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Topography Effects in the Athens 1999 Earthquake: The Case of Hotel DEKELIA

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ABSTRACT

The effects of surface topography on the seismic ground response of the site of Hotel DEKELIA, which partially collapsed in the Athens 1999 earthquake, is studied by the finite element method. The hotel site is located at the crest of a 40m high bank of a stream crossing the area. 2-D and 1-D analyses of seismic ground response were conducted using five accelerograms recorded in past earthquakes (including the Athens 1999 earthquake) as input motion. Geotechnical data for the site were obtained from the results of a geotechnical investigation conducted at the hotel site whereas a V_{so} vs. depth profile was estimated by using the SASW method. The ground response analyses were conducted by assuming both equivalent-linear and truly non-linear soil behavior. The results indicate that surface topography has the potential of amplifying the peak horizontal accelerations and the maximum spectral accelerations (for period values ranging from 0.35sec to 0.50 sec) at the hotel site by up to 35% and 100%, respectively. It was also found that the local soil conditions at the site may have amplified significantly the input motion. It is concluded that the combined effects of surface topography and local soil conditions may have contributed to the partial collapse of the hotel.

INTRODUCTION

It is now widely recognized that the seismic ground motion caused by earthquake base excitations can be significantly modified by local site effects (Bard and Thomas, 2000). These effects include the *surface topography* and the *near-surface geology* effects. At present the state of knowledge on surface topography effects is less advanced compared to the near-surface geology effects despite the numerous studies conducted on the subject during the last 30 years. These studies were recently reviewed by Athanasopoulos et al. (1999).

The results of the studies mentioned above (and of many others e.g. Sanò and Pugliese, 1999) indicate an amplification of motion at the crest of the slopes of ridge-like or canyon-type topographies. The values of amplification depends on the relative size of the irregularity (compared to the incident wave-length), the angle of incidence and the type of incident wave, i.e. SV vs. SH. Amplification values range from 3 to 4 in the spectral domain and are less than 2 in the time domain (Finn, 1992).

In addition to the theoretical predictions, the amplification of surface motion in ridge -or steep slope- type topography has also been verified from measurements during natural earthquake events (Huang and Chiu, 1999; Zaslavsky and Shapira, 2000). The data reported by Jipson, (1987) demonstrate the amplification of peak horizontal accelerations in the uphill direction of a slope in Matsuzaki area (Japan). The measurements indicated an amplification at the crest (relatively to the base) varying from 1.8 to 5.5 with a mean value of 2.5.

In terms of damage patterns, increasing damages have been reported (Celebi, 1987) along the slope and the top of hills after the Chile 1985 earthquake. A characteristic example of increased earthquake damages close to the crest of a step-like topography has been reported by Castellani et al., (1982) for the case of the Irpinia 1980 earthquake and is illustrated in Figure 1. In this case the damages of an Italian village sitting at the top of a hill, were concentrated close to the crest of a steep slope whereas they were insignificant in the direction away from the crest.

Due to the rather limited extend of knowledge on the effects of surface topography most seismic codes do not take these effects into account when specifying the design motions. Thus the need for an increase of available instrumental and observational data on surface topography effects becomes evident.

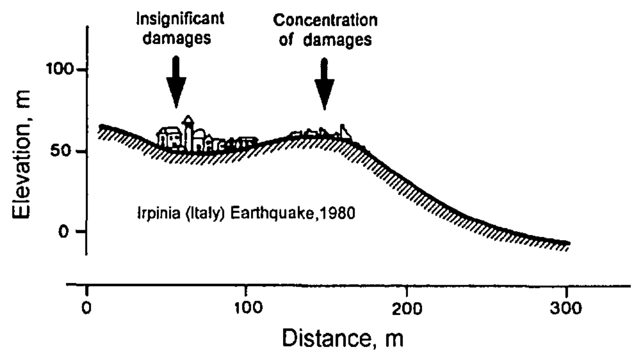

Fig. 1. Effect of surface topography on damage distribution in Irpinia (Italy) 1980 eathquake

The purpose of this paper is to present the results of a study on surface topography effects in the Athens 1999 earthquake. These effects are suspected to be responsible for the amplification of motion along the banks of a stream crossing the Athens area and for the partial collapse of the Hotel DEKELIA (and several other buildings) located on the banks of the stream.

EARTHQUAKE DATA

The Athens 1999 earthquake occurred at 2:55pm local time on September 7, 1999 with a surface wave magnitude Ms=5.9 and a focal depth of 18 km. The epicenter of the earthquake was located at about 20 km WNW from the center of city of Athens whereas the causative (normal) fault of the earthquake (Filis fault) is believed to have WNW direction and a length approximately equal to 16 km, as shown in Figure 2. Five accelerographs installed at distances of 15km to 17km from the epicenter recorded the free field surface motion of the main shock (with peak values of horizontal acceleration ranging from 0.07g to 0.53g).

The earthquake shook violently the buildings and other structures of the Athens metropolitan area, caused extensive structural damage and collapse of buildings and took the lives of 143 people. Preliminary reconnaissance and surveys of the affected area indicated a concentration of damage in the very near field of the event and the collapse of industrial buildings along the banks of a stream (Kifisos river) crossing the area in a general NE-SW direction. The Hotel DEKELIA was a three storey reinforced concrete building, with a soft ground floor, located at the crest of the west bank of Kifisos river, Figure 3. The hotel site is located 20 km from the earthquake epicenter and 5 km from the causative fault. The strong ground motion caused heavy structural damages to the hotel and the partial collapse of one of its wings. The hotel was demolished after the earthquake and is now being reconstructed.

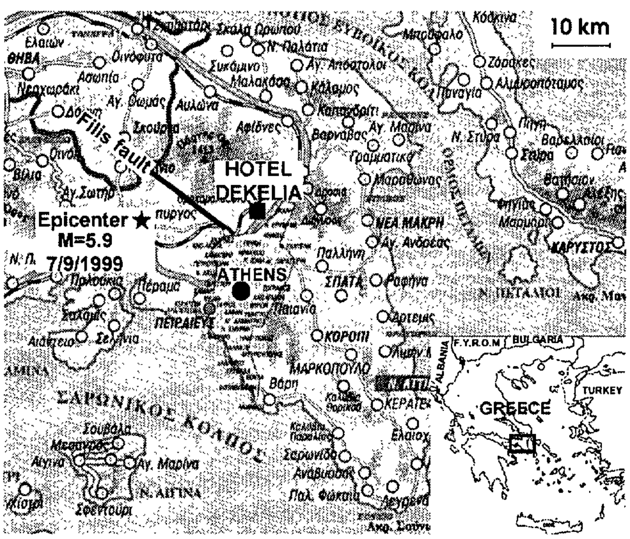

Fig. 2. Map of the greater Athens area showing the location of Hotel DEKELIA as well as the epicenter and causative fault of the 1999 Athens Earthquake

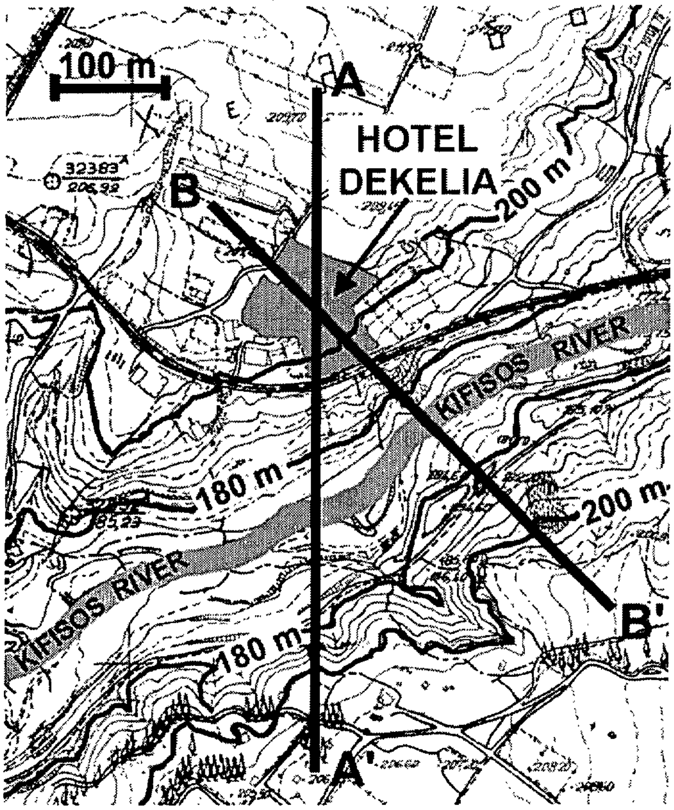

Fig. 3. Topographical map of the wider area of Hotel DEKELIA with the positions of the two cross-sections A-A' and B-B'

GEOTECHNICAL DATA

A geotechnical investigation was conducted at the hotel site including 4 exploratory boreholes (that reached a depth of 40m from ground surface), standard penetration tests (SPT) and sampling and laboratory testing. A simplified profile at the hotel site is shown in Figure 4. The profile indicates the presence of a surficial layer of fill with a thickness of 3m. The fill layer is underlain by a 3m thick layer of silty clay (CL-CH) which is, in turn, underlain by a silty gravel (GM) layer 2m thick. From the depth of 8m up to the maximum drilled depth of 40m the soil formations consist of silty clay (CL-CH). The values of blow count, N_{SPT}, of the subsoil of the site ranged from 10 to 95 indicating stiff/medium dense to hard/very dense soil formations. An average N_{SPT} vs. depth curve was estimated and shown in Figure 4b. No water table was encountered at the site up to the maximum drilled depth.

The low-amplitude shear wave velocity of soil, V_{so}, at the hotel site, was obtained as a function of depth by conducting in-situ tests of Spectral Analysis of Surface Waves (SASW) (Athanasopoulos and Pelekis, 1997). The depth of penetration of these tests reached 80m from ground surface. The diagram of Figure 5a depicts the variation of V_{so} vs. depth based on the results of SASW measurements. By using the value γ_t=19kN/m^3 for the unit weight of soil formations of the site the value of G_o was also estimated and plotted vs. depth in the

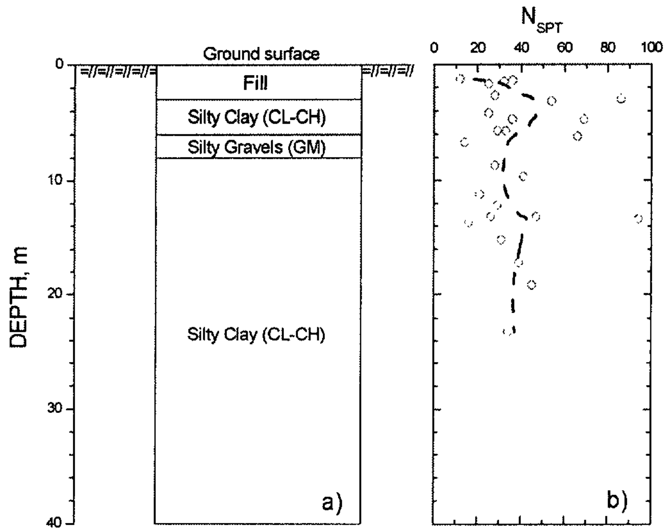

Fig. 4. a) Simplified soil profile at the site of Hotel DEKELIA b) measured values of N_{SPT} vs. depth

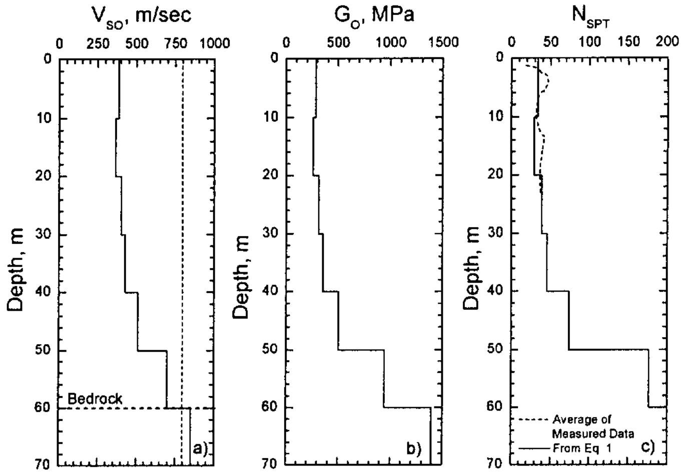

Fig. 5. a)Low amplitude shear wave velocity, b) shear modulus of soil formations vs. depth and c) comparison between predicted and measured values of N_{SPT}

diagram of Figure 5b. In the diagram of Figure 5a it is observed that the V_{so} value at the ground surface is 380m/sec. This value remains practically unchanged up to a depth of 40m at which the velocity starts increasing rapidly with depth and becomes equal to 800m/sec at a depth of 60m, which may be considered as a depth to the bedrock. The value of the fundamental period of soil column for vertical propagation of S-waves was estimated to be T_{so}=0.5sec.

In the diagram of Figure 5c, estimated values of N_{SPT} are plotted versus depth along with the measured values shown in Figure 4b. The estimated values were obtained by using an empirical V_{so}-N_{SPT} relationship (Eq. 1) developed by Athanasopoulos (1994, 1995).

$$V_{so}=107.6(N_{SPT})^{0.36} \qquad (1)$$

It may be seen in Figure 5c that the empirically derived (or estimated) values of N_{SPT} are in very good agreement with the measured values.

SEISMIC GROUND RESPONSE ANALYSES

The effect of surface topography on the seismic ground response of the hotel site was studied by conducting 1-D and 2-D analyses and comparing their results. Five accelelerograms of horizontal motion recorded in four past earthquakes (Patras 1993, Egion 1995, Athens 1999 and Kalamata 1986) were used as input motion in all analyses. The acceleration scale of these accelerograms was modified to make the peak value of horizontal acceleration equal to 0.16g. This value coincides with the peak value suggested by the new Hellenic Seismic Code (EAK 2000) for the seismic zone of the hotel site (Zone II). The time histories and corresponding acceleration response spectra (for 5% critical damping) of the five input earthquake motions are shown in Figure 6. It may be seen that the values of predominant period of the input motion range from 0.1sec

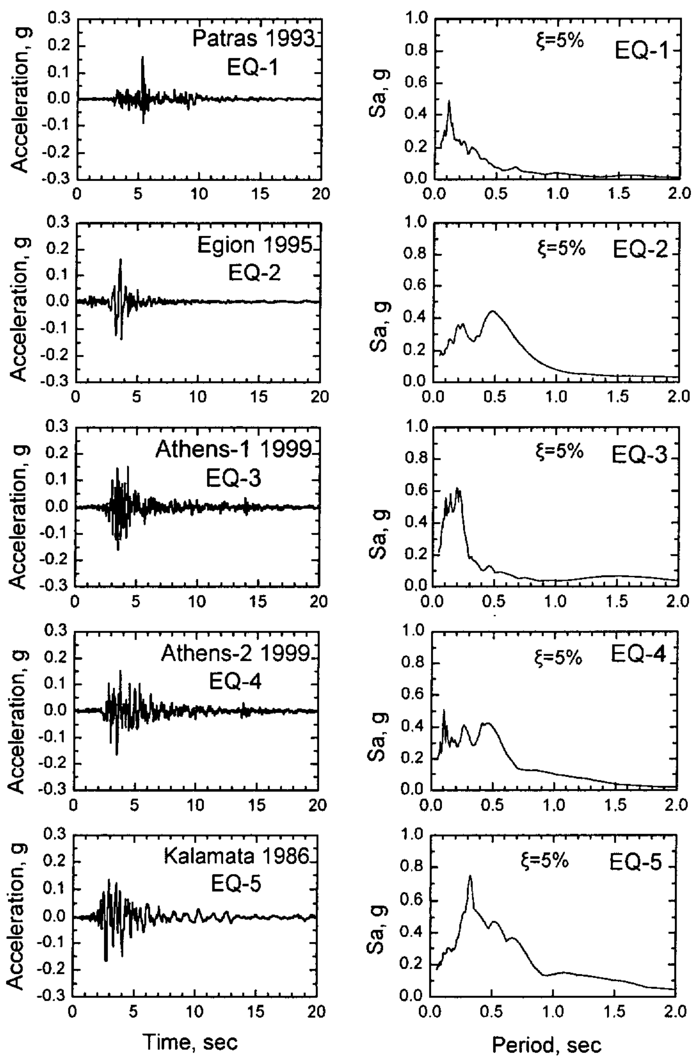

Fig. 6. Time histories and corresponding acceleration response spectra of the five input earthquake motions

to 0.6sec. It is expected that the fundamental period of the hotel building is contained in the above range of periods.

1-D Analyses

These analyses are conducted under the assumption of vertical propagation of shear waves. The rigid base was assumed to be at 60m below ground surface and the soil stratigraphy and V_{so} and G_o values were as shown in Figure 7. The analyses were conducted for equivalent-linear and non-linear inelastic soil behavior.

Equivalent Linear Analyses. These analyses were conducted with the finite element code FLUSHPLUS (EERI, 1991) in association with purpose written Pre- and Post- (visual) processing programs that greatly facilitate the input of data and the processing of output of the original code. The G/G_o vs. γ_c and D vs. γ_c curves used in the equivalent-linear analyses, and shown in Figure 8, were estimated by using the program NOLISM (Athanasopoulos et al., 1998). The results of analyses indicated that the local soil conditions at the hotel site are expected to amplify significantly the input motion (50% increase of horizontal acceleretions and 300% increase of spectral accelerations). The predominant period of surface motion was found to range from 0.50sec to 0.65sec.

Non-linear Inelastic Analyses. These analyses were conducted with the finite element code WAVES (Hart and Wilson, 1989) in which the soil behavior is described by a Ramberg-Osgood (R-O) curve. The values of parameters describing the R-O curve for the soil formations of the hotel site were estimated by using the program NOLISM (Athanasopoulos et al., 1998). In the diagram of Figure 9 the estimated values of these parameters are shown on the plot of the corresponding shear stress vs. shear strain curve.

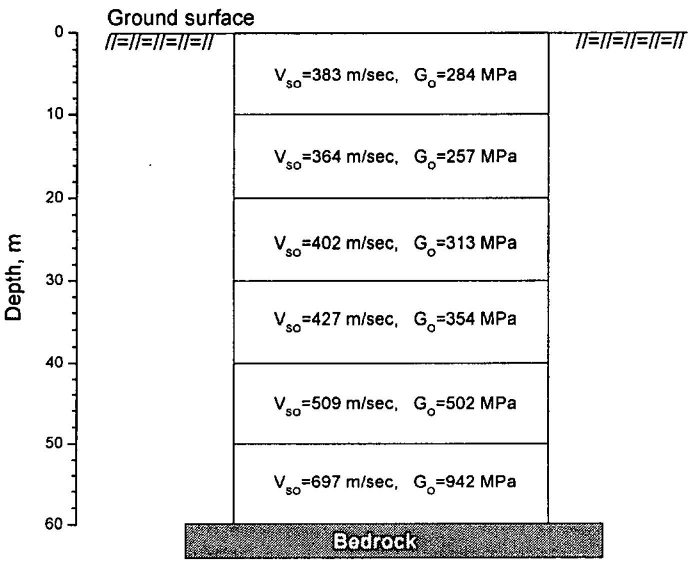

Fig. 7. Soil stratigraphy and parameter values used in the 1-D and 2-D ground response analyses

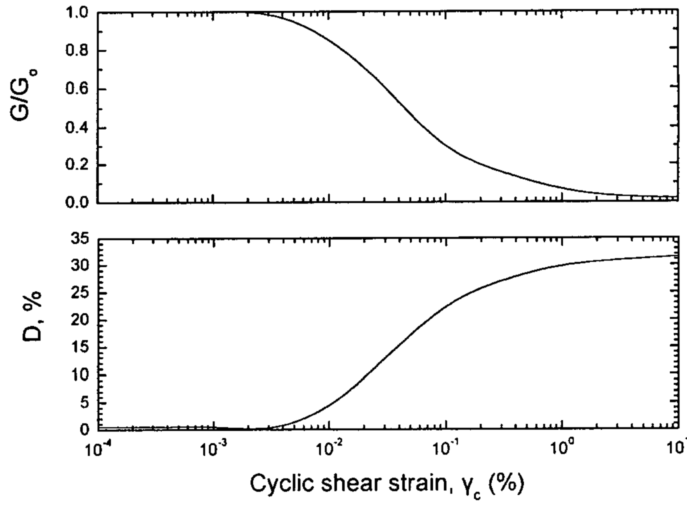

Fig. 8. The G/G_o vs. γ_c and D vs. γ_c curves used in the equivalent-linear ground response analyses

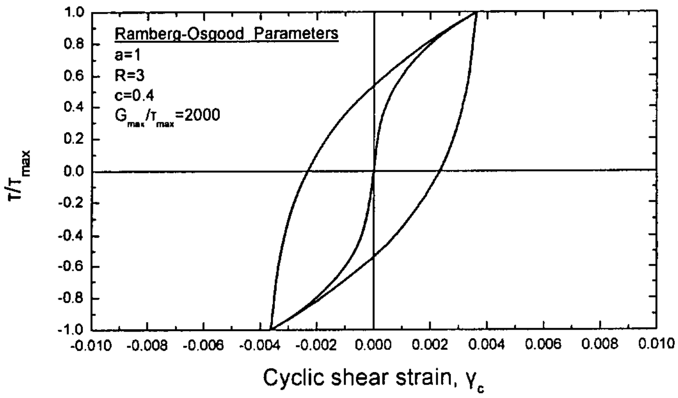

Fig. 9. The Ramberg-Osgood model used in the non-linear ground response analyses

The results of analyses showed similarity to the results of equivalent-linear analyses regarding the values of predominant periods. However, the intensity of surface motion was lower (as expected) by approximately 30% compared to the results of equivalent-linear analyses.

2-D Analyses.

The 2-D analyses of ground response were conducted by the finite element code FLUSHPLUS. The analyses were conducted for two cross-sections shown in Figure 3. The cross-section A-A' has a North-South direction and crosses in an oblique direction the river bank whereas the cross-section B-B' has a Northwest-Southeast direction and intersects the river bank at a right angle. The finite element meshes used in the analyses are shown in Figure 10. The two meshes have lengths equal to 600m and 500m, respectively, a height equal to 60m and are composed of 750 finite elements and 806 nodes. Viscous dampers were attached to the lateral boundaries of the meshes to simulate the infinite extent conditions of the mesh. The soil stratigraphy of the 2-D profile was established on the bases of the stratigraphy at the hotel site and the results of an

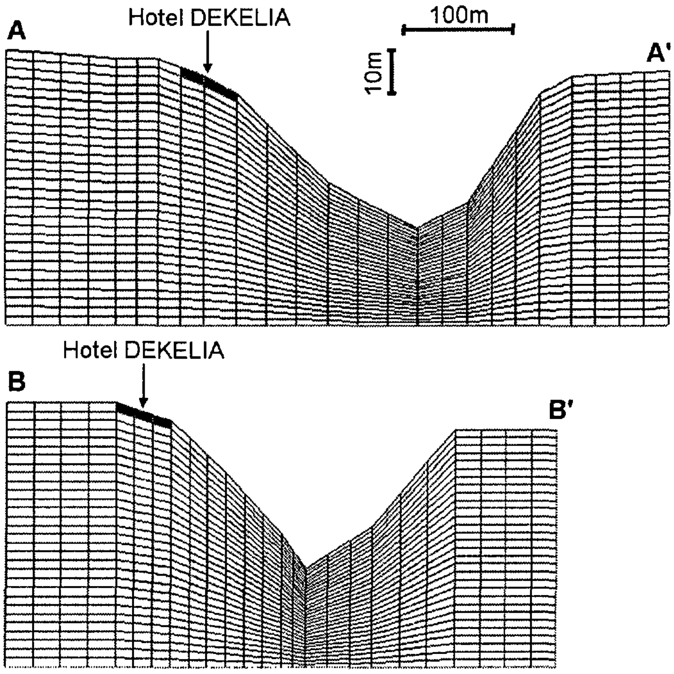

Fig. 10. The finite element meshes used for the 2-D ground response analyses along the sections A-A' and B-B'

older geotechnical investigation conducted in the east bank of the stream just across the hotel site. The diagrams of Figure 11 are based on the results of analyses and they depict the variation of peak horizontal accelerations along the section B-B' for the five input motions. These diagrams indicate that the surface topography may increase (compared to the results of 1-D analyses) the peak surface acceleration at the hotel site by up to 35%. It should be emphasized that the acceleration values shown in Figure 11 were derived by equivalent-linear soil behavior analyses and are 30% to 35% higher compared to the results of truly non-linear soil behavior analyses.

The effect of surface topography on the values of spectral accelerations at the hotel site are, according to the results of analyses, more significant. This may be observed in the diagram of Figure 12 depicting the acceleration response spectra at the hotel site estimated by 1-D (equivalent-linear and non-linear) and 2-D (equivalent-linear, sections A-A' and B-B') analyses, for EQ-4. According to Figure 12 the surface topography may increase the value of spectral acceleration for T=0.47sec by 50%. It is worth mentioning that this increase of spectral acceleration was estimated for EQ-4 which is one of the accelerograms recorded in the Athens 1999 earthquake. By considering the results of all analyses it was found that the maximum increase of spectral accelerations ranged from 20% to 100% for the five input motions used in this study.

5. CONCLUSIONS

1) The depth to the rigid base at the site of Hotel "DEKELIA" may be taken to be equal to 60m, according to V_{so}-depth profiles obtained by the SASW method.

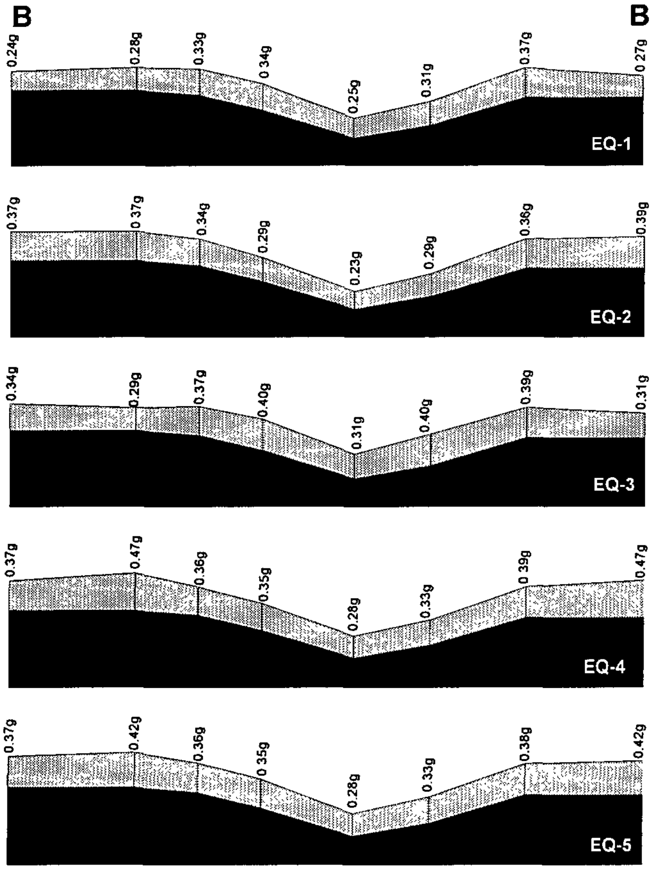

Fig. 11. Distribution of peak horizontal surface accelerations along the cross-section B-B' for the five input motions

2) The fundamental period of ground (for vertical propagation of shear waves) at the hotel site is expected to range from 0.50sec to 0.65sec for increasing values of ground shaking intensity.

3) The local soil conditions at the hotel site may amplify the peak values of the horizontal base accelerations by 30% and the maximum values of spectral accelerations by 200%

4) The surface topography of the area may amplify the horizontal motion at the hotel site: according to the results of analyses the peak horizontal accelerations may be amplified by up to 35% whereas the maximum spectral accelerations by up to 100%.

5) It is possible that in the Athens (1999) earthquake the combined effects of surface topography and local soil conditions have amplified the surface motion and contributed to the partial collapse of Hotel "DEKELIA". If the conditions along the route of Kifisos river are similar to the ones modeled in the present study, the results of analyses could be considered to be in agreement and partially explain, the concentration of heavy buildings damages along the banks of the river.

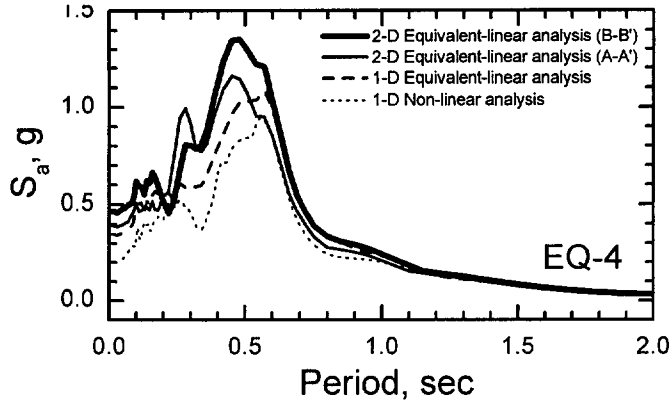

Fig. 12. *Acceleration response spectra at the Hotel DEKELIA site for the EQ-4 input motion*

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