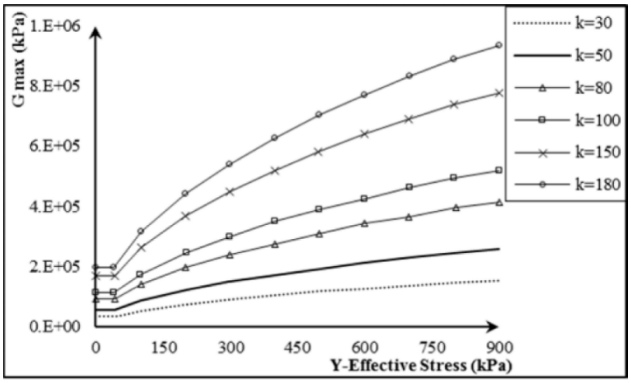


Fig.7. The changes of foundation shear modulus

We studied and compared the changes in acceleration, maximum shear stress, and shear strain resulting from the application of two different accelerograms in 9 different selected points on the central axis of the dam to investigate the seismic response of the wall dam. In order to display better the graph of changes in each of the above-mentioned parameters with the foundation

stiffness changes, the values obtained from the curves and presented in Figure 7 are averaged; furthermore, their mean is presented on the horizontal axis of the graph of parameter changes. When k=30 and k=180, the foundation is considered flexible and rigid, respectively.

The points selected on the wall dam are shown in Figure 8. These points are at a height of 65.57, 64.57, 54.57, 44.57, 34.54, 25, 17.5, 7.5, and 0 m from the base level.

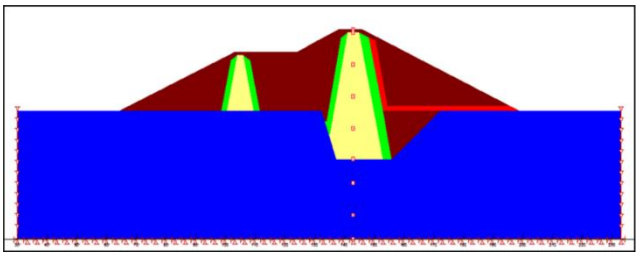


Fig.8. Selected points on the dam-foundation system

3.2.1. Changes in the Maximum Acceleration and Shear Stiffness in the Foundation

The maximum acceleration changes in the central axis of the dam along with the foundation stiffness changes under the Northridge and Elcentro earthquakes are presented in Figure 9.

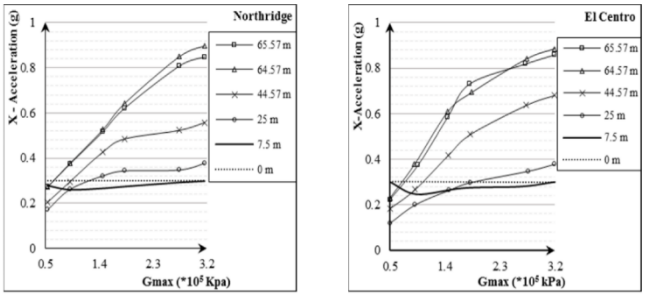


Fig.9. Maximum acceleration changes in the central axis of the dam versus the foundation stiffness changes

Observing and investigating the graphs related to the maximum acceleration changes indicate that the maximum acceleration at the dam increases along with the increase in the foundation shear stiffness (Fig. 9). On the other hand, when the foundation stiffness is less than all materials, especially the core materials, the maximum accelerations created at the dam will be less than the acceleration caused by the earthquake (0.3 g). Following that, the maximum acceleration will significantly rise along with the increase in the foundation stiffness.

The percentage of increase in the maximum acceleration along with the increase in the foundation stiffness under the Northridge earthquake is presented in Table 2 in 9 different heights of the dam. As it is observed, the maximum acceleration in the crest will be 0.273 g if the foundation is flexible; however, if the foundation is rigid, the maximum acceleration in the crest will be 0.848 g. In other words, the acceleration in the crest will increase by 210 percent along with the increase in the foundation stiffness.

Table 2. Acceleration increase percent in the case of the rigid foundation compared to the flexible foundation under the Northridge earthquake

Height of Points (m)	Maximum acceleration for the flexible foundation (g)	Maximum acceleration for the rigid foundation (g)	Percent of increase in acceleration for the rigid foundation
65.57	*0.273*	*0.848*	*210%*
64.57	*0.272*	*0.897*	*230%*
44.57	*0.205*	*0.558*	*172%*
25	*0.171*	*0.377*	*120%*
7.5	*0.278*	*0.298*	*7%*
0	*0.3*	*0.3*	*0*

3.2.2. Changes in both of the Maximum Shear Stress in the Central Axis of the Dam and the Shear Stiffness in the Foundation

The graph of the changes in both shear stress in the central axis of the dam and the foundation stiffness under the Northridge and Elcentro earthquakes is presented in Figure 10. This figure demonstrates that the maximum shear stress in the central axis of the dam increases along with the increase in the foundation stiffness .

In what follows, the percentage of increase in the maximum shear stress in the case of the rigid foundation is calculated compared to the flexible foundation under the Elcentro earthquake and is presented in Table 3.

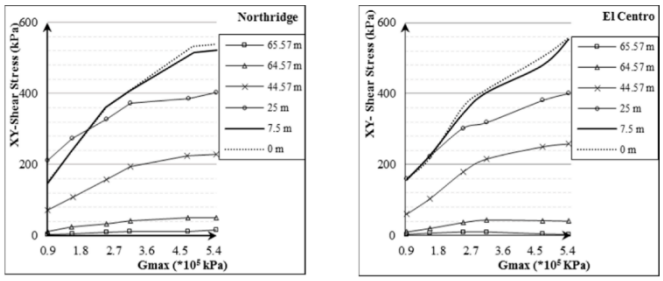


Fig.10.Maximum shear stress variations in the central axis of the dam versus the shear stiffness changes in the foundation

Table 3. Comparisons of increased percent of the maximum shear stress for the rigid and flexible foundations in nine different points under the El Centro earthquake

Height of Points (m)	Maximum shear stress for the flexible foundation (kPa)	Maximum shear stress for the rigid foundation (kPa)	Percent of increase in the shear stress for the rigid foundation
65.57	*3.22*	*7.34*	*128%*
64.57	*10.13*	*40.51*	*300%*
25	*160.58*	*400*	*149%*
7.5	*158.08*	*553.34*	*250%*
0	*160.58*	*557.66*	*247%*

3.2.3. Comparing the Changes in both of the Maximum Shear Strain in the Dam Core and the Shear Stiffness in the Foundation

Graph 11 illustrates the effect of the foundation shear stiffness parameter on the maximum shear strain in the dam core

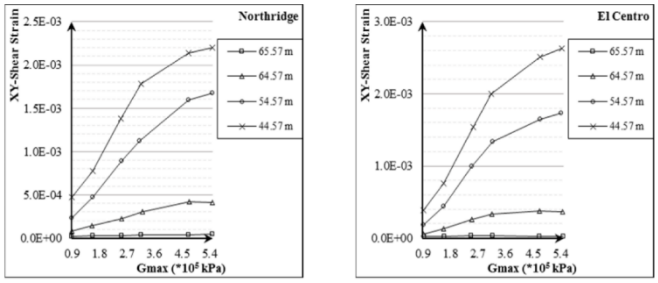


Fig.11.Maximum shear strain variations in the core versus the shear stiffness in the foundation

According to Figure 12, the shear strain in the dam core increases along with the increase in the foundation shear stiffness. The percentage of increase in the shear strain along with the increased stiffness in two cases of rigid and flexible foundations under the Northridge earthquake is presented in Table 4.

Table 4. Comparisons of increased percents of the maximum shear strain for the rigid and flexible foundations in different points of the dam core under the Northridge earthquake

Height of Points (m)	Maximum shear strain for the flexible foundation (g)	Maximum shear strain for of the rigid foundation (g)	Percent of increase in the strain for the rigid foundation
65.57	*0.0000103*	*0.0000392*	*280%*
64.57	*0.0000737*	*0.000418*	*467%*
54.57	*0.000239*	*0.00168*	*603%*
44.57	*0.000481*	*0.00221*	*359%*
65.57	*0.0000103*	*0.0000392*	*280%*

3.3. The Effect of the Height of Dam Embankment Foundation on the Dynamic Response of Dam Wall

Seven different heights of 15, 22, 30, 38, 45, 52, and 60 were used for the foundation to investigate the effect of the foundation height on the dynamic response of the embankment dam. By employing the dynamic analysis for each of the different heights in each of these modes, the changes in the maximum acceleration, the maximum shear stress, and the maximum strain, which resulted from two different accelerograms, were calculated and evaluated in 3 selected points in the dam wall by the Geostudio software. Figure 12 shows the points selected on the dam wall. These points are in the dam crest and at 1/3 and 2/3 of the dam height.

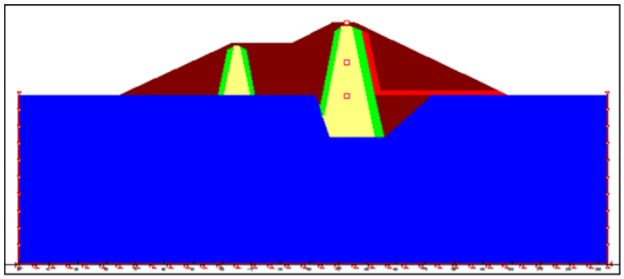


Fig.12. Selected points on the dam wall

3.3.1. Changes in both of the Maximum Acceleration in the Central Axis of the Dam and the Foundation Height

Figure 13 depicts the graph of the changes in both of the maximum acceleration in the central axis of the dam and the foundation height.

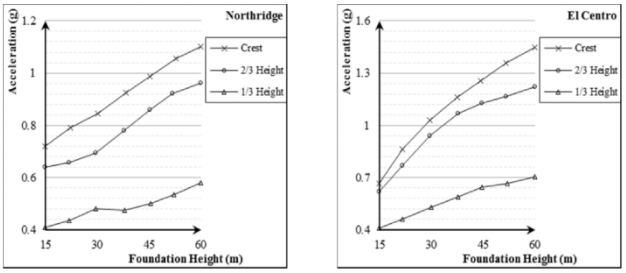


Fig.13. Comparison of the maximum acceleration changes in the central axis of the dam versus the foundation height changes

Considering the figures, the procedures show that the acceleration increases from 0.664 g to 1.44 g along with the increase in the foundation height from 15 m to 60 m under the Elcentro earthquake for a point at the dam crest. To put it more simply, the rate of the acceleration changes (graph slope) in the crest is equal to 0.017. Similarly, the rate of the acceleration changes is calculated for other parts (Table 5).

Table 5. Rate of the maximum acceleration variations in the central axis of the dam versus the foundation height under the El Centro earthquake

Points	Acceleration for a foundation with the height of 15 m (g)	Acceleration for a foundation with the height of 60 m (g)	Rate of the acceleration changes
Crest	*0.664*	*1.44*	*0.017*
2/3 height	*0.616*	*1.22*	*0.0134*
1/3 height	*0.406*	*0.706*	*0.0066*

The values presented in Table 5 show that by going far away from the foundation and approaching the crest, the rate of the acceleration changes will increase due to the increase in the foundation height.

3.3.1. Changes in both of the Maximum Shear Stress in the Central Axis of Dam and the Foundation Height

Figure 14 shows the changes in both of the maximum shear stress in the central axis of the dam and the foundation height .

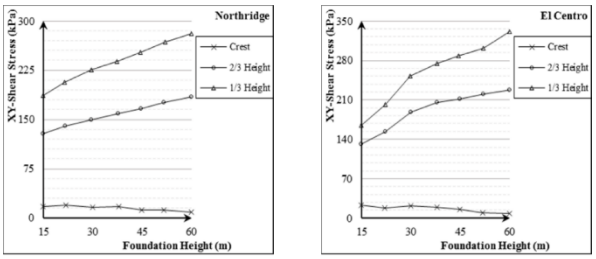


Fig.14. Variation of the maximum shear stress in the central axis of the dam versus the foundation height variation

According to the graphs, the maximum shear stress in the points in the core of the dam increases along with the increase in the foundation height (points at 1/3 and 2/3 of the dam height). On the other hand, the maximum shear stress at the dam crest decreases along with the increase in the foundation height. The rate of shear stress changes under the Northridge earthquake is calculated in different parts of the dam to provide a better judgment on the effect of the increase in the foundation height. The results of the calculations are presented in Table 6.

Table 6. Rate of the maximum shear stress variations in the central axis of the dam versus the foundation height changes under the Northridge earthquake

Points	Shear stress for a foundation with the height of 15 m (kPa)	Shear stress for a foundation with the height of 60 m (kPa)	Rate of the acceleration changes
Crest	*18.55*	*8.89*	*0.213-*
2/3 height	*127.61*	*183.078*	*1.25*
1/3 height	*187.44*	*277.45*	*2*

Figure 14 and Table 6 indicate that the rate of changes in both shear stress and foundation height decreases by going far away from the foundation and approaching the crest; therefore, the rate of changes in shear stress at the dam crest becomes negative. Although the shear stress at the crest decreases along with the increase in the foundation height, the rate of changes in shear stress at the crest is negligible compared to that in the core points in the dam.

3.3.2. Changes in both of the Maximum Shear Strain in the Central Axis of Dam and the Foundation Height

The graph of shear strain changes with different values of the foundation height is depicted first (Figure 15). Considering the trends of graphs, it is observed that the maximum shear strain in the points in the core increases along with the increase in the foundation height (points at 1/3 and 2/3 of the dam height). However, no significant changes are observed in the shear strain at the dam crest .

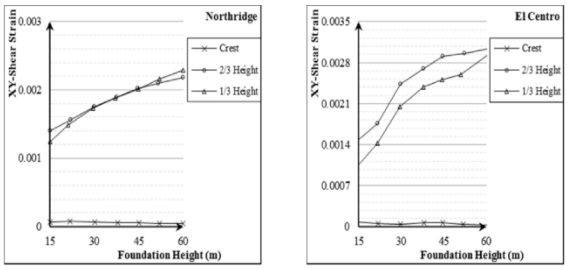


Fig.15. Variation of the maximum shear strain in the central axis of the dam versus the foundation height changes

In what follows, the rate of changes in both shear stress and foundation height under the Northridge earthquake will be calculated for each graph (Table 7).

Table 7. Variations rate of the maximum shear strain in the central axis of the dam versus the foundation height variations under the Northridge earthquake

Points	Shear strain in for a foundation with the height of 15 m	Shear strain for a foundation with the height of 60 m	Rate of the shear strain changes
Crest	*0.0000539*	*0.0000276*	*- 0.000000584*
2/3 height	*0.00141*	*0.00218*	*0.000017*
1/3 height	*0.00127*	*0.00228*	*0.000022*

Figure 15 and the rates of shear strain changes presented in Table 7 show that the rate of these changes decreases along with the increase in the foundation height by going far away from the foundation and approaching the crest.

4. Conclusion

Our findings suggest that the consideration of the contemporaneous wall and foundation modeling plays an important role in the accurate prediction of the seismic behavior of embankment dams. Accordingly, taking into account the real stiffness of the foundation, i.e. ignoring the rigid foundation in analyses, will reduce the acceleration response of the dam. Investigating the shear stress in the stability analysis or the slippage of the walls of embankment dams by the earthquake is of utmost importance. The stability of a soil mass will decrease along with the increase in the shear stress in this mass. We found that the rate of increase in the shear stress under the earthquake in embankment dams with rigid sites is far more than that in embankment dams with flexible sites. Concerning the shear failure, it is assumed that the shear failure will occur at points where the shear strain exceeds 15%. As we observed in this study, the shear strain in the dam core rose along with the increase in the foundation stiffness. This indicates that the possibility of shear failure in the core of the dam under the earthquake in the rigid sites is higher than that in the flexible sites. From the viewpoint of shear stress and strain, the construction of dams in highly rigid sites is not suitable. We also found that the acceleration in the dam wall soars along with the rise in the foundation height. In other words, the higher height of the foundation further strengthens the seismic waves and leads to the greater effect of the seismic waves on the dam wall. The rate of shear stress and strain in the core

will escalate along with the increase in the foundation height from 15 m to 60 m. This demonstrates the increase in the instability and the possibility of shear failure in the dam along with the rise in the foundation height. By considering the above-mentioned matters, we can conclude that a high height for the foundation is not suitable for the dynamic stability of dams.

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