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Assessment of Static and Dynamic Behaviour of Emarat Earth Dam by Finite Difference Method

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ABSTRACT: Behaviour of earth dams during the construction, at the end of construction, and during the first dewatering is very important and it is necessary to ensure the safety of the dam in these three stages. In recent years, a number of different approaches have been developed to solve the geotechnical problems including static and dynamic analysis of earth dams. Emarat dam is an earthen dam with a clay core on the Darehrood River, one of the branches Aras river constructed at a distance of 100 km from the Meshkinshar city. In this study, using FLAC2D software and the finite difference method, the strength characteristics of the body and foundation materials of this earth dam have been identified and the static and dynamic behaviour of Emarat dam during the construction and inundation has been investigated. Regarding to achieved analysis it can be declared that Emarat earth dam has been statically stable during the critical process of ending of construction, dewatering stage and after dewatering stage. Considering to input earthquake which its frequency is close to Emarat earth dam frequency, it is dynamically stable.

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INTRODUCTION

Considering extensive advances in civil engineering, the construction of different types of dams such as earth dams for drinking water supply, agriculture and industry is very important all around the world, and it is a common tasks; furthermore, the design, construction and recognition of these structures in different stages is also essential. With the advancement of science and its application in the construction of major projects, such as dams, the construction and installation of instrumentation for better understanding and prediction of dam's behaviour is inevitable. This issue has grown considerably in recent years (Rahimi, 2004). So these structures are properly protected and considering its diversity, it will helpful in prediction of the correct behaviour of materials used in the dam's body. High cost of the construction of dams and severity of the consequences of their instability and considering the increased safety factor in the project will increase the costs in ascending order, therefore guarantee of the stability of the dam is essential in all stages of design, implementation and operation. Considering the extensive applications of earth dams in comparison with the other types of dams in a high seismicity country such as Iran, seismic safety assessment of these dams is very important. Analysis and design of earth and/or rock fill dams against earthquakes are generally performed with quasi-static and dynamic methods. Quasi-static method, however, has a simple assumptions and it is easy to use, provides dam safety, but it can sometimes lead to unsafe and uneconomical results. Dynamic analysis method is mainly based on the stress and displacement analysis and it is usually performed with the help of numerical methods (finite element or finite difference). The present study has been done using FLAC2D software according to nonlinear dynamic analysis and with regard to the actual behavior of the materials and earthquake loads provides a better understanding of the safety of the structure under different earthquakes. Simple elasto-plastic behavioural model has been applied based on Mohr-Coulomb criteria in order to express the relationship between stress-strain of the soil and Rayleigh damping theory have been used for increasing hysteretic damping and compensation of deficiencies in hysteretic damping the analysis. Outputs of dynamic analysis includes acceleration due to the gravity at the crest and bottom of the dam. Estimates of seismic safety has been done by plotting the maximum shear stress and maximum displacement at the crest. In recent years there are many studies and useful experiences about the behaviour of earth dams. Nowadays, with the development of computer, the use of numerical methods in the analysis and design of dams against earthquakes has been more than the past. On the other hand, other methods such as quasi-static method, which are based on the limit equilibrium analysis, are still widely used because of

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simplicity. Especially they ultimately provide a safety factor against shear failure. Along with all the advantages of this method, in the earth dams which there is the possibility of increasing the pore water pressure, quasi-static method is not able to consider this factor in sustainability. San Fernando and Sheffield dam failures, which were designed based on quasi-static method, confirms this point that this method is not sufficient for design. Some researchers showed that by using dynamic analysis with finite element or finite difference methods, one can better predict dam's behaviour during the earthquake that led to more appropriate design of the structure. Furthermore, with the help of this analysis, one can quantitatively show the possible failure of structures during the earthquakes. While in the quasi-static method using the extreme analysis, the stability of structures under periodic motion of the earthquake is checked only by applying a coefficient of earthquake and does not provide an understanding of failure during the earthquakes. So, considering the dam's behaviour during an earthquake, a more appropriate plan to stabilize can be presented by using numerical methods. In the recent decades, the extensive studies have been done on seismic behaviour of dams. Abdul Ghaffar and Scott (1979) investigated the effect of "San Fernando" earthquake on the "Santa Felicia" earth dam and the showed the natural frequency and the shear wave velocity in the materials and the relative contribution of the relative contribution of different vibration modes and compared this frequency with the natural frequencies obtained from shear beam theory. Prevost et al. (1985) used "DYNA Flow" software to investigate two- and three-dimensional responses of "Santa Felicia" dam against two different earthquakes and compared the results with the recorded data. For this analysis, they used multi-level theory of plasticity with full kinematic hardening. In this calculation, the effect of third dimension on the dynamic response of dam, especially on a permanent deformations was shown. They also examined and evaluated the capability of two-dimensional analysis in order to calculate the dynamic response of dam, especially on a permanent deformation. Abdel-Ghaffar and Elgamal (1987) used an analytical-numerical method for two- and three-dimensional nonlinear dynamic analysis of heterogeneous earth dams and applied Galerkin relations for equations of motion. For modelling the behaviour of materials, they used the similar assumption to developmental plasticity idea of Prevost and compared the results of "Santa Felicia" dam with the results of Abdel-Ghaffar and Elgamal. Mahin Roosta (2007) studied the dynamic response of Alborz Dam by comparing linear and non-linear methods and concluded that the magnification of acceleration in nonlinear analysis is less than linear analysis. Fatemi and Kazemzadeh (2000) performed two-dimensional dynamic analysis of Mamlou earth dam and by examining the displacement created in the dam, they concluded that these displacements is in the allowable limit of the dam and are less than one percent of the dam height.

In this research, the authors has tried to predict quantitatively the dam safety using FLAC2D software and according to nonlinear dynamic analysis and the use of appropriate safety indicators. In Greece, Gikas and Sakellariou (2008) studied the subsidence of 30-years Mornos earth dam using the finite element method and measured deformations and control of geodetic. Experience in design and analysis of this project showed that the combination of finite element method with the results of actual measurements is a suitable approach to examine or calibrate the geometric changes of the modelling studies. Zhu et al. (2011) conducted a study in China on static analysis of Shuibuya dam. They by using a combination of the finite element method and hybrid genetic algorithm to re-analysis of the dam. Comparison of actual data with regression analysis showed that there is a good agreement between observed and calculated data. The overall results indicated that the dam was stable. Farivar (2005) evaluated the behaviour of the Tabarakabad dam during the construction and his results showed that the Tabarakabad dam has shown a good behavior in terms of pore water pressure and the subsidence. MirGhasemi et al. (2003) assessed the instrumentation system of Lar and Panzdah Khordad dams. Barzgar et al. (2010) evaluated the static behaviuor of Alborz rockfill dam and stated that by increasing the embankment level, the subsidence of various parts of the dam will be significant. In this study, using FLAC2D software and the finite difference method, and by applying an appropriate behavioural method for soil of foundation and body of the dam, the static and dynamic behaviour of Emarat dam during the construction and inundation has been investigated.

MATERIAL AND METHODS

Introduction of Software and solving the problem

Due to the growing advances in Geotechnical engineering softwares, selection of a suitable program needs to pay attention to such issues as modelling methods, characteristics of the used materials in model, an appropriate behavioural model for materials, various methods such as finite element analysis or finite difference. FLAC2D Software using the finite difference method has the capability of modelling the rocky and soil environments at different material modes, such as elastic and plastic behaviours with the help of different types of behavioural models or different types of defined models. This software is used to evaluate the behaviour of different stages. The default behavioural model known as Mohr-Coulomb is more common among the Geotechnical engineers; therefore, in this study, this model has been used. So, in order to investigate the behaviour of Emarat rockfill dam during the construction and inundation, the

FLAC2D software has been used. Different parts of the dam in a section with the highest elevation and with full details was taken and then modelled. Based on the available documents on the construction of the dam, embankment elevation graph was plotted vs. time for all materials of the dam. Emarat earth dam with 90 m height has been built in a dam in the river valley with a gentle sidewall slope. This dam has been constructed with 12 inhomogeneous layers with an equal thickness. According to the diagram of executive process of clay core and the upstream and downstream shells is coordinated. The foundation thickness is approximately considered equal to 80 m. The bottom and boundary nodes of the foundation were constrained in x and y directions and in x direction, respectively. In order to achieve more precise results, reservoir modeling has been done as step by step and in 12 layers. For modelling the dam inundation, the time for body and dam foundation seepage and deformation resulting from consolidation, given the permeability of shell and foundation materials and filter, is so different that it can be assumed that these processes slightly affect each other. Therefore, flow calculations are separately done until reaching the steady seepage, and then the effects of change in the pore water pressure and water weight in the reservoir in the dam deformation along with the analysis in mechanical calculations are applied. To study the behavior of the Emarat earth dam during construction and inundation, it is supposed to the reservoir inundation is performed after the dam construction.

In building and networking the environment, the size of zones should be large enough to minimize the effect of boundaries on the behavior of the model; meanwhile, the permittivity criteria of waves through the environment affecting the networking and the model geometry should be considered. In the finite element or finite difference methods a number of preliminary computations is necessary in order to determine the optimum size of components or area of computation. To ensure the proper wave transmissions, the size of specific area (the largest size) should be smaller than one-tenth of wavelengths induced by the highest frequency waves input into the system. It can be assumed that the following conditions must be met for permittivity of waves:

$$f = \frac{C}{10\Delta l}$$

in which, f is the maximum permittivity frequency of the system and C is the minimum speed of the wave. Modelling is done by a Layer method. Thus, the entire body of the dam is considered in 12 layers and each layer will be analyzed in a separate step. In other words, each layer is placed on the previous layer and new mechanical analysis is performed for the entire problem. After static analysis, mechanical pressure of the water on upstream boundaries is applied and additional static analysis will be performed. The results of this analysis with the dam immediately after the inundation. Because it is assumed that EMARAT earth dam has experienced the discussed earthquake after reaching steady-state of seepage, it is necessary to determine the static conditions in the reservoir after reaching this state. For supporting conditions, like static analysis, the fixed or elastic boundaries can be placed in the proper distance from the desired range. In the dynamic problems, such boundary conditions cause wave reflection released into the model and prevent the dispersion of the necessary energy. Because the damping material absorbs wave energy reflected away from the boundaries, the use of larger models decreases this problem. But larger models can increase the volume of calculations. Appropriate approach is the usage of Gentle borders (absorbent) or laminar (attractive) boundaries. The model of structures is shown in Figure 1 based on the discussed issues.

Behavioral model and properties of the material

Mohr-Coulomb Elastic-Plastic behavioral pattern for body material of the dam and its foundation has been considered in static analysis. Parameters related to the used materials are shown in Table 1.

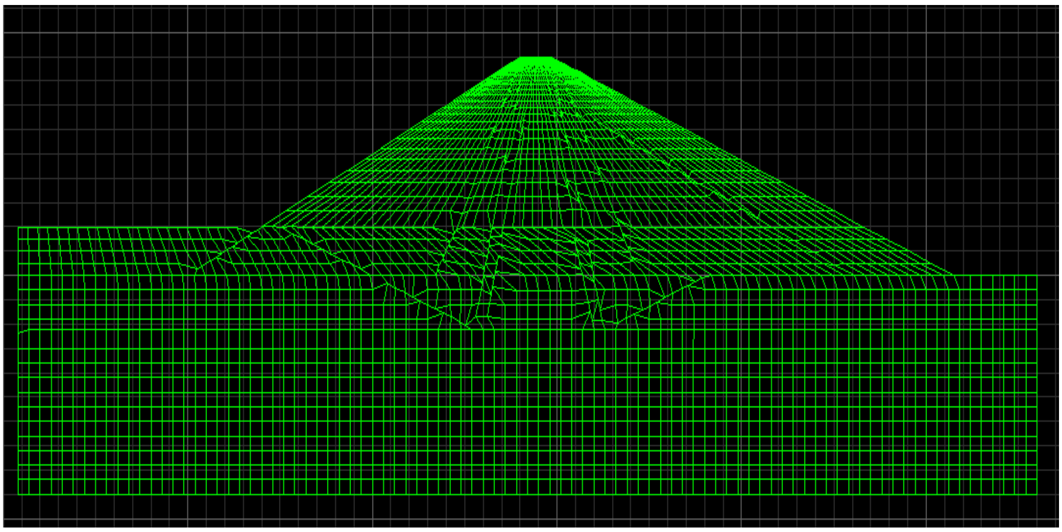

Figure 1. Finite Difference Network for EMARAT earth dam

Table 1. Parameters related to the used materials in numerical analysis (Bandab Consulting Engineers, 2004)

Material parameters	Dry density (t/m^3)	Saturated specific weight (t/m^3)	Angle of repose (degree)	Cohesion (t/m^2)	Modulus of elasticity (t/m^2)	Poisson coefficient	Porosity	Permeability coefficient (m/day) k_x	Permeability coefficient (m/day) K_y
Core	2.03	2.17	20	10	5000	0.35	0.35	$8.64x10^{-4}$	$6.91x10^{-4}$
Filter and Drainage	2.15	2.20	30	0	10000	0.25	0.2	86	86
Transition	2.18	2.33	36	0	20000	0.25	0.15	18	9
Alluvial surface	2.18	2.33	38	0	25000	0.25	0.15	18	9
Rock fill surface	2.33	2.41	45	0	50000	0.25	0.15	100	100
Alluvium	-	2.1	28	0	15000	0.25	0.2	0.86	0.43
Bed stone	-	2.3	30	5	250000	0.15	-	0.25	0.25

RESULTS AND DISCUSSIONS

Final step of the dam construction (before inundation)

In the step by step construction, the dam has been modeled as layered and after implementation of each layer, horizontal and vertical displacements of the nodes over the layer is zero. In fact, this displacement is compensation of embankment due to the subsidence of that layer. Vertical displacement in each horizontal alignment occurs at the central axis of the dam and decreases towards upstream and downstream faces of the dam. Maximum vertical displacement at this stage is 52 cm which is equal to 0.57 percent of the total height of the dam from the alluvial bed (Figure 3). Compensation for the reduction in dam height should be considered in order to ensure sufficient materials. Horizontal displacement along the central axis of the dam is zero and increases towards the upstream and downstream faces of dam, which indicates the tendency of the dam to be opened. Maximum horizontal displacement is also about 5 cm which is a small value in comparison with the width of the dam (Figure 4). Shear stress on the central axis of the dam is approximately zero and increases from the high to low levels (maximum value is 4.25×10^5). Maximum vertical effective stress is also equal to 3.3×10^6 for the dam body. At this stage, the maximum shear strain is equal to 1.64 percent and according to the criterion for dam failure (15 percent), the dam is stable in this respect. The safety factor for the upstream and downstream slopes is 1.65 and 1.63, respectively and according to the permissible values for the stability in no-earthquake (equal to 1.25) the dam is also stable in this respect. According to the analysis, just a few parts of figures has been shown.

After inundation

After completion of the step by step construction, inundation stage will start. At this stage, after flow calculations, a steady seepage occurs. Then the hydrostatic force in the dam is worked on the body of the dam and mechanical computation will continue. As it is evident, the hydrostatic force of the water in the reservoir is mainly worked on the core, due to the high permeability of the surface and existence of drainage; so, the maximum horizontal deformation in the core and downstream slope is 18 cm. The amount is not large in comparison with the width of the dam and it is stable in this respect. Maximum vertical deformation after inundation is equal to 65 cm. This amount is not so high in comparison with the free board of the dam (4 m). There is no instability in the water surface or overflow from the top of the crest after inundation. Maximum shear stress after inundation stage is about 5.8×10^5 pa which this amount is so high in comparison with the previous inundation (Figure 4).

Distribution of normal effective stress at the end of inundation from the dam is shown in Figure 5. Maximum value of the vertical effective stress is equal to 2.6×10^6 pa at the dam's body. In this case, the effective stress is reduced at the upstream slope that this is justified due to the principle of effective stress.

According to Figure 8, it can be seen that the maximum shear strain is equal to 1.85 percent which less than that of for non-failure criterion (15 percent). So, in the next step of inundation, the dam is also stable. In this case the safety factor for downstream slope is equal to 1.58 percent. Given that the allowable amount for the stability of a full reservoir is 1.5, dam is also stable in a full condition.

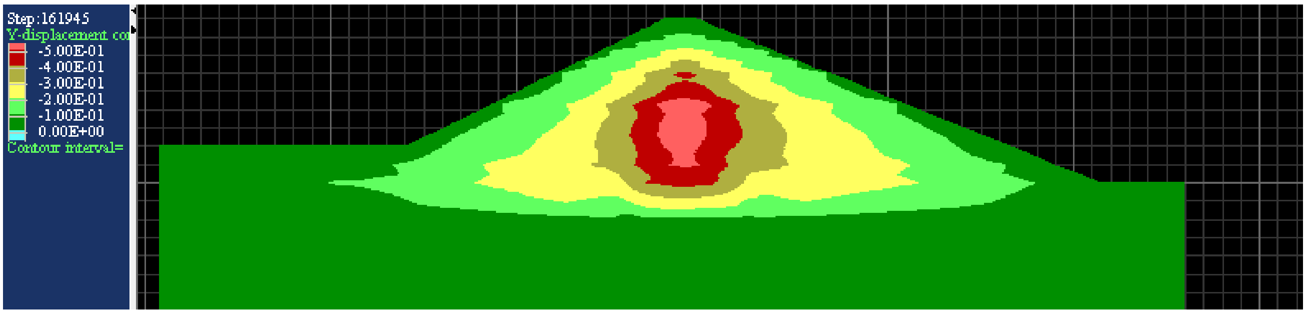

Figure 2. Vertical deformation after construction

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Figure 3. Horizontal deformation after construction

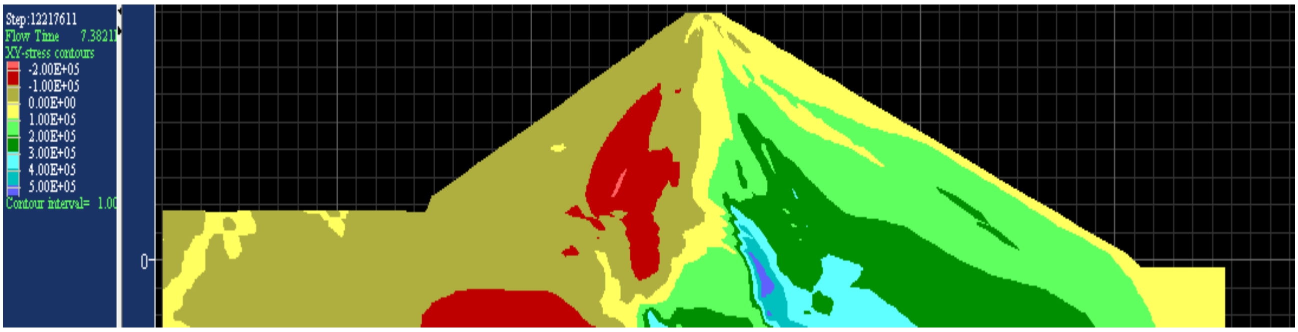

Figure 4. Distribution of shear stress on the dam after the inundation

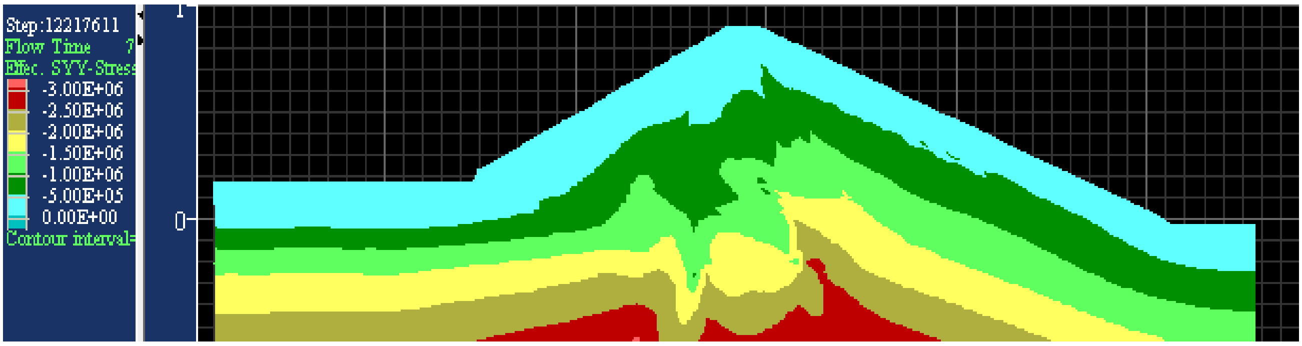

Figure 5. Vertical effective stress

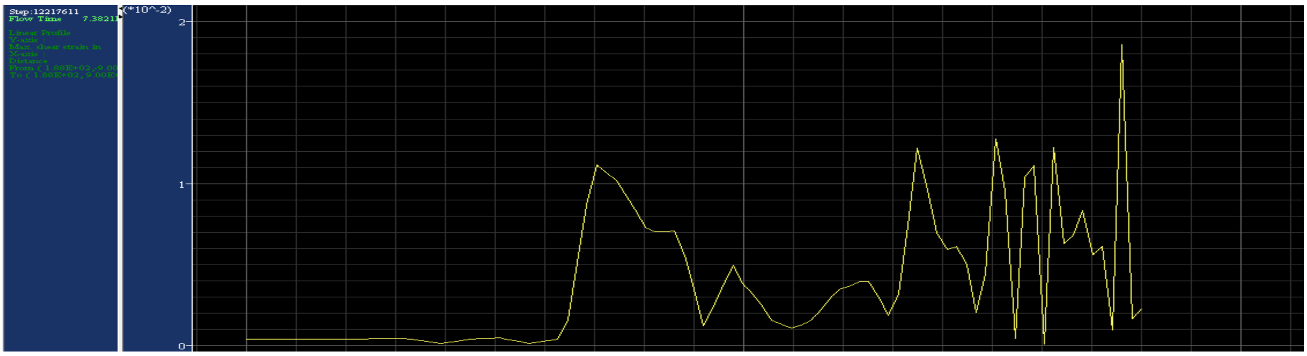

Figure 6. The maximum shear strain relative to the dam height

Record of earthquake

In order to perform the dynamic analysis of EMARAT dam, three records from earthquake accelerograms has been used. These earthquakes include Manjil earthquake, Sitak earthquake (took place in Armenia) and the Kobe earthquake. Earthquake accelerograms for Manjil has a maximum acceleration of 26.73 g and duration of 0.515 s.

In Figure 7, the earthquake accelerograms, velocity, and displacement of the earthquake have been shown. Earthquake accelerograms for Spitak earthquake has a maximum acceleration of 0.2 g and duration of 19.87 s. In Figure 8, the earthquake accelerograms, velocity, and displacement of the earthquake have been shown for this earthquake. For the Kobe earthquake, these values are respectively equal to 0.83 g and 23.97 s (Figure 9).

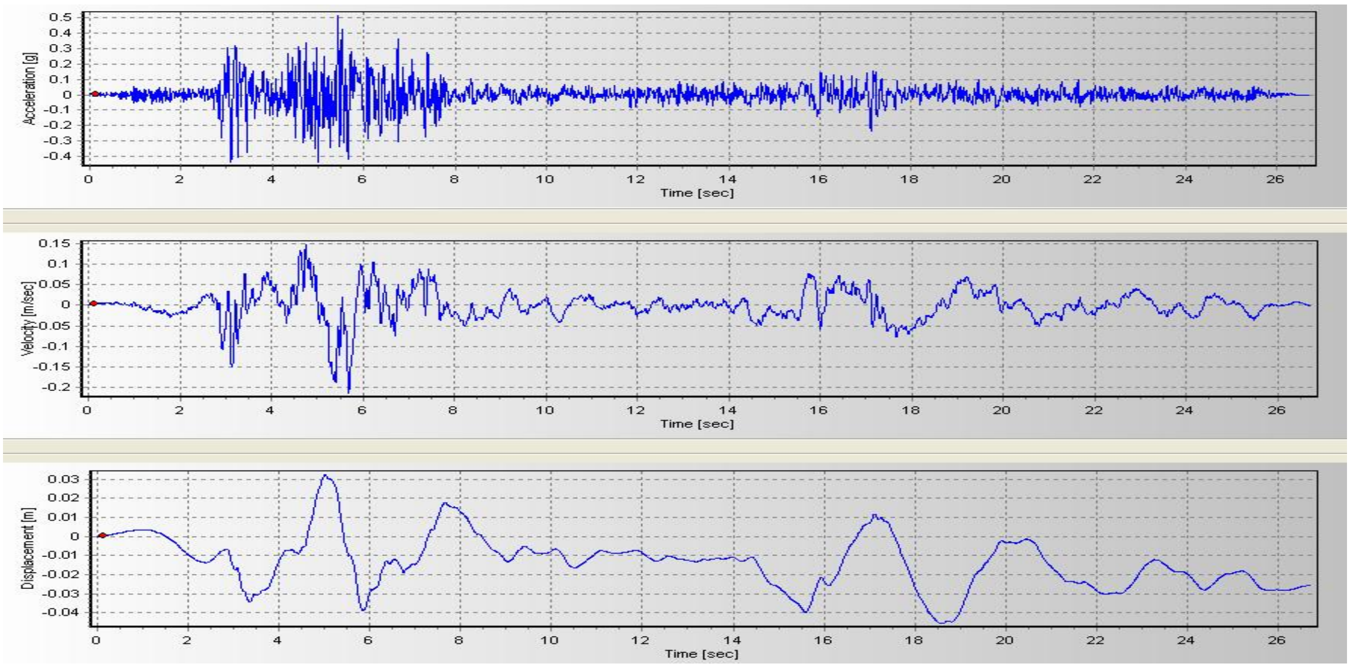

Figure 7. Earthquake accelerograms, velocity, and displacement of Manjil earthquake

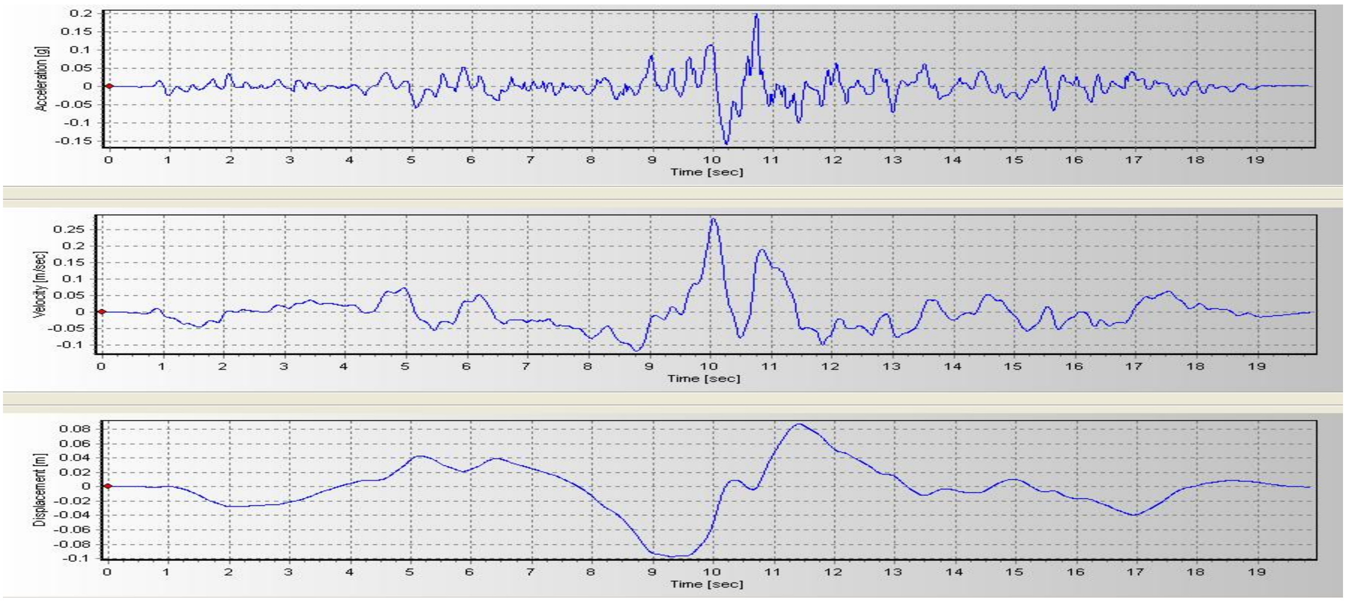

Figure 8. Earthquake accelerograms, velocity, and displacement of Spitak earthquake

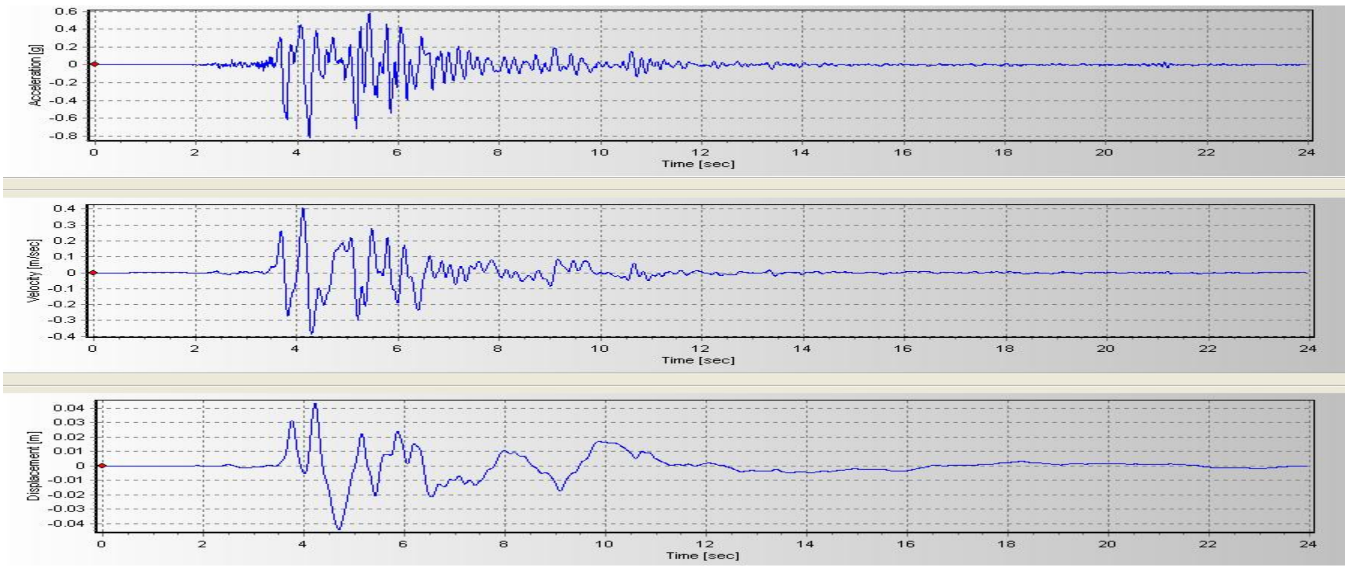

Figure 9. Earthquake accelerograms, velocity, and displacement of Kobe earthquake

Results of dynamic analysis

Horizontal acceleration at the crest of dam: History of horizontal accelerations at the crest for accelerogram of Manjil, Sitak, and Kobe are presented in Figures 10 to 12. As can be seen in Figure 10 for Manjil earthquake, the maximum response acceleration at the crest is 0.72 g, which is a little bit larger as compared with the maximum input acceleration of the earthquake. For Spitak earthquake (Figure 11), the maximum response acceleration at the crest is 0.42 g, which is larger in comparison with the maximum input acceleration. Kobe earthquake is much more destructive than the other earthquakes and has the maximum response acceleration of 1.4 g at the crest, which is more than the input acceleration due to the enlargement.

As can be seen, the maximum acceleration created at the crest for Kobe earthquake is more than Manjil earthquake and for Manjil earthquake is larger than Spitak earthquake. According to the maximum acceleration in the accelerograms, these three earthquakes are reasonable and acceptable.

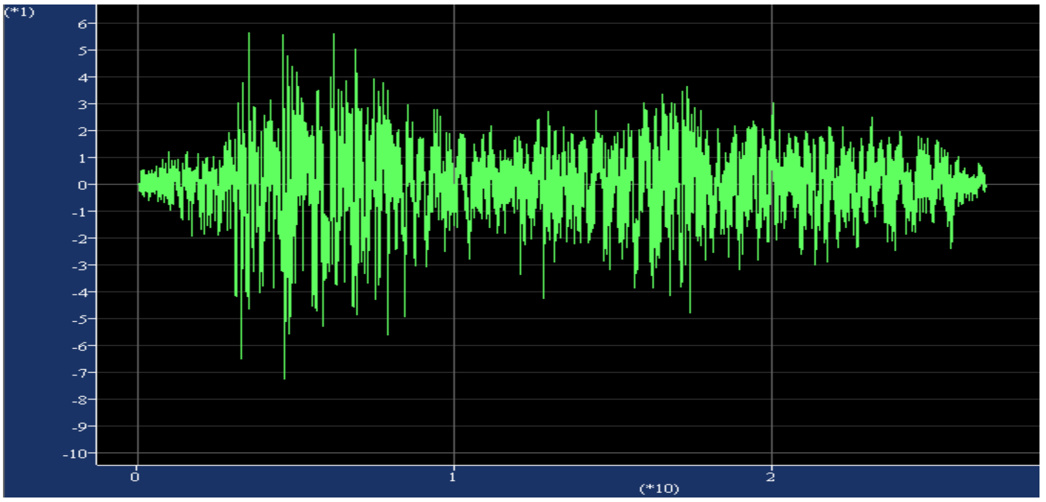

Figure 10. Historical diagram for response acceleration at the dam crest for Manjil earthquake.

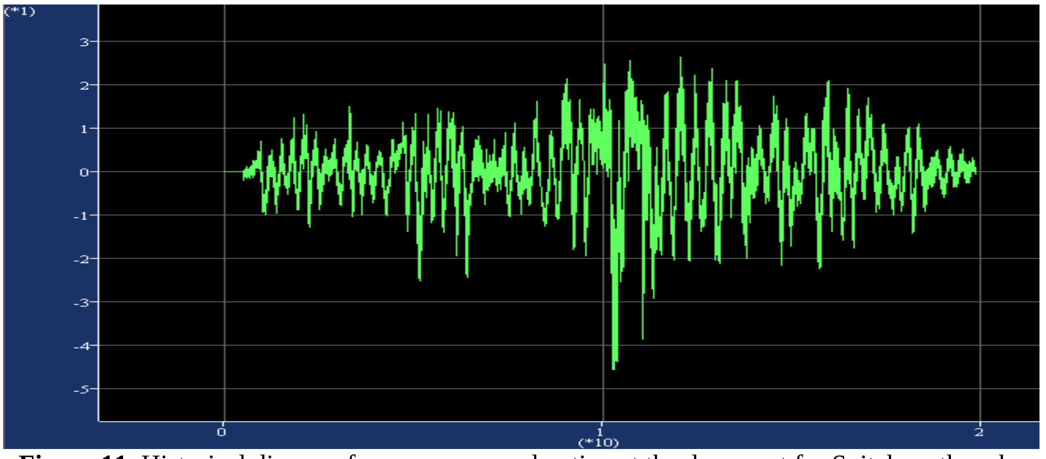

Figure 11. Historical diagram for response acceleration at the dam crest for Spitak earthquake

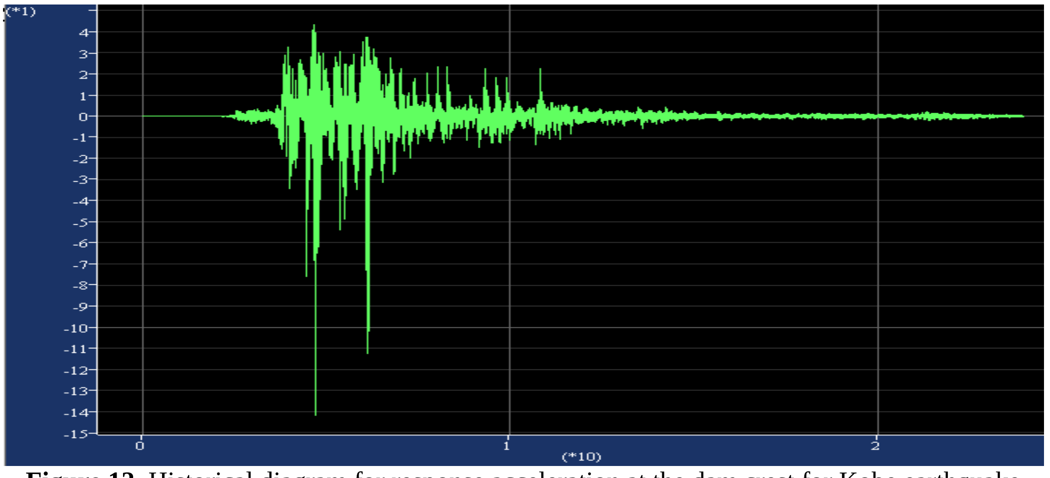

Figure 12. Historical diagram for response acceleration at the dam crest for Kobe earthquake

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The maximum horizontal and vertical displacements at the crest

According to the history of vertical displacement at the crest due to the Kobe earthquake, as can be seen in figure 13, the greatest vertical displacement at the dam crest due to this earthquake equals to 1.10 m. Given that the minimum free board of EMARAT earth dam is 4 m, the highest vertical displacement at the crest is less than the dam height, so the failure (overtopping) has not occurred and the dam is stable in this respect. The maximum horizontal displacement at the crest is equal to 0.4 m (Figure 14), which this value is a small value and does not cause instability in the dam. Maximum value of horizontal displacement has occurred in the downstream slope of the dam (1.09 m) and this amount is also small in comparison with the width of the dam. According to the historical diagram of vertical displacement at the crest of dam due to the Manjil earthquake (Figure 10), it can be seen that the maximum vertical displacement during the earthquake is equal to 0.59 m, and as compared to free board of the dam (4 m), it can be seen that the failure (overtopping) does not occur. The maximum horizontal displacement of dam's crest in this case is 0.26 m (Figure 11), that is a small amount in comparison with the dam width and as a result does not cause instability. The maximum horizontal displacement in the dam occurs at the downstream slope (0.73 m). This amount is insignificant as compared to the overall width of the dam, and the dam is stable. Also, as can be seen in Figure 12, maximum vertical displacement due to the Spitak earthquake is equal to 0.48 m, which is insignificant in comparison with the free board of the dam (4 m) and no failure (overtopping) occur due to this earthquake. As can be seen in the Figure 13, maximum horizontal displacement of dam crest due to the Spitak earthquake is 0.42 m, which is a small value as compared to the width of the dam and there is no instability in the dam. The maximum horizontal displacement in the dam due to the Spitak earthquake occur at the downstream slope (0.45 m). This amount is not a significant value in comparison with the width of the dam and does not affect instability due to this earthquake.

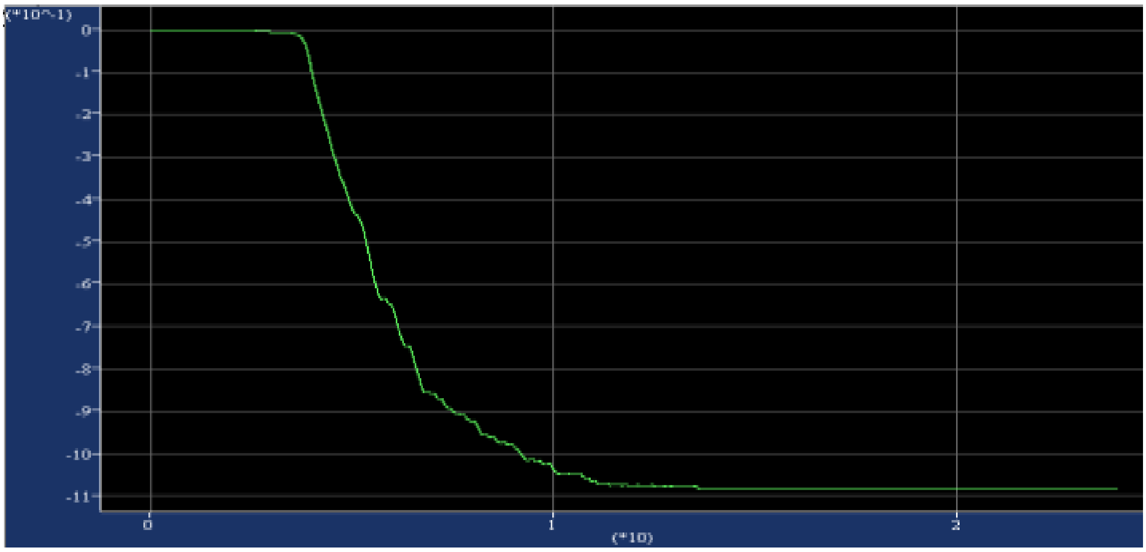

Figure 13. Historical diagram of vertical displacement at the dam crest due to Kobe earthquake

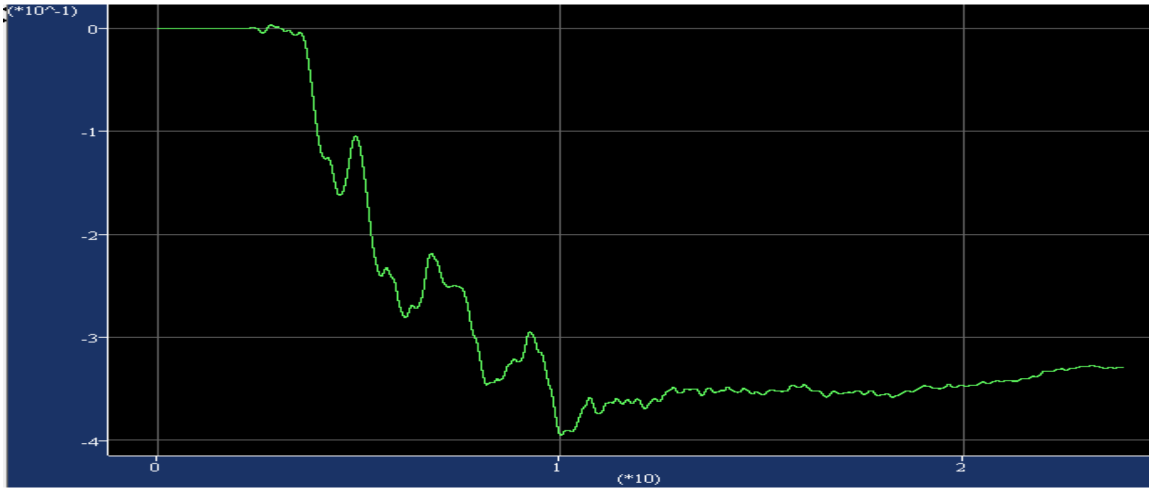

Figure 14. Historical diagram of horizontal displacement at the dam crest due to Kobe earthquake

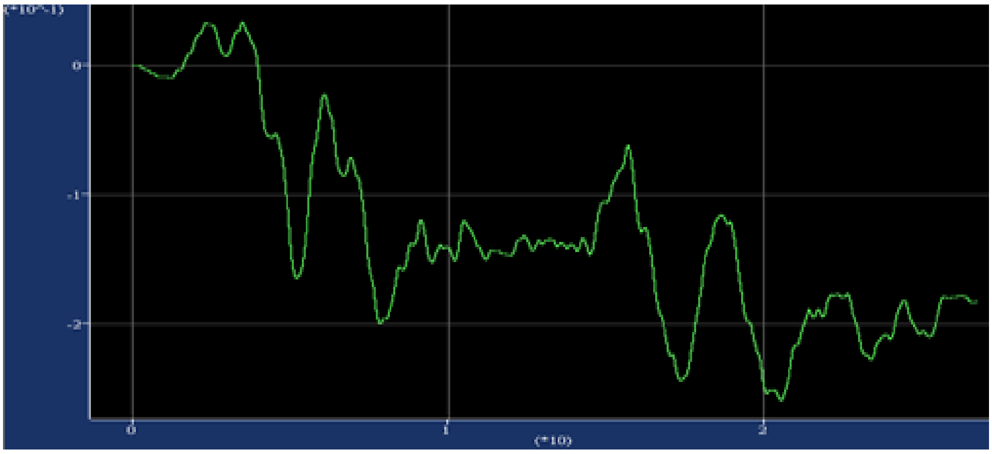

Figure 15. Historical diagram of vertical displacement at the dam crest due to Manjil earthquake

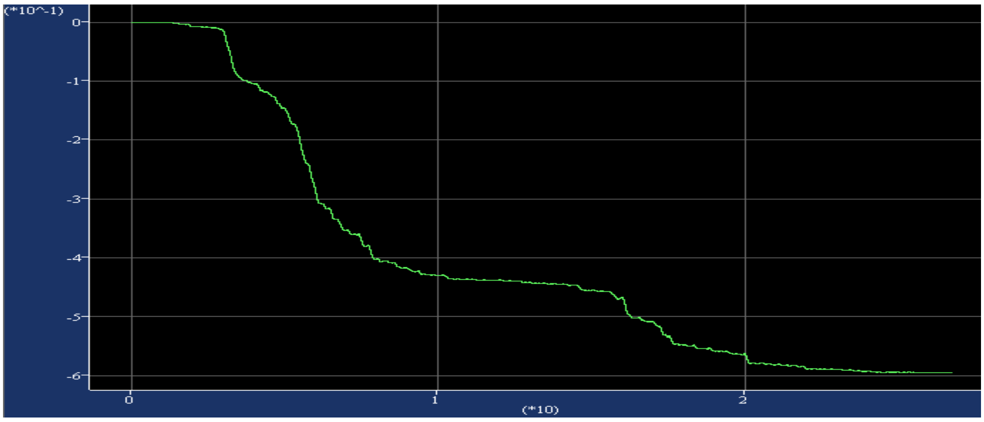

Figure 16. Historical diagram of horizontal displacement at the dam crest due to Manjil earthquake

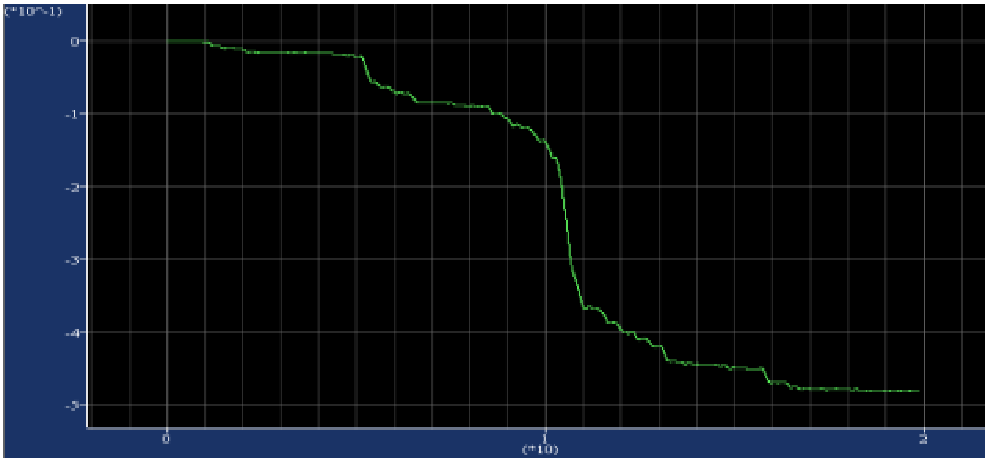

Figure 17. Historical diagram of vertical displacement at the dam crest due to Spitak earthquake

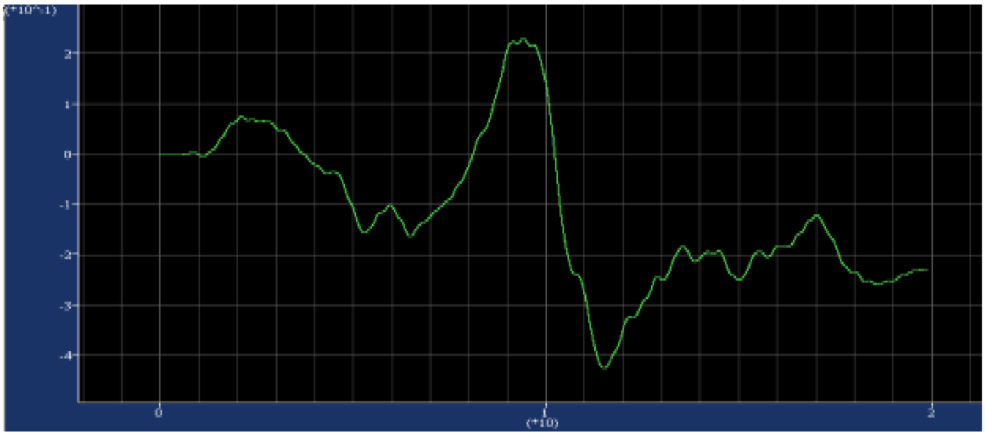

Figure 18. Historical diagram of horizontal displacement at the dam crest due to Spitak earthquake

The maximum shear strain at the dam

With investigating the shear strain generated at the dam's body from the rule to the crest due to the Kobe earthquake (Figure 19), maximum shear strain equals to 11 percent. Considering the criteria for failure is 15 percent, the dam is stable in this respect. According to the figure 20, it can be seen the maximum shear strain generated at the dam's body due to the Manjil earthquake equals to 7 percent, and given that criteria of shear failure is 15 percent, the dam is stable in this respect and there are vertical cracks at the dam's body. As can be seen in figure 20, it can be seen the maximum shear strain generated at the dam's body due to the Spitak earthquake equals to 3.3 percent, and this value is so small in comparison with criteria of shear failure, and the dam is stable in this respect and no vertical cracks be created.

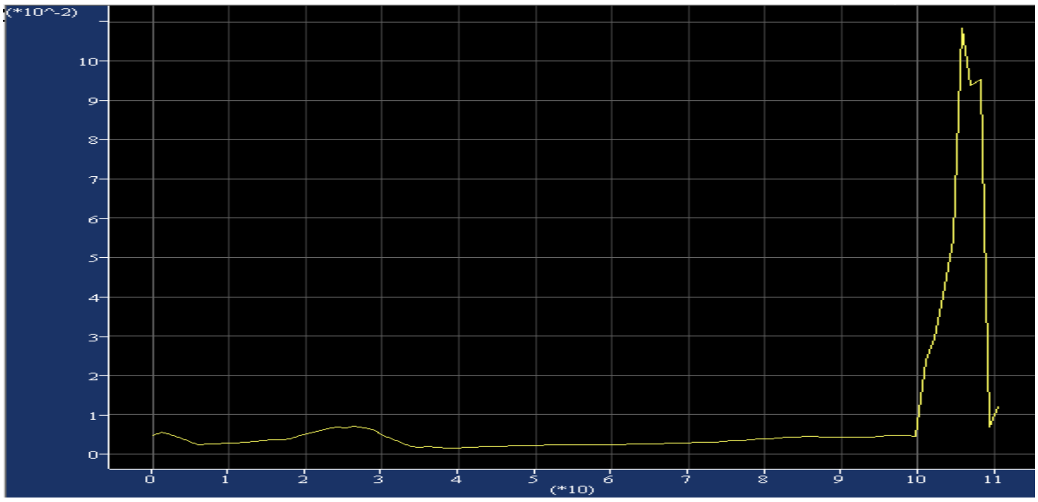

Figure 19. Diagram of shear strain in the dam due to Kobe earthquake

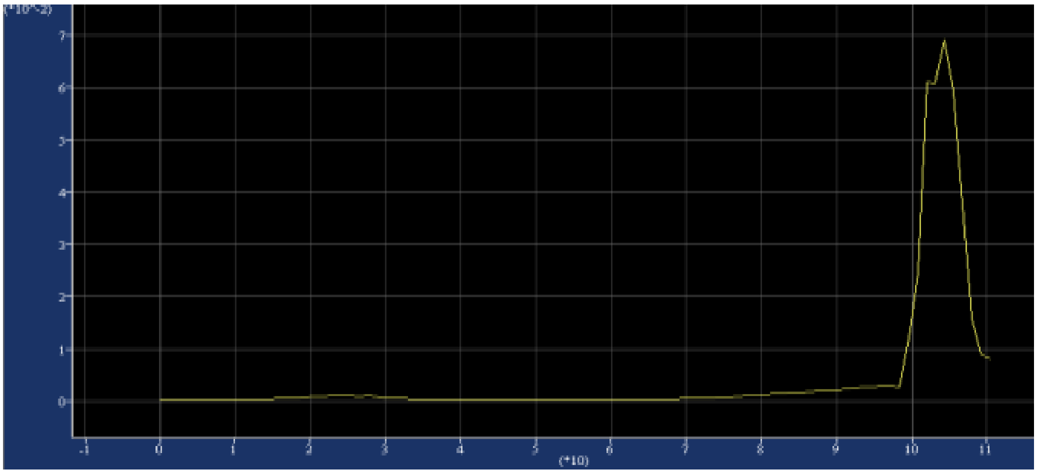

Figure 20. Diagram of shear strain in the dam due to Manjil earthquake

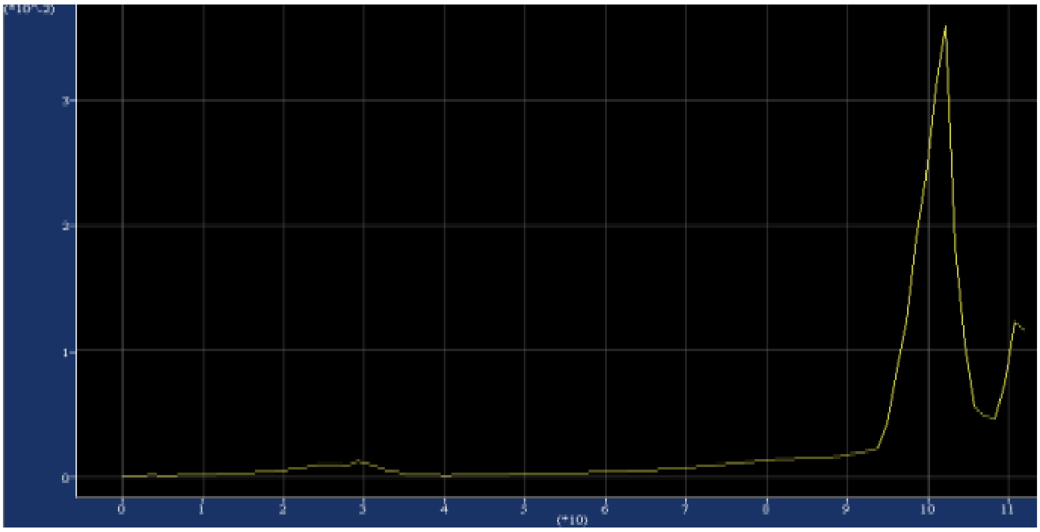

Figure 21. Diagram of shear strain in the dam due to Spitak earthquake

CONCLUSION

According to the analysis performed in this study, the following results can be achieved:

- Dewatering the dam will increase the horizontal and vertical deformations.
- Considering the EMARAT earth dam has been constructed as step by step method and as a result it has been modelled using as step by step method, the maximum normal stresses along the dam's body have been obtained.
- Vertical effective stress distribution at the end of the construction of the dam is symmetrical. While this stress is reduced after the inundation in the upstream skins.
- Overall, according to the results of stability analysis at the end of construction, before and after inundation and comparison of these results with the allowable values, it can be concluded that EMARAT dam has a reasonable performance and its stability is sufficient.

According to the dynamic analysis the following results can be achieved:

- The behaviour of dam in terms of acceleration response, and considering the maximum acceleration response for Spitak earthquake was more than Kobe earthquake, it has a logical, reasonable, and acceptable trend.
- Maximum vertical deformations created by the dam are 1.1, 0.59, and 0.48 m for Kobe, Manjil, and Spitak earthquakes, respectively, which according to the maximum input acceleration, these earthquakes have a logical trend. Given that the free board of EMARAT dam is about 4 m, therefore, this amount will meet to deformations obtained by the three earthquakes.
- Maximum horizontal deformations created by the dam are 1.09, 0.73, and 0.45 m for Kobe, Manjil, and Spitak earthquakes, respectively, which according to the maximum input acceleration, these earthquakes have a logical trend. Given that the width of different parts of the dam, these amounts will meet to horizontal deformations obtained by the three earthquakes.
- Maximum shear strains in the Emarat dam are 11, 7, and 3.3 percent for Kobe, Manjil, and Spitak earthquakes, respectively, which these values occur at the core and near the crest which according to the maximum input acceleration, these earthquakes have a logical trend and no vertical cracks be created.
- In total, dynamic analysis conducted on EMARAT dam due to these three earthquakes, indicates the adequacy of the design.

Competing interests

The authors declare that they have no competing interests.

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