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Three-Dimensional Effects on the Dynamic Response of the Dariyan Dam

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Abstract

The Dariyan dam with 180m height is one of the highest rockfill dams in IRAN. The dam is located in high seismic zone. The ratio of crest length to the dam height is a little over 2. So, three dimensional effects of the valley on the dynamic response of the dam are not negligible. To study the dynamic response of the dam in three-dimensional conditions, linear and nonlinear dynamic analyses were performed by means of FLAC3D software. These analyses have been demonstrated that the maximum crest acceleration in three-dimensional analysis is much higher than 2D analysis and also permanent displacements of the dam body in 3D analysis are increased.

Keywords: Rockfill dam, Dynamic analysis, Three-dimensional analysis, Nonlinear analysis.

1. INTRODUCTION

The Dariyan dam is constructed on Sirvan River which is located in north-west of IRAN. The dam is one of the most important components of the Garmsiri project. Since the dam is located in a relatively narrow valley and in a high seismic zone, the three dimensional effects will not be negligible in earthquake conditions. Therefore, 3D dynamic analysis was performed by FLAC3d software in order to make a more accurate evaluation of the dam body behavior during seismic loading.

Developing more sophisticated softwares makes it possible to perform more realistic analyses. However, most studies in this field specially in academic activities have been focused on the effect of the shape of valley on dambody response and less attention has been paid to the amount of deformation. In most cases, the studies have been done by using linear or equivalent linear analyses. For instance, Ambraseys & Hatanaka in 1960 compared result of 2D and 3D analyses in rectangular shape of the valleys. They concluded that the results of the 3D analysis in L/H greater than 4 are similar to the results of 2D analysis. A similar study was performed by Makdisi in 1982 on triangular shape of valley that shows more Differences between the results of two and three-dimensional analyses. A more comprehensive study in this field was performed by Gazetas and Dakoulas in 1992. The results are summarized in Figure 1. As can be seen, in L/H ratios larger than 6, 3D effects are somewhat negligible. Based on these studies, natural period of the dam could be decreased 50 percent in very tight valleys.

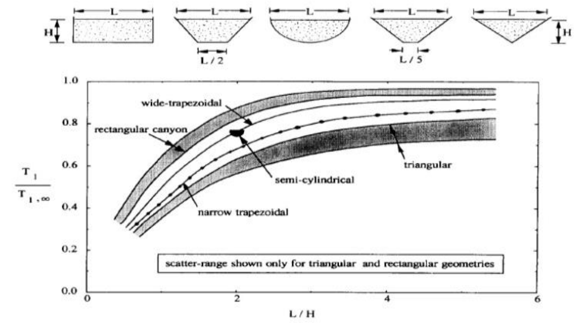


Figure 1. Comparing the 3D to 2D natural period of the dambody in different L/H [10]

2. CONSTITUTIVE MODELING AND ANALYSIS APPROACH

Cyclic loads in the unloading and reloading stress paths often create hysteresis loops. In equivalent linear method of analysis, area of a hysteresis loop represents energy dissipation factor or damping ratio and inclination of a hysteresis loop represents equivalent shear stiffness of the material. However, under realistic triaxial conditions, not only the damping and the stiffness changes with increasing shear strain during unloading-reloading condition but also plastic strain could occur due to loading. Actual behavior of a soil sample under cyclic loading compared to equivalent linear behavior is shown in figure 2 schematically. According to the above description, combination of equivalent linear parameters with a non-linear model is closer to real behavior of the material under cyclic loads. Thereupon, Mohr-Coulomb elasto-perfectly plastic model with adjustment of the stiffness and damping ratio for every element was used in nonlinear analysis. Unfortunately, because of numerical instability, it was not possible to perform fully non-linear analysis with strain hardening model.

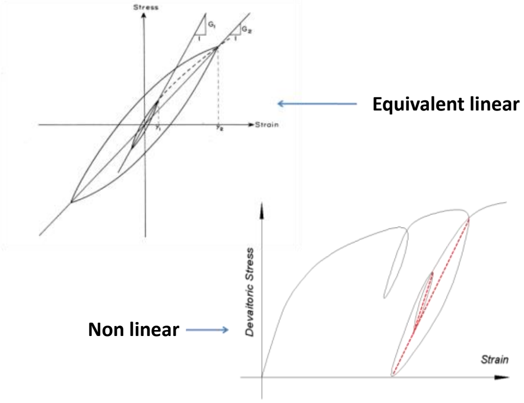


Figure 2. Comparison of equivalent linear behavior and actual behavior of materials in cyclic loading

3. ZONING AND GEOMETRY OF THE NUMERICAL MODEL

Cross section of the dam which is considered in two-dimensional analysis is shown in Figure 3. By some simplifications, dam body and the abutments are modeled in 3D analysis. Finite difference mesh of 3D model is shown in Figure 4. The model is composed of 19310 elements.

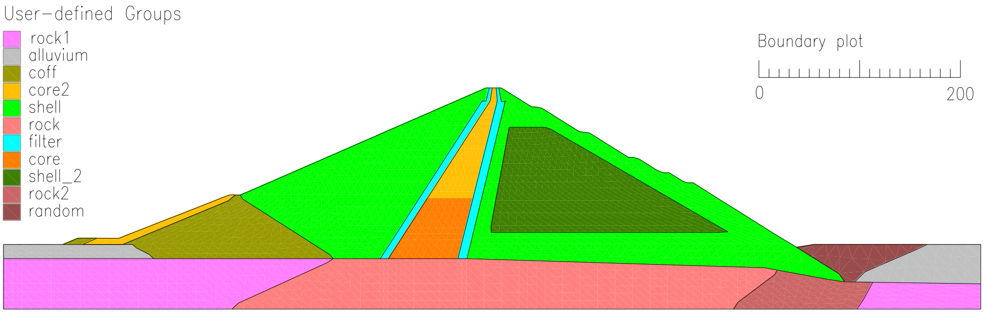
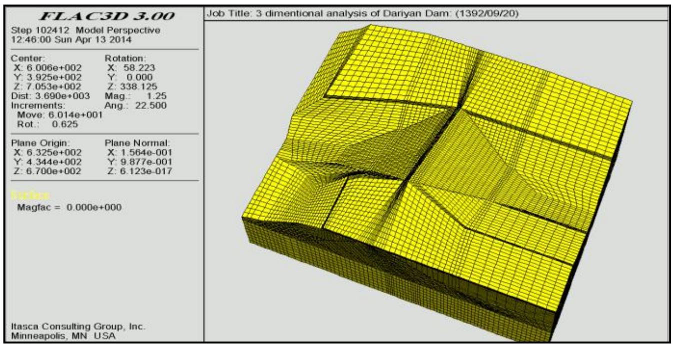


Figure 3. Cross section of the dam in two dimensional analyses



FLAC3D 3.00
Step 102412 Model Perspective
12:46:00 Sun Apr 13 2014

Center:
X: 6.006e+002
Y: 3.925e+002
Z: 7.053e+002
Dist: 3.690e+003
Increments:
Move: 6.014e+001
Rot.: 0.625

Rotation:
X: 58.223
Y: 0.000
Z: 338.125
Mag.: 1.25
Ang.: 22.500

Plane Origin:
X: 6.325e+002
Y: 4.344e+002
Z: 6.700e+002

Plane Normal:
X: 1.564e-001
Y: 9.877e-001
Z: 6.123e-017

Magfac = 0.000e+000

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Figure 4. FDM mesh of the dam and abutments in 3D model

Numerical model shown in figure 4 was used in Static analyses including the construction stages and impounding. Since dynamic analysis of the dam body and foundation together was very time consuming, in dynamic stage the foundation and abutments of the model were removed and the scaled time histories of acceleration components were applied to the boundary of the dam body and foundation. In dynamic analysis, time step is dependent on the element size and stiffness. The time of calculations not only increases with increasing number of elements but also increases when the time step decreases. Therefore, analysis that considers the abutments took several months to perform. Shear modulus of the foundation is very high compared to the dam body material, therefore, considering top of the foundation as a seismic base is a reasonable assumption. Obviously, by removing the abutments, amplification effects of the abutments are neglected.

4. INPUT PARAMETERS

Table 1 presents the assumed shear strength parameters for different zones of the model.

Table 1- Shear strength parameters of dam body zones

Zone	□$_d$□ *(gr/cm^3)*	*C* *(KPa)*	□$_f$ *(deg)*
(Shell)	2.2	70	39.5
(Shell_2)	2.2	60	38
(Core)	1.75	10	25
(Core2)	1.65	20	21.5
(Filter)	1.8	0	32
(Alluvium)	1.7	5	16.5

Maximum shear modulus (G_{max}) for different materials were defined as follows:

$$G_{\max} = 13000\frac{(2.17-e)^2}{1+e}\times(\sigma'_{ave})^{0.55} \qquad (kokusho\,\&\,Esashi, 1981) \qquad \text{Rockfill (Shell)} \qquad (1)$$

$$G_{\max} = 3270\frac{(2.97-e)^2}{1+e}\times(\sigma'_{ave})^{0.5} \qquad (Hardin\,\&\,Black, 1968) \qquad \text{Clay Core} \qquad (2)$$

$$G_{\max} = 220\times 60\times(\sigma'_{ave})^{0.5} \qquad (Seed\,\&\,Idriss, 1970) \qquad \text{Filter} \qquad (3)$$

$$G_{\max} = 220\times 90\times(\sigma'_{ave})^{0.5} \qquad (Seed\,\&\,Idriss, 1970) \qquad \text{Alluvium} \qquad (4)$$

In equations (1) to (4) *e* is void ratio which was considered 0.4, 0.3 and 0.2 for Core, filter and shell material, respectively. Poisson's ratio was assumed equal to 0.3 for core and filters materials and equal to 0.2 for the rockfill shells. Variation of shear modulus and damping ratio versus cyclic shear strain are shown in figure 5.

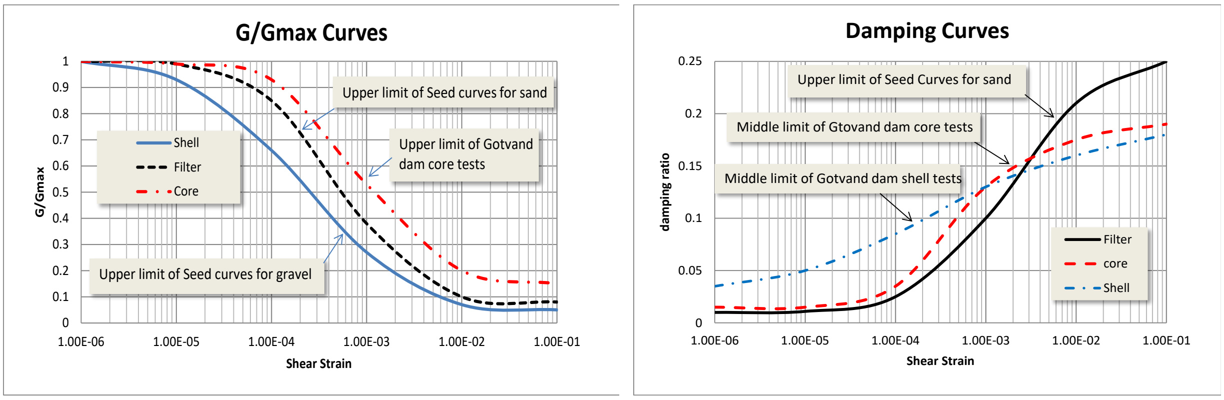

Figure 5. Damping ratio and G/G_{max} versus cyclic shear strain

5. INPUT MOTIONS

Khorgu scaled time history for Safety evaluation was used in the analyses. Horizontal and vertical components of acceleration are shown in figure 6. Maximum horizontal and vertical acceleration components are almost equal to 0.6g.

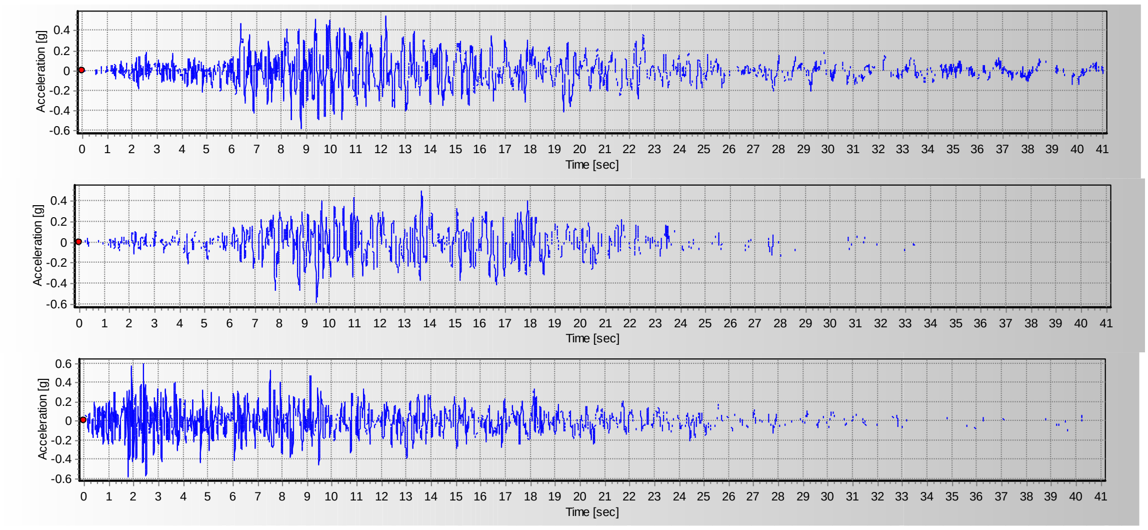

Figure 6. Khorgu scaled accelerograms components in the MCL

6. EQUIVALENT LINEAR ANALYSIS

Using the equivalent-linear method (Seed and Idriss 1969), a linear analysis was performed with some initial values assumed for damping ratio and shear modulus in the various regions of the model. **B**y reference to defined curves that relate damping ratio and secant modulus to amplitude of cycling shear strain, the maximum cyclic shear strain was recorded for each element and used to determine new values for damping and modulus. The new values of damping ratio and shear modulus were then used in a new analysis of the model. The whole process is repeated several times, until there is no further changes in properties.

The G/G_{max} ratio contours at the end of equivalent linear analysis at the middle section of the model are shown in figure 7. The Damping ratio contours are shown in figure 8. As can be seen, minimum G/G_{max} ratio in the dam body is calculated less than 0.3. Maximum damping ratio is about 13% and 10% for core and shell respectively. Horizontal and vertical components of acceleration at the middle of the dam crest are shown in figure 9. Maximum horizontal acceleration at the middle of dam crest is estimated more than 3.1g and 2.5g for upstream to downstream direction and for the direction parallel to the dam axis, respectively. Maximum vertical component aligned with the Earth's gravity is calculated more than 2.1g. While, based on 2D analysis, maximum horizontal and vertical components of the crest acceleration were calculated equal to 1.4g and 0.8g, respectively. Maximum acceleration in different elevations of the core axis for 2D and 3D analysis are compared in figure 10. In 2D analysis amplification of acceleration occurs near to the dam crest while in 3D analysis, the acceleration was amplified strongly even in middle of the dam height.

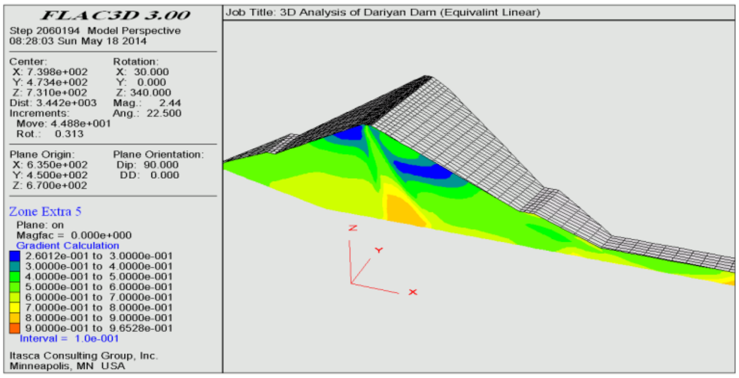

Figure 7. The G/Gmax ratio contours at the end of equivalent linear analysis

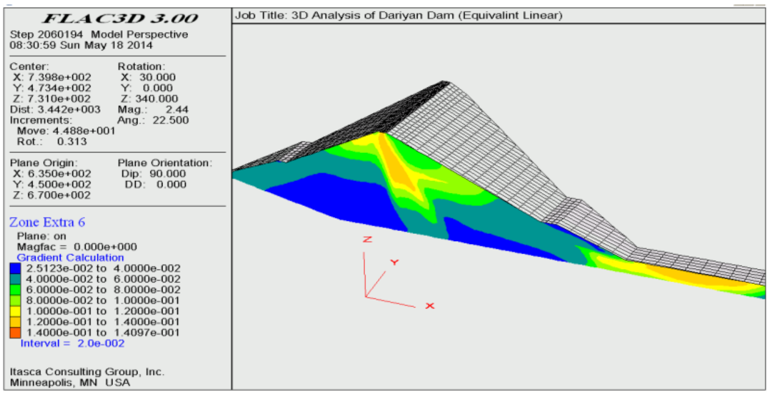

Figure 8. The Damping ratio contours at the end of equivalent linear analysis

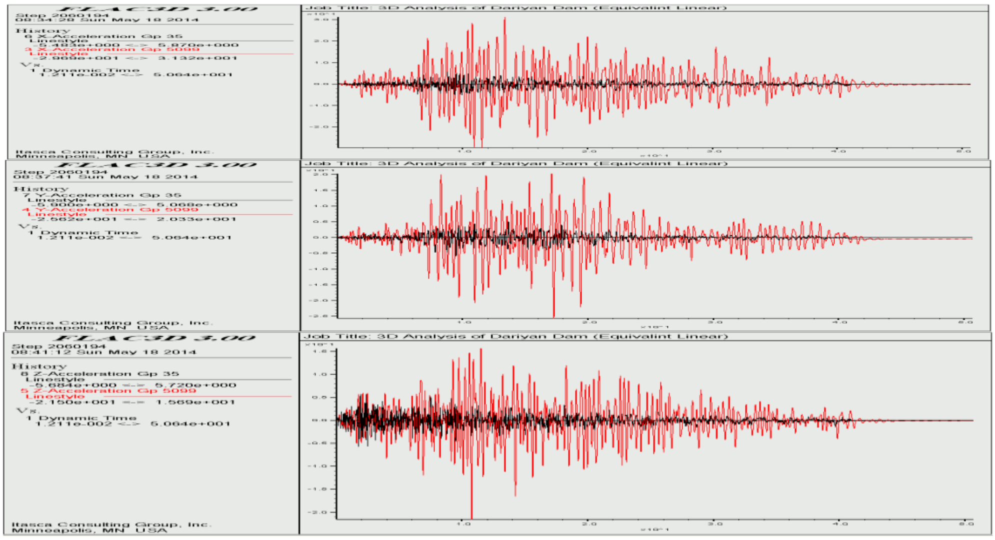

Figure 9. Crest acceleration components records

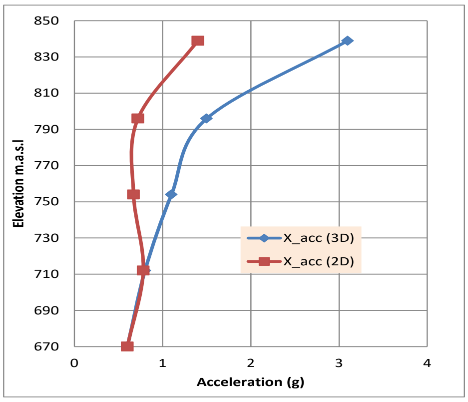

Figure 10. Comparison between 2D and 3D analysis
(Maximum horizontal acceleration of different elevations of the core)

7. NONLINEAR ANALYSIS

In a nonlinear analysis, permanent displacements of every nodes at the end of the dynamic analysis will be directly visible. Mohr-Coulomb elasto-perfectly plastic model was used in nonlinear analysis. The results of this analysis are presented in Figure 11. In this figure, the horizontal displacement contours along with displacement vectors are shown on the middle cross section of the dam. The result of 2D analysis is shown in Figure 12. As can be seen, the pattern of displacements of 3D analysis is similar to the 2D analysis. The crest settlement in 3D analysis is estimated about 2.2 m which is about 20% higher than the 2D analysis. Main features of 2D and 3D analysis results are summarized in table 2. Based on nonlinear analysis, maximum horizontal acceleration at the middle of dam crest is estimated more than 2.0g and 1.6g for upstream to downstream direction and direction parallel to the dam axis, respectively. Maximum vertical component in the opposite direction of gravity is calculated more than 2.6g and in the direction of gravity, it is close to 1.2g. The acceleration components near the dam crest are strongly amplified in 3D condition. According to the literature, Natural period of the dambody in 3D condition reduced and resonance condition is occurred. In addition, by applying another component of acceleration, the input energy increases. Despite the significant increasing of the crest acceleration response in 3D condition, the permanent displacement was increased to a lesser extent.

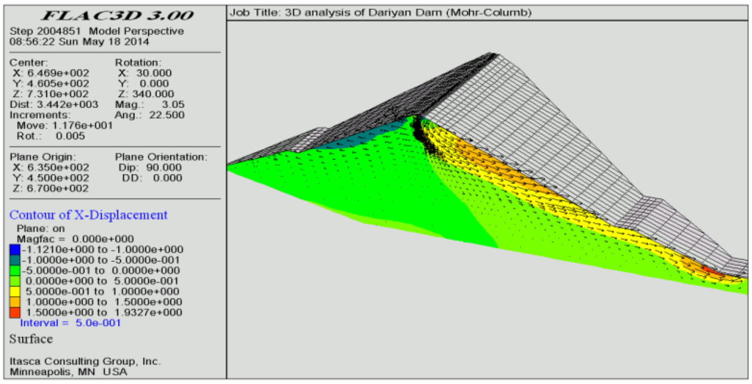

Figure 11. Horizontal displacement contours with displacement vectors on the middle cross section of the dam

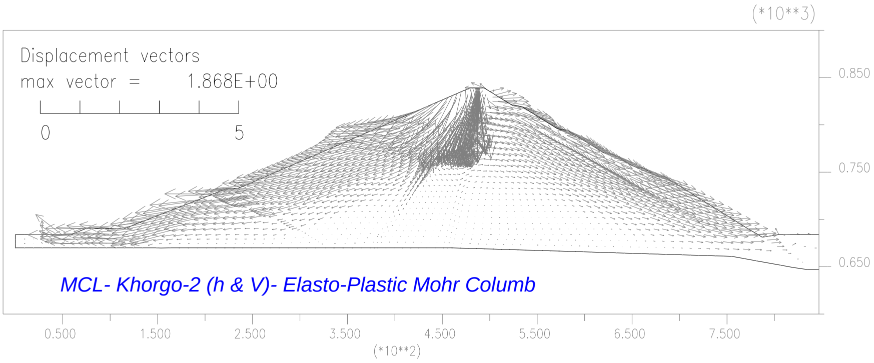

Figure 12. Displacement vectors of 2D analysis

Table 2- Summary of 2D and 3D linear and nonlinear dynamic analyses

Main features		unit	Equivalent linear			Nonlinear(Mohr Coulomb)		
			2D	3D	3D/2D	2D	3D	3D/2D
Maximum crest acceleration	horizontal (cross)	(g)	1.50	3.10	2.07	1.60	2.00	1.25
	horizontal (axis)		-	2.50	-	-	1.60	-
	vertical		0.80	2.10	2.63	1.00	2.60	2.60
Maximum U/S berm acceleration	horizontal (cross)	(g)	1.30	1.80	1.38	0.80	1.28	1.60
	horizontal (axis)		-	1.55	-	-	1.20	-
	vertical		0.40	0.85	2.13	0.70	0.75	1.07
Maximum D/S berm acceleration	horizontal (cross)	(g)	1.50	1.30	0.87	0.90	1.10	1.22
	horizontal (axis)		-	1.90	-	-	1.40	-
	vertical		0.55	1.40	2.55	1.00	1.00	1.00
Crest settlement		(m)	-	-	-	1.80	2.20	1.22
Maximum Horizontal Displacement	U/S face	(m)	-	-	-	1.00	1.50	1.50
	U/S berm		-	-	-	1.20	2.00	1.67
	D/S face		-	-	-	0.55	1.20	2.18

8. CONCLUSIONS

Considering the three-dimensional effects of the valley, leads to a further increase in dam crest acceleration. The ratio of amplification of 3D analysis to 2D analysis was more than 2. Both reducing of natural period of the system and inducing of input energy can explain the differences. However, in the 3D analysis acceleration near the dam crest was increased more than 2 times (compared to 2D analysis), the crest settlement has increased by about 20 percent. It should be noted that because of the densification of the rockfill materials due to shaking, the displacements may be actually higher than the calculated values. Although, the amount of displacements is higher than some of recommendations presented in the technical literature, since there is enough freeboard (11m), there will be no great concern about the dam safety during earthquake loading.

9. ACKNOWLEDGMENT

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