16 Aug 2008, 8:45am - 12:30pm

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ABSTRACT

In this research, dynamic behavior of a rockfill dam with asphalt-concrete core has been studied utilizing numerical models and centrifuge model tests with material parameters determined by laboratory tests including static and cyclic triaxial tests and also wave velocity measurements. The case study selected is the Meyjaran asphalt core dam, recently constructed in Northern Iran, with 60 m height and 180 m crest length. The seismic response analyses have been performed using a non-linear three dimensional finite difference software under various hazard levels of earthquake loadings. Their results showed that the induced shear strains in the asphalt core are less than 1% during an earthquake with a_{max}=0.25g and the asphalt core remains watertight.
Also, the small scale physical models of the asphalt core dam have been tested on centrifuge, under impact loading and response accelerations and induced deformations were recorded by instruments installed within and on the models. The recorded data and observations of the centrifuge model tested at 80g acceleration showed that the induced deformations in the asphalt core under an impact load with a large acceleration of 7.6 m/s^2 were very small. Comparing the results of centrifuge tests with the results of numerical dynamic analyses of a prototype dam indicated that the numerical results corresponded well with the data recorded during centrifuge tests.

INTRODUCTION

Monitoring of existing asphalt core dams has indicated their good behavior during operation, which is mainly related to the visco-elastic plastic properties of asphalt concrete (Hoeg, 1993). However, the behavior of thin asphalt cores under earthquake shaking needs further investigation. Particularly in recent years, construction of this type of dam in the seismic areas of the world such as Japan, China and Iran has caused researchers to focus on the dynamic behavior of asphalt cores (NGI, 2005).
In the last decade, improvements in the different numerical methods have resulted in widespread use of these methods to study dynamic behavior of all types of earth dams.
Hoeg (1998), and later Gurdil (1999) and Ghanooni and Roosta (2002) presented results of two-dimensional dynamic analyses of asphalt core dams. They showed that relatively large shear strains may develop in the top of the asphalt core due to dam crest amplification of the ground motion, but concluded that the dams investigated would behave safely.
2-D response analyses of Meyjaran asphalt core dam and also three-dimensional dynamic analysis of the Alborz dam carried out by the authors (Salemi and Baziar, 2003 and Baziar et al., 2004) showed that the induced shear strains in the asphalt core were small enough to keep it watertight.
Few researchers have investigated the stress-strain behavior of asphalt concrete used as watertight elements for dams by laboratory tests. The first experimental research on the earthquake resistance of asphalt concrete core materials was conducted by Breth and Schwab (1973) in Germany. They performed special cyclic triaxial tests on the asphalt concrete samples and concluded that the asphalt material under the specified cyclic stresses, behaved like an elastic body.
Wang (2004) recently reported a series of cyclic loading tests on triaxial specimens of asphalt concrete and concluded that there was no sign of cracking or deterioration of the asphalt concrete. However, no physical modeling of an asphalt core dam has up to date been reported in order to study its dynamic behavior, particularly at field stress levels. In the absence of field observations, physical modeling can be very useful for geotechnical engineers to predict field performance of asphalt core dams for different situations especially during earthquake events.
The history of centrifuge modeling originates in the 1930's (Pokrovski and Fiodorov, 1936), although major use of centrifuge geotechnical tests in western nations began only in the early 1970's with the tests of Avgherinos and Schofield (1969). Since the 1980's there has been a rapid increase in world-wide interest in centrifuge modeling of dynamic problems such as

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vibration of structures, pile driving and liquefaction (Liu and Dobry (1993), Adalier and Elgamal (1998). However, earthquake engineering and the effects of blasts or impacts are two areas which have found considerable use of centrifuge modeling in the last decade.

In this research, the seismic response of the Meyjaran rockfill dam, due to its location in a narrow valley, has been investigated using a three-dimensional finite difference method (FLAC3D). Also, dynamic behavior of the asphalt-concrete core dam under impact loading has been studied, using centrifuge model tests, and the recorded data have been compared with the results of numerical analyses of the prototype model. To determine the geotechnical properties of asphalt concrete for using in the numerical and physical models, laboratory tests including static, cyclic triaxial tests and wave velocity measurements have been carried out.

LOCATION AND TECHNICAL FEATURES OF MEYJARAN DAM

Meyjaran dam, a rockfill dam with an asphalt concrete core, is located 20 km south-east of Ramsar City in northern Iran. It has been constructed on the Nesa River in order to supply irrigation and drinking water. It is 60 m high and has 180 m crest length. The vertical asphalt concrete core has 1-meter width and has upstream and downstream filter and transition zones. Figure 1 shows a typical cross section of the dam. The dam is placed in a V-shaped and fairly symmetric valley underlain by a conglomerate foundation. This conglomerate is classified, based on RMR classification, as fairy good rock.

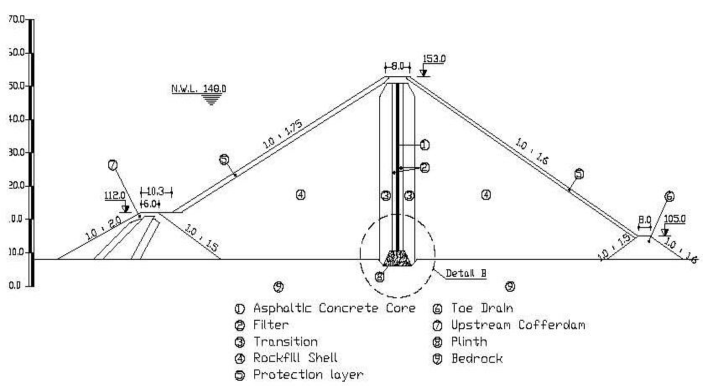

Fig.1. The typical cross section of Meyjaran dam

Meyjaran dam site is located in Alborz seismic zone where active periods have been observed. One of the most important earthquakes that occurred in this area is the June 1990 Manjil earthquake, with Mb=7.3 and Ms=7.7. The epicenter of this earthquake was about 160-km west of the Meyjaran dam site.

LABORATORY TESTS TO DETERMINE GEOTECHNICAL PARAMETERS

In order to investigate the stress-strain behavior of asphalt concrete under static and dynamic loading and also to determine parameters of the asphalt concrete, laboratory tests including static and cyclic triaxial tests, and measurement of P- and S-waves velocities have been carried out.

The laboratory triaxial specimens were prepared in a mould with diameter of 70mm and a height of 140mm. The dry aggregates, in accordance with the weight proportions shown in Table 1, were preheated at 160°C. This is the same material as used in the asphalt core of Meyjaran dam (after removing the grains bigger than 18mm). The B60 bitumen was preheated at 150°C. The hot aggregates and bitumen were placed in a heated mixer. At a temperature between 140° to 150°°C, the mixture was placed and compacted in a preheated cylindrical mould. The compaction method used to prepare the specimens was similar to the Marshall Compaction procedure described by Wei Biao and Hoeg (2002).

Static Triaxial Tests

All the static triaxial tests were strain-controlled compression tests with axial stress increasing and lateral confining stress held constant. The confining stress was varied from 0.1 to 0.5 MPa. The strain rate was 0.1% per minute. The magnitude of axial stress, axial strains and volumetric strain were recorded throughout the tests. The testing temperature was 19 °C.

The test results summarized in Table1, show very ductile plastic behavior after the strength level has been reached. Brittle failure was not observed in any of those tests. Young modulus (secant modulus at 1 percent axial strain) is between 90 to 150 MPa for the various specimens with 6.0% bitumen content. The average secant shear modulus, G, at the same axial strain is obtained to be around 45 MPa.

Table1: The static triaxial test results

Test No.	Confining stress , σ_3 (MPa)	σ_1 at failure, (MPa)	σ_1/σ_3 at failure	Axial strain at failure	Young's modulus (MPa)
TS-1	0.1	1.2	12	0.16	90
TS-2	0.2	1.9	9.5	0.16	95
TS-3	0.3	2.7	9	0.12	100
TS-4	0.4	3.2	8	0.14	140
TS-5	0.5	3.8	7.6	0.14	150

Cyclic Triaxial Tests

Cyclic triaxial tests were carried out on samples prepared with the specifications mentioned above. These tests were loaded under isotropic consolidation with different confining stress and also under an-isotropic consolidation with σ_3/σ_1=0.25 to simulate in-situ conditions. These states of static stresses were superimposed by a cyclic shear stress of 0.1 to 0.2 MPa with a frequency of 2 Hertz. This range of cyclic loads corresponds approximately to the load of earthquakes with Richter magnitude 6.0 to 6.8, acting on Meyjaran rockfill dam with asphalt concrete core. Figure 2, as an example, shows the variation of axial displacement during cyclic loading in one test ($T_5S_3C_4$). As it is seen, the cyclic strain amplitudes under cyclic stress remain almost constant and the residual strains are negligible. In other words, the induced deformations at this level of strain are virtually elastic.

The 200 load cycles imposed did not change the structure and strength properties of the samples. The induced deformations were small and there was not any sign of fissuring or cracking in the specimens. The maximum shear strain recorded in the samples with 6.0% of bitumen was 0.4%.

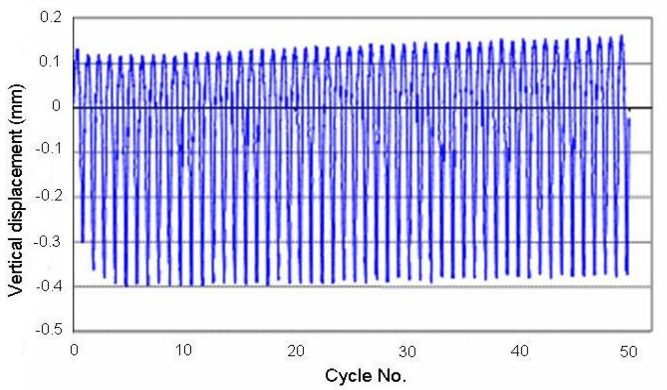

Fig.2. Variation of vertical displacement during cyclic loading

Figure 3 shows the shear modulus vs. shear strain (G-γ) relationship of the asphalt concrete in one cycle during increasing load. It can be seen that the dynamic shear modulus, G, of the asphalt mixture is strongly dependent on the shear strain. At very small strains, the G values are very high but decrease rapidly with increasing shear strain. At γ= 0.003%, the G value is around 1600 MPa, but decreases to about 100 MPa (less than one tenth of its initial value) at γ= 0.1%.

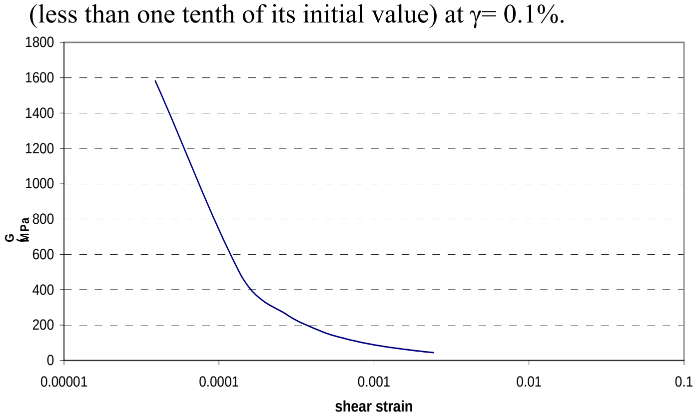

Fig.3. G-γ relationship of the asphalt material

<u>Measurement of P-wave and S-wave Velocities by the Pulse Method</u>

P-wave and S-wave velocities were measured in asphalt specimens with 5cm and 14cm length. In these tests, a sensor is connected to each end of the sample and an electrical pulse is transmitted to the top sensor and the input pulse is received at the other end. The time interval (Δt) between sending and receiving of signals is recorded and monitored by oscilloscope. The wave velocity is obtained by dividing the length of sample with the time interval. The results of the tests are shown in the Table 2 which indicates a high value of 3800-4100 MPa for the shear modulus of the asphalt concrete, compatible with the results of the cyclic triaxial tests at very low shear strains.

Table2: S-waves Velocities using Pulse Method

Length of Sample (cm)	Time for receiving S-wave (μ s)	S-waves average velocity (m/s)	Shear modulus $G=V_s^2\rho$ (MPa)
14	110.6	1266	3846
5	38.06	1314	4143

<u>Determination of shear modulus</u>: From Fig.3, for asphalt material, a value for G_{max} of 1000 MPa was selected for the shear strain of $\gamma=5*10^{-5}$. However, sensitivity analyses showed that the change of maximum shear modulus in the range of 800-1800 MPa did not have significant effects on the dynamic response of the dam (Salemi, 2006).

To determine the shear modulus of various granular soils and rockfill at very low levels of strain, (G_{max} or G_0), a number of empirical formula based on laboratory tests (resonant column and cyclic triaxial tests) have been proposed by several researchers (Ishihara, 1996). For coarse-grained soil and for a sufficiently small shear strain of $\gamma=10^{-5}$, the shear modulus, G_0, is given by Kokusho (1981) as follows.

For filter material, G_0 was calculated using equation:

$$G_0 = 8400 \frac{(2.17-e)^2}{1+e}(\sigma_0)^{0.60} \tag{2}$$

For the shell material of the dam, G_0 was calculated by the equation:

$$G_0 = 13000 \frac{(2.17-e)^2}{1+e}(\sigma_0)^{0.55} \tag{3}$$

where σ_0 is the mean effective stress, G and σ_0 are both in kPa and "e" is the void ratio of the material.

SIESMIC RESPONSE ANALYSES

The numerical modeling for the static and dynamic analyses has been performed using the FLAC3D program (Itasca1997), which is based on the finite difference method. The dam with its foundation (down to 60m) was modeled three-dimensionally by generating different types of elements including bricks, wedges, pyramids and tetrahedrons. The boundaries have been considered as viscous in the dynamic analyses. Figure 4 shows the geometry of the model and its grid.

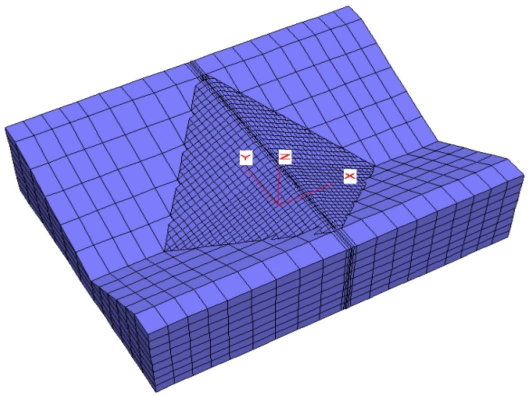

Fig.4. Three-dimensional model of the dam and its foundation

The dam embankment construction was modeled with 20 layers of compacted fill. The hyperbolic stress-strain model proposed by Duncan and Chang (1970) was used for the static stress calculations.
Dynamic response analyses were carried out for the end of construction stage, under different earthquakes, using the Mohr-Coulomb model for material behavior. The geotechnical parameters for the dam body are presented in Table3.
These analyses were carried out using an elasto-plastic model (Mohr-Coulomb) for the dam body materials and asphalt core and an elastic model for its rock foundation.

Table3: Geotechnical parameters of Meyjaran dam

Material	k*	n*	k_b**	M**	C kg/cm^2	Φ	γ_{wet} gr/cm^3
Asphalt core	280 to 355	0.36 to 0.62	759 to 1710	0.32 to 0.68	3	25	2.4
filter	864	0.64	977	0.7	0	40	2.10
gravel	700	0.6	500	0.6	0	45	2.05

** "k" and "n" are the model parameters (constants) relating to the initial modulus, E_i, in a hyperbolic model. Where $Ei=k\,P_a\,(\sigma_3/P_a)^n$ and P_a is the atmospheric pressure.*
*** "k_b" and "m" are dimensionless parameters (constants) relating to bulk modulus, B, in a hyperbolic model. Where $B= k_b\,P_a\,(\sigma_3/P_a)^m$.*

These analyses were performed under different earthquake loadings with two levels of seismic risk (ICOLD, 1989) as follow:

- The Friuli earthquake in Italy (1976) with the magnitude of Mb=6 and a_{max}=0.25g as a design basis level (DBL).
- The Irpinia earthquake in Italy (1980) with the magnitude of Mb=6.8 and a_{max}=0.5g as a maximum design level (MDL).

According to the ICOLD classification, Meyjaran dam is not classified as a very high-risk dam. Therefore to design this dam, the seismic loads are derived from MDL and DBL earthquakes, and controlling for the earthquake level of MCE is not required.
RESULTS OF DYNAMIC ANALYSES

The acceleration time history of the Friuli Earthquake (a_{max}=0.25g) as input motion is shown in Fig.5.
A comparison between the response acceleration at the dam crest (Fig.6) with the input motion shows that the maximum horizontal acceleration at the dam crest has reached 0.73g giving a magnification factor of 2.9.
In spite of this high acceleration at the dam crest, the induced displacements are small. The maximum horizontal displacement at dam crest is equal to 6.3cm.
The results also show that the induced shear strain in the asphalt core is less than 1% (Fig.7).

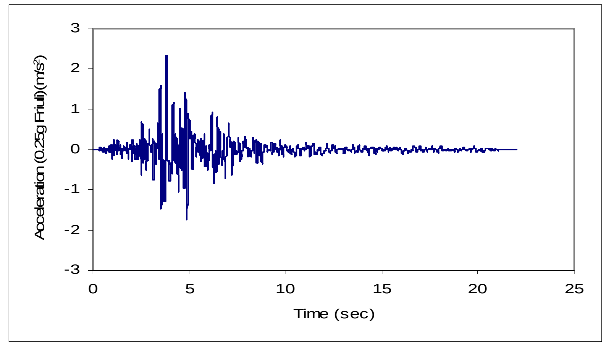

Fig.5. Acceleration time history of Input Motion

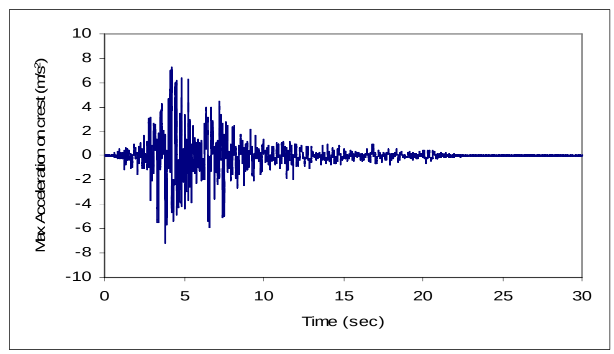

Fig.6. Acceleration response of dam at crest

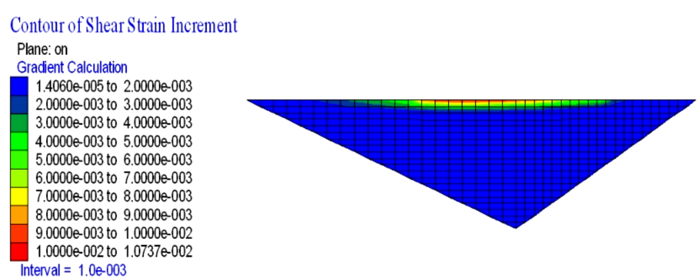

Fig.7. Shear strain levels on the longitudinal section of asphalt core wall (Friuli Earthquake)

The analyses of induced stresses in the asphalt core dam shows that the normal stresses in all parts of core are in compression, and no tensile stress is induced in the core even under strong motions (Fig.8). Therefore, no tensile cracking should be expected.

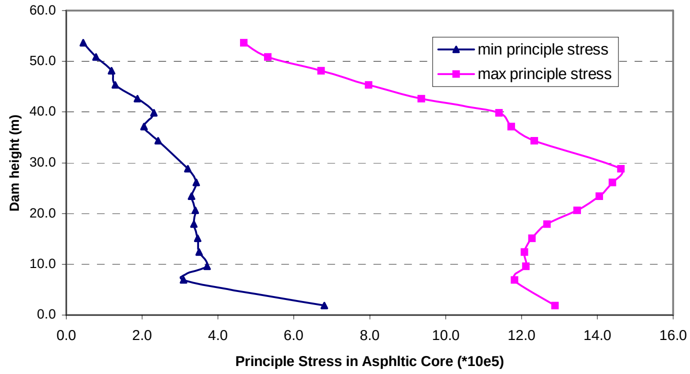

Fig.8. principal stresses in the core along the height of dam

After scaling to the maximum design level earthquake, Irpinia Earthquake (a_{max}= 0.5g) was used as other input motion. At this stage, the dam crest horizontal displacement is 18.7 cm. With this input motion, the seismic waves were strongly amplified in the dam body (and its foundation), and the dam crest motion was much stronger than the base motion. The shear strains induced in asphalt core are less than 6%. Based on the results of permeability tests performed on the asphalt samples imposed axial strains of 6% which corresponds to shear strains of 8.7%, the permeability of the asphalt concrete was not increased significantly and therefore the asphalt still remained virtually watertight (Salemi, 2006). A summary of obtained results for the dam deformations is presented in Table 4.

Table 4: Summary of results of dynamic Analysis of the asphalt core dam

Description	E.Q. Loading	
	DBL. E.Q. a_{max}=0.25g	MDL. E.Q. a_{max}=0.5g
Max.Acceleration at dam Crest. (g)	0.73	0.89
Max.Horizontal disp. at dam crest (cm)	6.3	18.7
Max. vertical disp.at Core (cm)	2	10
Max shear strain at core (%)	<1	6

CENTRIFUGE MODEL TESTS

Nowadays, centrifuge model tests are widely used to study many geotechnical phenomena. The main advantage of centrifuge modeling in this case is the use of a small-scale model being subjected to the stress levels similar to those found in the full-scale situation. Therefore, centrifuge test results provide a valuable insight into the correct performance of field scale structures as soil behavior is stress level dependent.

In this research, the centrifuge tests have been carried out on the small scale models of the asphalt core dam, in the P.W. Rowe laboratory geotechnical centrifuge in Manchester University, UK. Table 5 gives the technical specification of the centrifuge.

Table 5: Technical specification of the P. W. Rowe centrifuge

Maximum soil/equipment mass	3500 kg
Maximum acceleration	142g @ 200rpm
Working acceleration	10-100g
Base plate radius	3.2 m

The strong box is 2m long by 1m wide by 0.6m deep and capable to carry a total mass of some 3,500kg, located at a maximum radius of 3.2m. The tests have been carried out at 80g and 100g acceleration of centrifuge.

Model Preparation

The model at a height of 25cm and 90cm width at the base was a 1:80 scale simulation of a rock fill asphalt core dam of 20m height. The asphalt core was 1cm thick and manufactured as a pre-cast panel. The base of the dam model consisted of an aluminum plate that was set on a high- density (HD) rubber sheet, as shown in Fig.9.

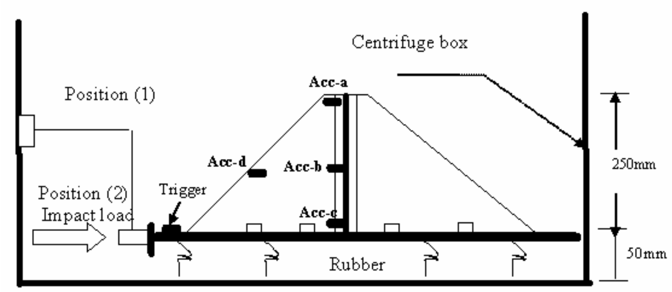

Fig.9. Centrifuge model (schematically)

A special loading mechanism including a pendulum with a drop weight of 1.8 kg was used to apply an impact load to the base of the dam model (Fig.9). The test models were instrumented with four miniature accelerometers placed at three different levels within the dam body. An accelerometer was placed at the point of impact acting as the trigger for the transient recorder. The other three were placed at the base, middle height, and crest of the dam model. Fig. 9 shows the location of the accelerometers. To measure the settlement of the asphalt core, a linear voltage displacement transducer (LVDT) was installed at dam crest, on the top of asphalt core. A video camera was strategically placed to monitor the behaviour of the dam in flight.

Materials of the model: The gradation curves of the rockfill material at field scale and after scaling to 1:80 are presented in Fig.10. A mixture of 50% crushed limestone and 50%sand with a grain size distribution in the allowable range, was selected as shell material for the dam model (Fig.10). The geotechnical parameters of this material were very similar to the real dam material (Baziar et al., 2007).

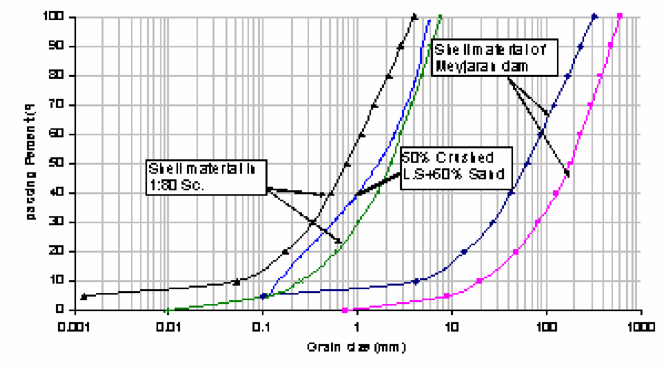

Fig.10. Gradation curve of shell material in real scale and 1:80

Pre-formed asphalt panels (25cm x 25cm) with 1 cm thickness were used as impervious core in the model. These panels were made of fine aggregate with bitumen content of 7.2%. To obtain the properties of the fine mix material a number of laboratory tests have been performed on the asphalt specimens prepared according to the Marshall Method (Baziar et al., 2007).

Centrifuge test results

Among the total of five centrifuge tests were performed on various models (Baziar et al., 2007), the results of one test, (Test-5) carried out at 80g acceleration, are presented in this paper.

Response acceleration: An impact load with large acceleration of 7.6m/s^2 has been applied in a very short time of 0.30sec to the base of centrifuge model (Fig.11). The response acceleration time histories at the base and crest of the dam are shown in Fig. 12.

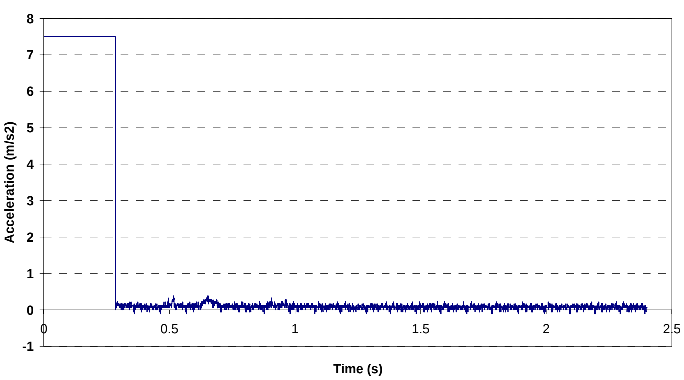

Fig.11: Input Motion (Test-5 at 80g Acc. of centrifuge)

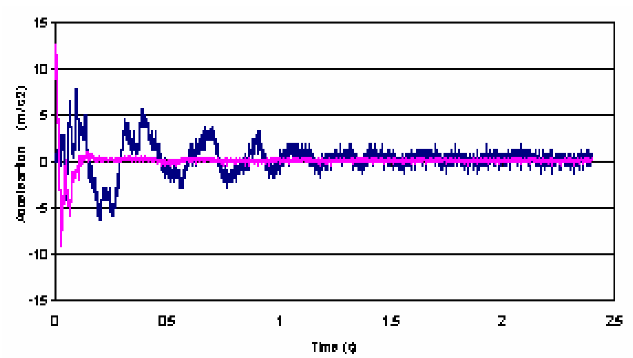

Fig.12. Response Acceleration at Dam Crest (Test-5, 80g)

Deformation: The data obtained in the test and model observations suggest that the induced deformations at different parts of the dam were very small and also no sliding or failure occurred in the dam body. Monitoring data of LVDT shows that a settlement of 9 mm, under static and dynamic loading (scaled at 1:80) was induced at top of the asphalt core. The lateral displacement of asphalt increases from the bottom to the top such that it is at its maximum at the dam crest is equal to 8mm (under static and dynamic loading) (Fig.13). Maximum shear strain of 1.8% is occurred at asphalt core under impact loading.

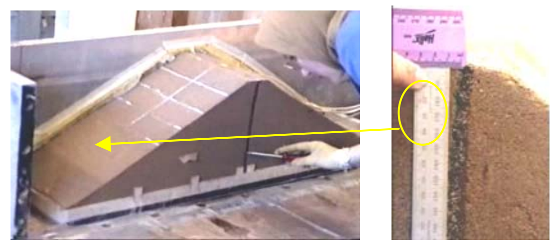

Fig.13. Displacement of asphalt core in centrifuge model test

NUMERICAL ANALYSIS OF THE PROTOTYPE MODEL UNDER IMPACT LOADING

The results of numerical analysis of prototype model utilizing the FLAC3D software which was prepared with the same conditions as those prevailing in the centrifuge model tests under impact load shows that the response acceleration and induced deformations are very similar to the results obtained from centrifuge tests and the asphalt core has a same behavior in both numerical and physical models. The same outcomes have been obtained from the other centrifuge tests and their related numerical models (Baziar et al., 2007). Table 5 presents the induced deformations in the asphalt core dam under impact loading for both methods of modeling.

Table 5: deformation of asphalt core of the prototype model under impact loading

Method	Shear strain of asphalt Core (%)	Lateral displacement of asphalt core (cm)	Settlement of Asphalt Core (cm)
Numerical Model	1.4	24	3.2
Centrifuge model (Test-5, 80g)	1.8	32	2.2

CONCLUSION

In this research, in order to investigate the dynamic behavior of asphalt concrete core dam, numerical analysis was carried out under earthquake loading. To determine deformation properties for use in the numerical models, laboratory tests including static and cyclic triaxial tests and wave velocity measurements by the pulse method have been performed on asphalt samples.
Also, the dynamic behavior of an asphalt core dam has been

studied using centrifuge model test at 80g acceleration.
From the results of this study, the following conclusions have been drawn:

- The cyclic triaxial tests data show that the dynamic shear modulus, G, of asphalt material is strongly dependent on the shear strain.

- The triaxial tests under cyclic shear stress of 0.1 to 0.2 MPa, which corresponds approximately to the load of earthquakes with Richter magnitude 6.0 to 6.8, acting on Meyjaran asphalt core dam, show that the induced deformations on samples of asphalt concrete core material are very small and there is no sign of any material deterioration or cracking.

- Under moderate earthquake loading using the Friuli Earthquake with a_{max}=0.24g, and a strong earthquake; Irpinia with a_{max}=0.5g, the induced deformations in dam body are small and the asphalt core remains watertight.
- The centrifuge test results shows that under an impact loading with a large acceleration of 0.76g at the base of model, the induced deformations in the dam body were small and there was no sign of failure or sliding. Lateral displacements of asphalt core which increases from the bottom to the top of the core is also small such that the maximum induced shear strain reaches 1.8% .

- The numerical results correspond well with the observations and monitoring data from the centrifuge tests. It is concluded that numerical models can simulate dynamic behavior of asphalt core dams reliably.

ACKNOWLEDGEMENTS

The authors would like to thank Professor Hoeg (Norwegian Geotechnical Institute) for his fruitful discussion about this subject and valuable comments on this research. Sincere thanks are also due to Dr. Ali Noorzad (Iran Water Resources Management Organization, IWRMO) for his assistance and support during this study and Dr. M.K. Jafari (International Institute of Earthquake Engineering and Seismology) for his support to perform the cyclic triaxial tests.

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