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Three Dimensional Dynamic Analysis of Alborz Dam with Asphalt and Clay Cores

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ABSTRACT

Alborz rockfill dam with a clay core is under construction in North of Iran, an area of heavy rainfall. Because of the difficulties in the construction of a clay core in a wet area, an alternative for the watertight element (asphalt core) was considered. During the design of Alborz dam, a dynamic response analysis of the asphalt core was performed using two-dimensional modeling based on the equivalent linear method. Considering the shortage of study on the seismic behavior of asphalt core dams and also the high level of risk of earthquakes in Iran, it was necessary that the dynamic behavior of this dam was studied using three-dimensional models.

In this study, the dynamic response of Alborz dam for both variants of clay and asphalt cores has been investigated and three-dimensional dynamic (non-linear) analyses have been carried out using the explicit finite-difference program, FLAC$^{3\text{-}D}$, under various hazard levels of earthquakes (DBL and MCL). The results obtained included: time histories of the response acceleration, displacement, shear stress and shear strains are presented in this paper. The dynamic response of the dam with a clay core and asphalt core are compared with each other.

1 INTRODUCTION

Dynamic behavior of embankment dams against earthquakes, as one of the most important structures, has attracted the attention of researchers and dam designers.

The 1960's have witnessed the first implementation of the "Finite Element Method" in studying the seismic response of earth dams. In 1973, other researchers incorporated the iterative 'equivalent linear' scheme in 2-D variable damping finite element code (QUAD4). They used 2-D 'equivalent linear' finite element response analysis to assess the causes of failure of the San Fernando Dam (Idriss & Lysmer, 1973).

After 1980, many investigators focused on refining, expanding, and verifying the basic dynamic model, developed in the 1960's, to predict the seismic response of earth dams. They applied the finite element numerical model to evaluate the seismic response of earth dams (Pinto et. al, 1992).

In recent years, improvement of the different numerical methods including: finite elements and finite differences, has resulted in widespread use of these methods for studying dynamic behavior of all types of earth dams.

On the other hand, since there isn't any valuable recorded data of the behavior of asphalt-concrete core dams during earthquakes, the numerical response analysis of such dams is a feasible method in predicting their seismic behavior.

Hoeg (1993) presented the results of dynamic analyses of Strovan dam in Norway (by using finite element method) and showed that relatively large shear strain may occur in the core, but considering the self-healing property of asphalt, it behaved safely.

The similar results were obtained by Gurdil (1999). He analyzed the dynamic response of the Kopru asphalt core dam using the equivalent linear method. He concluded that cracking could occur in the core but it would be stopped by the self-healing properties of asphalt.

The authors of this paper in Iran (Salemi & Baziar, 2003) carried out the response analyses of Meyjaran asphalt core dam using the finite element method and an elasto-plastic model. The results obtained showed that the induced shear strain of the asphalt core was small enough to keep it watertight

All of these studies have been carried out using two-dimensional modeling.

In this study, the response analyses of Alborz rock fill dam have been investigated for the two alternatives of asphalt and clay cores using three-dimensional modeling.

2 LOCATION OF THE DAM AND ITS TECHNICAL FEATURES

Alborz dam, under construction in north of Iran is located 269 km north east of Tehran. It is constructed on the route of the Babol River to supply agricultural and drinking water. It is a clay core rockfill dam 74m high from the riverbed, and 85m from the foundation and with an 838m-crest length. Figure 1 shows typical cross section of the dam.

As an alternative, a vertical asphalt-concrete wall of 1m-width was considered as a watertight element surrounded by filter zones with the slopes increased to 1:2 and 1:1.8 respectively for up/downstream (Figure 2).

Alborz dam has been placed in a wide valley. The geological formation of the site is mainly Marlstone, which is covered with a layer of alluvium, and weathered rock with varied thickness.

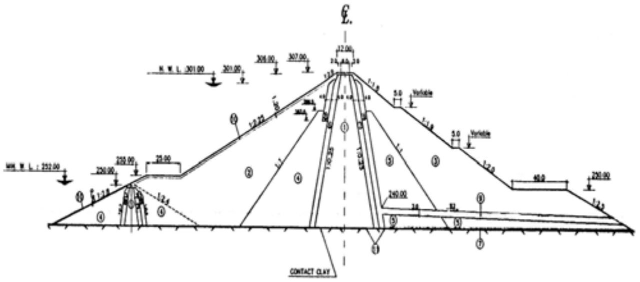


Fig. 1: Typical cross section of Alborz dam with clay core

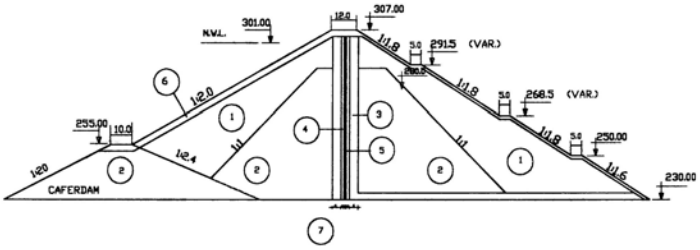


Fig. 2: Typical cross section of Alborz dam with asphalt core

The dam is located in a high seismic region, the Alborz Zone, where active periods have been observed occasionally. The characteristics of the main faults in this area are summarized in Table 1(Mahab Ghodss, 1999).

Table 1: Characteristics of the main faults in the vicinity of dam

Fault Name	Length of Fault (Km)	Seismic Potential (Ms)	Distance to Dam site(Km)
Kari-Kola	10	6.4	0.25
Pasha-kola	13.5	6.5	0.75
Northern Alborz	46	7	4 -5.5
Sookhtesara	27	6.8	6
Shirgah	55	7.1	11
Laleh-Band	45	7.0	11.5
Khazar	60	7.2	20

3 NUMERICAL MODELING

The numerical modeling for the static and dynamic analyses has been done using the FLAC^{3-D} program (Itasca, 1997), which is based on the finite difference method. The dam with its foundation (down to 60m) was modeled by generating different types of zones including bricks, wedges, pyramids and tetrahedrons. The boundaries have been considered as viscous in the dynamic analyses. Fig 3 shows the geometry of the model and its grid.

4 STATIC ANALYSES

The stress-strain analyses in the static condition were carried out for the various stages including the end of construction. These analyses were performed using a Mohr Columb model for the material behavior. The parameters of material are given in Table 2.

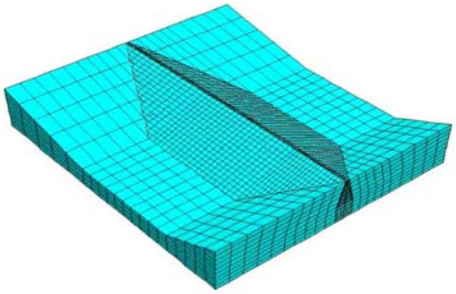


Fig. 3: Three3-Dimensional model of the dam and its foundation

Table 2- Material parameters used in this study

Material	C (kN/m^2)	Φ^o	γ (kN/m^3)	υ
Shell	0	42	21	0.25
Filter	0	35	19	0.3
Transition	0	38	19	0.3
Clay (CU)	50	11	19.5	0.45
Asphalt	360	28	24.2	0.45
Foundation	100	28	23.5	0.35

Asphalt Core Dam

The contours of vertical stress for the cross section at the middle of the dam axis are shown in Figure 4. As it is seen, the stresses suddenly change in the core due to the difference between the stiffness of the asphalt and transition materials. The maximum vertical and shear stresses are 1.5MPa and 0.3 MPa in the dam body respectively.

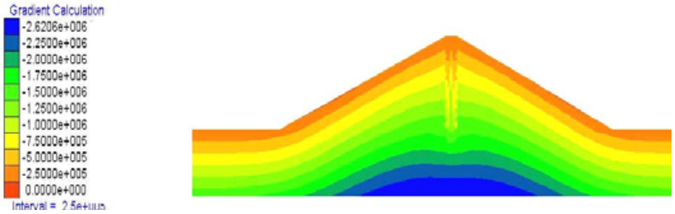


Fig. 4: Vertical stress contours on dam cross-section

Figure 5-A and 5-B show the displacement distribution on a dam cross-section and its foundation for the section at the middle of the dam axis. It is observed that the maximum settlement occurred at the middle height of the dam in the core and transition zones and was of the order of 39cm. The horizontal displacements were symmetrical, as was expected and the maximum value was 5.5cm at the downstream and upstream shells.

The maximum shear strain in the core was equal to 0.02, which was regarded as small .

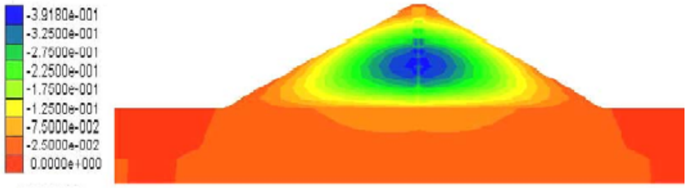


Fig. 5-A: Settlement contours on dam cross section

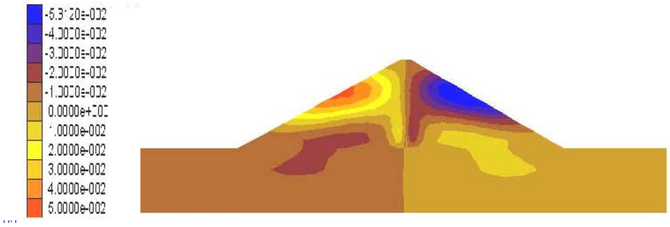


Fig. 5-B: Horizontal displacements contours

<u>Comparison of Clay core with Asphaltic Core</u>

Similar analyses for static conditions for the dam with a clay core have been conducted. Their results are summarized in Table 3. It can be seen that by changing the clay core to an asphalt core, the induced displacements haven't increased in spite of steeper slopes.

Table 3: Summery results of static analyses

Description	Asphalt core	Clay core
Max. x-disp. (cm)	5.3	15
Max. y-disp. (cm)	6.6	20
Max z-disp. (cm)	39.2	127
Ver. stress (MPa)	1. 5	1.75
Hor. Stress (Mpa)	0.5	0.6
Shear stress (Mpa)	0.3	0.4

Figure 6 shows the contours of y-displacement (along the longitudinal dam axis). It is seen that in the main part of dam length, y-displacements were very small, which could be disregarded.

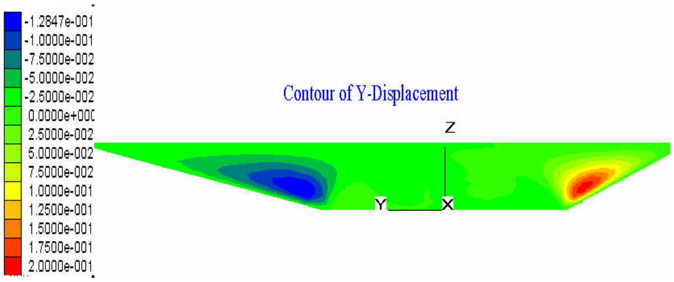


Fig. 6: Contours of Y-displacements on longitudinal section of dam

Therefore, it could be expected that the two-dimensional plane strain modeling gives similar results for the main part of the dam.

However near the abutments, considerable displacement values appeared and the plane strain assumptions didn't appear to be true for this part of the dam. Other analytical works, which have been carried out by the authors (Heidari, 2003), using two-dimensional models, corroborated the above result.

4 DYNAMIC ANALYSES

The three dimensional response analyses were carried out using an elasto-plastic model (Mohr-Coloumb) for the dam body materials and an elastic model for its rock foundation. These analyses were performed under different earthquake loadings with two levels of seismic risk (ICOLD, 1989) as follow:

- The Design Basis Level (DBL) with a_{max}=0.24g
- The Maximum Credible Level (MCL) with a_{max}=0.60g

The values of material parameters are given in Table 2.
The shear modulus (G_{max}) for filter material was calculated using equation (1) (Idriss&Seed, 1970):

$$G_{max} = 1000\, k_{2max}\, (\sigma_m) \tag{1}$$

σ_m is the mean effective stress. G_{max} and σ_m are both in lb/ft^2. k_{2max} is the coefficient which corresponds to the relative density of compacted sand. In this study the k_{2max} has been selected for compacted sand with relative density of 80%.
For the shell of the dam, G_{max} was calculated by the Equation below (Prange,1981):

$$G = 7230 \frac{(2.97 - e^2)}{1+e} (\sigma_0)^{0.38} \tag{2}$$

Where σ_0 is the mean effective stress. G and σ_0 are both in kPa and e is the void ratio of the shell material.
The dynamic shear modulus of clay material was equal to the value, obtained in a similar clay core dam. For the asphalt core, Gmax was selected to be 100 MPa.

4-1 RESULTS OF RESPONSE ANALYSES FOR ASPHALT CORE DAM

<u>Design Basis Earthquake Level (DBL) As Input Motion</u>

At this level of seismic risk, two different earthquakes were originally used as input motions:

I) Friuli Earthquake in Italy (1976) with magnitude of Richter 6 and amax=0.25g.

II) Tabass Earthquake in Iran (1978) with a magnitude of Richter 7.5 after scaling to 0.24g

Since the effect of earthquake loading on the dam in Case II was more severe, it induced larger deformations and stresses than Case I, so the results of loading of Case II are discussed in this paper.

The acceleration time history of input motion is shown in Figure 7.

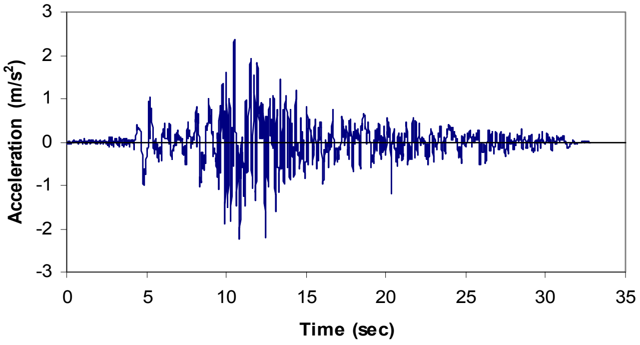


Fig. 7: Acceleration time history of Input motion (DBE)

The results show that peak response acceleration is equal 0.84g. The induced shear strains are very small (less than 0.01). However, the maximum shear strain near abutments reaches 0.03. Therefore within this range of deformation, asphalt material remains elastic (Breth, 1990 and ICOLD, 1982).

Maximum Credible Earthquake Level As Input Motion (MCL)

The Tabas earthquake was selected as the input motion after scaling to 0.6g (Fig 8). It is a very severe earthquake with a relatively high acceleration.

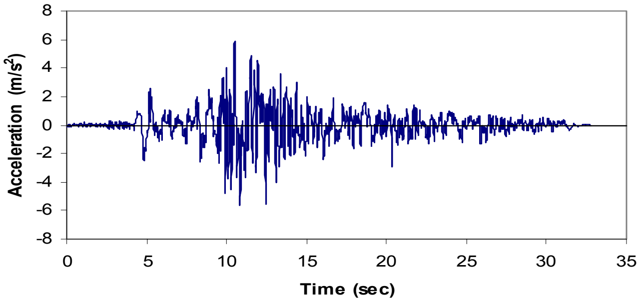


Fig. 8: Acceleration time history of Input Motion (MCL)

Figure 9 shows the variation of maximum response accelerations along the height of the dam and also in the foundation. It can be seen that seismic waves are strongly amplified in the foundation and the dam motion is stronger than the input motion.

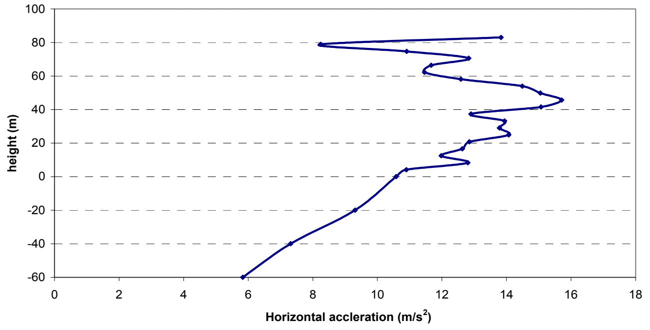


Figure 9: Maximum accelerations along the height of dam

Figure 10 shows the variation of horizontal acceleration at the crest along the longitudinal dam axis. It is seen that the maximum acceleration occurred near the middle of the dam with values of 1.4g. Since the ratio of height to the length of the Alborz dam is about 1:10 this behavior can be expected.

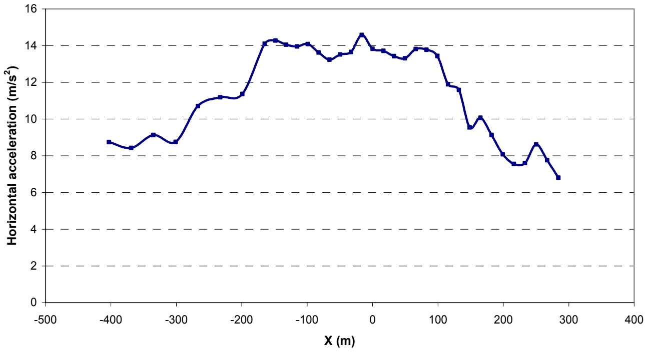


Fig. 10: Variation of horizontal acceleration at dam crest along the longitudinal axis.

Figure 11 shows the shear strain contours on the longitudinal section of the core wall. It is seen that the induced shear strains at all locations within the core were small and were less than 0.03, except for the part of dam crest near abutments. Therefore strains and deformations in the main part of the dam were in the range of elastic and the asphalt core remained watertight. The maximum value of 0.09 shear strain was observed near the abutments, where the bedrock is close to the surface. However, the results of laboratory tests on the asphalt-concrete samples by Breth and Arslan (1990) showed that the permeability of asphalt core wasn't significantly increased even in the state of stress corresponding to a shear deformation equal to 0.2 as applied to the sample.

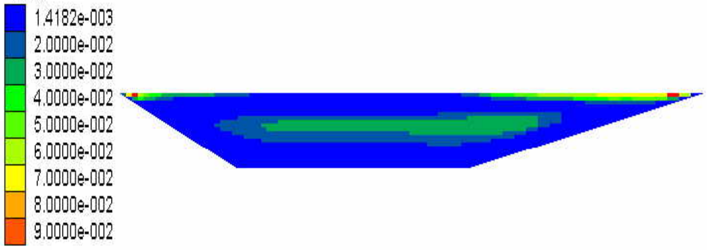


Fig. 11: Shear strain contours on the longitudinal section of asphalt core wall

In spite of low deformations in the asphalt core, there was a high-induced deformation and shear strain in the transition material adjacent to the core.

Figure 12 shows the variation of the shear strains in the core and filter along the height of dam, at the cross section at the middle of the dam axis. It is observed that the core and transition zone have similar deformations and act together in the range of small strains up to a height of about 55m and thereafter, filter shows very high strains and large deformations. Therefore for the lower part of the dam (about 2/3 height) the filter and core have an elastic behavior while at the upper part, the filter behaves completely as a plastic material but the core remains elastic with small strain. The largest strain in the asphalt core occurred at the starting point of plastic behavior of the filter. It seems at this point, the core is affected by the filter. Thereafter it is released and its deformation is decreased. This result indicates good performance of the asphalt core and its elastic behavior. A similar situation can be seen for the DBL earthquake loading but with very smaller values of strains in the core and filter.

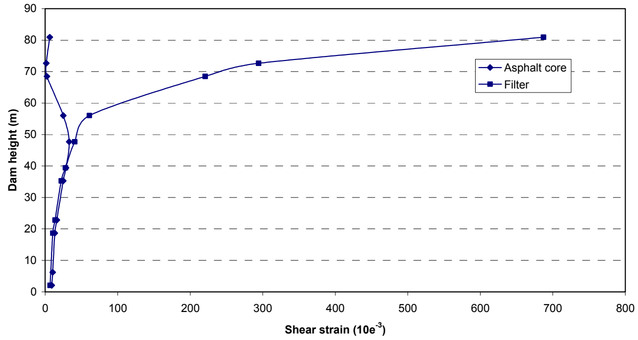
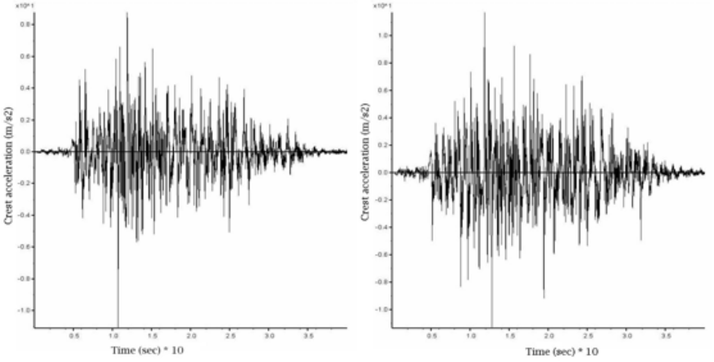


Figure 12: Variation of the shear strains in the core and filter along the height of dam

Investigation of induced stresses in the core dam showed that the normal stresses in all part of the asphalt core are in compression and no tensile stress is induced in the core even under very strong motions. Therefore tensile failure of asphalt core shouldn't be expected.

4-2 DYNAMIC RESPONSE OF A CLAY CORE DAM

The response acceleration time histories at the dam crest for the maximum cross section of the clay core are shown in Figure 15. It is seen that the peak acceleration in the DBL level earthquake is equal to 1.1g and shows a large magnification. Although the maximum response acceleration in the MCL level of loading is the same, the other values of acceleration have been magnified more strongly.



15-a: DBL Earthquake 15-b: MCE Earthquake

Fig.15: Time history of response acceleration

The time history of induced shear stresses at the base of the dam for the MCE earthquake is observed in Figure 16. The high shear stress values around 0.2 MPa occurred at the clay core dam base. However, in the asphalt core dam, the induced shear stresses are considerably higher than in the clay core dam and it reached 0.35 MPa at the dam base.

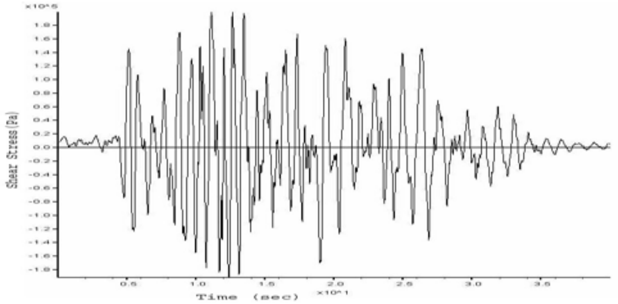


Fig. 16: time history of induced shear stresses at the base of dam

It is the difference between shear stiffness of clay and asphalt, which causes the asphalt material to absorb more energy and attract greater level load.

It is clear that under DBL loading, the induced shear stresses were smaller such that their maximum value reached 0.12 MPa and 0.18 Mpa for the clay core and asphalt core respectively.
The results show that the vertical stress in the clay core for both levels of earthquake is the same with the maximum of 1.5 Mpa. The earthquake level, therefore, doesn't appear to have a considerable effect on the vertical stress.

5 COMPARISON OF THE DYNAMIC BEHAVIOR OF CLAY CORE DAM WITH AN ASPHALT CORE DAM

The results of dynamic analyses show that the response acceleration and also normal stresses, which occurred in the dam body, are very similar for both variants. However, the induced displacements and deformations in the asphalt core dam body is smaller than in clay core, in spite of its steeper slopes of the down/up stream faces.
Regarding the seismic behavior of thin asphalt wall, the shear strains, which occurred under DBL loading, are small and they are in the range of elastic deformations. The dam, therefore, remains functional during the earthquake. Furthermore, under MCE level of earthquake loading, in spite of applying very high shear stress to the asphalt core, the shear strains which occur in the dam core, are small.
In both types of the core, the large displacements occur in a small part of the downstream and upstream faces under MCE loading. Some recorded data on the rockfill dam behavior under very severe seismic loading have also confirmed this result.
The field vibration test and recording of the response of some existing rockfill dam in Japan, has shown that the dam mass characteristics are unaffected by dynamic loading and the dam shows little deformation in the elastic range. But at the dam crest and partially at the face regions, where the tie-in forces are smaller, the displacements are 5-10 times larger because of reciprocal displacements between neighboring rock blocks (Priscu et. al, 1985).
However, the satisfactory behavior of existing rockfill dams in many regions with high level risk of earthquakes shows that using the simple design measures such as construction extended berms at d/u stream, placing riprap on the faces, and increasing the freeboard can prevent most of the expected damage.

6 THE DIFFERENCE BETWEEN A TWO DIMENSIONAL AND A THREE DIMENSIONAL MODEL

Considering the length of the Alborz dam (more than 800m), for the main part of the dam length the results obtained of three-dimensional analyses are similar to the results of two-dimensional modeling, which is expected. However, the higher magnitudes of induced displacements and strains along the longitudinal dam axis in the areas near abutments show that two dimensional plane strain models cannot simulate the real condition of stress-strain for these sections. Therefore, to study the seismic behavior of asphalt core walls in total length including on the abutments, particularly located in narrow valleys, utilizing the three-dimensional models will provide more realistic results.

7 CONCLUSION

Three-dimensional dynamic analyses (non linear) of Alborz rockfill dam with two options of clay core and asphalt core under different levels of earthquake loading were carried out. This study has shown that:

- Under MCE level of loading, the filter material has a large deformation at the upper part of the dam and behaves plastically while the asphalt core shows small deformation level.

- The induced shear strains in most parts of the asphalt core zone under MCE loading are small and they are in the elastic range, except for the upper parts of core, above the abutments, where the strain reaches 0.09. According to the laboratory tests results, it is predicted that in this range of strain, the asphalt core remains watertight. On the other hand, by considering the limited area of the location of these deformations, any probable crack will not cause hazardous damage.

- In spite of the high shear stresses at the base of dam, the results show that no part of asphalt core is in tension. Tension cracks, therefore, do not appear to occur in the asphalt core.

- The response acceleration at the dam crest level for asphalt and clay cores, are very similar and it has been observed that the input motion in the dam body, particularly in the foundation, is strongly amplified.

- Although the shear stress, which occurs at the base of the dam with an asphalt core is higher than that in clay core, the induced displacements and deformations in its body (with steeper slopes of d/up stream) are smaller than those in a clay core dam.

These results have indicated that the asphalt-concrete core behaves safely even under an extremely severe earthquake and it satisfies the seismic design criteria under both of DBL and MCL level of earthquake loading. Therefore, it may be considered to be a good choice particularly for Alborz dam located in wet an area, which may cause difficulties to construct the clay core.

Considering the shortage of study on seismic behavior of asphalt core dams and lack of recorded data on these dams during earthquakes, this study can be improved and the results obtained can be modified when new data on seismic behavior of asphalt core dams become available.

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