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DYNAMIC RESPONSE OF MASJED-SOLEYMAN ROCKFILL DAM

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SUMMARY

Masjed-Soleyman zoned rockfill dam with 177 m height was constructed and impounded in South-West of Iran in 2001. Seismicity and risk of earthquake hazard in this region is high. After impounding, few earthquakes, greater than 5 Richter magnitude; occurred close to the dam site. The response of dam body was recorded using accelerometers installed at the crest and downstream shell.

In this paper the time and frequency history of recorded accelerations are presented and it is tried to estimate dynamic properties like fundamental frequencies of the dam from these records.

In the second part of the paper, the dynamic response of dam is estimated using two constitutive models named equivalent linear and elasto-plastic nested surface models. In both analyses three dimensional idealization of dam considering the stiffness of abutments is assumed. Finally the real recorded dynamic characteristics of dam are compared to the estimated ones obtained from numerical analyses. The real recorded response of dam is comparable to those obtained from elasto-plastic three dimensional numerical method.

INTRODUCTION

Observation and prediction of dynamic response of embankment dams to earthquake motions is extremely important. Earth dams are large three-dimensional non-homogeneous structures constructed from inelastic materials, sometimes in narrow valleys. Nonlinear behavior of soil materials in large strains such those induced in earth dams during strong ground motions is one of the main mechanical characteristics of these materials. In addition many test results has shown that these materials have non-elastic and hysteretic behavior in cyclic loading. Comparison of several dynamic analysis and recorded response of earth dams in actual earthquakes have shown that accounting nonlinear behavior of materials is one of the most important parameters in predicting the actual response of earth dams in earthquakes [1]. Installation of reliable and sufficient quantity of motion measuring devices is very important in monitoring and recording dam responses.

In this paper behavior of a high rockfil dam, Masjed-Soleyman Dam; subjected to some moderate earthquakes is studied. At first part response of dam at location of installed accelerometers in crest and

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downstream slope, due to moderated seismic excitations are presented. In the second part prediction of three dimensional dynamic response of dam using two numerical methods, are presented. To account nonlinearity in material behavior two methods are considered. Equivalent linear method and an elasto-plastic model in time domain are used and comparison between their results is made. In current engineering practice the dynamic response of earth dams is evaluated by determining the response of the maximum section using two dimensional (2-D) analyses. However, for dams located in narrow canyons, like Masjed-Soleyman Dam; the assumption of plane strain condition is not valid and the response of dam has three dimensional (3-D) nature. Finally, the specification of the recorded and computed at dam crest are compared.

MASJED-SOLEYMAN DAM

As the highest embankment dam in Iran, Masjed-Soleyman dam is a zoned rockfill dam constructed in South West of Iran, in Khuzestan province. The dam is located in Zagros Mountains (North 32^0, East 49.4^0) on Karun River. The risk of earthquake hazard in this region is high. It was constructed on rock foundation and is 177 *m* high and has crest length of 490 *m*. Upstream and downstream slopes are at 2:1, 1.7:1, respectively. Figure 1 shows the maximum cross section, a longitudinal cross section and a plan view of the dam. The crest length to height ratio of this dam is about 2.8, which implies presence of three dimensional effects in static and dynamic behavior of dam. The construction of dam was completed on year 2000 and the first impounding was started on 19th of December 2000. Also in Figure 2 the aerial view of the dam after completion and first reservoir impounding is shown.

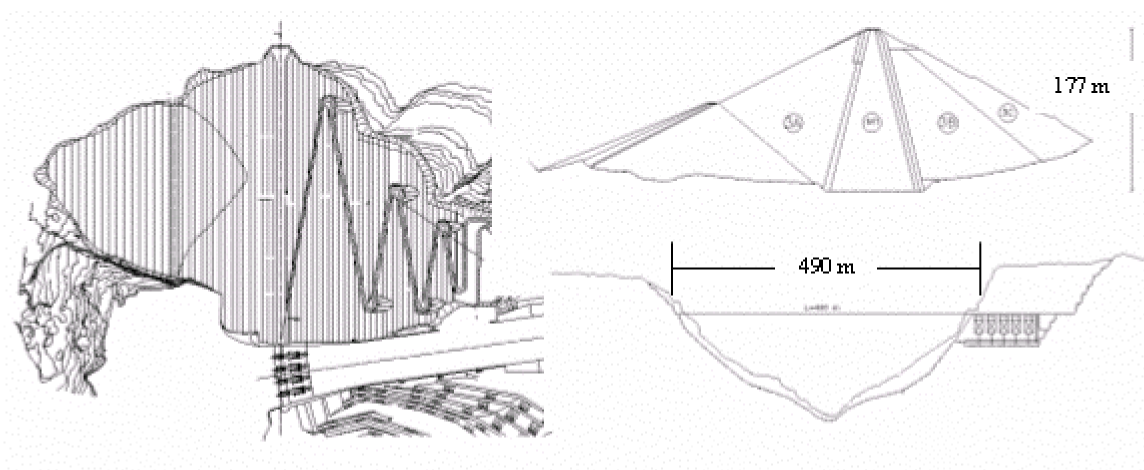

Figure 1: Plan view, maximum and longitudinal section of Masjed-Soleyman dam

DAM SITE GEOLOGY AND SEISMICITY

The rock types in the dam site comprise a variety of sedimentary rocks of alternation soft and resistant weathering characteristics. Rock types include Bakhtyari, Aghajari, Mishan and Gachsaran formations, combined with intense seasonal rainfalls.

The area is subjected to ongoing compression forces, which have warped the sediments into a series of folds and given rise to high angle reverse fault movement throughout the basement rocks.

Over the past century that modern seismic instruments have been installed, a large number of high level earthquakes were recorded in the region. Major earthquakes in Khuzestan are shallow and have focal depths in the range of 8 to 15 *km*; some where below the level of sedimentary rocks in the crust. Masjed-Soleyman dam site is located in an active seismic region and the seismic hazard and risk rating according to the ICOLD recommendation is extreme (*IV*) at the dam site. Based on statistical, probabilistic and deterministic methods, the peak horizontal and vertical ground acceleration (*PGA*) obtained 0.26g and 0.19g, respectively; for design basis level (*DBL*) motion [2].

DAM INSTRUMENTATAION

Due to the importance of this dam, a very dense instrument network was deployed inside and around the dam. Concerning high seismicity of the region 7 accelerometers were installed. Also, other types included pore and soil pressure meters, inclinometers, surface check points; were placed. The strong motion recorders are *SIG* type. In Figure 3 installed accelerometers at crest and left abutment are shown. 5 numbers of these accelerometers are placed in maximum cross section, called chainage 260 *m*. This maximum section and position of the accelerometers at this section is shown Figure 4. Accelerometers named as *EA2* and *EA3* located inside the dam body were found not to responding few weeks after installation and progress of dam embanking. Later inspections reviled that these two are not working due to cutting of their connecting cables and it was not possible to replace them, unfortunately. Also, bottom accelerometer called *EA4* has not been installed due to damage possibility to it by ongoing activities in the *GTB* bottom grouting tunnel.

Figure 2: Arial view of Masjed-Soleyman Dam on 2001

DAM RESPONSE TO GROUND MOTIONS

From September 2002 to March 2003 many weak to moderate quakes were occurred in the region and recorded by the available installed accelerometers. As mentioned, these motions were recorded by only two accelerometers installed at crest (*EA1*) and downstream dog way (*EA5*). Response of the dam excited by some of these motions at the mentioned locations is studied at this part.
Figures 5, 6 and 7 show the time and frequency history of dam recorded at two locations (crest: *EA1* and

Figure 3: Photos of installed *SIG* strong motion recorders

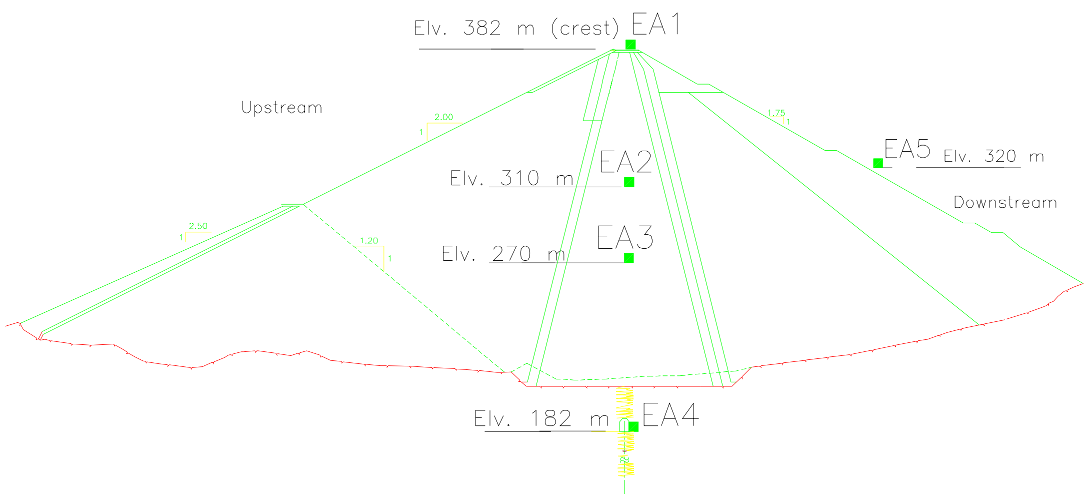

Figure 4: Maximum dam cross section and location of deployed accelerometers in and on this section (Ch. 260 *m*)

dog way: *EA5*) during seismic excitations on 2002.10.4; 2002.10.7 and 2002.10.31; respectively, in longitudinal and transverse directions.

Also, in Table 1 general specifications of the four seismic events recorded at the mentioned period are summarized.

NUMERICAL SIMULATIONS

In this section the results of some numerical simulations related to dynamic response of Masjed-Soleyman dam is presented. The detail explanation of the analyses could be found in an ICOLD 2003 paper [3 & 4], and some brief information is presented here.

Table 1: Recorded peak accelerations at crest (*EA1*) and dog way (*EA5*) due to four excitations

Date	Record Location	Peak Acceleration Value (*mg*)		
		X (L)	Y (T)	Z (V)
2002.10.4	*EA1*	67.36	24.00	42.00
	EA5	29.44	81.60	105.92
2002.10.7	*EA1*	73.36	21.74	41.60
	EA5	27.68	56.00	41.84
2002.10.31	*EA1*	90.00	28.56	67.12
	EA5	53.92	82.72	60.64
2002.12.30	*EA1*	15.52	22.24	12.16
	EA5	10.08	15.76	22.80

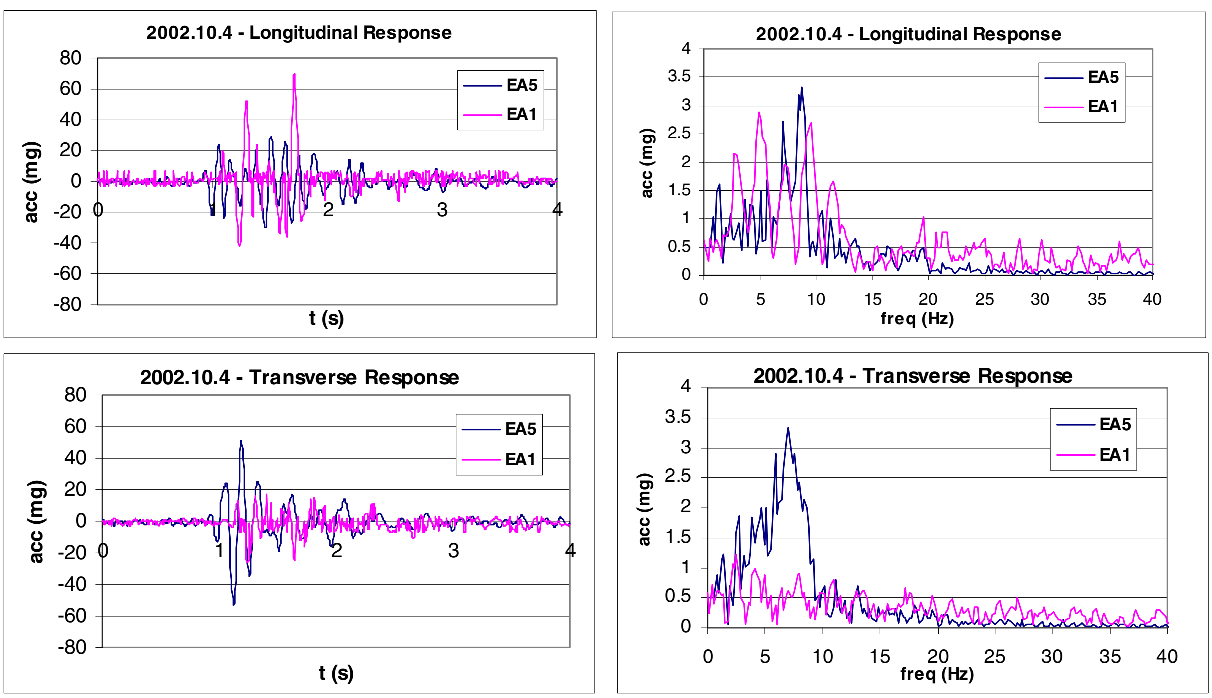

Figure 5: Time and frequency history of dam recorded at two locations (crest: *EA1* and dog way: *EA5*) during seismic excitation on 2002.10.4, in longitudinal and transverse directions

Geometry

Three dimensional dynamic response of the dam is estimated using finite element analyses. Figure 8 shows the 3D model, with 874 eight node isoparametric elements and 1162 nodes.

Input Ground Motions

The model is subjected to two different levels of ground motions, which were proposed in the earthquake hazard analysis report of dam. For the first input motion referred to DBE level for dam site, (NS) component of San Fernando record is used which is normalized to 0.19g, maximum acceleration. In the

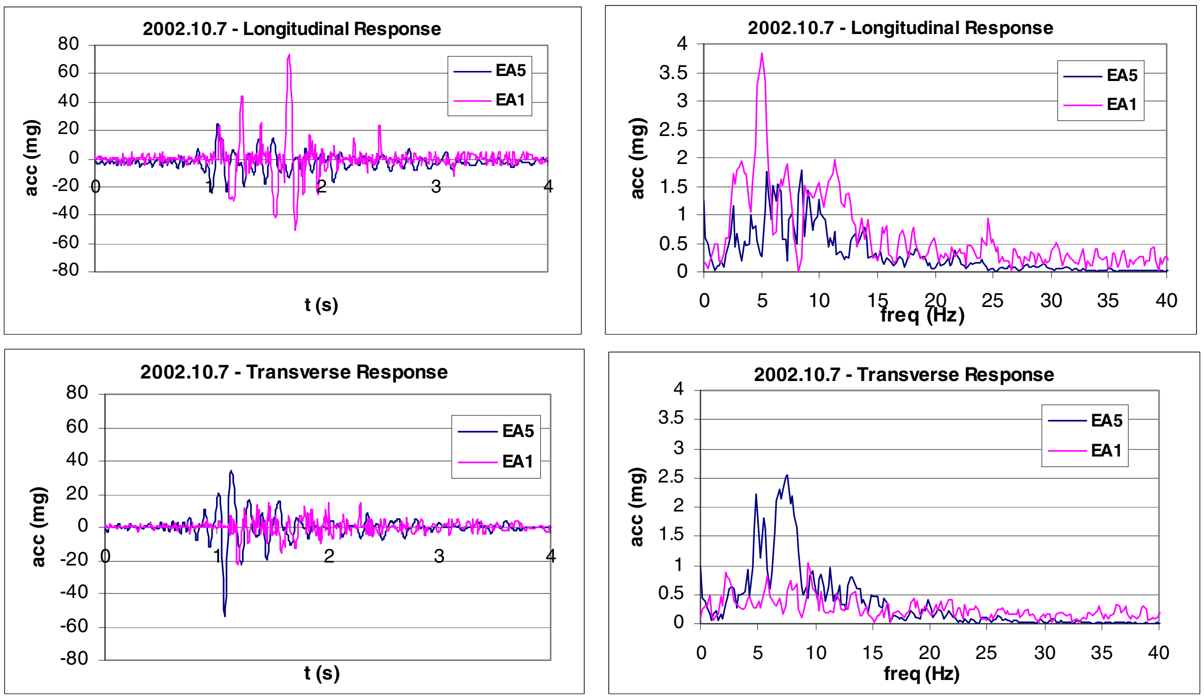

Figure 6: Time and frequency history of dam recorded at two locations (crest: *EA1* and dog way: *EA5*) during seismic excitation on 2002.10.7, in longitudinal and transverse directions

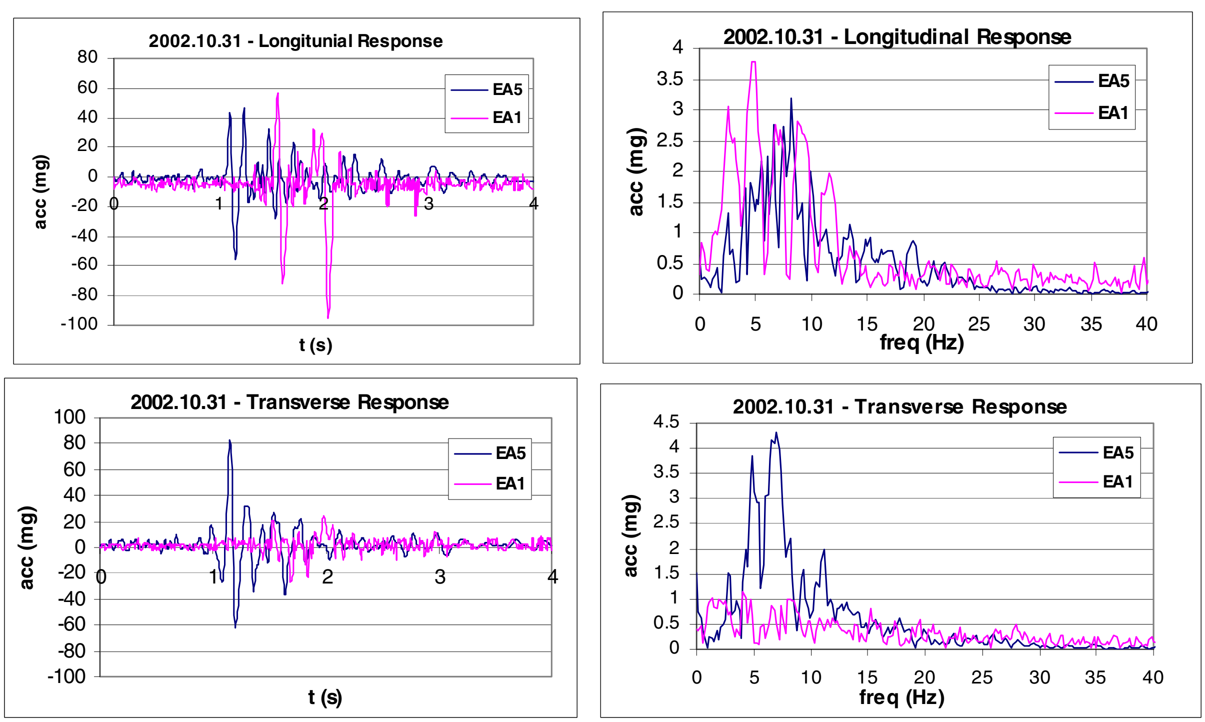

Figure 7: Time and frequency history of dam recorded at two locations (crest: *EA1* and dog way: *EA5*) during seismic excitation on 2002.10.31, in longitudinal and transverse directions

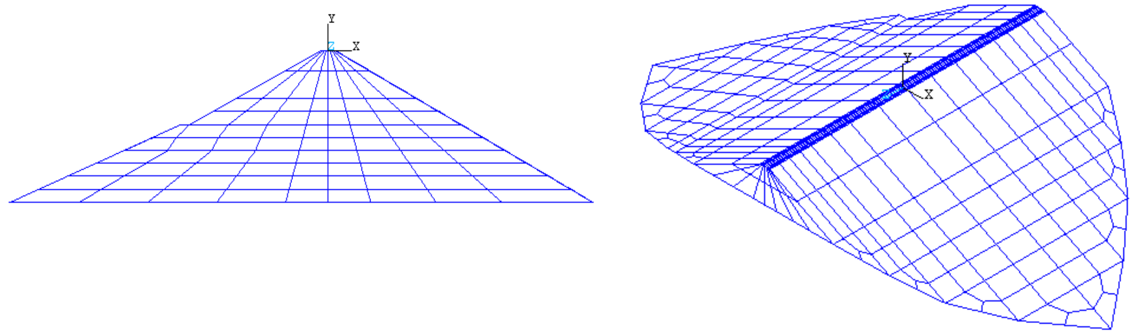

Figure 8: Three dimensional finite element model of the dam (maximum section and isometric view)

following we name this record as load case No.1. The second input motion referred to MCE level and is the (L) component of Manjil earthquake (1991) record normalized to 0.37g, maximum horizontal acceleration. This is the load case No.2. Fig. 4 shows the input acceleration time histories and their Fourier amplitude spectra. The input motions were applied in the transverse or upstream-downstream direction to the nodes at the base.

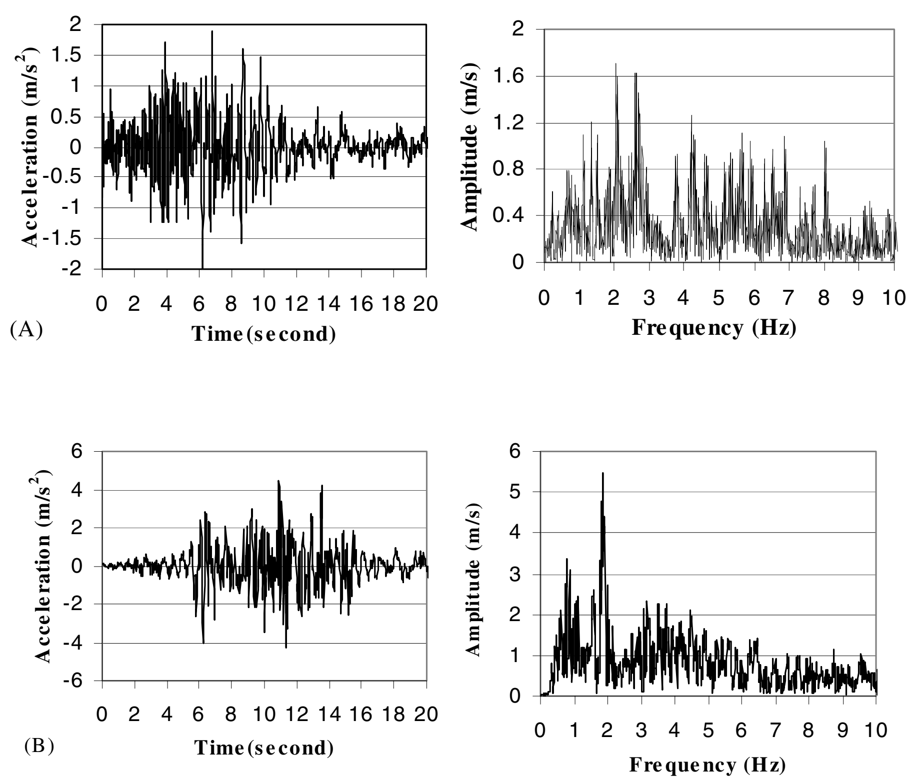

Figure 9: Dynamic characteristics of two excitations used in numerical analyses: (A) NS component of San Fernando Eq. - load case 1; (B) L component of Manjil – Iran Eq. - load case 2

Material Models

Two numerical methods are used for dynamic analyses. First equivalent linear method as a simple and well known method for modeling non-linear and hysteretic behavior of materials. Second method for modeling nonlinear hysteresis behavior of soil materials is using plasticity based mathematical models.

In first model the hysteresis loop is modeled by its general slope and its internal area, which shows the energy dissipated in one cycle of loading. Damping ratio is introduced by ratio of this dissipated energy to the elastic energy. These parameters depend on the shear strain level induced in the soil elements; thus an iterative procedure is required to obtain consistent stiffness and dissipation parameters with shear strain level.

In the second method used in this paper, the nonlinear stress- strain relation is represented by multi-linear kinematic hardening model. This model is a simple total stress multi yield surface plasticity model. Here it is assumed that because of the relatively short duration of loading, a significant change in soil strength caused by a change in pore water pressure is unlikely [5]. The model in simple shear experiment would predict a typical Masing type behavior. In three dimensional stress space, the surfaces are visualized as a family of cylinders with axis parallel to the hydrostatic axis or space diagonal.

Results of Numerical Analyses

Nonlinear analyses can only be performed in time domain. For solution of time domain equations, Newmark algorithm with α=0.2525, β=0.505 is used. As mentioned, for modeling material nonlinearity two methods are used: equivalent linear method and multi yield surface plasticity model with kinematic hardening. Hyperbolic model is used for stress-strain curves. For each element according to the static stresses, stress-strain curve is approximated with 15 pieces of lines. Since 15 yield surfaces are used which their sizes remain constant for each element during loading. ANSYS computer program is selected for this purpose and some additional subroutines are added to it in order to perform both equivalent linear and nonlinear elasto-plastic analyses. Time and frequency history of dam response at dam crest is shown in Figure 10. It could be seen that the earthquake energy is transmitted by higher frequencies using elasto-plastic nonlinear method comparing to equivalent linear one.

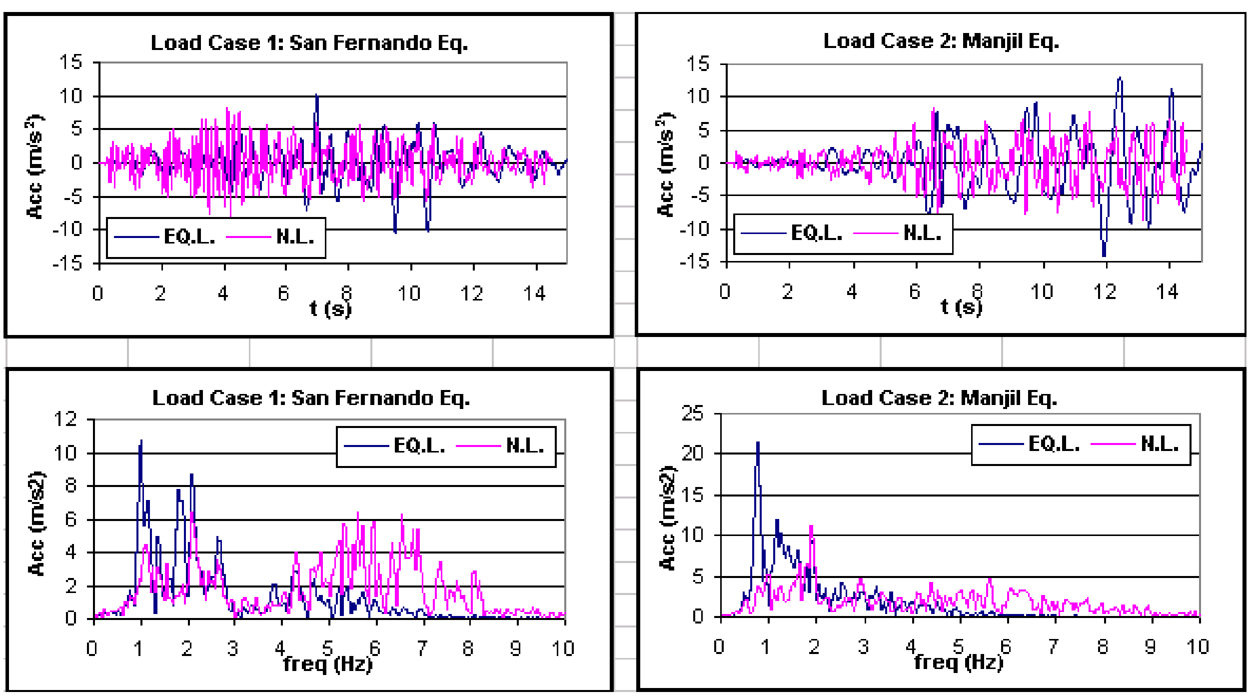

Figure 10: Crest acceleration time histories and their Fourier amplitude spectra in EQL and NL analyses for two load cases.

DISCUSSION

As mentioned before the input motions of the considered excitations in this paper occurred on October 2002 were not recorded due to some problems. Therefore, in this part the recorded response of dam at crest due to some moderate excitations are compared to the estimated of response of dam at crest level to some strong ground motions (load cases 1 and 2). It was mentioned that the 3D numerical analyses were conducted for one direction excitation (transverse direction) and they should be compared to the corresponding records. Figures 5, 6 and 7 are the recorded response in both horizontal directions; and Figure 10 presents dam behavior estimated using two numerical methods. Comparisons could be focused on frequency histories. It could be seen that the main part of the earthquake energy is transmitted between 2 to 10 Hz for both *EA1* and *EA5* accelerometers (Figures 5, 6 and 7). This parameter is between 0.7 to 3 Hz for EQL analyses, and 1 to 8 Hz for NL one (Figure 10). Therefore, although the results do nit quite agree with each other, it could be seen that the results of nonlinear elasto-plastic analyses are more close to the real recorded responses. Some reasons could be blamed for the difference between recorded and computed behavior such as: difference in the amplitude and frequency content of recorded and analytical excitations; interaction of the three components of the excitations for each seismic event which was ignored in computations.

CONCLUSION

Dynamic response of a high zoned rockfill dam is considered. Masjed-Soleyman Dam with 177 *m* height was excited by some moderate ground motions. The recorded three components of acceleration time histories due to some moderate ground motions were presented at two locations. Time and frequency histories of acceleration at crest and down stream slope of dam recorded by accelerometers; are analyzed. It was observed that the peak and predominant frequency of the recorded waves were different for crest and down stream slope.

Also, the behavior of dam during earthquake shakings was predicted numerically using two methods: equivalent linear and elasto-plastic methods, in both dam geometry was model three dimensionally for covering the effect of narrow valley of dam site. Comparison of the observed responses and estimated ones showed that elasto-plastic analyses are in good agreement with recorded waves, from natural frequency band point of view.

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