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Original Research Article

SEISMIC BEHAVIOR OF EARTH DAMS WITH DIFFERENT RESERVOIR WATER LEVELS UNDER NEAR-FIELD AND FAR-FIELD EARTHQUAKES

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Abstract

The height of reservoir water is one of the important factors affecting the seismic behaviour of earth dams. A large number of earth dams have been constructed in different countries that are sometimes located in a high-risk geographical zone. The studies on the seismic behaviour of earth dams have been conducted for several decades. However, this study, considering the importance of the subject, it investigates the seismic behaviour of Sumbar rock-fill embankment dam under near- and far-field earthquakes with variation in the water level behind the dam. The ratio of water height of the dam to dam height is considered as an important indicator to investigate the seismic performance of these structures. The analyses were performed using the ABAQUS finite element platform, under 7 near-field and 7 far-field earthquake records. In this research, the changes in dam stresses, displacements, and failure of the dam have been discussed. The results indicated that the effect of near-field earthquakes on the seismic behaviour of earth dams is more significant than far-field earthquakes.

Keywords: seismic behaviour, earth dam, reservoir water levels, near-field, far-field, finite element modelling

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1. INTRODUCTION

One of the main causes of earth dams' instability is the impact of earthquake loads on them (earthquake-induced failure). When the earthquake load is applied, the dam has a reservoir water level which is an important factor in dam stability. Ahmadi & Kavouszadeh have investigated the effect of rock slope gradient on the magnitude of water seepage in a dam body. The results showed that by increasing the slope in the negative state, the magnitude of pore water pressure decreases. This value increases up to a maximum of 12% for a slope model of 6% more than no slope model [1].

Another study has been performed on the behaviour of earth dams with respect to dam height and its behaviour. The results showed that the increase in earthquake acceleration from the base to the crest of the dam is not universal. It can be confined to rigid dams whose behaviour during the earthquake remains elastic or about weak earthquakes [2].

The seismic stability of earth dams has been studied by some authors as well. In a recent study, it was observed that foundation in the primary and distal parts of upstream and downstream areas is susceptible to liquefaction [3].

On the effect of core slope for slope stability of earth dam another study has been conducted. The results indicated that due to different slope angles in the analysis of Amand dam, the inclined core, on average is 12% more stable than the vertical core. In dynamic analysis, it is, on average, 27% more stable than the vertical core [4].

On the analysis and stability of non-homogeneous earth dams, studies have been conducted. The results show that when the dam reservoir is full, with changing the internal friction angle, the stability factor of the upstream slope can be changed by about 1%. However, when the reservoir is empty or rapid discharge occurs in the reservoir, the variation of the internal friction angle on the stability factor of the soil is about 25% [5].

The laboratory modelling using nano-silica on the seal curtain of the earth dam has been carried out in another study. In general, nano-silica increases soil strength and decreases soil permeability, hence the overall dam performance will be improved [6].

Another study on the dynamic analysis of the earth dam has been conducted by Sharafi & Mohammadi. It was observed that horizontal and vertical displacements of the dam during an earthquake are within a range that does not compromise the safety of the dam[7].

In relation to the impact of reservoir water height on seismic behaviour of earth dams (Case study of Masjed Soleiman Dam), studies have been done. The obtained results are related to the comparison of the mean values of maximum acceleration and maximum displacement. The minimum safety factor in the possible wedge of failure and the magnitude of permanent displacement on downstream were studied [8].

In a case study of Kabudwal Dam, the impact of drainage type on the settlement related to the construction time of earth dams has been investigated. The results showed that the changes and values of the total displacements, horizontal displacements, and vertical settlement in the three models with the presence of three different types of drainage are almost the same. The only difference in the horizontal displacement values relative to the mid-point, upstream, and downstream sections, has been observed [9].

The stability of Masjed Soleiman earth dam under rapid reservoir discharge conditions has been investigated. A good agreement was observed between the results obtained from the pore water pressure, total stress, and crust displacement with the results of the instrumentation [10].

On the geogrid behaviour of reinforcing earth dams under static and dynamic loads, another study has been conducted. By comparing results, it was concluded that by increasing the slope angle of the earth dam, the dam embankment volume has decreased [11].

On time-dependent earthquake modelling for an earth dam, various studies have been carried out. A recent study showed the necessity of complementary data from onsite experiments to determine the behaviour and feedback parameters of existing dam behaviour under recorded seismograms for model calibrations [12].

On one-dimensional seismic analysis of earth dams (an example from the Lentini site) studies have been carried out. The results compared to the maximum horizontal acceleration characteristics showed excellent agreement between the different by-laws [13].

On the dynamic analysis of a 2011 Tohoku earthquake-damaged earth dam, a study has been carried out. Therefore, the failure mechanism may be due to a relatively small elastic modulus of materials or the quality of the compacted material in the upper part [14].

A study has been conducted on the seismic performance evaluation of the Curit Dam. The differences between the earthquake records were obtained due to changes in earthquake characteristics [15]. Another study has been done to evaluate the seismic performance of an earth dam according to its reservoir level. The results show that by increasing the water level, the safety factor (F.S) decreases. Also, F.S always has values between 2 and 2.2[16].

On the safety and seismic behaviour of earth dams during the 2011 Tohoku earthquake, several studies have been conducted. It was found that more than 10% of all dams inspected were damaged during this seismic event and this proportion increased to 18% for earth dams [17].

The behaviour of the San Fernando embankments under seismic loading has been investigated. The analysis involved the importance of investigating a dynamic

analysis and emphasizing acceleration reinforcement through the embankment and attempting to communicate with the rigidity of the soil [18].
On the behaviour of earth dam under seismic load, studies have been carried out. The results showed that considering the nonlinear behaviour in the modelling procedure, increases the safety in the seismic stability of the earth dam [19].
Studies of earthquake deformation modelling during earthquakes have been conducted by Fattah et al.. According to the results, the values of seismic displacement depend on the elasticity modulus ratio of the dam crest to the dam base [20].
On the dam-reservoir interactions in the nonlinear seismic response of earth dams' studies have been carried out. It is recommended that the effects of the upstream reservoir on earth dams should not be completely ignored, but should be examined more precisely with respect to the actual nonlinear soil behaviour of the earth dam [21].
A study of the analysis of earthquakes affected by the 2001 earthquake in Bhuj, India has been carried out. The results of this analysis were consistent with the pattern of permanent earth dam deformation observed after the earthquake [22].
In the current study, attempts have been done to consider an adequate number of records for both near- & far-field earthquakes. Besides, the variations in water levels have been considered more precisely compared to previous researches. The dam which has been studied is located in Iran. Reservoir water level variations have been from empty to full reservoir with a stepwise growth of 20%. The stability and seismic safety of the studied dam against each of these categories were examined.

2. THE CASE STUDY

The purpose of this study has been to investigate the seismic behaviour of an earth dam with different reservoir water levels under near- and far-field earthquakes. The case study is Sumbar dam located in Iran in accordance with the geometry given in Figure 1. The construction of Sumbar dam is been shown in Figure 2. In this study, the dam has been investigated by changing the ratio of water height to dam height of 0.0, 0.2, 0.4, 0.6, 0.8, and 1.0 under near- and far-field strong ground motions. Figure 3 shows examples of modelling done in the ABAQUS FE program.

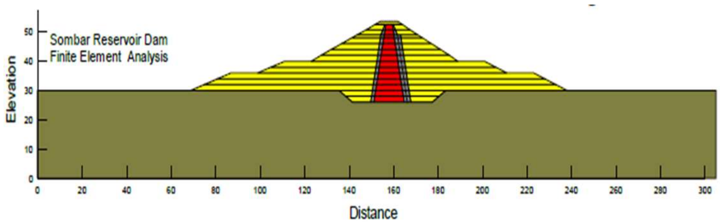

Fig. 1. The geometry of the Sumbar dam

Fig. 2. Construction of the Sumbar Dam

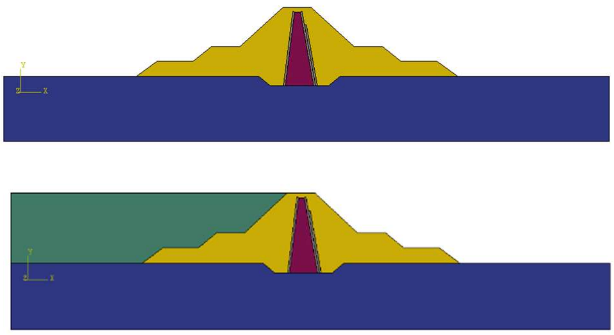

Fig. 3. Modelling of the Sumbar dam in ABAQUS a) [Hw / Hd = 0], b) [Hw / Hd = 1]

3. SOIL CHARACTERISTICS

The components of the Sumbar dam have different geotechnical characteristics that should be used for analysis purposes. These specifications include dry specific weight, saturated specific weight, internal-friction angle, and soil adhesion. Table 1 summarizes the geotechnical characteristics of the Sumbar Dam for its components.

The mechanical behaviour of soils may be expressed by different behaviour patterns with different accuracies in the FE programs. In this study, the Mohr-Coulomb model has been used.

Table 1. Geotechnical characteristics of Sumbar Dam

Layer	Dry Specific weight (kN/m^3)	Saturated Specific weight (kN/m^3)	Degree of Internal Friction (Deg.)	Adhesion (kPa)
Shell	22	23	42	0
Core	20	21	27	32
Foundation	19	20	20	50
Filter and Drainage	20	21	33	0

The Mohr-Coulomb behaviour model is the result of the Coulomb internal friction law for general stress states. In this case, it is assumed that the Coulomb internal friction law applies to all material plates. The Mohr-Coulomb elastoplastic model is estimated to be an average at an average rigidness in each layer. The calculations are very fast, as the rigidness is uniform across the entire layer. The Mohr-Coulomb model of the plastic state is associated with the development of irreversible strains. In other words, a yield function "f" is introduced as a stress and strain function to evaluate the plastic state event in its calculations. A yield function is often represented as a surface in the space of the main stresses. A completely plastic model is the main model with a fixed yield surface. That means a yield surface that is completely determined by the model parameters and does not change by the plastic strains. For the stress states presented by the points in the yield surface, the behaviour is quite elastic and all strains are reversible. The principle of elastoplastic behaviour is that the strains and strain rates are decomposed into unit elastic and plastic parts.

$$\varepsilon = \varepsilon^e + \varepsilon^p \tag{3.1}$$

Hooke's law is used to relate stress rates to elastic strain rates. In Hook's Law, we have:

$$\dot{\sigma}' = D^e(\dot{\varepsilon} - \dot{\varepsilon}^p) \tag{3.2}$$

According to classical plasticity theory, plastic strain rates are proportional to the derivative of the yield- stress function. This sentence means that the plastic strain rates are represented by vectors that are orthogonal to the yield surface. This classical form of theory is called unified plasticity. However, for the Mohr-Coulomb yield functions, the unified plasticity theory leads to the prediction of dilation. So, in addition to the yield function, a plastic potential function "g" is introduced. The case g ≠ f refers to the non-unified plasticity state. In general, plastic strain rates are written as follows.

$$\dot{\varepsilon}^p = \lambda \frac{\partial g}{\partial \sigma'} \tag{3.3}$$

Where λ is the plastic coefficient. λ is equal to zero for quite elastic behaviour, while λ is Positive for plastic behaviour. An ideal strain-stress model of an elastic-perfectly plastic material and the used Mohr-Coulomb criterion are depicted in Figures 4 and 5.

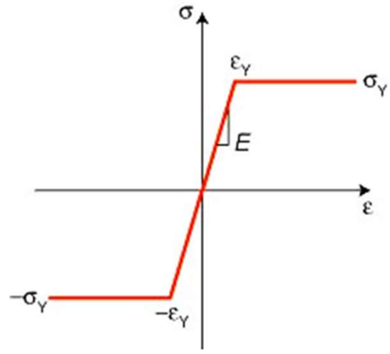

Fig.4. The basic idea of an Elastic-Perfectly Plastic Material

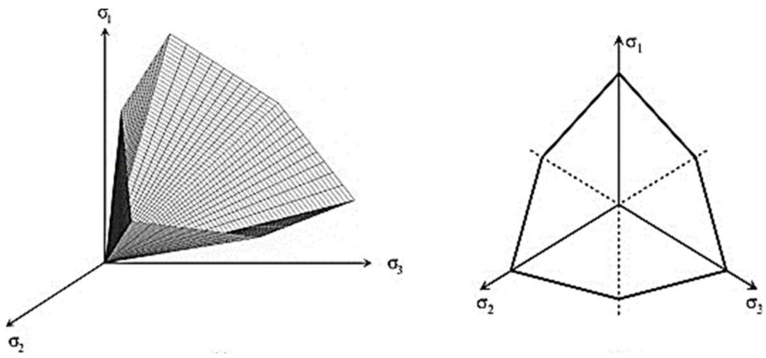

Fig.5. Yield surface of the Mohr-Coulomb model in the space of main stresses (C = 0)

4. SELECTED STRONG GROUND MOTIONS

According to the seismic design codes, the accelerograms used to determine the effect of the earth movement should, as far as possible, reflect the actual movement of the earth at the site of construction, at the time of the earthquake, and have the following characteristics:

- Accelerograms belong to earthquakes that include project earthquake conditions.

- The accelerometer site should be as similar as possible in terms of geology, seismology, and especially the characteristics of the soil layers with the building site.
- The accelerated movement time of the Earth in accelerometers should be at least 10 seconds.

Records used in this study are taken from the FEMA P-695 [23].

Table 2. Earthquake records characteristics used in this study

Near-Field Records				
No.	EQ. Record	Effective Duration (s)	PGA (g)	Magnitude (Mw)
1	El Centro#6	39.03	0.25	6.5
2	Parachute	22.34	0.43	6.5
3	Saratoga	39.95	0.23	6.9
4	Petrolia	35.98	0.28	7.0
5	Lucerne	48.12	0.30	7.3
6	Northridge	19.90	0.260	6.7
7	Chi-Chi-65	89.90	0.290	7.6
Far-Field Records				
8	San Fernando	27.90	0.39	6.6
9	Delta	39.48	0.19	6.5
10	El Centro#11	39.40	0.26	6.5
11	Capitola	39.95	0.27	6.9
12	Coolwater	48.90	0.32	7.3
13	Mulhol	28.98	0.27	6.7
14	Chi-Chi-45	52.47	0.43	7.6

5. MODAL ANALYSIS

In this section, the dam alternation period with respect to modal analysis and by changing the reservoir water level has been discussed. That’s due to changes in the ratio of water behind the dam to dam height given in Table 3.

Table 3. Vibration Periods of the investigated models

Period / Water level	**T_1 (sec.)**	**T_2 (sec.)**	**T_3 (sec.)**
0	1.765	1.025	0.823
0.2	1.911	1.180	0.925
0.4	2.196	1.220	1.058
0.6	2.586	1.458	1.125
0.8	2.635	1.582	1.136
1.0	2.725	1.628	1.382

Based on the materials used in the earth dam, like other structures, the dam has several vibration mode shapes. These periods will be extractable according to the frequency of the main dam modes. Obviously, these periods do not have any time or spatial dependence on the shape and type of loadings. Depending on the type, dimensions, size, and height of the dam (structural features), the deformation in the separate vibrational states of a structure (earth dam) is investigated. Based on the vibrations, the period values of the structure (earth dam) were extracted. In the table below the numbers have been obtained for the dominant vibration modes represented by T_1, T_2, T_3.

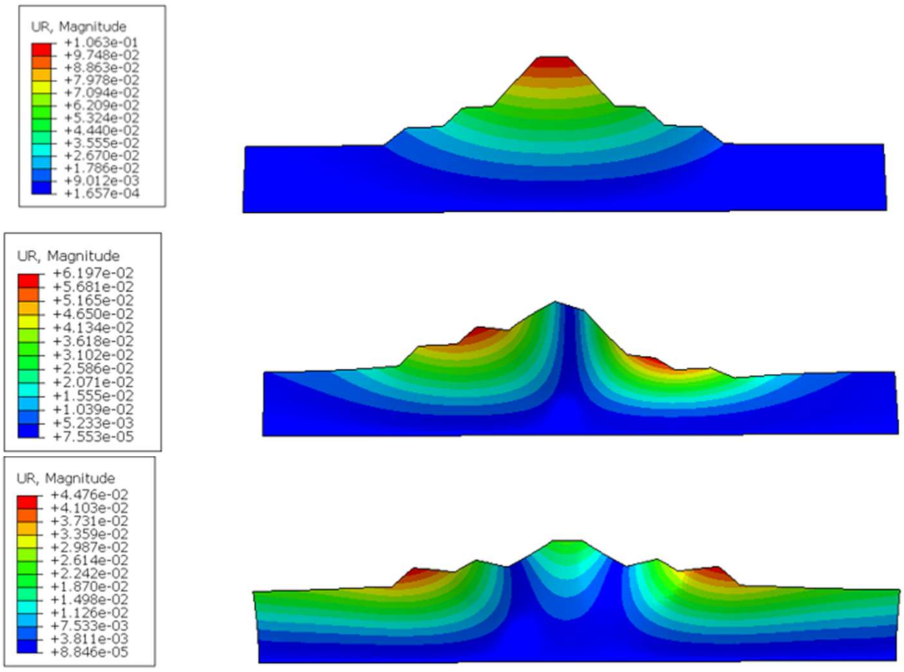

Fig.6. Mode shapes (1, 2 and 3) (Hw/Hd=0)

In recent years, modal analysis has been considered as a tool to determine and improve the dynamic properties of structures. The earth dam movement is a combination of the magnitude of displacement and the displacement amplitude coefficient of that dam obtained from the modal analysis. The analysis results carried out for the case of the empty reservoir state (Hw=0) are shown in Figure 6.

6. TIME HISTORY ANALYSIS

Dynamic analysis of time history predicts the force requirements and shifting location (failure) of each member of structural systems with sufficient accuracy. Therefore, this method can be considered as a suitable method for the seismic evaluation of structures and infrastructure. This subject includes the exposure of a structural model (earth dam) under one or more earthquake records. Each of which is scaled to different levels of earthquake intensity. Ultimately, to create one or more structural response curves results an earthquake intensity level. According to the results of FE analyses and determination of the desired parameters in relation to the time parameter, time history graphs based on displacement parameter in the time of record applied to the earth dam have been extracted. In the next section, the extracted results have been given and discussed. in the time history graphs extracted, it has been tried to choose between accelerograms and earthquake records which have had the most critical influence on the investigated model. This study has aimed to investigate the maximum effects of earthquake records, both near- and far-fields on the considered model.

7. STRESS CHANGES

After analyzing the models, the results showed that increasing the height of the water behind the dam leads to increasing the hydrodynamic pressures on the structure and the magnitude of stress on the dam body. The maximum stress was observed in the dam crest.

The nature of the tensile, compressive, and shear stresses was determined in terms of the critical points and the critical values of stress with respect to the software outputs related to the values presented, and the comparison with the allowable values, according to the behavioral criteria introduced to the software with respect to the magnitude of bearing and the stability of the earth dam is determined.

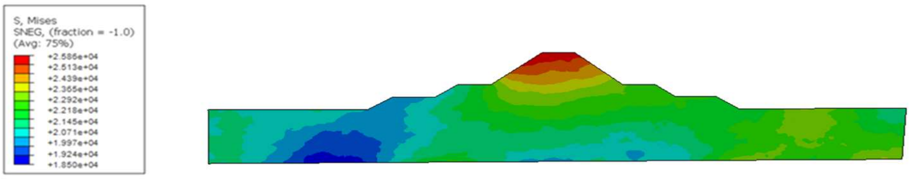

Fig.7. Stress change presentation (Case Hw = 40%), Parachute Earthquake

8. EFFECT OF WATER LEVEL ON SEISMIC BEHAVIOUR

Initially, the changes of stress and displacement of Sumbar earth dam, under near-field earthquakes by changing the ratio of water behind the dam to dam height equal to 0.0, 0.2, 0.4, 0.6, 0.8, and 1.0 has been done. According to the presented results, when the ratio of water behind the dam to the height of the dam is between 0.4 and 0.6, the stress changes on the dam body are negligible. On average, the most optimal control mode of seismic behavior for the ratio of water behind the dam to the dam height is between 0.4 and 0.6. Although, in some other locations, there are minor stress variations such as when the ratio of water height to dam height changes between 0.6 and 1. However, points 0.4 and 0.6 apply milestones for stress changes.

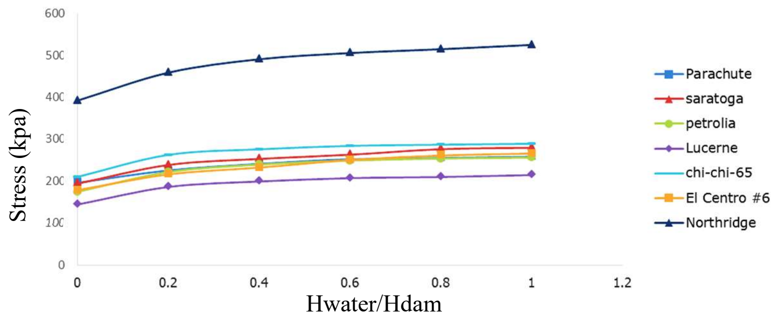

Fig.8. Sumbar dam stress changes under near-field earthquakes

According to Fig. 8, the results show that the Sumbar dam under the Northridge earthquake in the near-field region is completely failed. The dam, as it is observed, under Parachute, Saratoga, Chi-Chi, Petrolia, and El Centro earthquakes due to the change in reservoir water height to dam height ratio, have been failed after 0.4. The Sumbar Dam, under the Lucerne earthquake, remains quite stable and secure for all levels of water behind the dam.

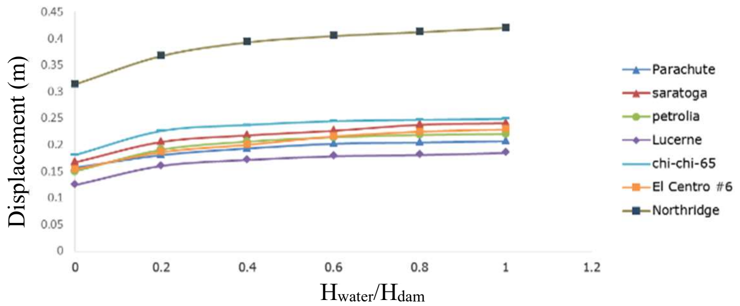

Fig.9.Sumbar dam displacement under near-field earthquakes

According to Fig. 9, the results show that Sumbar dam, under the Northridge earthquake has experienced the maximum displacement. Also, the slope of the displacement on average has the maximum magnitude with a change in the ratio of water height to dam height, from 0 to 0.2. And then, respectively, the average displacements for El Centro, Petrolia, Parachute, Saratoga and Chi-Chi earthquakes have been increased.

Results of far-field earthquakes on the investigated model are as well presented in Figs. (10-11). According to the results, when the ratio of water behind the dam to the height of the dam is between 0.4 and 0.6, the stress changes on the dam body are negligible. On average, the optimal seismic behavior control for the ratio of water behind the dam to dam height is between 0.4 and 0.6. Although in some other locations, there have been minor changes in stress, such as when the ratio of water height to dam height changes between 0.6 and 1.

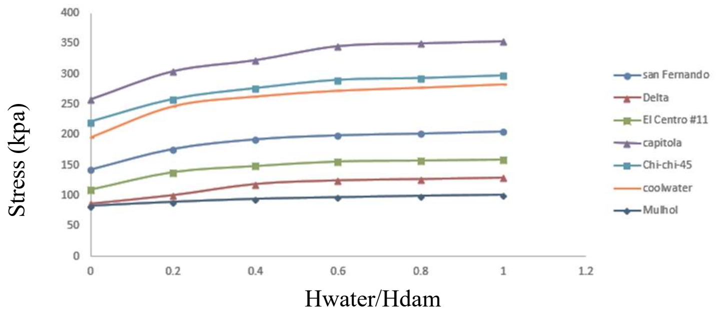

Fig.10.Sumbar dam stress under far-field earthquakes

According to Fig.10, the results show that the Sumbar Dam under the Capitola Far-field earthquake is completely failed, and under the Coolwater and Chi-Chi earthquakes due to the change of water level has been failed after the 0.4 water level.

The El Centro, San Fernando, Mulhol, and Delta earthquakes did not cause any failure on the Sumbar earth dam during its operation, and the dam remains completely stable and safe.

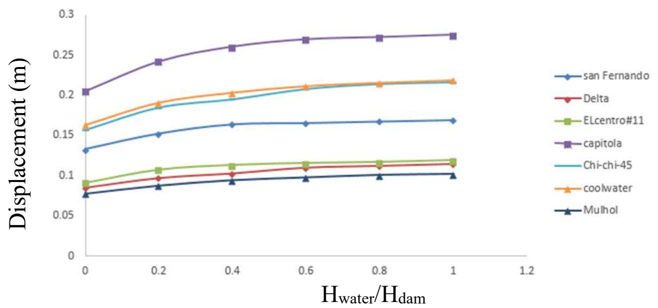

Fig.11.Sumbar dam displacement under far-field earthquakes

Following the results presented in Fig. 14, it can be noted that Sumbar dam, under the Capitola earthquake, has the highest displacement. Also, the slope of displacement changes is, on average, the highest in the ratio of water height to dam height, from 0 to 0.2. The Mulhol earthquake has the lowest displacement on the Sumbar dam compared to other earthquakes.

In summary, Figures 12 and 13 have been depicted to compare the average results of near-field and far-field earthquakes. The average changes of stress and displacement values in the Sumbar earth dam under near- and far-field earthquakes are presented below.

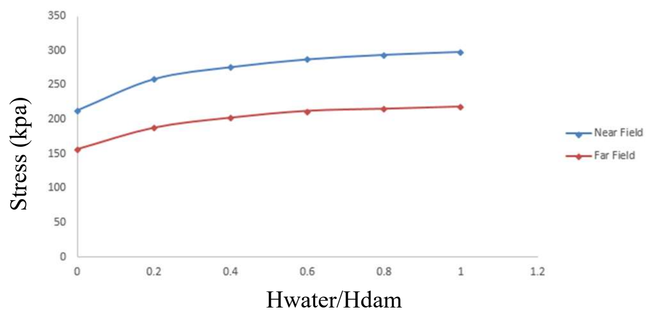

Fig.12.Sumbar dam average stress changes under near-field and far-field earthquakes

As can be observed, the magnitude of stress and impact of near-field earthquakes on Sumbar dam is more than the magnitude of stress and impact caused by far-field earthquakes, on this dam. Also, the slope of the stress changes, on average, has the maximum rate by changing the ratio of water height to dam height, from

0 to 0.2. If the numerical average of the stress is defined as an indicator, it can be concluded that the near-field earthquakes will clearly produce greater tension and less safety in the dam stability domain than the far-field earthquake.

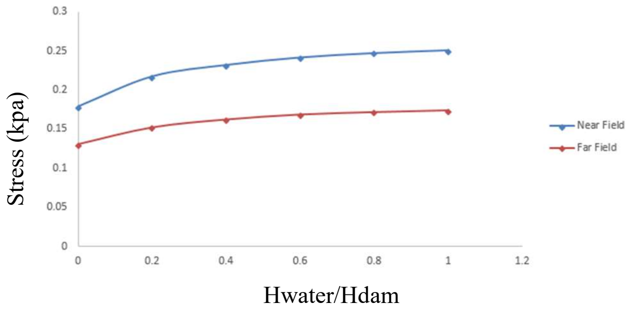

Fig.13.Sumbar dam average stress changes under near-field and far-field earthquakes

In the case of the Sumbar dam displacements, a similar result can be inferred from the situation of stresses, such that the magnitude of displacement of Sumbar Dam due to the excitation and impact of the near-field earthquakes is more than that of far-field earthquakes. Also, the slope of the displacement changes has, on average, the maximum state by changing the ratio of water height to dam height from 0 to 0.2.

9. CONCLUSIONS

The purpose of this study has been to investigate the seismic behavior of an earth dam with different levels of reservoir water under near- and far-field earthquakes. For this purpose, the change of water ratio behind the dam to dam height is considered as an indicator that can be used to introduce parameters affecting the seismic response of an earth dam. In this study, by changing the ratio of water behind the dam to the height of Sumbar dam equal to 0,0.2,0.4,0.6,0.8,1 this action has been taken. The FE simulation and analysis has led to the following conclusions:

- The magnitude of stress and impact of near-field earthquakes on Sumbar dam has been more than the magnitude of stress and impact caused by the far-field earthquakes, on this dam. Concerning the displacements of the Sumbar dam, a similar result can be inferred.
- The Sumbar Dam, under the Northridge near-field earthquake, has been failed.
- The Sumbar Dam has been completely failed under the Capitola Far-field earthquake.

- For other earthquakes, both in near- and far-field regions, the failures started to happen after 0.4 water level.
- For the Sumbar dam, the maximum stress among all near-field earthquakes has been equal to 525.67 (kPa) and the maximum stress has been equal to 354.53 (kPa).
- For the Sumbar dam, the maximum displacement among all near-field earthquakes was equal to 0.401 (m) and the maximum displacement was equal to 0.292 (m).

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