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Original Paper

The Effect of Core Shape on the Seismic Behavior of Earth-fill Dams

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Abstract

The two-dimensional study of the seismic behavior during an earthquake and earthquake resistant designs of earth fill dams usually are studied by assuming plane-strain problems. For a given earthquake loading, the results of the dynamic analysis depend on many parameters of which the core shape contributes more. The present study is concerned analysis of the seismic response of earth dams affected by different core shapes. In addition to the material properties and the shape of the dam body, foundation and abutments, the core shapes can amplify or attenuate the input earthquake loading during seismic analysis of earth fill dams. This paper evaluated the influence of core shape on behavior of earth fill dams during earthquake. All sections are described using the simple and popular non associated Mohr-Coulomb criterion. Results reported in this paper represent 3D numerical parametric study of an earth fill dams subjected to earthquake loading and 3D effects on its seismic performance. Emphasis is put on the effects of the core shape on vertical stress, pore water pressure and settlements. Also, the arching ratio and the acceleration response are taken into account during analysis. The assumed 3D model is simulated in finite difference numerical code, FLAC3D. Results regarding the importance of the core shape on the seismic response of earth fill dams show that in different sections of dams by increasing the core slope, pore water pressure increases. On the other hand, dam's settlement is affected by the core shape. In fact, by increasing the core slope, the settlement decreases. Also, the core shape have little effect on vertical stress and arching.

Keywords: Seismic behavior, Earth fill dam, Core shape, Mohr-Coulomb, Flac3D.

1. Introduction

Dams are generally constructed in river valleys for water storage, power generation, and for flood control purposes [1]. The general philosophy in design of these dams has been to utilize locally available geologic materials. Earth fill dams are a preferred choice for sites with wide valleys and difficult foundation condition because of their flexibility. However, soil is a difficult engineering material because of its three-phase nature, diverse composition and our incomplete understanding of its behavior under all of the stress and boundary condition usually encountered in the field. Earthquake engineering of earth fill dams is somewhat in its formative states. Although a great deal has been learned and put to use in design and construction of newer dams, there exist in the field a large number of dams designed and built without the benefits of modern understanding of soil behavior and improved construction techniques. Earthquakes may affect earth dams in various ways. Seismic forces may be transmitted directly from the foundation to the dam [2].On the other hand, the behavior of earth fill dams, as one of the most important structures, under earthquake loading has attracted the attention of many researchers and dam designers. In the last decade, improvements in the different numerical methods have resulted in

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widespread use of these methods to study dynamic behavior of earth dams and using three dimensional models has revealed various aspects of dam response to seismic shaking [3]. It is essential the static analysis results need to be combined with the dynamic analysis results in order to estimate the response of an earth dams to an earthquake [2]. In addition, earth dams are characterized by two zones - an inner zone of earth or soil (core) and an outer zone of rock fill (shell) [4]. Since the core is one of the most important parts of the earth dam, its impact on the seismic assessment of the dams plays crucial role. Therefore, it seems to be a specific need to investigate and analyze the influence of the core characteristic, dynamic analyses and settlement of embankment during the earthquake. Despite the previous studies, the static and dynamic analysis of earth dams and the important factors affecting the seismic response of dams, the core shape of the dam has experienced less attention. Core shape due to the economic conditions, time, or available materials, in some cases may have detrimental effects such as dam failure. Dams' failure like other natural phenomena has attracted the attention of humans, because it is one of the factors that threaten their lives and their property. Due to the experience of the terrible dam failure during earthquake in many countries such as: Italy, Japan, Iran, Mexico and Yugoslavia in recent years, associations and institutions have formed for the practical and continuous study of dam break phenomena to provide ways to stabilize and prevent their hazards. In recent years, experts and engineers established several papers on landslide during an earthquake.

Methods for assessing the seismic behavior of earth dams during earthquakes have evolved steadily since the early twentieth century, when the first attempts at modeling the effects of seismic shaking on slopes were developed. These early efforts, based simply on adding an earthquake force to a static limit-equilibrium analysis, were formalized by Terzhagi (1950) and comprise what came to be known as pseudo-static analysis. Soon after, finite-element modeling, a type of stress-deformation analysis, was developed and eventually would be applied to slopes [5]. In these early years, however, this type of analysis was profoundly complex and computationally daunting.

Rajesh et al, 2014 have reported stability analysis carried out on 185 m high earth and rock fill dam with upstream slope of 1V:2.50H and downstream slope of 1V:1.80H. Thickness of the vertical core was varied from 1V:0.25H to 1V:2.65H and its effect on slope stability was analyzed under three critical conditions i.e. during and end of construction, steady state seepage and rapid draw down for both upstream and downstream slope of dam in static condition by Limit Equilibrium Method using SLIDE 5.0 software. They were observed from the analysis that by varying the thickness of vertical core of earth and rock fill dam, thinner core up to 1V:1.30H gives more stability and further increase in thickness of core tends to sharp decline in factor of safety both for upstream and downstream slope under different critical conditions [6].

Another research by Rajesh et al, 2015 has investigated the results of an analytical study undertaken to identify the zone within which the inclination of a thin upstream inclined core has no influence on the stability of upstream slope of earth and rock fill dams. A 180 m high earth and rock fill dam section, founded on strong base, having section and slopes similar to a high dam in the northern India was used as a base section for analysis. The critical core inclination with vertical was identified, beyond which the factor of safety of upstream slope of the dam was observed to undergo reduction. Stability analysis was carried out for two conditions, namely end-of-construction (EOC) and rapid-draw-down (RDD) for upstream slope with different parameters under static conditions. The study shows that a thin upstream inclined core does not influence the stability of upstream slope of earth and rock fill dams, if it is positioned such that its inclination varies from vertical to 1 V: 0.50 H. Its inclination is beyond 1 V: 0.75 H, a thin upstream inclined core causes reduction in the stability of upstream slope of earth and rock fill dams. In the intermediate cases, the magnitude of reduction of factor of safety as well as critical inclination of core is significantly influenced by relative strength of shell to core and the pore water pressure parameter [7].

Zhang and Zhang, 2013 studied dynamic triaxial test data of dam materials. Combining with construction of a high core rock fill dam, several key issues, such as dam seismic response, seismic slope stability, dam permanent deformation, filter layer anti-liquefaction, and dynamic strength of the core wall are analyzed using 3-D dynamic effective stress analysis method. Some useful conclusions and regularity are obtained in aspects of seismic response and anti-seismic properties. The analysis method and conclusions could be referred to the analogous engineering [8].

Tsai et al. presented the dynamic response of the Pao-Shan II Dam subjected to the Chi-Chi earthquake (ML=7.3) in Taiwan by using FLAC3D which elastic modulus of the dam is considered to vary with mean. Staged construction, seepage, static equilibrium and dynamic response are sequentially analyzed. Fourier power spectra are analyzed as the earth dams subjected to a sweep frequency dynamic loading. Influences of core dimensions on the dynamic responses of the earth dam are investigated. The influence of the core width-height ratio and length-height ratio of the dam on the first natural frequency is studied. The results show that 3D effect could be neglected for $\eta > 4$ cases. The first natural frequency decreases with the increase of core width-height ratio or length-height ratio of an earth dam. The first natural frequency increases slightly after the seepage phase. The stiffness of the dam decreases at the end of an earthquake which causes the first natural frequency to decrease [9].

Baziar et al, 2006 reported seismic behavior of a rock fill dam with asphalt-concrete core utilizing numerical models with material parameters determined by laboratory tests. The case study selected for these analyses, is the Meyjaran asphalt core dam in Northern Iran, with 60 m height and 180 m crest length. The numerical analyses have been performed using nonlinear three dimensional finite difference software and various hazard levels of earthquakes. The results showed that due to the elasto-plastic characteristics of the asphalt concrete, rock fill dams with asphalt concrete core behave satisfactorily during earthquake loading. The induced shear strains in the asphalt core, for the case presented in this research, are less than 1% during an earthquake with amax=0.25g and the asphalt core remains watertight. Due to large shear deformations caused by a more severe earthquake with amax=0.60g, some cracking occurred towards the top of the core and the core permeability increased in the top part [10].

The above and other studies have provided valuable insight into the effects of the core shape on the response of dams. The present study was undertaken with objective of identifying how the core slope change in an earth dam influences the settlements, pore water presser and stresses. From such a study, it is possible to identify the critical angle which core causes a reduction in settlement of the dam. Further, it was studied how the core shape is influenced dynamic acceleration response and arching ratio. The numerical parametric study subjected to Manjil-Rudbar (21 June 1990, Northern Iran, Mw=7.4) earthquake loading. The calculations have been executed in time domain by using an explicit finite difference based numerical code, FLAC3D and Elasto-Plastic Mohr-Coulomb constitutive behavior model. The 3D models contain all dam body details and foundation materials of assumed earth fill dam except core slope. Three types of dam in 3D condition with same properties, thickness of the foundation and height were analyzed. The only difference is in the core slopes angle which 0, 10 and 20 degree have been selected. First static analysis and then dynamic analysis will be done. There are 3 steps in dam construction including: End of Construction, First Impounding and Steady State Seepage. For each core slope angle, mentioned above steps should be applied.

2. Numerical Model for the Study

2.1 Earth Dam Geometry

A typical configuration and finite difference mesh for the dam was generated and discretized by FLAC 3D, as shown in Fig. 1. The dam with 80 m height, 420 m length and with 20 m core width is assumed to be situated above alluvial foundation. Therefore, the base of the dam is assumed to be impermeable and fixed. In addition, the crests are placed at both sides of the core and the filter blanket presented below the downstream shell. This 3D model first assumed for static analysis and then dynamic analysis. Since there are mountains located at both sides of the dam, the side boundaries are assumed to be fixed and impermeable at both sides of the dam. All the three models as the initial layout was drawn in AutoCAD and then transferred all points and nodes transferred to FLAC3D.

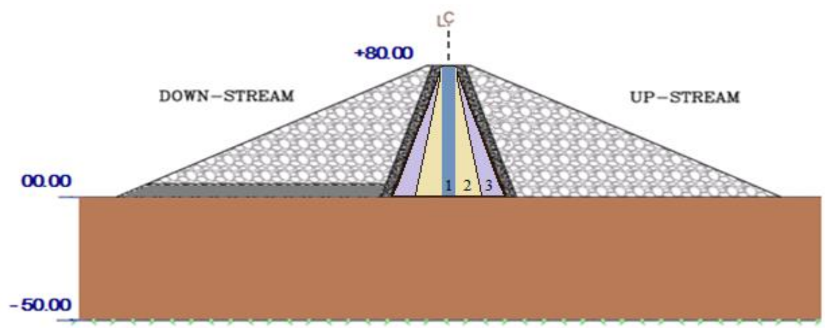

Figure 1. A typical cross-section of an earth dam

2.2 Dam Materials

For the numerical analysis all sections of the dams are assumed to be satisfied to the Mohr-Coulomb model. The engineering properties for the simulation are listed in Table 1. The stiffness could be different in any location. Therefore, the soil modulus will be considered to vary with the mean stress as:

$$E = KP_a \left(\frac{P}{P_a}\right)^n, \tag{1}$$

Where K is the modulus constant, n is the modulus exponent and Pa is the atmospheric pressure. Instead of Young's modulus and Poisson's ratio, using bulk modulus and shear modulus proposed by the software.

Table 1. Material properties

Material	Dry unit weight (KN/m^3)	Bulk modulus (MPa)	Shear modulus (MPa)	C (kPa)	φ (°)	Porosity	Permeability (m/s)
Core	2020	60	6.2	50	10	0.4	10^{-8}
Shells	2050	102	22	0	40	0.3	2×10^{-3}
foundation	2200	90	60	5	30	0.3	10^{-5}
Abutment	2200	90	60	5	30	0.3	10^{-5}

The dam is formed by simulation of stage construction using 12 layers. When a layer is added, a new static equilibrium for the dam is carries out. After end of construction and first impounding , static analysis is carried out. Uncoupled with mechanical analysis, steady state seepage of the dam for a 75 m water level is then performed. The final state of static equilibrium, called initial stress state, of the dam was then computed again after the steady state seepage has reached. By using the same grade and the obtained initial stress, the acceleration time history recorded during Manjil-Rudbar earthquake is applied to the base of the dam. In addition, baseline corrections for the acceleration time histories are also made for zero velocity and displacements after integration. From Fourier spectrum analysis, the natural frequency of a dam can be obtained as its response is amplified. If the source is a harmonic loading with multiple exciting frequencies, it should be possessed the same amplitude in all forced vibration frequencies, which is the same energy in all exciting frequencies is fair subjected. Therefore, it could be rational as the vibration source with the same acceleration amplitude in all exciting frequencies. The exciting acceleration of multiple frequencies can be expressed as the following:

$$a(t) = \sum_{n=1}^{1000} 10^{-6} \sin\left(\frac{i\pi t}{50}\right) \tag{2}$$

In which t is time, the acceleration amplitude is limited to a small value of 10^{-6} to assure it is in elastic range. It is found that the stress field inside a dam and the following analyses are not influenced according to the acceleration level. A FISH program is also coded in FLAC in order to apply a multiple frequencies (0.01~10Hz) harmonic acceleration to the base of the dam [9].

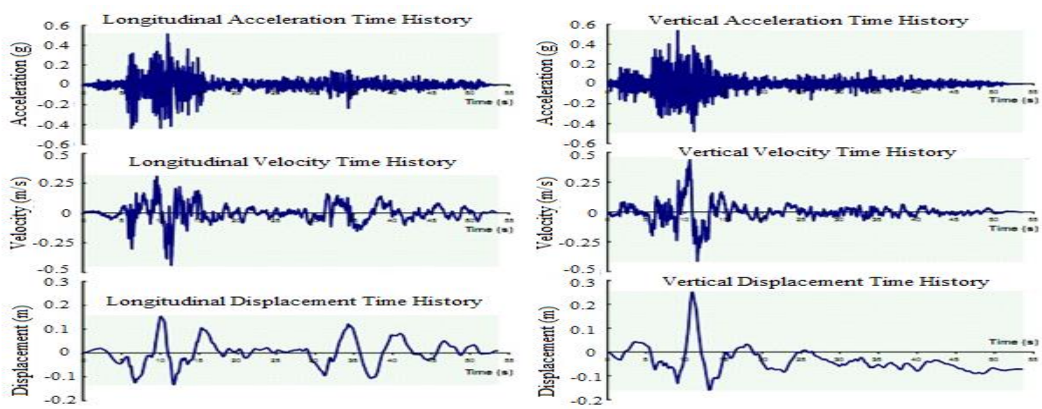

Figure 2. Manjil-Rudbar earthquake (21 June 1990, Northern Iran, Mw=7.4) acceleration time histories

Mesh dimensions play an important role in dynamic analysis, because when the mesh size increase, the number of nodes reduces. Therefore, the accuracy of computations reduces. On the other hand, if the mesh dimensions become too small, the calculation time will go up and cause some problems. Kollimmer and Leismer ,1973 showed that, in order to ensure the correct transmission of waves in a meshed model, the largest dimension of the elements should be less than one tenth to one eighth of the wavelength created by the highest frequency of the inputs to the system. In other words:

$$\Delta l \leq \frac{\lambda}{10\sim 8} \tag{3}$$

Which λ is the wavelength created by the largest frequency component of the input waves to the system that is capable of generating energy. By studying the earthquake acceleration data, highest frequency (f_{max}) can be achieved. In modeling all dams, the dimensions will consider 10 m. The effect of earthquakes is usually applied in the form of plate waves beneath the foundation and moves toward the dam. The Free-Field Boundaries are used to absorb the outward waves originating from the structure. This system of boundary condition involves the execution of free-field calculations in parallel with the main-grid analysis. The lateral boundaries of the main grid are coupled to the free-field grid by viscous dashpots to simulate a quiet boundary.

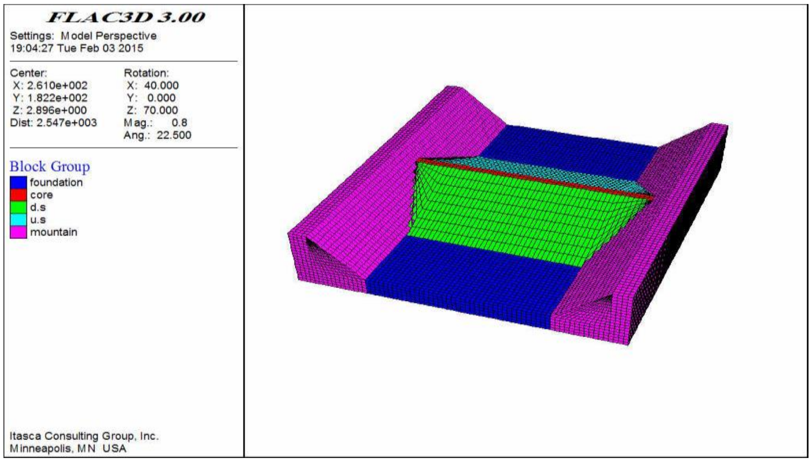

Figure 3: Primary grid of the dam with different sections

3. Results

3.1 End of Construction

3.1.1 Vertical Settlement

Fig. 4 depicts the influence of core slope angle on settlements in the center section of simulated earth fill dams. Settlement rate is one of the most important factors in assessing dam performance during construction and operation. For further investigations, the settlement changes in the dam core in middle sections from core toe (Z=0) to top of the crest (Z=80) are presented. It is noted form Fig. 4 that for variation of core slope from 0 to 10 and 20 degree, there is significant decrease in vertical settlement rate.

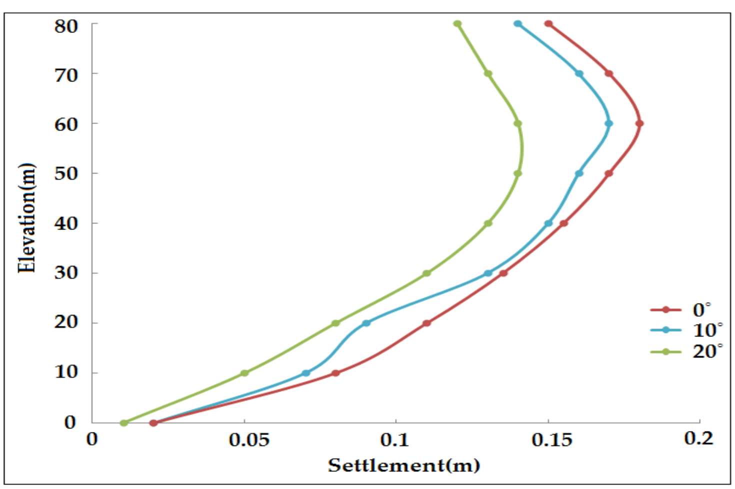

Figure 4. Settlement of dam at core in the end of the construction for different core slope

From the values obtained, it can be concluded that maximum settlements occur in the upper one third of the dam and its location is in all angles at height of 60 m. The settlement with 20° core slope is lower than the others. Settlements for dams with core slope of 0° and 10° in comparison the dam with a slope of 20° increased by 24.65% and 6.43 %, respectively.

3.1.2 Pore Water Pressure

Maximum pore water pressure for all three core slopes occurs at bottom part of the dam and its value for core with slope of 20°, 10° and 0° are 166, 124 and 103 kPa, respectively. From the results it can be deduced that when the core slope is low, or the width of the core is thin, the pore water pressure in the dam body is low.

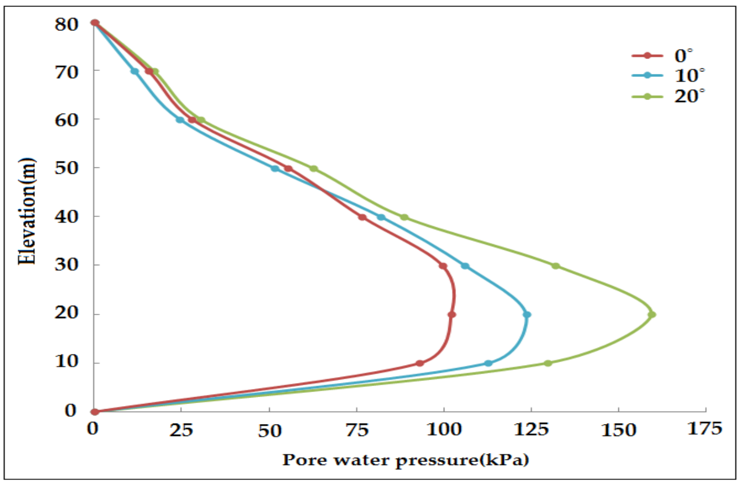

Figure 5. Pore water pressure of dam at core in the end of the construction for different core slope

3.1.3 Arching

In earth dams, arching may occur due to differential settlements between various parts of the dam, especially the central core and the shells or the dam abutments. The degree of arching in the core of earth and rock fill dams may be determined using the Arching Ratio (AR), which is defined at any point using the following relationship:

$$\text{Arching Ratio} = \frac{P}{\gamma h} \tag{4}$$

in which p is the vertical stress measured by the total pressure cell at the current point, γ is the unit weight of soil and h is the height of soil above the current point. The AR is inversely proportional with the degree of arching. A lower AR is an indication of greater arching [12]. Changes in arching ratio in various core slopes are compared in Fig. 6. It is obvious the lowest arching ratio occurs of the distance of 5 m from the center axis of the dam inside the core at Z= 60 m (height of dam). The minimum arching ratio at Z=20 m and Z=40 m of the dam body are 0.79 and 0.76 respectively. By increasing the height of the dam, the arching ratio decreases and as a result, arching becomes more important at the upper levels of the dam. At core range, arching ratio is less than 1 in all core slopes, but this ratio is strongly increased by moving away from the core range. On the other hand, by comparing the curves of arching for different core slopes, it can be concluded that the slope of core does not affect this ratio significantly.

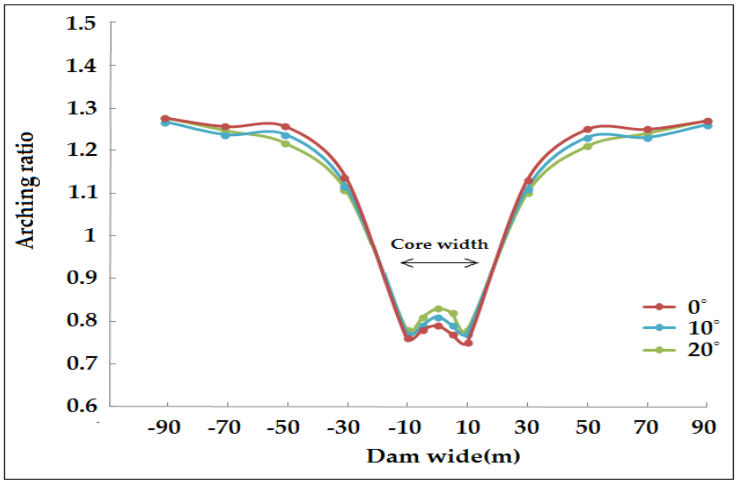

Figure 6. Arching ratio changes at the end of the construction for different core slopes

3.1.4 Vertical Stress

Vertical stresses were obtained for all three core slope shown in Fig. 7. As an example, results obtained from different elevation such as: Z=20 m, Z=40 m and Z=60 m. Fig. 7 shows the calculated vertical stress at the end of construction for core slope of 0°.

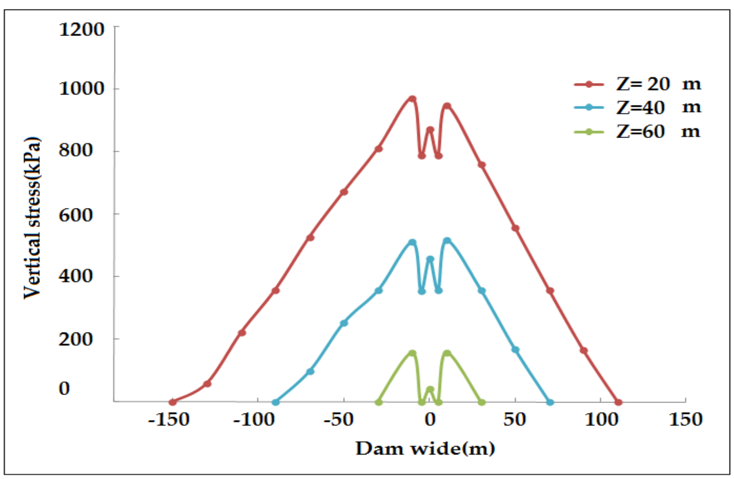

Figure 7. Vertical stresses changes at the end of the construction in different elevations

3.2 Steady State Seepage

3.2.1 Vertical Settlement

Vertical settlement changes at the steady state seepage are shown in Fig. 8. By comparing these figures with the results of vertical settlements in first impounding, it is obvious that the settlements have not changed. Meanwhile, by comparing the settlement changes in the three steps, end of construction, first impounding and the steady state seepage, it can be concluded that the maximum settlement occurred at a level of 0.6h~0.65h. In addition, when the core slope decrease, the settlements will decrease.

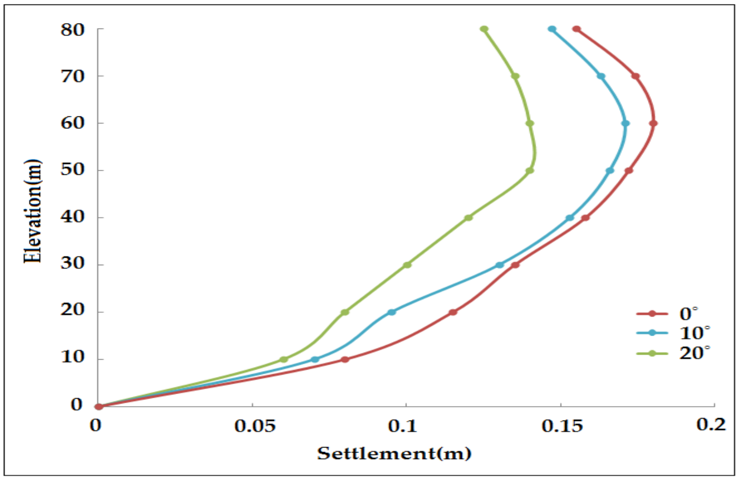

Figure 8. Settlement of dam at core in the steady state seepage for different core slope

3.2.2 Pore Water Pressure

The horizontal drainage blanket is embedded in the lowest level under the downstream shell. The height of this layer is 10 meters. In a numerical model, the pore water pressure in all elements of the downstream must be fixed, except for the elements of the drainage blanket. Fig. 9 represents the pore water pressure in steady state seepage.

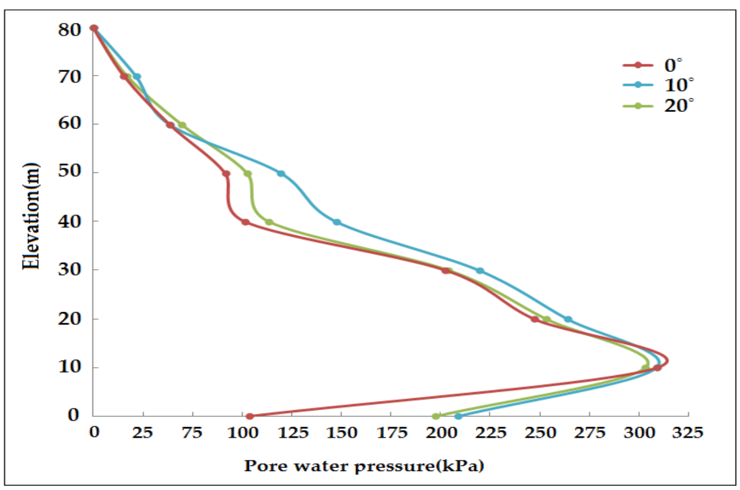

Figure 9. Pore water pressure of dam at core in the steady state seepage for different core slope

3.3 Dynamic Analysis

Since the probability of an earthquake during end of construction and first impounding stages is very low, in this research, dynamic analysis is evaluated just in steady state seepage stage. One of the methods for evaluating the dynamic response of a dam is to apply an input earthquake acceleration for dynamic analysis, then take a record of vertical displacements, pore water presser and acceleration changes by height of dam. According to corrected acceleration time history of Manjil-Rudbar earthquake and the record of acceleration 0.51g at ground level, the definition of the input earthquake at FLAC3D would be an equivalent acceleration at 50 m below the dam, which at the ground level it will be 0.51g.

3.3.1 Vertical Settlement

The maximum settlement occurred in dynamic analysis at a height of 53 m from the river bed. In fact it has a reduction of 7 m in comparison to the static analysis which was at 60 m. In static analysis, the maximum settlement in 0° core slope was 0.173 m which at the core slope angle in the dynamic analysis is 0.185 m. While, the maximum settlement in dynamic analysis occurred in 10° core slope by 0.21 m.

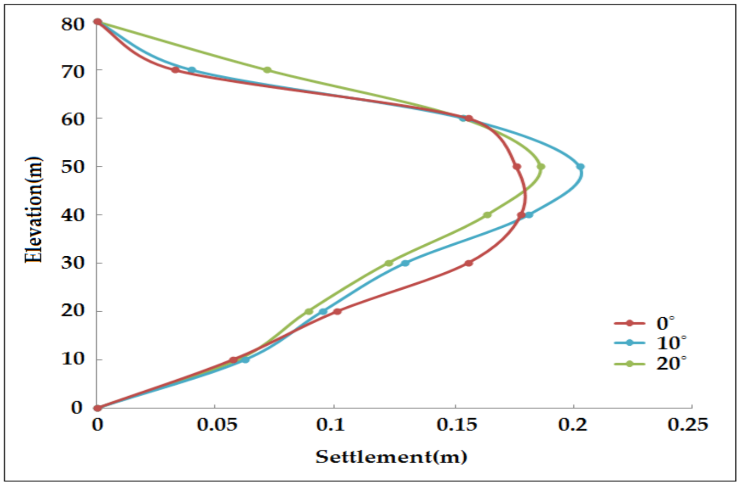

Figure 10. Settlement of dam at core in the dynamic analysis for different core slope

3.3.2 Pore Water Pressure

The maximum pore water pressure is at an elevation of about 10 m from the bottom of the dam body. These values at this level for the dam with core slope of 0°, 10° and 20° are 817, 833 and 789 kPa.

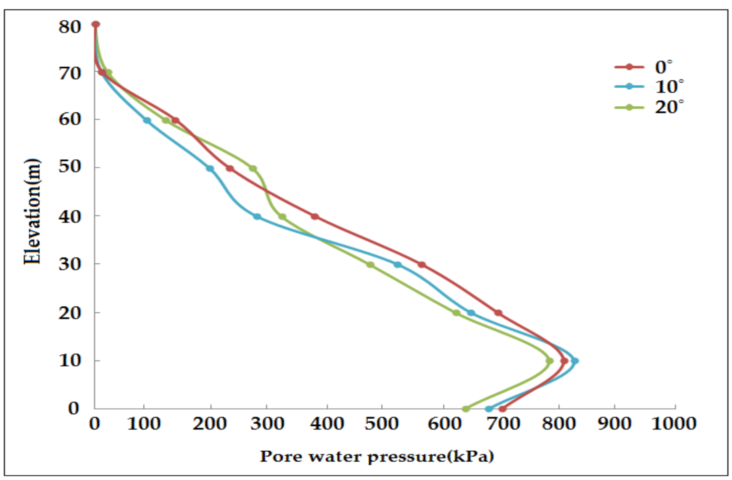

Figure 11. Pore water pressure of dam at core in the dynamic analysis for different core slope

3.3.3 Acceleration

In this study, generated acceleration by seismic loading is evaluated at certain points of dam. According to Fig. 12 the input earthquake begins at a depth of 50 m from the river bed and after passing through the earth's surface, it enters the dam and continues to the crest. The maximum positive acceleration created along the river for dams with core slope of 0°, 10° and 20° are 0.673 g, 0.883 g and 0.989 g respectively.

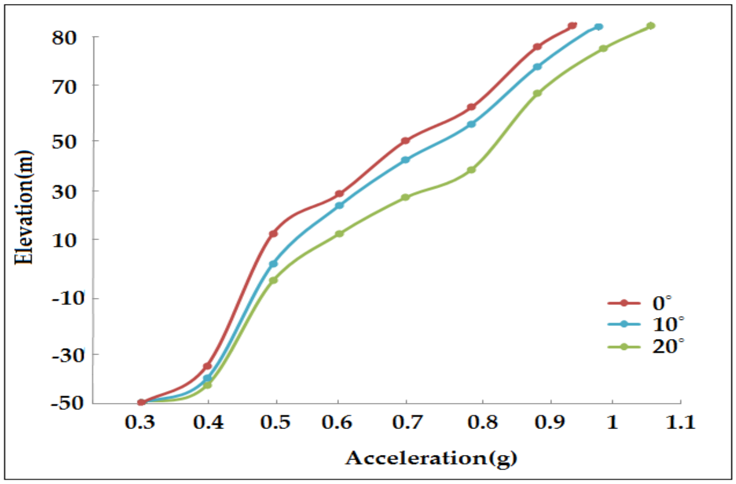

Figure 12. Acceleration changes affected by core slope at dynamic analysis

4. Conclusion

According to the results of static analysis, the minimum settlement is 0.124 m at the dam with 20° core slope. While, the maximum settlement is 0.179 m at the dam with 0° core slope in end of the construction stage. The maximum settlement at first impounding and steady state seepage are approximately the same as in the end of construction. Meanwhile, maximum settlement in all dams occurs between 0.6h~0.7h.

Also, at the end of construction, the maximum pore water pressure is 166 kPa for dam with 20° core slope at height of 0.1h~0.2h. In all core slopes, the maximum pore water pressure is at bottom one third of the dam height. It can be claimed that at low core slope, the pore water pressure decrease. In steady state seepage conditions, due to the presence of drainage blanket in the bottom part of the downstream, pore water pressure decreases 160 kPa compared to the first impounding condition.

Vertical stress has not changed in all dams and in all three stages including: end of construction, first impounding and steady state seepage. Therefore, it can be concluded that the slope of the dams' abutments has no effect on the arching ratio.

After assuring the accuracy of the static analysis results, dynamic analysis was conducted along the river. The pore water pressure was increased by 2 times in comparison with static analysis. The location of maximum pore water pressure decrease about 10 m. By studying the pore water pressure graphs, core slope have no effect on pore water pressure. The settlement in dynamic analysis increased 25% in comparison with static analysis results. The maximum settlement location was reduced about 5 m and the maximum settlement occurred at the dam with 10° core slope and the minimum settlement was for the dam with 0° core slope. So, settlement is affected by the dams' abutments slope. Finally, despite the fact that vertical stress and arching ratio have increased 2 times, core slope has no effect on vertical stress and arching ratio like static analysis and this increase refers to earthquake force.

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