Geotechnical aspects of the 1995 Aegion (Greece) earthquake

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ABSTRACT: Results are presented from multidisciplinary studies regarding the M_S=6.2, 15 June, 1995 Aegion Earthquake (Gulf of Corinth, Greece). From a seismological point of view this event deserves attention since it is the first well documented earthquake resulting from low angle (33^o) normal faulting. From a geotechnical point of view, attention is focused upon the high acceleration (0.54g), long period (0.40-50s) ground motion recorded in the city of Aegion, which is attributed to the coincidence of a number of independent factors: directivity of rupture, soil amplification and topography effects. In addition, the analysis of structural damage within the city of Aegion and ground failures along both coasts of the Gulf provides new insight to earthquake-induced failure mechanisms.

1 INTRODUCTION

The June 1995 Aegion earthquake ruptured the western part of the Gulf of Corinth, in southern Greece. With a magnitude M_S=6.2, the earthquake caused significant destruction, including structural damage, liquefaction and ground ruptures. The most severe effects occurred at Aegion, a town located at an epicentral distance of about 15 km on the southern coast of the Gulf. Namely, about 1000 buildings suffered major damage and had to be repaired or even rebuilt, while 26 people were killed from the collapse of two multi-story buildings.

This paper summarizes the findings from a number of multidisciplinary studies performed in the wider area, with the aim to assess the factors which contributed to the severity of the earthquake. Emphasis is placed upon geotechnical issues (soil and topography effects, liquefaction and related ground failures). However, attention is also focused on some unusual seismological evidence, which had crucial effect on the seismic excitation.

2 FAULT RUPTURE AND DIRECTIVITY

The Gulf of Corinth has long been recognised as one of the most active rifts in the highly seismic Aegean. The 1995 Aegion earthquake is the largest event recorded in the Gulf since the 1981 sequence which ruptured its eastern part. To identify the rupture mechanism of the earthquake, a two-week seismotectonic field study was initiated by Bernard et al (1997), including: the temporary installation of a seismological array, aftershock studies, the surveying of GPS points whose monitoring had been initiated in 1991-1994 and a detailed investigation for surface breaks along the well known onshore active faults.

The final fault model established from this study is shown in Figs. 1 and 2, together with the aftershocks and the active faults in the wider area. In brief:

a) The rupture initiated at 10km depth, 15km away from the damaged city of Aegion. It lasted 4 to 5 s and propagated southward, on a north-dipping normal fault, with 33^o dip angle. This is an unusually low angle normal faulting, apparently one of the first well-documented cases of its kind.
b) The seismic moment estimated from GPS and InSAR data is 3.9x10^5 kNm and provides a 0.87 m mean slip over a fault area of 9.5km x 15km.
c) The fault plane is probably connected to the surface by a steeper segment cutting through the thick sediments of the Gulf and reaching the sea floor within the active submarine slumps of the southern coast.
d) The aftershock seismicity is concentrated to the west of the rupture area, suggesting that the crustal stress state in that part is closer to failure than the eastern part which has been relaxed earlier, by the Galaxidi 1992 earthquake.

The above description of the rupture mechanism already implies considerable directivity effects, a hypothesis which is further substantiated by the few available recordings of the main shock. For instance, Fig. 3 compares acceleration records at two stations, at comparable epicentral distances from the fault

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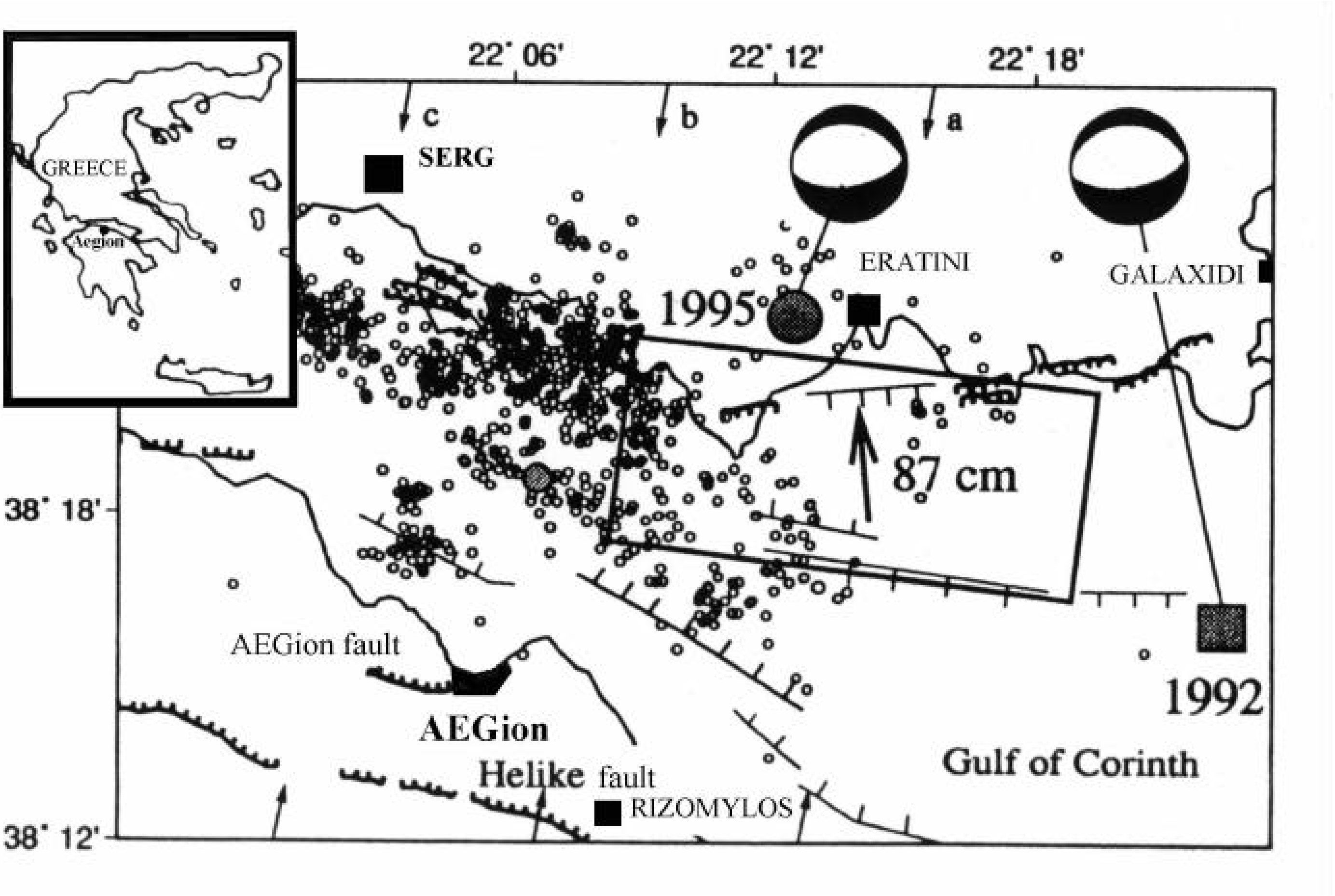

Figure 1. Epicenter and rupture zone of the 1995 Aegion earthquake (based on Bernard et al. 1997).

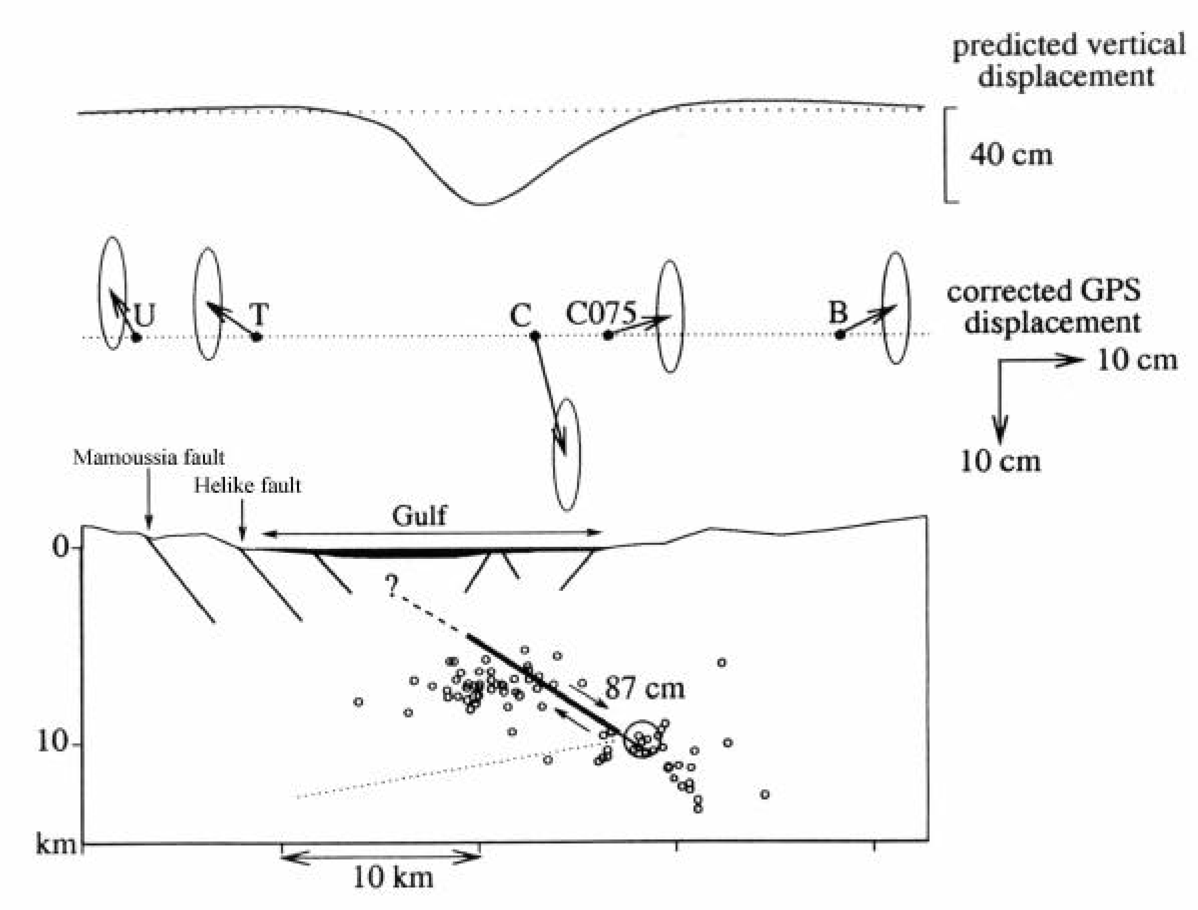

Figure 2. Cross section of the fault plane of the 1995 Aegion earthquake (based on Bernard et al. 1997).

(Fig. 1): SERG to the W-NW of the fault plane and AEGion (at the center of the town of Aegion) to the S-SW. It is readily observed that peak horizontal accelerations in Aegion station, in the hypothesized direction of rupture, are more than quadraple the peak horizontal acceleration in SERG station, opposite to the direction of rupture. Furthermore, the duration of very strong shaking in AEGion station is about 1s as compared to 2 s in SERG station.

Fig. 4 shows the time histories of acceleration, velocity and displacement, as well as, the elastic response spectra (5% damping) of all seismic motions recorded at AEGion station. This recording is characterized by high horizontal PGA (0.54g and 0.50g) and a long predominant period of about 0.50s. This long-period pulse results in high horizontal PGV values (51.8 and 40.3 cm/s) and an especially high velocity step ÄV≈ 80 cm/s. There is ample evidence in the literature that such long-period pulses are related to directivity phenomena (Singh, 1985, Somerville & Graves, 1993, Naeiem, 1993). However, it is shown next that the soil conditions and the topography at AEGion station may have also contributed to the creation of this high acceleration, long period seismic recording.

3 GEOLOGICAL AND GEOTECHNICAL DATA

Fig. 5 shows a N-S geological section passing through the center of Aegion. It is observed that the northern side of the city is essentially bounded by a normal fault running on an E-W direction, parallel to the nearby coast. This fault produces an almost vertical drop of about 90 m. The residential part of Aegion lies mostly on the upthrow region of the fault, while the harbor is built on the downthrow region. It is emphasized here that this geologic fault was only indirectly related with the causative fault of this earthquake. Nevertheless, in its western part it produced a small surface breakout, 1 km in length and 10mm in width.

The figure also shows two typical soil profiles for the upthrow and downthrow regions: one at AEGion station within the city, and the other at the harbor. In brief, the subsoil in the city area consists of 20 - 40 m of alternating layers of relatively stiff low-plasticity sand-silt-clay mixtures, overlying 100-150 m of conglomerate. Under the conglomerate, there is a bed of neogene marl that reaches great depths. The shear wave velocity at the surface layers ranges between 200 and 600m/s while in the conglomerate it increases gradually with depth from 800 to 1200m/s. The soil conditions at the harbor area are similar, with one important exception: the recent soil deposits on the surface are of marine origin, having a larger percentage of fines, a larger thickness (in excess of 50m) and a much smaller shear wave velocity (less than 200m/s).

4 SOIL AND TOPOGRAPHY EFFECTS

The only available recording of the main event within the city limits comes from AEGion station, installed at the basement of the two-story telecommunications building. Hence, the investigation of possible soil and topography effects during the earthquake has been based on analytical predictions rather than actual data from recorded motions. The analyses were performed with computer codes SHAKE (Schnabel et al 1972) and QUAD4M (Hudson et al 1994), for 1-D and 2-D conditions respectively. The soil parameters were mostly evaluated from geological and geophysical data, as well as data from in-situ SPT, Crosshole and Downhole measurements (Tsiambaos et al 1996). In many cases, the available data were supplemented via empirical correlations from the literature (Imai and Tonuchi 1982, Kalteziotis et al 1992, Zervoyannis et al 1987, Vucetic and Dobry 1991).

As a first step, soil effects were decoupled from topography effects and evaluated assuming 1-D wave propagation, from the seismic bedrock upwards. Fig. 6 shows typical results obtained for the recording site, in the form of elastic response spectra (5% damping) and peak ground accelerations for all three components of motion: TRANSverse (N150^{o} E), LONGitudinal and VERTical. The results are shown for the ground surface and at the top of the conglomerate and the marl. Attention is drawn on the following points:

a) At the marl-conglomerate interface, the elastic response spectra for both horizontal components are practically identical and in remarkable agreement with the frequency content of the spectrum for the vertical motion. This is an indication that the seismic ground motion at this level bears the source characteristics, with a minimum effect from the overlying soil. In that case, the strong motion from the source arrived rich in periods around 0.10s and between 0.25 and 0.50s.

b) Passing through the conglomerate layer, the horizontal elastic spectra are amplified uniformly by an average factor of 1.50, while spectral accelerations at periods between 0.40 and 0.70s may be amplified even more, forming a well defined peak at 0.50s.

c) The top 24m of recent soil deposits amplify spectral amplifications by another 50% on average. The amplification appears to be more intense at periods between 0.10 and 0.30s, resulting in a second local peak at 0.20s.

Subsequently, the effects of topography were computed from 2-D seismic response analyses, for a representative N-S section through AEGion recording station (Fig. 6). The seismic excitation was estimated from 1-D deconvolution of the recorded motion and assigned to the top of the neogene marl.

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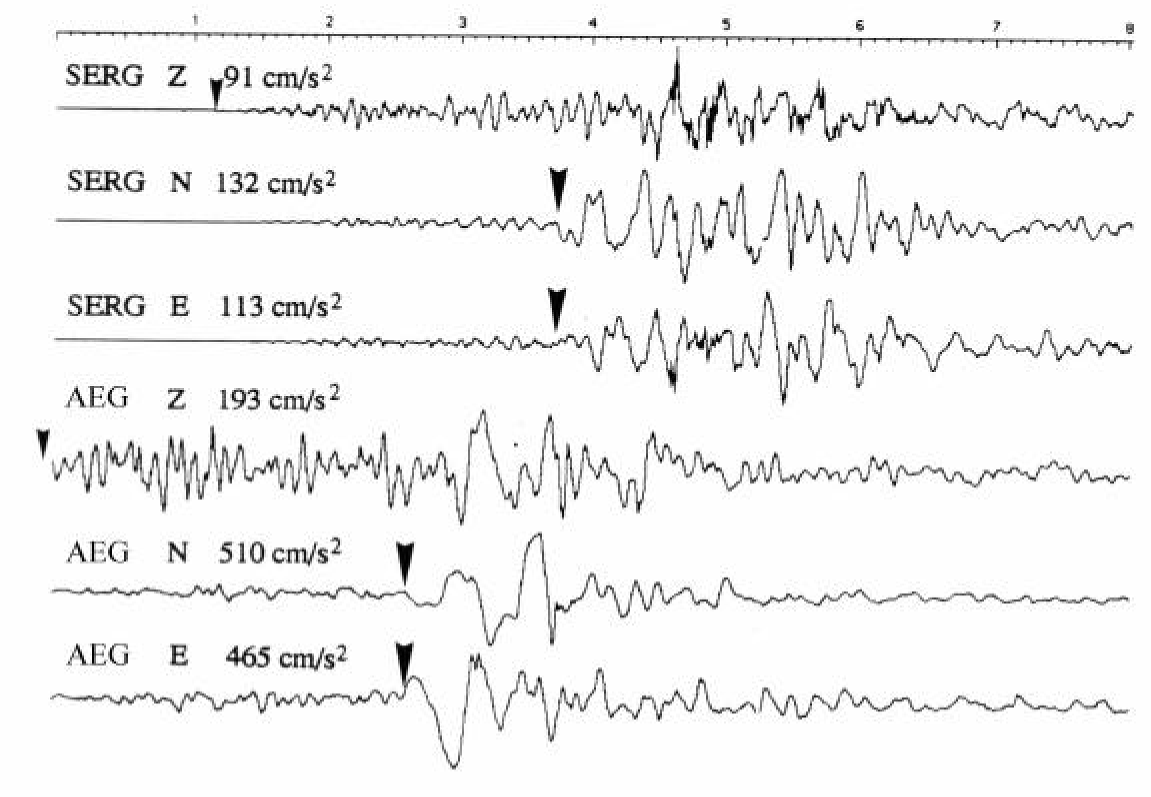

Figure 3. Acceleration records at SERG and AEGion stations (from Bernard et al. 1997).

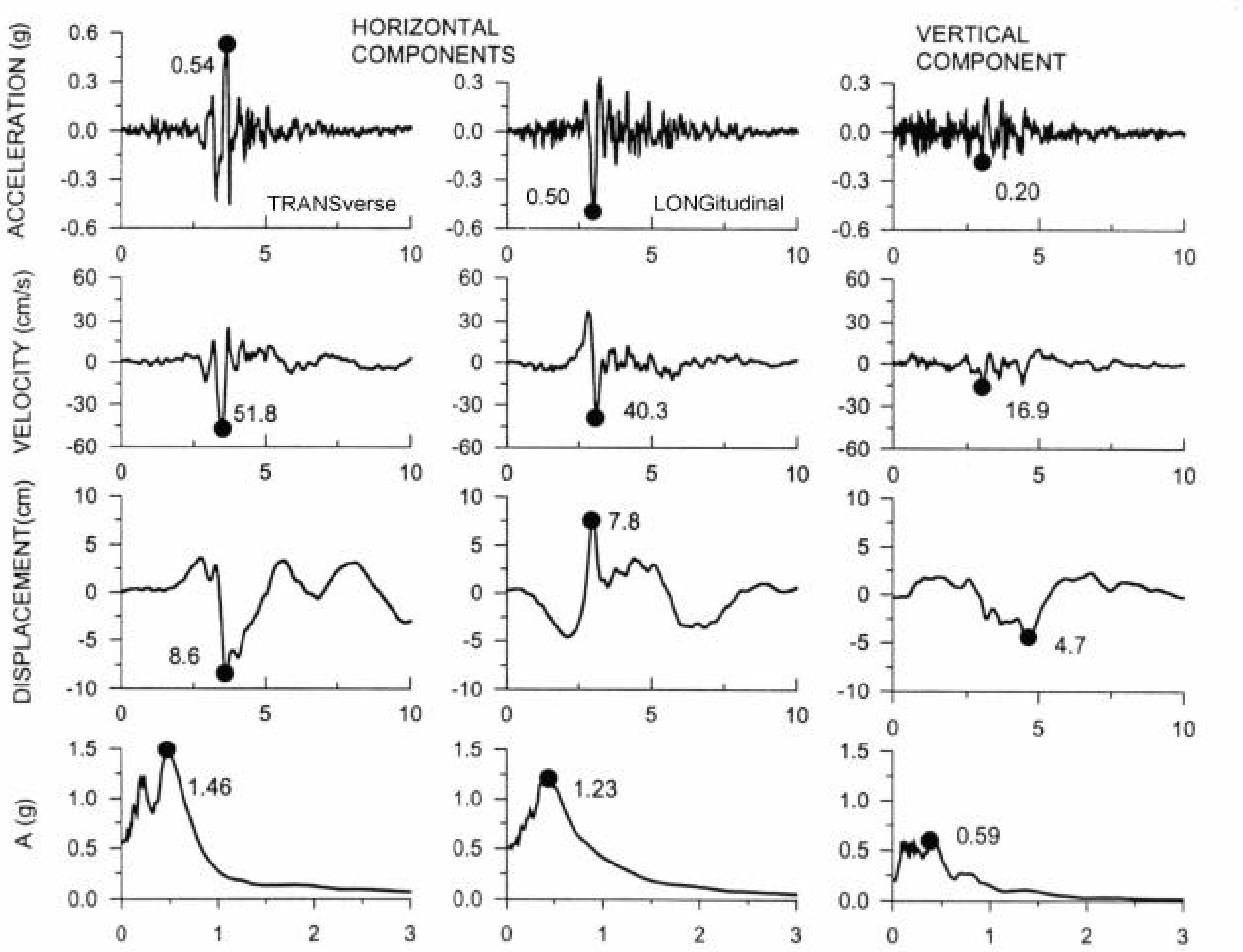

Figure 4. Recored ground motions and corresponding elastic response spectra at AEGion station (from Gazetas 1995).

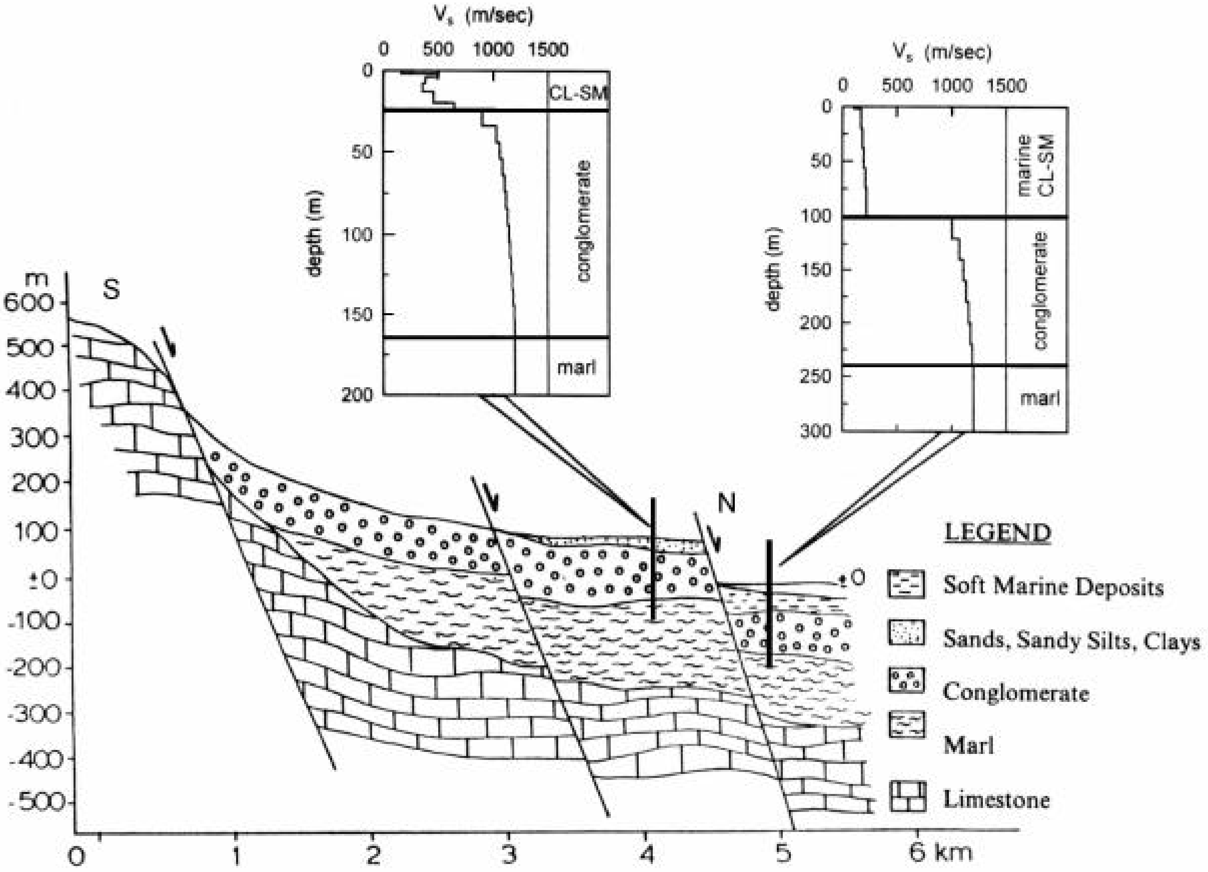

Figure 5. N-S geological cross section of the Aegion area.

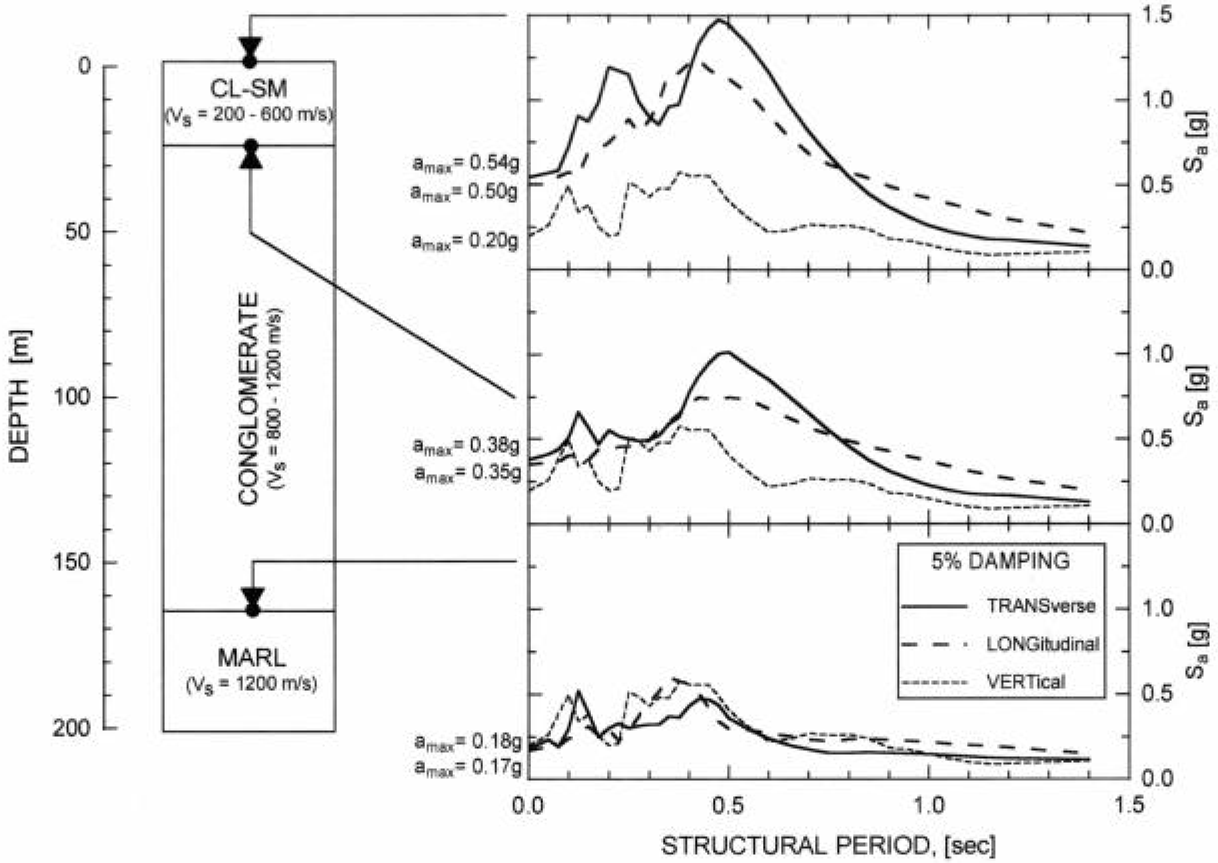

Figure 6. Computed effect of soil conditions on AEGion main shock recording.

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The results of the 2-D analyses were finally calibrated against the peak ground acceleration of the recorded motion.

Fig. 7 shows the N-S variation of computed peak ground acceleration, as well as elastic spectral acceleration (5% damping) for a structural period of 0.40s. To distinguish topography from soil effects, the results of the 2-D analyses are compared to results from 1-D analyses performed in the previous step. It is observed that the role of topography is neither simple nor uniquely defined. Still, there is clear evidence that the presence of the fault escarpment may have amplified the intensity of ground shaking in its vicinity, i.e. 50 to 600m to the south and up to 100m to the north. In addition, it is important that Aegion station falls within one of these zones and consequently the main shock recording has sustained a frequency dependent amplification. This is shown in Fig. 8 where computed elastic response spectra in the area of the recording have been normalized against the spectrum at a large distance (to the south) from the fault, where topography effects vanish. In this way, it is seen that the harmonic components of motion with periods between 0.20 and 0.45 may have been amplified disproportionally due to the presence of the fault escarpment.

Combined site (soil and topography) effects in the entire city area were assessed by performing 1-D analyses for 14 borehole sites, and consequently correcting the results for the topography effects implied by the 2-D analysis. (Bouckovalas et al, 1996, Papadimitriou and Bouckovalas, 1997). Final ground motions show considerable spatial variability that may explain, in part at least, the non-uniform distribution of observed structural damage. Similar conclusions had been reached by Gazetas (1995) and Athanasopoulos et al (1998) who analyzed the seismic response of distinct sites within the city and the harbor area.

Of particular interest is the substantial overall de-amplification of ground motions that apparently took place in the soft and deep clayey deposits in the harbor area. The resulting reduced intensity of motion (PGA computed to be in the range of 0.10-0.20g) literally saved the gravity-type, 10m-high harbor quaywall, which displaced merely by 5 to 10cm. Such a de-amplification of motion by the 60m or more soft clayey deposit is reminiscent of: (a) the reduced acceleration levels recorded at the surface of the Port Island 80m-deep borehole array during the 1995 Kobe earthquake (Iwasaki & Masaru, 1997), and (b) the reduced macroseismic intensity documented for the coastal deep alluvial sites during the 1996 Kalamata, Greece, earthquake (Gazetas et al 1990).

5 STRUCTURAL DAMAGE

Among the 1159 reinforced concrete (RC) buildings of the town, 30 had to be evacuated and another 231 had to be repaired. Damage was more severe in masonry buildings. In a sample of 706 masonry houses, 361 had to be evacuated and 212 required major repair. In general, the structural damage was concentrated in the central and eastern parts of the city. On the contrary, very little damage was observed in the harbor and the western parts of the city. These findings agree well with the analysis of site effects discussed earlier. For instance, the difference in the intensity of damage between the harbor and the city center could be readily foreseen based on the variation of the peak ground and spectral accelerations along the N-S section presented in Fig. 7.

Particularly sensitive to the long-duration, high-amplitude pulse of the ground motion proved to be the flexible low-rise buildings with a “soft” first story. Namely, in three cases the first story of such buildings collapsed (Gazetas, 1995). The sensitivity of elastoplastic flexible structures to near field, directivity affected ground excitations has been well documented in the literature following the pioneering work of Bertero after the 1971 San Fernando earthquake (Bertero et al, 1978).

Following the earthquake, an extensive effort was initiated to map and evaluate structural damage in the wider area of Aegion (Fardis and Karantoni, 1999). The results demonstrate the severity of ground shaking, but they also provide indirect evidence in support of site effect analyses presented earlier. It is noted that this study is still in progress and consequently all results presented herein should be considered preliminary.

Table 1. Scale of structural damage to masonry buildings

Degree of Damage (D.D.)	Description of damage
0	no damage
1	a few fissures of 1mm width
2	a number of cracks with 5mm average width or isolated cracks with 10mm average width
3	intense cracking, masonry walls beginning to disintegrate
4	disintegration of masonry walls, total or partial collapse

Table 2. Categorization of masonry buildings

Category	building type (No. of stories)	fundamental period
MAS1	adobe(1), stone(1), brick (1&2)	0.1s
MAS2	adobe(2), stone(2)	0.4s

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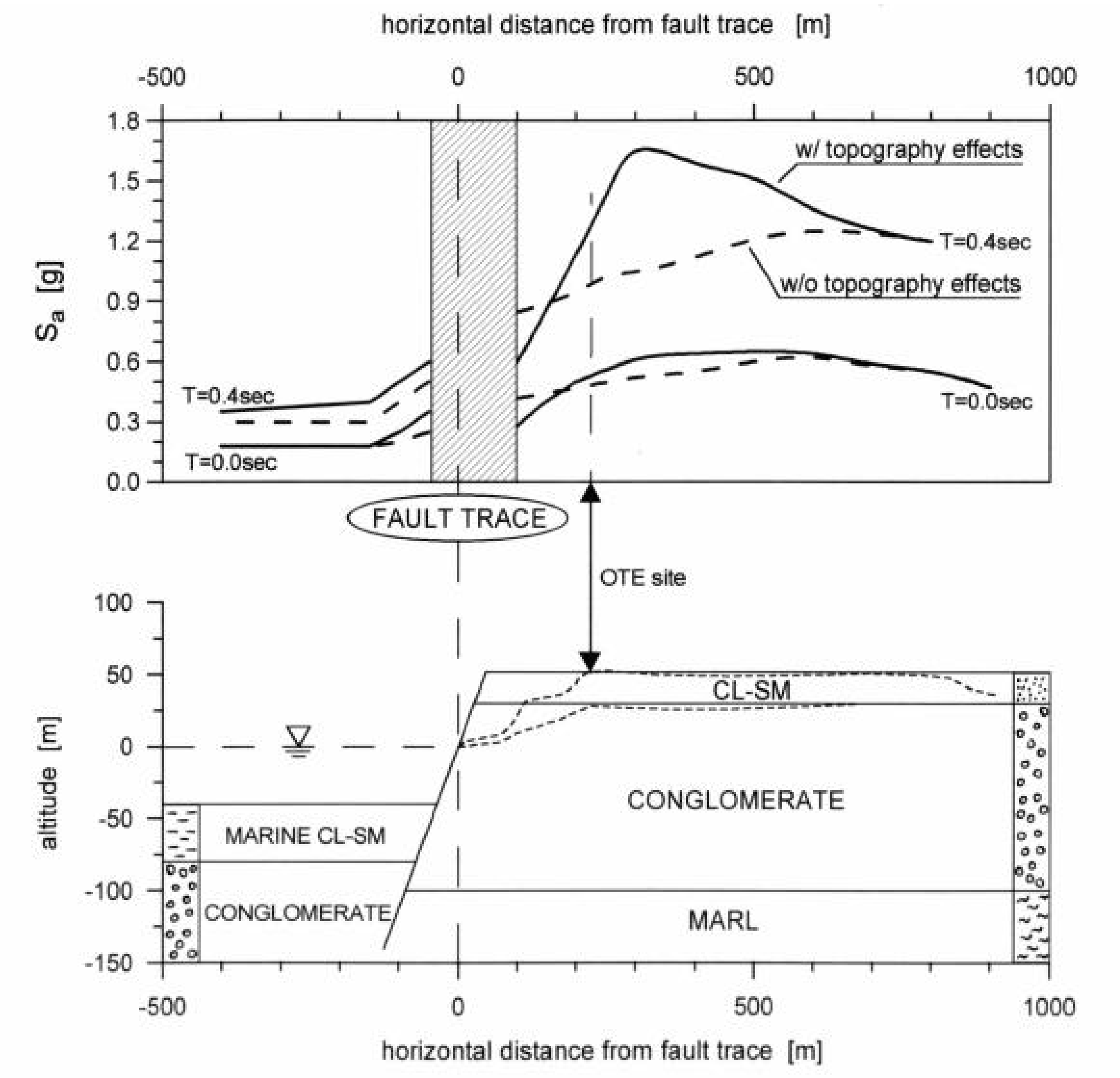

Figure 7. Computed soil and topography effects along a typical N-S cross section of Aegion.

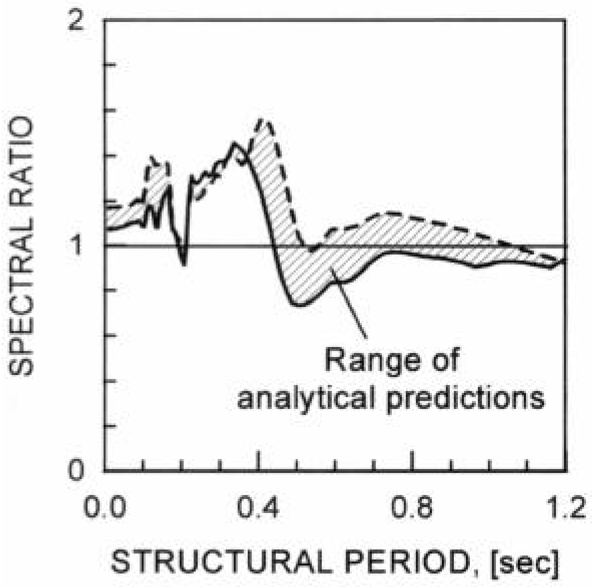

Figure 8. Computed topography effects on horizontal spectral acceleration (5% damping) at AEGion station.

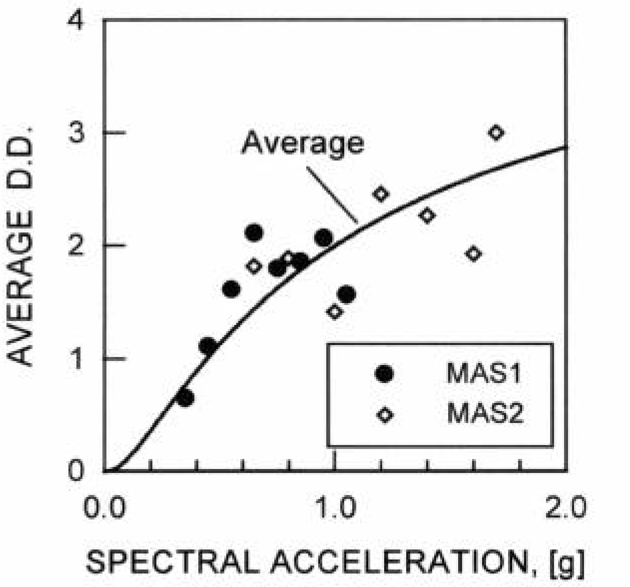

Figure 9. Correlation between structural damage to masonry buildings and seismic ground motion intensity.

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For a systematic correlation of observed damage and ground motion intensity, the average Degree of Damage (D.D.) of masonry buildings has been related to elastic spectral accelerations (Fig. 9). The average D.D. has been evaluated according the criteria listed in Table 1, while spectral accelerations have been estimated based on the fundamental period of vibration of the building and the analytical computations of site effects. However, no similar evaluation of structural damage was available for RC buildings to generalize the above conclusion.

In the analysis presented herein, all masonry buildings are grouped into two categories, MAS1 and MAS2, according to their fundamental period of vibration (Table 2). The number of buildings in the two categories are very similar, so that the two statistical samples data are equally reliable.

As shown in Fig. 9, the correlation between observed damage and spectral acceleration, computed taking into account site effects, is satisfactory since:

- it portrays the expected increase of the average D.D. with spectral acceleration for both categories of masonry buildings, and
- the scatter is fairly small, given the uncertainties of the analysis.

One point of further interest in this plot, is that buildings in category MAS2 sustained larger accelerations and suffered relatively greater structural damage. This may be attributed to the proximity of their fundamental structural period to the predominant period of the earthquake (0.40 - 0.50 s).

6 GROUND FAILURES

In addition to structural damage, the earthquake caused extensive ground failures in the form of liquefaction and lateral terrain movement. These phenomena have been systematically investigated for two locations (Fig. 1):

a) Rizomylos, a village located on the south coast of Corinthian Gulf, at a distance of 8km southeast of Aegion and 18km south of the epicenter (Athanasopoulos et al, 1998).
b) Eratini, a small town located on the north coast of the Gulf, within the epicentral distance of the earthquake (Bouckovalas et al 1998).

The occurrence of liquefaction at Rizomylos was manifested by sand boils, expulsion of ground water at the ground surface, sand blows, as well as limited lateral spreading and ground rupture parallel to the coast line. Fortunately, the damage caused by these phenomena was minor: cracking of the concrete floors and the walls of coastal buildings and also settlement, tilting and cracking of a RC walk way along the water front.

Geotechnical investigations at this area revealed that the subsoil consists of a 5m thick layer of sand and gravel, followed by a loose to medium dense layer of sand (N_{SPT}=10-20) of about the same thickness, and a layer of clay. The liquefaction resistance of sand, estimated empirically according to Seed et al (1985), corresponds to a horizontal peak ground acceleration of 0.16 to 0.18g. These values are likely to have been much lower than the actual seismic accelerations at the site.

Ground failures in Eratini were far more intense. In four sites, one within the fishing harbor of Eratini and three along the nearby 2 km beach, the coastline advanced 5 to 15 m inland. In addition, water front barriers collapsed, paved park areas cracked and sunk into the sea, while the seaside retaining wall of a coastal road was threatened by scouring of the foundation soil.

Submarine geophysical surveys have shown that, in three of the above sites, the earthquake caused extensive landslides accompanied by debris flows and block rotations (Fig. 10). Reconstruction of the pre-earthquake topographic profiles along the main axis of the landslides indicates that the failure zones extended to a maximum depth of 6 to 10m within the loose alluvial deposits which cover the seabed.

Geotechnical exploration, based on static cone penetration with skin friction measurement, revealed that the soil profile at the failure sites is characterized by a continuous interchange between silty-sand and clay layers. This profile favors the development of excess pore pressures which may remain trapped within the clay-sealed silty sand layers for a long time after the end of shaking. Thus, zones of reduced shear resistance are created into the soil leading to a static massive failure, even for relatively small surface gradients.

Table 3 summarizes some characteristic data obtained from the geophysical and geotechnical exploration of the area, as well as, from the liquefaction and slope stability analyses. From a practical point of view, the following points are worthy of attention:

a) Post-earthquake landslides occurred for ground slopes as low as 12.0 %, corresponding to a static factor of safety of 2.0.
b) At all sites, except from A, ground failures were triggered by excess pore pressure build up in very thin silty sand layers, with average thickness between 0.24 and 0.36m. Such layers can be easily missed during a conventional geotechnical exploration or intentionally overlooked on the grounds that they probably luck lateral continuity.
c) Assuming complete liquefaction of the silty sand layers, the relevant analyses indicate that the horizontal peak ground acceleration in the area must have exceeded 0.29g. This is a relatively high value, but it is readily justified by the small epicentral distance of Eratini.

Table 3. Summary of results from the analysis of Eratini earthquake-induced ground failures

SITE	THICKNESS OF LIQUEFIABLE LAYERS (m)		MINIMUM LIQUEFACTION RESISTANCE(1)		AVERAGE SLOPE OF SEABED(2)	SF(3)	GROUND FAILURE	
	MAX.	AVERAGE	$a_{max,l}$(g)	DEPTH (m)	(%)		ERROSION (m)	LAND-SLIDE
A	3.00	1.10	0.29	8.5	17.0	3.3	5.0	YES
B	0.40	0.24	0.15	6.3	12.0	2.0	5.0	YES
C	0.60	0.34	0.20	8.0	12.0	2.5	10.0	NO
D	0.80	0.36	0.21	9.4	18.0	1.5	10.0 - 15.0	YES

(1) According to Seed et al. (1985), (2) Prior to the earthquake, (3) Estimated from infinite slope stability analysis.

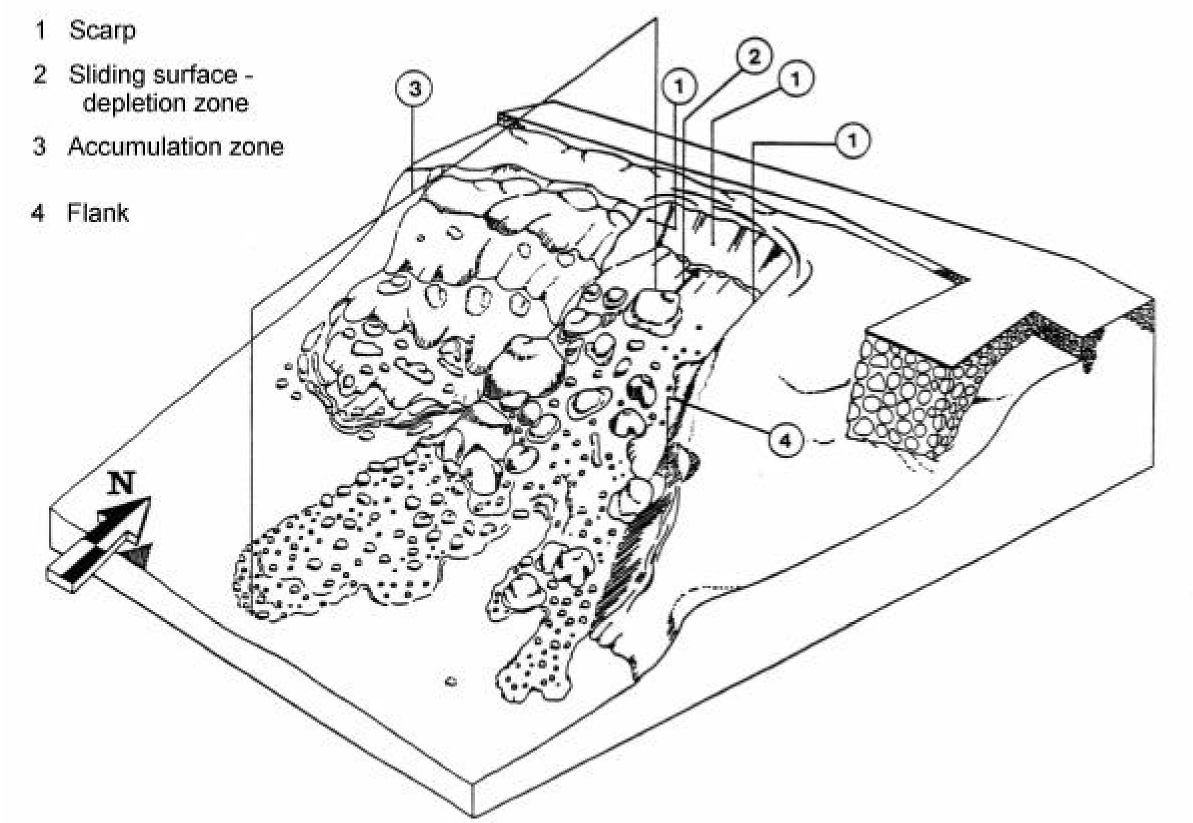

Figure 10. 3-D perspective of a typical earthquake-induced landslide at Eratini Gulf.

d) The depth of minimum liquefaction resistance, ranging between 6.3 and 9.4 m, compares well with the maximum depth of the failure surface estimated from reconstruction of the pre-earthquake topography.

e) Sites B and C developed different forms of ground failure, despite an apparent similarity in soil conditions and topography. This is an indication that, although the prediction of liquefaction per se has become a rather trivial issue, prediction of liquefaction-induced ground failures may still pose a challenge to geotechnical engineers.

Concluding this brief overview, it is noted that similar ground failures have been reported for a number of other locations along both coasts of the Gulf. However, they did not affect human activity and consequently they did not become the subject of systematic investigation.

7 CONCLUSION

Despite its moderate size (M_S=6.2), and the fact that it stroke a thinly populated area, the earthquake event of 15-06-1995 revealed to some extent many of the important seismological, geotechnical and structural aspects observed in the far more destructive earthquakes of Northridge 1994 and Kobe 1995. Furthermore, this event shed light to seismotectonic and geotechnical factors which interacted over the past centuries to shape the wider zone of the Corinthian Gulf, and will probably affect the area in the future.

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