Available online at www.sciencedirect.com
SCIENCE DIRECT®
Engineering Geology 82 (2005) 12–31
ENGINEERING GEOLOGY
www.elsevier.com/locate/enggeo

The 2003 Lefkada earthquake: Field observations and preliminary microzonation map based on liquefaction potential index for the town of Lefkada

G. Papathanassiou [a,*], S. Pavlides [a], A. Ganas [b]

[a] Department of Geology, Aristotle University of Thessaloniki, 54124, Greece
[b] Institute of Geodynamics, National Observatory of Athens, 11810, Greece

Received 26 May 2005; received in revised form 19 August 2005; accepted 29 August 2005
Available online 2 November 2005

Abstract

A strong earthquake (Mw = 6.2) occurred offshore the island of Lefkada (or Lefkas) on August 14, 2003. The maximum intensity has been evaluated Io = VIII (EMS) at Lefkada municipality, while VI to VII+ intensities were evaluated at many other villages of the island. The offshore NNE–SSW oriented strike-slip right-lateral fault was activated by the main shock. This fault is the northern termination of the Cephalonia transform fault. The most characteristic macroseismic effects were extensive typical ground failures like rock falls, soil liquefactions, subsidence, densification, ground cracks and landslides. These macroseismic effects are remarkably similar to those reported from some historical Lefkada shocks, e.g. 1704, 1914 (Ms = 6.3) and 1948 (Ms = 6.5). Sand boils and ground fissures with ejection of mud were observed at the seaside of the town of Lefkada, and in the villages of Nydri and Vassiliki.

In situ soil profiles are obtained based mainly on borings after the earthquake. Boreholes records with SPT values (standard penetration test) are obtained and the “simplified procedure” originally developed by Seed and Idriss was employed to evaluate the liquefaction resistance of soils. The results indicated that the silty sandy layer, which lies beneath the artificial fill in the coastal zone in Lefkada town, had liquefied during the 14 August Earthquake. An attempt was also made to establish a preliminary microzonation map for Lefkada town using the data from Liquefaction Potential Index analyses. Our map was validated by the occurrence of liquefaction phenomena inside the town.

Keywords: Historical seismicity; Ionian sea; Liquefaction potential index; Lefkada earthquake 2003; Sand boils

1. Introduction

In the morning of August 14, 2003 (05:14:53.9 GMT; 08:14:54 local time), a strong (Ms = 6.4, Mw = 6.2, $a = 0.42$ g) damaging earthquake occurred offshore the NW coast of Lefkada Island (Ionian, Greece). According to the National Observatory of Athens, Institute of Geodynamics (NOAGI), its focus was located at 38.79°N, 20.56°E (Fig. 1) at depth $h = 12$ km. Because of the main shock, and secondary by the greatest aftershock, many houses suffered minor damage, while few of them were severally damaged across the island. The maximum intensity has been evaluated Io = VIII (EMS) (Papadopoulos et al., 2003; Pavlides et al., 2004), at Lefkada municipality.

Although earthquake events of such a magnitude are very frequent in the Greek area, especially in the Ionian

---

* Corresponding author.
E-mail address: gpapatha@geo.auth.gr (G. Papathanassiou).

0013-7952/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.enggeo.2005.08.006

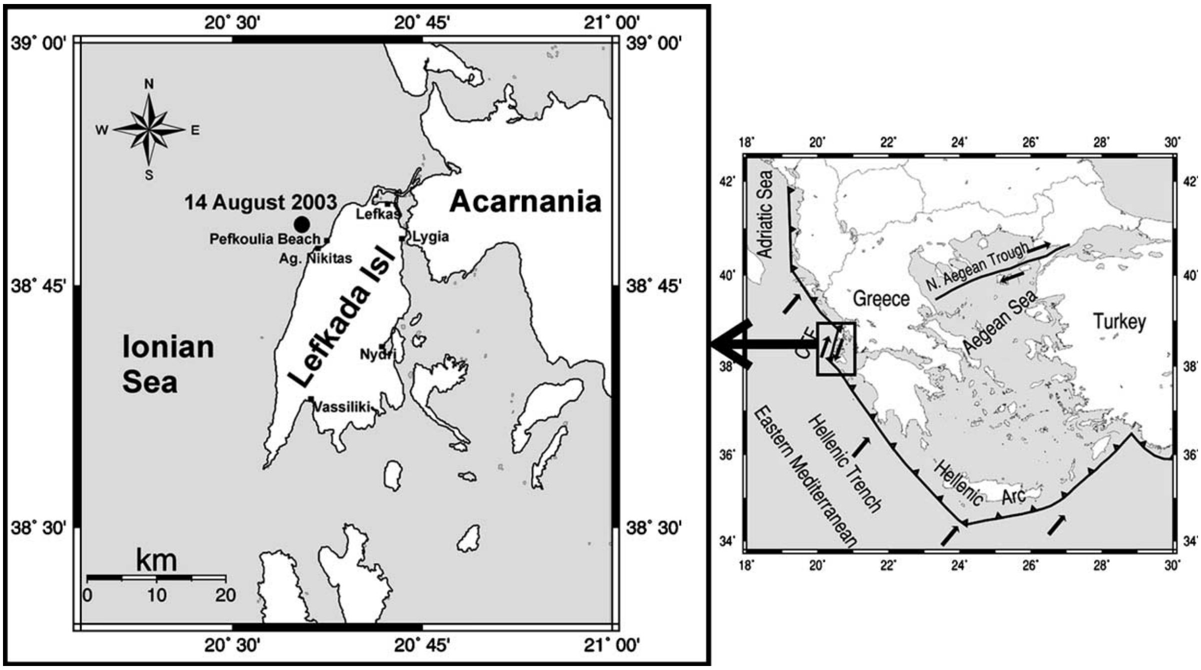

Fig. 1. Left: Map of Lefkada showing the epicenter (solid circle) of the 14 August 2003 eartquake. Right: Main seismotectonic properties of the Aegean and surrounding region (Papadimitriou, 2002). The study area is indicated by the square.

Islands, which show the highest seismicity in the Mediterranean region, it is of special importance to study this particularly event because it provides data on the present-day stress field, on the geometry and kinematics of the North Lefkada segment and on the strong motion pattern.

In this paper we report ground failures triggered by the earthquake which were widely distributed at the island of Lefkada. In addition we mapped rock falls, ground settlement and lateral spreading which caused several damages to the road network and to port facilities. In the town of Lefkada and in the villages of Nydri and Vassiliki (Fig. 1) sand boils and ground fissures were observed along the waterfront. We also carried out an evaluation of the liquefaction resistance of soils in terms of factor of safety and of liquefaction potentially index. Our field observations were taken place some hours after the main shock and the days after (14–15 and 23–31 August).

2. Geology—tectonics

The region of the South Ionian Islands (Lefkada, Ithaca, Cephalonia and Zante) is characterized by high seismicity rate with earthquake magnitudes up to 7.4 (Papazachos, 1990; Louvari et al., 1999). This is explicable by the complex crustal deformation resulting from the subduction of the African plate towards NE and the Apulian platform continental collision further to the northwest (Fig. 1). The Cephalonia–Lefkada transform fault, CTF, plays a key role in this geodynamic complexity (Sorel, 1976; Mercier et al., 1987; Taymaz et al., 1991; Le Pichon et al., 1995; Papazachos and Kiratzi, 1996; Louvari et al., 1999) which joins the active subduction and the continental collision. Its slip-rate is about 15 mm/year according to GPS measurements (Andizei et al., 2001) while according to seismological data is about 3 cm/year (Papazachos and Kiratzi, 1996).

The geology of the Lefkada island, which has been studied in detail by Bornovas (1964), comprises: (1) a carbonate sequence of the Ionian zone, (2) limestone of Paxos (Apulia) zone restricted in the SW peninsula of the island, (3) few outcrops of ionian flysch (turbidites) and Miocene marls-sandstones mainly in the northern part of the island (Cushing, 1985; Rondoyanni-Tsiambaou, 1997). Pleistocene and especially Holocene coastal deposits are extended in the northern edge of Lefkada, where the homonym capital town is founded, in the valley of Vassiliki and in the coast Nydri (Fig. 2).

The main structures are thrust faults of the Ionian limestone on to Miocene marls from NE towards SW

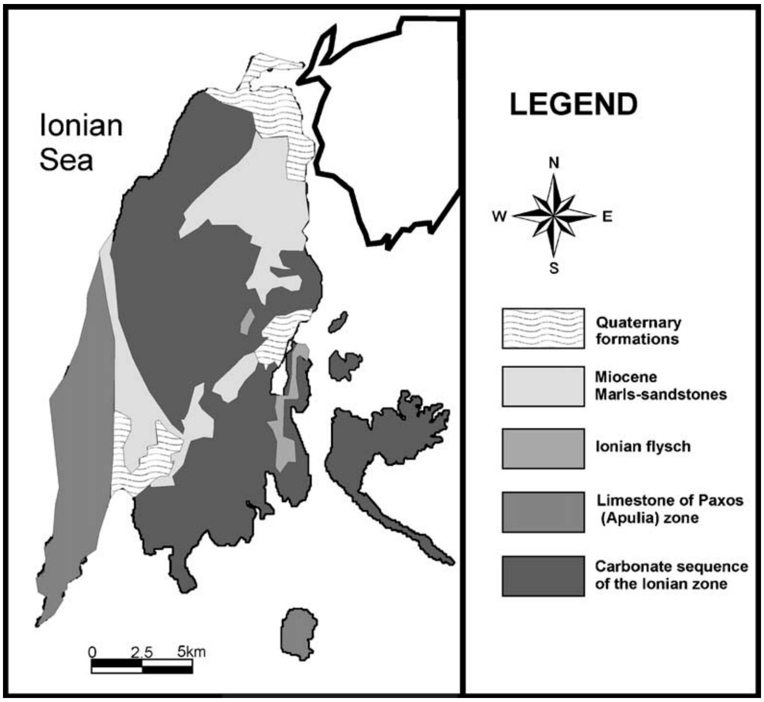

Fig. 2. Simplified geological map of Lefkada (after Rondoyanni-Tsiambaou, 1997).

and a system of neotectonic faults. The NE–SW to NNE–SSW trending neotectonic main faults are normal structures with a significant right-lateral component, while some minor faults NW–SE trending show left-lateral character. Typical normal dip-slip faults are oriented ENE–WSW and N–S. By using morphotectonic criteria most of them can be considered as active or possibly active structures. Since the kinematic history of faults is defined mainly by kinematic indicators contained on the fault surfaces, quantitative analyses of striation data have shown (Pavlides et al., 2004) a stress pattern of transtensional type. That is, $\sigma_1=90°/80°$ axis, $\sigma_2=250°/10°$ and $\sigma_3=341°/3°$ trending NNW–SSE. T is compatible to σ_3 and P to σ_2 axes.

3. Historical-instrumental seismicity

The Ionian Islands have suffered from many destructive earthquakes. There is reliable detailed information for at least 23 events, since 1612 which induced ground failures at the island of Lefkada. Our evaluation of past earthquake damage is based on eye-witness accounts and reports published by the Newspapers “Anthropistis”, “Ethnikipsichi”, “Kiriks”, Archive of Lefkada for the seismicity of the island, Barbiani, and Barbiani (1864), Stamatelos (1870), Galanopoulos (1955), Rondoyannis (1995), Papazachos and Papazachou (1997) and Papazachos et al. (2000). A list of historical earthquakes which occurred in Lefkada island, and their macroseismic effects, is shown in Table 1 (Intensities in MSK). The focal parameters and the maximum intensity of the events have been collected from the seismic catalogue of Papazachos et al. (2000) except of the case EqID 13, which was collected from Galanopoulos (1981).

A first conclusion arising from the list of historical events is that earthquakes appear in couples (twin or cluster events) with time period of occurrence ranging between 2 months and 5 years, e.g. 1612–1613 (16 months), 1625–1630 (5 years), 1722–1723 (10 months), 1767–1769 (2 years), 1783–1783 (2 months, possible aftershock), 1867–1869 (2 years), 1914–1915 (2 months), 1948–1948 (2 months). The island suffered extensive ground failures both to the northern part, like the present event and the 1625, 1630, 1704, 1914 shocks, and to the southern part. The 2003 earthquake can be considered as the result of the reactivation of the northern Lefkada fault segment.

Among the historical events at least 5 earthquakes induced ground failures similar to those that were observed during the latest shock. The 17 March 1820 shock caused settlement of the central square of Lefkada town while the 24 May 1911 earthquake

Table 1
Focal parameters and description of the damages triggered by the earthquakes that occurred in the area of Lefkada island

EqID	Date (dd/mm/yy)	Lat (N°)	Lon (E°)	Ms	Imax	Description
1	26 May 1612	38.8	20.6	6.6	VIII	Damaging shock, ground cracks were reported, long period of aftershocks.
2	12 October 1613	38.8	20.8	6.4	VIII	Strong earthquake, extensive damages in the northeastern part of the island.
3	28 June 1625	38.8	20.7	6.6	IX	Many damages in the northwestern part including the Lefkada town.
4	22 November 1704	38.8	20.7	6.3	IX	Damaging earthquake, several destructions in the northern part, Ground cracks and landslides
5	5 June 1722	38.6	20.7	6.4	VIII	Strong earthquake induced damages in the southwestern part of Lefkada.
6	22 February 1723	38.6	20.7	6.7	IX	Damaging earthquake in the northern part, damages in Lefkada.
7	12 October 1769	38.8	20.6	6.7	IX	Devastating earthquake in Lefkada, Damages in the northern part.
8	23 March 1783	38.7	20.61	6.7	X	Devastating earthquake in the southern island mainly, Rock falls. (At 7th June 1783 a possible aftershock caused the collapse of houses in the northern part).
9	17 March 1815	38.8	20.7	6.3	VIII	Collapse of many houses in the town of Lefkada.
10	21 February 1820	38.8	20.6	6.4	IX	Sequence of damaging earthquakes, houses were collapsed, main square of Lefkada was sink.
11	19 January 1825	38.7	20.6	6.5	X	Destruction of the town of Lefkada. Houses collapsed with casualties (northwestern part), ground cracks and Rock falls. (strong aftershock occurred at 29 September of the same year, and a second strong event happened a year later at 26th of January 1826).
12	28 December 1869	38.8	20.65	6.4	X	Devastating earthquake, damages in the northwestern part. (This event can be considered as twin event with Kefallonia 4th of February 1867 very strong earthquake).
13	14 December 1885	38.5*	20.75*	5.7	VII	Rock falls and damages in the western and central part.
14	24 May 1911	38.7	20.7	5.3	VII	Damages in the town, ground cracks in the pier of Lefkada.
15	27 November 1914	38.65	20.62	6.3	IX	Destructive earthquake, Several damages in the northwestern part (Almost the same villages and sites with the same phenomena were affected).
16	13 March 1938	38.8	20.6	5.8	VIII	Ground cracks in the piers of the town of Lefkada.
17	22 April 1948	38.68	20.57	6.5	IX	Devastating earthquake induced several damages in the Southern part of the island.
18	30 June 1948	38.8	20.6	6.4	IX	Damages in the northwestern part, particularly in the town of Lefkada.
19	4 November 1973	38.9	20.5	5.8	VII+	A shock caused damages in the town of Lefkada, is rather associated the NW–SE thrust system.
20	18 January 1976	38.68	20.48	5.6	VII	Damages in the northern part of the island.

Key for parameters: Lat = latitude, Long = longitude, Ms = surface-wave magnitude, Imax = maximum seismic intensity in MSK scale. The focal parameters and the maximum intensity of the events have been collected from the seismic catalogue of Papazachos et al. (2000) except of the case EqID 13, which was collected from Galanopoulos (1981).

induced ground fissures, parallel to the coast, with length of 150 m and width of 5 cm (Galanopoulos, 1995). The 27 November 1914 event caused ground deformations due to liquefaction-induced lateral spreading along the quay in Nydri, damages in the seaside of Lefkada town, slope failures in 3 km length along the Agios Nikitas-Pefkoulia road and ground crater, probably due to densification, in the sandy beach of Pefkoulia (Critikos, 1916, Galanopoulos, 1955). The 30 June 1948 earthquake induced ground cracks with length of 150 m and width of 12 cm in the waterfront of Lefkada town. Also a vertical displacement of 12 cm was evident in the same area. In the beach of Pefkoulia, a ground crater of 3 m and depth of 1 m was reported (Rondoyannis, 1995). The ground failures triggered by these four events were concentrated

Table 2
Parameters of the main shock of the August 14, 2003 earthquake (Mw 6.2) and its aftershocks

EqID	Date–Time	Epicentre Lat–Lon	Magnitude Mw	Depth	Focal plane parameters
1	August 14, 2003–05:14	38.79–20.56	6.2	12	Strike 13 Dip 84 Rake 172
2	August 14, 2003–08:41	38.81–20.56	4.7	14	Strike 16 Dip 79 Rake 180
3	August 14, 2003–12:18	38.76–20.67	5.2	8	Strike 14 Dip 31 Rake 121
4	August 14, 2003–16:18	38.75–20.66	5.4	9	Strike 3 Dip 24 Rake 94

The focal plane data and Mw determinations are from the Quick RCMT catalogue (http://mednet.invg.it/rcmt/rcmt/htm). Epicenter locations are from the on-line catalogue of NOA (www.gein.noa.gr).

in the northern part of the island. The 22 April 1948 earthquake caused ground failures in the Vassiliki town which is situated in the southern part of the island. Ground cracks with length of 40 m and width of 5 cm were observed in the coastal zone of Vassiliki (Galanopoulos, 1955).

4. The 14 August 2003 earthquake

The main shock was followed by 17 aftershocks of ML=4.0–5.4 up to 31 August 2003, and by 324 events ML>2.9 while the three (ML>5.0) larger aftershocks happened during the first 24 h (Table 2). Nobody was

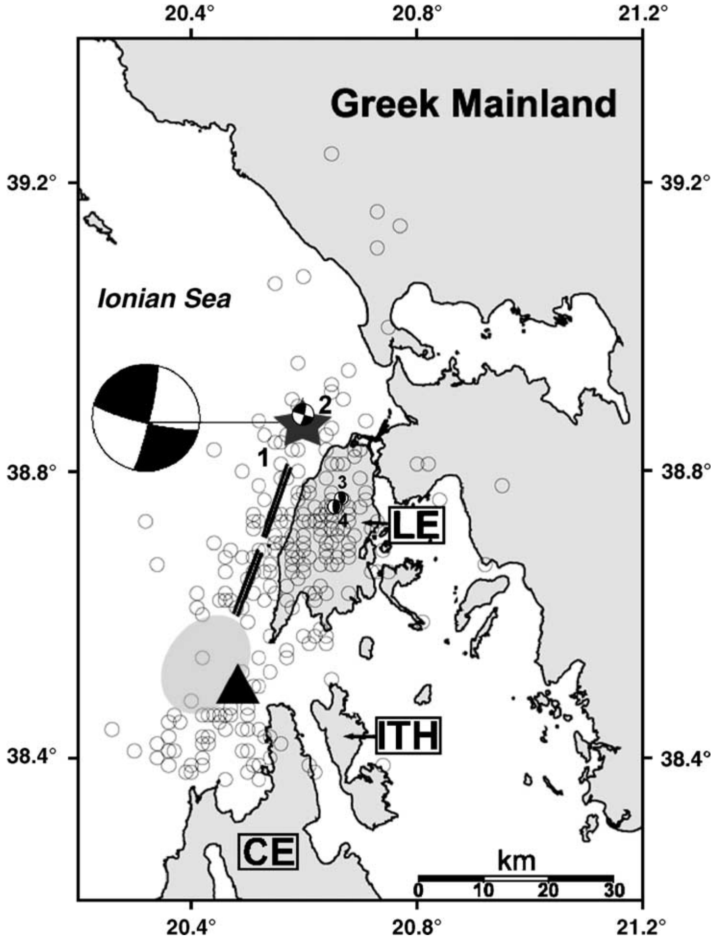

Fig. 3. Aftershock epicenters (circles) of the 14 August 2003 main shock (solid star) in the Lefkada fault segment (double dashed line), Papadopoulos et al., 2003). Focal mechanisms of the aftershock sequence reported in Table 2. Equal area, lower hemisphere projections of fault planes with black indicating compressional quadrant. Note that strike slip faulting predominates. Each mechanism is identified by its number (EqID, Table 2). The north and south aftershock clouds are separated by a free of epicenters region (ellipse). Triangle shows the epicenter of the 22 April 1948 earthquake (Ms 6.5). Epicenters of the 27 November 1914 (Ms 6.3) and 30 June 1948 (Ms 6.4) earthquakes are nearly identical with the 2003 main shock epicenter. Key for geography: LE=Lefkada Isl, CE=Cephalonia Isl, ITH=Ithaki Isl.

killed and only 3–4 injuries were reported. The shock was felt over the Ionian islands, western and central Greece from Peloponnesus to Albania coast. The maximum intensity has been evaluated Io = VIII (EMS) (Papadopoulos et al., 2003; Pavlides et al., 2004) at Lefkada municipality, where 550 buildings out of 800 were damaged. Based only on ground deformations the intensity at the NW coast of the island (Agios Nikitas village, Pefkoulia beach) can be considered VIII+. In other villages intensities range from VI to VII+, where the damaged houses rank from 25% to 50% of the total houses of each village.

Fault plane solutions determined teleseismically indicated the following nodal planes: NP1 (strike/dip/slip): 104°:82°:6° (USGS),); 285°:86°:− 30° (Harvard), NP2 (strike/dip/slip): 13°:84°:172° (USGS), 17°:60°:− 175° (Harvard). The NNE–SSW elongation of the aftershock area (Fig. 3; Papadopoulos et al., 2003; Pavlides et al., 2004) and the western Lefkada fault pattern implies that the nodal plane 2 of the USGS-Harvard solution represents the seismic fault. The focal mechanism of the 2003 event and the focal mechanisms of small earthquakes in association with, the neotectonic pattern on land, as well as GPS measurements, indicate that the seismic fault was a right lateral strike-slip fault with a small dip-slip component, which strikes NNE–SSW (10–20°) and dips to the ESE with high angle (Fig. 3). According to seismotectonic models it is a 40-km long and 15-km wide structure (Louvari et al., 1999). Taking also into account Fault Length–Magnitude empirical relationships (Wells and Coppersmith, 1994; Ambraseys and Jackson, 1998; Pavlides and Caputo, 2004) the surface fault length capable to produce co-seismic ruptures for *M* 6.2–6.4 earthquakes could be between 6 and 19 km. That is one half or one third of the Lefkada fault zone was activated during the 2003 earthquake, that is only the northern segment, as it was emphasized in Pavlides et al. (2003). This observation is in good agreement with the aftershock distribution, that is the cluster of aftershocks is concentrated along the 16-km northern segment (Karakostas et al., 2004).

The area affected by the shock falls in zone IV of the Greek seismic code (EAK, 2000), with design acceleration 0.36 g, the highest of Greece. According to EERI (2003), the largest peak horizontal ground acceleration (PGA) was recorded at the LEF1 station which is situated at the center of Lefkada town. The value of PGA was $a_g = 0.42$ g having a period of about 0.5 s (Fig. 4). The duration of strong ground motion was estimated at 18 s (EERI, 2003).

5. Field observations

5.1. Ground failures

The most characteristic co-seismic effects were typical ground failures like rock falls, soil liquefaction, ground cracks and slope failures (Fig. 5). Rock falls were widespread on the whole island and especially in the northwestern and central area, on both natural and cut slopes, as well as, on downstream road embankment slopes. The most characteristic rock falls, with diameters up to 4 m (Fig. 6), were observed along the 6 km long road of Tsoukalades-Agios Nikitas, which is very close to the epicentral area, and are accompanied by gravel, small rock and soil slides. In this region, the rock falls follow the trace of a 300-m high morphological scarp, and especially a 10–40 m high artificial slope. They are associated to a NNE–SSW to NE–SW high fractured zone with normal and right-lateral sense of movement, which is responsible for the high-angle dipping coasts and the deep sea bathymetry. In most cases rock falls are directly associated with pre-existing tectonic discontinuities and steep slopes within the Ionian limestone. Although many slope failures-flows were observed, only few of them can be considered as typical landslides like those along the road to Kalamitsi and Agios Petros villages (Fig. 7). In the center of the island, Karya village (Fig. 5), a landslide is clearly associated to the pre-existing faults and fractures.

At the sandy beach of Pefkoulia, 1 Km to the north of the village of Ag. Nikitas (Fig. 5), four sand craters were observed, probably due to the densification of the

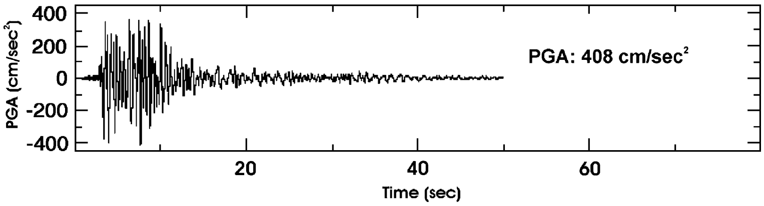

Fig. 4. Horizontal component with the highest ground acceleration of the recorded accelerogram of the mainshock at the station in Lefkada town (ITSAK, 2003).

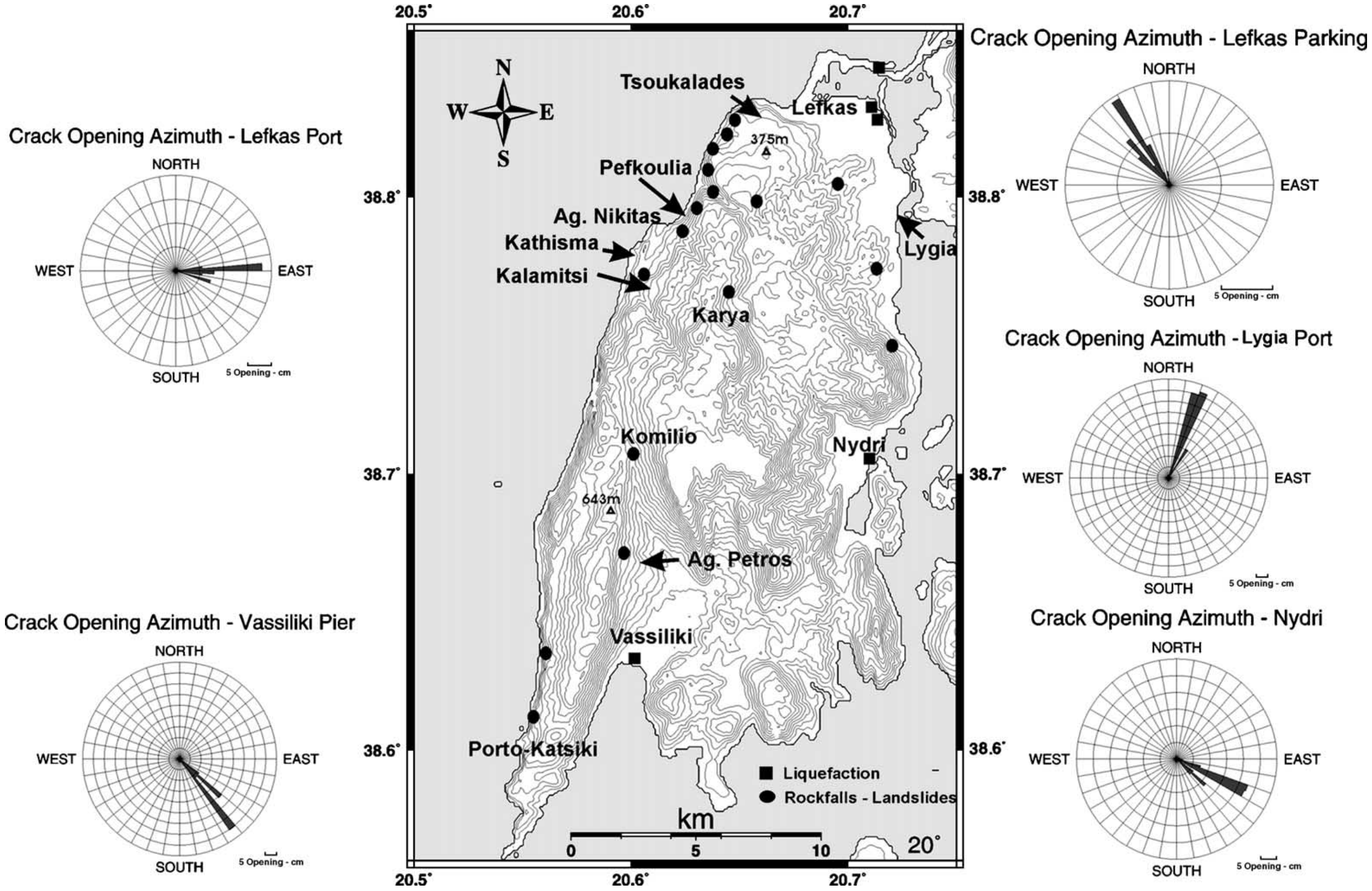

Fig. 5. Map showing the ground failures triggered by the 14 August 2003 earthquake. In this figure can be viewed the topography in the form of contours and its relation to the numerous rock falls and landslides. Moreover, crack plots (length, azimuth) as polar histograms are plotted. Width of azimuth sectors: 10°, length radius of openings every 5 cm.

Fig. 6. Rock falls on the road Tsoukalades—Ag. Nikitas (photo taken by Pavlides, 14/08/2003).

upper sandy layer. The diameter of these craters ranged between 1 and 3 m and their depth between 0.4 and 2 m, respectively (Fig. 8A, B). The same phenomena have been triggered by the 1914 and 1948 earthquakes (Galanopoulos, 1955). Similar phenomena were observed at the beaches of Kathisma and Myloi (Fig. 5), which are situated at about 2 km to the south of the Pefkoulia beach.

5.2. Ground failures and structural damages to port facilities

During the field investigations, several structural damages to port facilities as settlement of quays and movements of pavements towards the sea were observed. In most of these sites clear evidences of liquefaction occurrence, like sand boils and ground fissures with ejection of mud-water mixture, were mapped. Liquefaction-induced failures appeared to be concentrated in the areas formed by recent coastal, alluvial and fluvial deposits.

In the town of Lefkada, liquefaction occurrences (sand boils and vent fractures) were observed mainly in the waterfront area as shown in Fig. 9, and caused damages to pavements and sidewalks behind seawalls. According to eyewitnesses, muddy water was ejected at a height of 50 cm from cracks in a pavement surface near the waterfront, indicating high excess pore pressure generating during earthquake shaking. Furthermore, we observed that the asphalt pavement was

Fig. 7. Landslide on the road Ag. Petros–Kalamitsi (photo taken by Ganas, 25/08/2003).

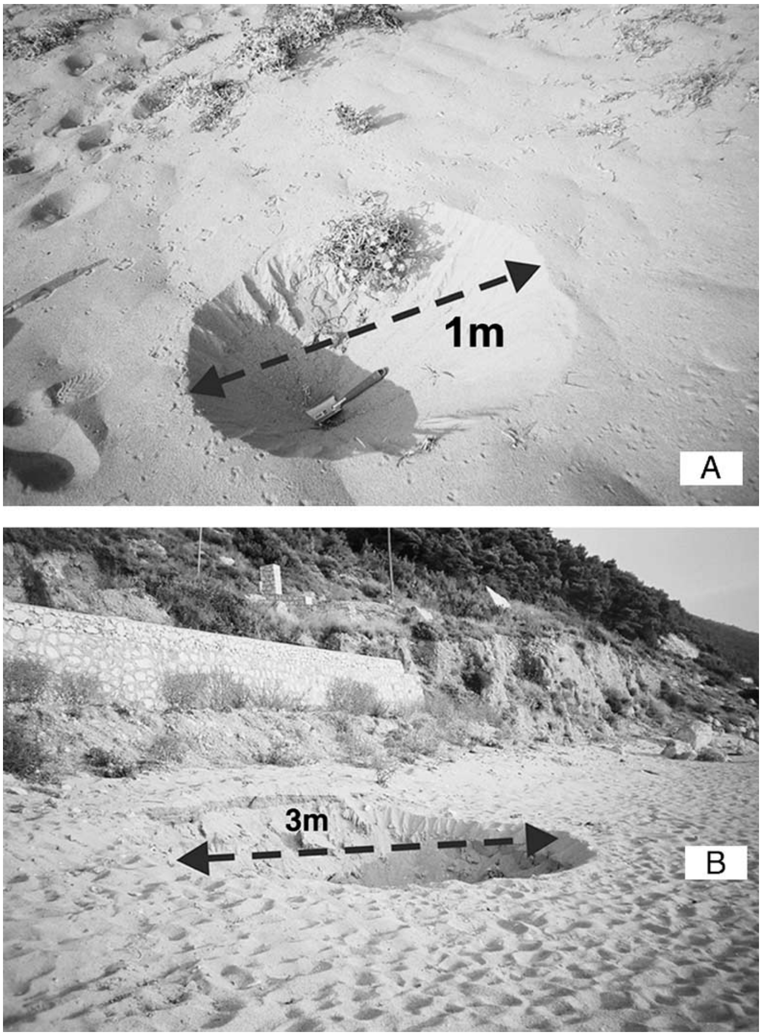

Fig. 8. Sand craters due to densification in Pefkoulia beach (photos taken by Papathanassiou, 25/08/2003).

covered by a thin sandy-silty layer which was ejected from the ground fissures (Fig. 10). The length of the fissures varied from few meters to tens of m and their width from a few millimteres to 8 cm. The mean direction of them was parallel to the coastline. In the marina district of the town, a horizontal displacement towards the sea was observed. According to EERI (2003), near the castle of Lefkada lateral spreading and ground settlement occurred.

In Nydri (Fig. 5), the consequences of liquefaction were less severe. Ground cracking with horizontal displacement of few centimeters towards the sea and vertical subsidence of 3 cm of the pavement behind the seawall was observed. At the old mouth of Dimosaris River, an eyewitness reported that muddy water was ejected from four different places at a height of 1 m. In this area we mapped typical examples of soil liquefaction like sand craters and vent fractures (Fig. 11). According to EERI (2003), at the river mouth of the Aspropotamos the event triggered the regression of the coastline of 1–20 m damaging sport facilities.

In the village of Vassiliki (Fig. 5), the main shock induced major damage to the port facilities as shown in Fig. 12. The new pier of the port was laterally shifted and overturned. At the old pier only ground cracks were triggered. Their width ranged between 3 and 7 cm. In addition, a vertical displacement of approximately 2 cm was observed. Inside the village there was no clear evidence of liquefaction. On the contrary, at the river mouth of a torrent (Fig. 13), 400 m to the west of the village, we mapped sand craters and vent fractures.

Finally, in Lygia (Fig. 5) no typical examples of soil liquefaction were observed. At the dock of the

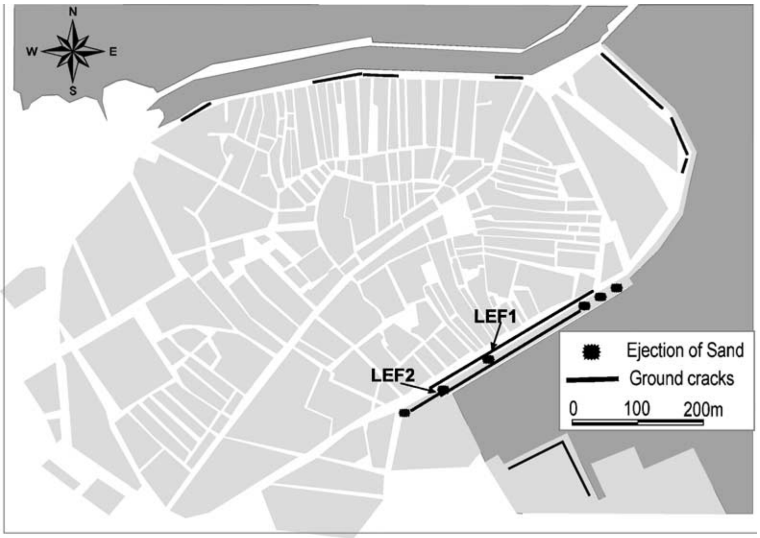

Fig. 9. Map of liquefaction-induced ground deformation in the town of Lefkada.

village, the seawall had been overturned and laterally towards the sea. Furthermore, a ground crack of the pavement behind the seawall, parallel to the coastline, with width of 3 cm approximately was observed (Fig. 14). Moreover, in the port of the village, we measured a ground vertical displacement of 44 cm.

6. Geotechnical assessment

6.1. Investigations of liquefaction susceptibility of Lefkada soils

To assess the liquefaction hazard in an area, it is important to examine initially the liquefaction suscep-

Fig. 10. Liquefaction induced ground failures in the town of Lefkada; (A) sandy silt ejected from ground cracks, (B) ground cracks in the waterfront area, (C) horizontal displacement of the pavement and ejected of sandy material in the marina district (photos taken by Papathanassiou, 15/08/2003).

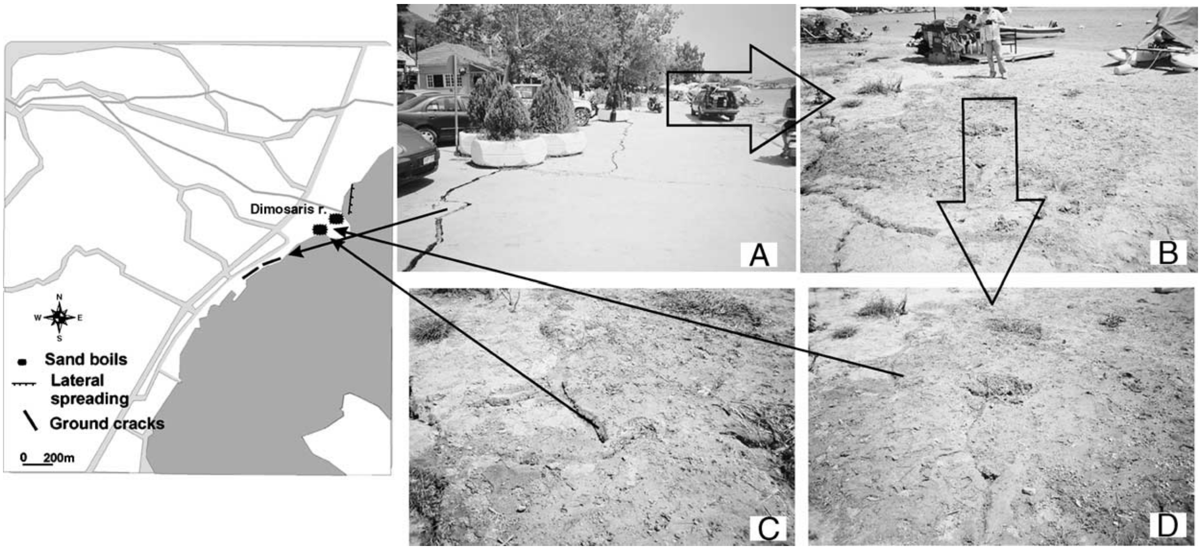

Fig. 11. Liquefaction induced ground failures in the village of Nydri; (A) ground cracks at the pavement surface, (B–D) ground fissures and sand craters at the river mouth of river Dimosaris (photos taken by Papathanassiou, 15/08/2003).

tibility. The criteria, by which this susceptibility can be judged, include historical, geologic and compositional data (Kramer, 1996). In this paper we examined the evaluation of these criteria before proceeding to the main geotechnical investigation of the liquefaction potential. Initially, the relationship between the epicentral distance of liquefied sites and surface-wave magnitude was examined. The epicentral distances of the town of Lefkada, Nydri, Lygia and Vassiliki are 12, 18, 14 and 21 km, respectively. According to Ambraseys (1988), Papadopoulos and Lefkopoulos (1993) and Papathanassiou et al. (2004) for an earthquake Ms = 6.4, these areas are considered as susceptible to liquefaction (Fig. 15).

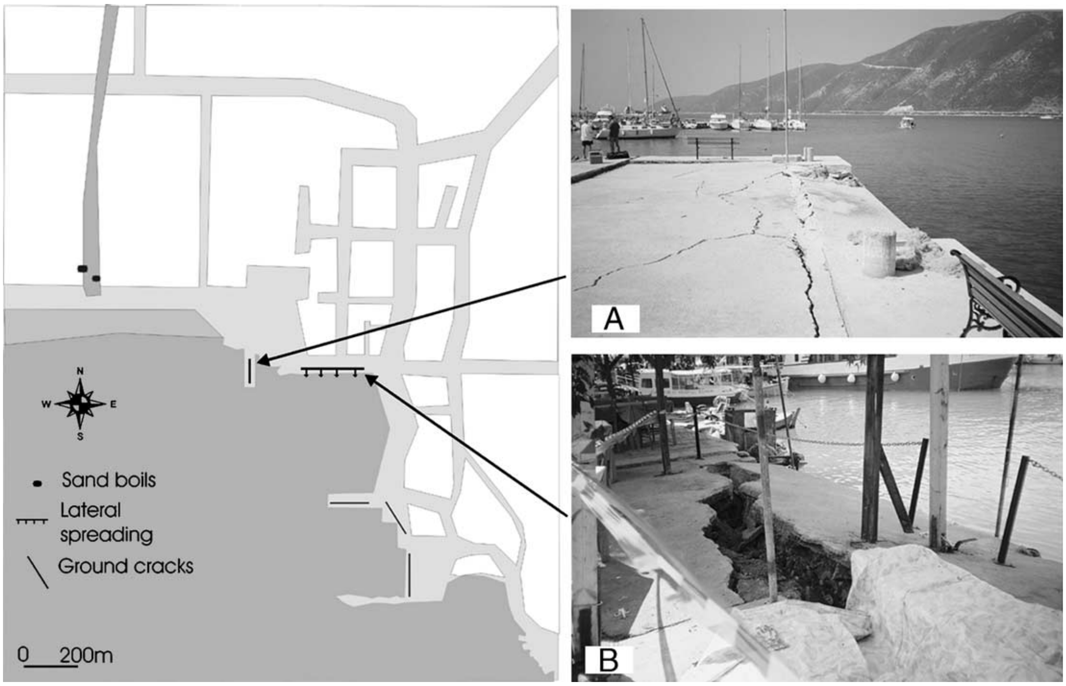

Fig. 12. Damages to the waterfront of Vassiliki. Left: Distribution of the failures induced by the earthquake of 14 August 2003. Right: (A) Ground cracks in the quay, (B) Lateral spreading and overturned of the pavement (photos taken by Pavlides, 15/08/2003).

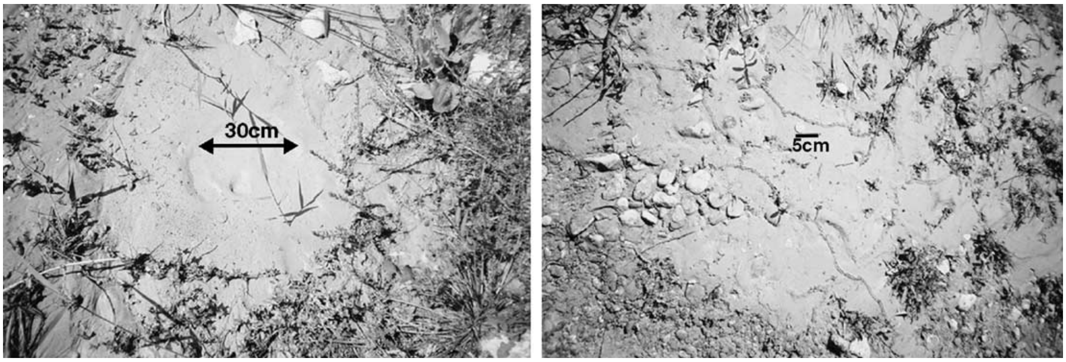

Fig. 13. Sand boils at the river mouth of torrent, in the village of Vassiliki (photo taken by Papathanassiou, 15/08/2003).

Furthermore, the sites where typical examples of liquefaction were observed consist of recent formations of Holocene coastal and fluvial deposits. The estimated susceptibility of these deposits to liquefaction during strong seismic shaking is high based on the geological criteria suggested by Youd and Perkins (1978).

Few hours after the main shock field observations were taken place. During these investigations we collected ejected samples from vent fractures and sand boils in the town of Lefkada (Lef1, Lef2) and in the villages of Nydri and Vassiliki, with a view to examine their compositional characteristics, which include grain size distribution, liquid limit and plasticity index (Kramer, 1996). The laboratory testing of the collected material was performed at the Laboratory of Engineering Geology and Hydrogeology of the Department of Geology at the Aristotle University of Thessaloniki.

The two collected ejected samples (Lef1, Lef2) from the waterfront in Lefkada town are classified as silty sand (SM) and sandy silt (ML) with low plasticity. The fines content of these soils are 60% and 45% and their clay content is 5.11% and 4.98%, respectively. The liquid limit and the plasticity index of the Lef1 sample (Fig. 16) are 25% and 3%. In the case of the Lef2 sample (Fig. 17), the laboratory test results indicated that its liquid limit is equal to 24% and the plasticity index was equal to 1.6%. The results indicate that both of the ejected samples had probably come from the same soil layer. The presence of a thin non-liquefied clayey cap layer may overestimate the fines content of the in-place liquefiable soils. In Vassiliki, sand boils and vent fractures formed outside of the village, at the river mouth of a torrent (Fig. 13). The results of grain size analyses of sand boils indicate that the content of silt and clay is 45% and 10%, respectively. The liquid

Fig. 14. Ground cracks in the village of Lygia (photo taken by Papathanassiou, 15/08/2003).

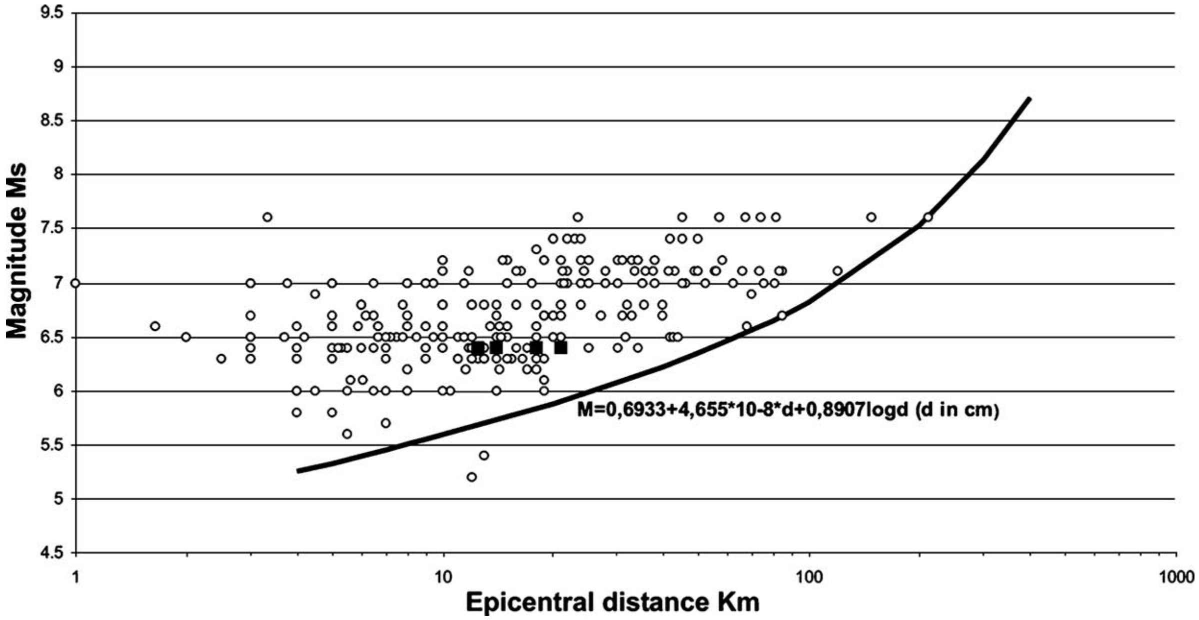

Fig. 15. Magnitude (Ms) versus epicentral distance (Re). With open circles are indicated the epicentral distances of sites in Greece at which liquefaction had been observed and with solid squares are indicated the epicentral distances of liquefied sites from the 14 August 2003 earthquake. Solid line indicates the boundary curve proposed by Papathanassiou et al. (2004) for discriminating the susceptibility of liquefaction based on the epicentral distance.

limit is 25% and the plasticity index is 2%. According to these results the ejected sample is classified as sandy silt with low plasticity (ML).

In the village of Nydri, typical examples of soil liquefaction such as sand boils and vent fractures were observed in the river mouth of Dimosaris River. The soil, which had been ejected, is classified as sand (SP) with uniform grading (Fig. 11). The content of fines sized grains is 1.93% while the content of fine- to-medium-sized sand grain is 92%.

The results of grain size analyses of the samples are compared with the proposed curves by (Tsuchida, 1971) for well graded soils and for soils at uniform grading as shown in Fig. 18. Their grain size distributions curves are within the suggested range of possibility of liquefaction, therefore these layers seem to be susceptible to liquefaction in terms of their grain size. For the ejected samples containing more than 35% fines content (Table 3), the criteria suggested by Andrews and Martin (2000) were employed. Based on these criteria, the soils from Lef1, Lef2 and Vassiliki are evaluated as susceptible to liquefaction.

Fig. 16. Sand boil in the seaside in the town of Lefkada, sample ID: LEF1 (photo taken by Papathanassiou, 15/08/2003).

6.2. Subsurface geology and geotechnical characteristics

In the town of Lefkada the authors used 13 boreholes logs, performed by the Central Research Institute

Fig. 17. Ejected sand from fissures in the pavement of the seaside in the town of Lefkada, sampleID: LEF2 (photo taken by Papathanassiou, 15/08/2003).

of the Ministry of Public Works after the earthquake (KEDE, 2004), to prepare simplified cross-sections. In Fig. 19, a map of Lefkada town is shown with the locations of borings and the surface traces of the sections. At the waterfront area (section A–A′), the borehole data indicate that an artificial soil with low SPT-N values, and thickness between 1 and 5 m, overlies a non-plastic silty sand layer. The thickness of this SM layer varies between 5 and 9 m. The content of silt and clay-sized grain ranged between 21% and 55% and the soil is classified as a nonplastic SM. Between the artificial fill and the SM layer, three of the five boreholes logs indicate the existence of a thin low plasticity clay layer (CL) which in some depths turns into a high plasticity clay (CH) soil. The liquid limits ranged between 45% and 65% with an average of 47%. The plasticity indexes in this layer varied from 28% to 43%. Based on the criteria by Andrews and Martin (2000) these soils are evaluated as non-susceptible because their liquid limit is more than 32% and their clay content is more than 10%. A silt layer with constant thickness about 2 m lies beneath the silty sand layer. Based on the USCS classification, this soil is evaluated as low plasticity silt (ML). The SPT-N values in it ranged between 14 and 95 with an average of 41. The ML soil overlies a layer of marls with a very high

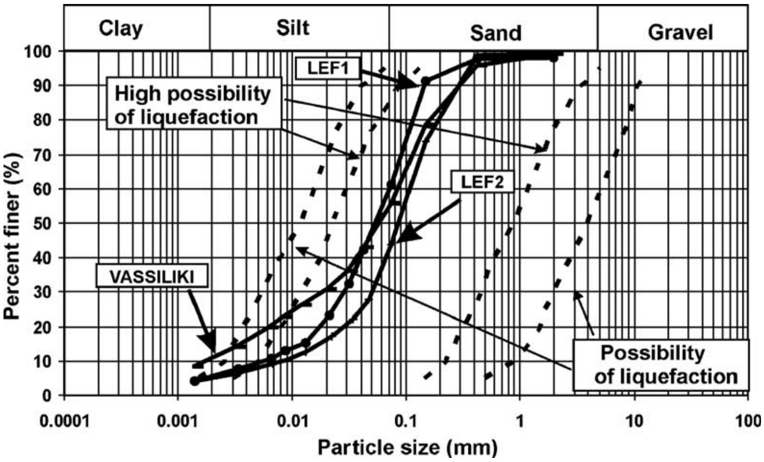

Fig. 18. Comparison between the grain size distribution curves of the collected samles LEF1, LEF2, Vassiliki and boundaries curves for most liquefiable soils suggested by Tsuchida (1971).

Table 3
The laboratory testing results of the ejected samples

Site	Fines content	Clay content	Liquid limit	Plasticity index
Lef1	60%	5.11%	25%	3%
Lef2	45%	4.98%	24%	1.6%
Vassiliki	55%	10%	25%	2%
Nydri	1.93%	–	NP	NP

content of fines, approximately 95%, and high SPT-N values. Since the most critical depth for liquefaction assessment is 20 m, boreholes in the cross-sections are limited to this depth. The depth of the groundwater table varied from 0.6 to 1 m indicating shallow groundwater table.

The second cross-section B–B′ is situated to the north from the first one, in an area where no liquefaction phenomena were occurred. Available borehole logs (KEDE, 2004) from 4 sites suggest that the thickness of the artificial soil in this area is less than 2.5 m. A low plasticity clayey layer with thickness between 4.5 and 6.5 m lies beneath the artificial fill. The soil falls into CL soil class. The SPT-N values varied from 4 to 9 with an average of 6. This CL soil in some depths turns into a sandy clayey soil as shown in Fig. 20. At the bottom of this layer, the boreholes data indicate the appearance of very thin sandstone layers. This layer overlies a low plasticity silty layer with thickness between 1.2 and 4.5 m and SPT-N values from 7 to 19 with an average of 13. Based on USCS classification, this soil is classified as a ML. Beneath lies a layer of marls with the same characteristics as in the first cross-section that has been described above. The soils in this area are evaluated as non-susceptible to liquefy according to the criteria of Andrews and Martin (2000). The depth of the groundwater table ranged between 1 and 3.1 m below ground surface.

6.3. Evaluation of liquefaction potential index

The severity of foundation damage caused by liquefaction depends to a great extent on the severity of liquefaction. In order to quantify the severity of liquefaction, Iwasaki et al. (1982) developed the method of liquefaction potential index (LPI). They assumed that the severity of liquefaction should be proportional to the:

1. thickness of the liquefied layer;
2. proximity of the liquefied layer to the surface, and
3. the factor of safety of the liquefied layer is far less than 1.0.

The prediction by the liquefaction potential index is different than that made by the simplified procedure of Seed and Idriss (1971). According to Toprak and Holzer (2003), the simplified procedure predicts what will happen to a soil element whereas the index predicts the performance of the whole soil column and the consequences of liquefaction at the ground surface.

Sonmez (2003) modified this method by accepting the threshold value of 1.2 of factor of safety as the limiting value between the categories of marginally liquefiable to non-liquefiable soil.

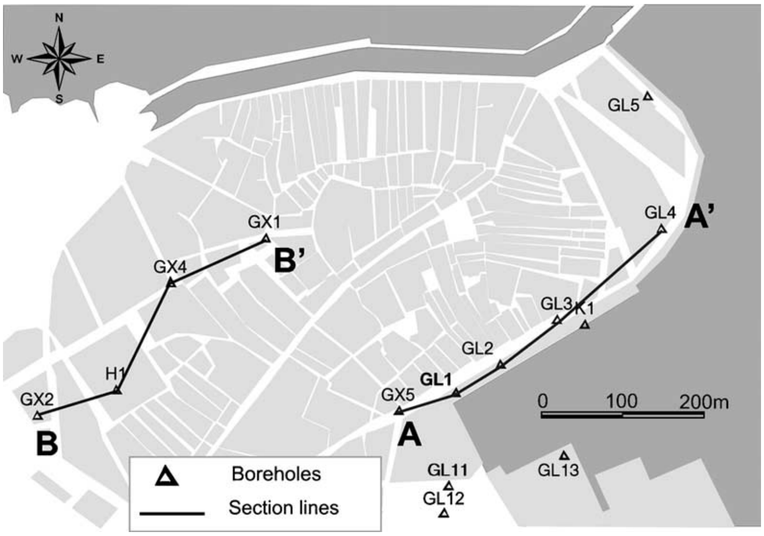

Fig. 19. Map showing the locations of boreholes and the section lines in the town of Lefkada.

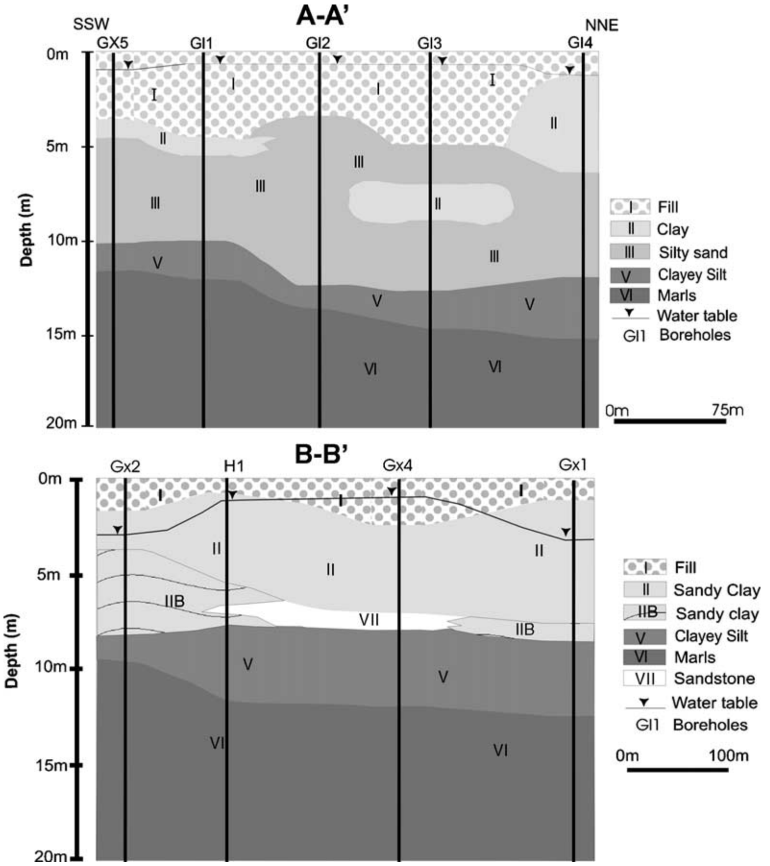

Fig. 20. Cross-sections showing subsurface conditions in the town of Lefkada.

Thus, the LPI is defined as:

$$\mathrm{LPI} = \int_0^z F(z)W(z)\mathrm{d}z. \quad (1)$$

Where z is the depth below the ground surface in meters; $F(z)$ is a function of the factor of safety against liquefaction, Fs, where $F(z)=1-\mathrm{Fs}$ when $\mathrm{Fs}<0.95$, $F(z)=2\cdot10^6\ \mathrm{e}^{-18.427\mathrm{Fs}}$ if $0.95<\mathrm{Fs}<1.2$ and if $\mathrm{Fs}>1.2$, $F(z)=0$ (Sonmez, 2003). Eq. (1) gives the values of LPI ranging from 0 to 100. Severe liquefaction is likely at sites with $\mathrm{LPI}>15$ and is not likely at sites with $\mathrm{LPI}=0$ (Iwasaki et al., 1982; Sonmez, 2003). For LPI between 5 and 15 the liquefaction potential is high, while when LPI ranges between 2 and 5 the potential is moderate. For LPI between 0 and 2 there is low liquefaction potential (Sonmez, 2003).

6.3.1. Methodology and data

In order to evaluate the liquefaction potential index (LPI) of the subsoil in the town of Lefkada, we assessed borehole records with SPT values. Except one borehole (H1), all borings and the laboratory testing of the soils were performed by the Central Research Institute of the Ministry of Public Works after the earthquake. Initially, we computed the factors of safety against liquefaction with the simplified procedure proposed by Seed and Idriss (1971) and Seed et al. (1985). The ability of a soil element to resist liquefaction is defined as liquefaction factor of safety, Fs, and two variables are required for its calculation: the cyclic resistance ratio CRR and the earthquake induced cyclic stress ratio CSR at a specific depth for a given design earthquake. Layers with factors of safety greater than 1.2 and between 1.0 and 1.2 were considered as non-liquefied and marginally liquefiable, respectively (Tosun and Ulusay, 1997; Ulusay and Kuru, 2004).

Modifications suggested by Youd et al. (2001) were also taken into consideration in our assessment. Furthermore, we normalized the SPT-N values using the overburden correction (C_n) proposed by Liao and Whitman, 1986 in order to estimate CRR. The value of C_n was limited to a maximum value of 1.7, suggested by Youd et al. (2001). Another important factor is the energy transferred from the falling hammer to

Fig. 21. Liquefaction susceptibility map based on liquefaction potential index.

the SPT sampler. An energy ratio (ER) of 60% was generally accepted as the appropriate average of the free-fall theoretical energy. In addition, the SPT-N values were corrected based on a borehole diameter factor. $(N_1)_{60}$ values greater than or equal to 30 were not considered in liquefaction analyses (Ulusay and Kuru, 2004).

The CSR values were calculated using the equation proposed by Seed and Idriss (1971):

$$\mathrm{CSR} = 0.65(a_{\max}/g)(\sigma_{\mathrm{vo}}/\sigma_{\mathrm{vo}}')r_{\mathrm{d}}. \tag{2}$$

Where, CSR is the cyclic stress ratio induced by a given earthquake, 0.65 is weighing factor, introduced by Seed, to calculate the number of uniform stress

Table 4
Evaluation of liquefaction potential, based on SPT data from Lefkada town and the villages of Nydri, Lygia and Basiliki

Site	Borehole ID	Depth of layer (m)	Depth of groundwater table (m)	SPT-N	Fs	LPI
Lefkas town	GL1	2.5	0.6	9	0.49	17.274
	GL1	9.75	0.6	16	0.575	3.426
	GL2	1.75	0.6	6	0.405	9.38
	GL2	2.85	0.6	4	0.202	6.029
	GL3	5.75	0.6	1	0.242	6.972
	GL3	6.75	0.6	1	0.228	2.87
	GL4	7	1	20	0.873	0.82
	GL4	8.2	1	12	0.422	3.71
	GL4	10.5	1	12	0.542	7.07
	GL5	6.2	1.2	7	0.357	4.062
	GL5	7.5	1.2	6	0.374	6.7
	GL11	10.2	2.5	24	1.014	0.177
	GL12	7.2	1	21	0.859	2.352
	GL12	10.6	1	22	0.945	0.575
	GL13	–	1.6	–	–	0
	GX1	–	3.1	–	–	0
	GX2	–	3	–	–	0
	GX4	–	1	–	–	0
	GX5	2.1	0.8	4	0.322	16.09
	GX5	6	0.8	16	0.685	6.369
	GX5	8	0.8	21	0.897	1.181
	GX5	9.9	0.8	16	0.658	1.383
	H1	–	1.3	–	–	0

The empty fields in some boreholes indicate the no-existence of liquefied layers.

cycles required to produce the same pore water pressure increase as an irregular earthquake ground motion, $\sigma_{\text{vï}}$ is the total vertical overburden stress, $\sigma'_{\text{vï}}$ is the effective overburden stress, $a_{\max}$ is the peak horizontal ground acceleration, unit is in grams and r_d is a stress reduction coefficient determined by Liao and Whitman (1986).

For the evaluation of liquefaction potential in the town of Lefkada we employed an $a_{\max}$ value equal to 0.4 g and a magnitude Ms of 6.4. This value of PGA was recorded by the permanent network of ITSAK during the main shock at the center of the city, while the Ms value corresponds to the one of the 2003 earthquake (Ms = 6.4), and is similar to the maximum earthquake magnitude that occurred in Lefkada island (after 1911) according to historical seismicity of the area. The depth of groundwater table for each boring was based on in-situ tests. In Table 4 are listed the Fs values of the susceptible to liquefaction layers (Fs < 1.2) for each borehole in the town of Lefkada.

Afterwards the evaluation of factor of safety per layer, we estimated the liquefaction potential index for each borehole. Iwasaki et al. (1982) in their study considered a depth of 20 m for liquefaction assessment. For SPT profiles not extending to 20 m, the last N measured was assumed for depths up to 20 m. The values of LPI for each soil column are listed in Table 4. Based on these values of LPI, an attempt was made to prepare a preliminary map of liquefaction susceptibility for Lefkada town. The isoliquefaction index contours were constructed by using the inverse distance to a power method. As it can be observed in Fig. 21, this preliminary map confirms the distribution of damages induced by soil liquefaction in the seafront of the town. The calculations of liquefaction potential index in this study were performed with the aid of a computer program, SLIQUE, developed by Sonmez (2003).

7. Conclusions

The 14 August 2003 Lefkada earthquake (Mw = 6.2) was another strong shock in a sequence of more than known 20 historical events with similar size. The evaluated intensities in the island range from VI to VIII+ while the maximum one have observed in the northern part of the island (VIII in Lefkada town, VIII+ Peukoulia beach; Fig. 1). The extensive ground failures are rock falls, landslides (slope failures mainly), coastal or dock's cracks and soil liquefaction. Although these phenomena appeared all over the island, rock falls are more concentrated on the northwestern edge and liquefaction on the quaternary deposits at the northern and eastern island coasts, which are considered to be of high potentially liquefiable type. The macroseismic effects are remarkably similar with that of some past earthquakes (1625, 1630, 1704, 1914, 1948). The island suffered extensive ground failures and macroseismic effects during almost all the known earthquakes, either to its northern part, like the present event, or to its southern.

We observed evidences of liquefaction occurrence as sand boils and ground fissures with ejection of mud and water mixture at the waterfront areas in the town of Lefkada and in the villages of Nydri and Vassiliki. Ejected samples from these sites were collected with a view to examine the liquefaction susceptibility of the soil layers. The liquid limits (LL) of the Lefkada's collected samples (Lef1 and LEF2) are 25% and 24%, respectively, while the value of plasticity index is 3% for LEF1 and 1.6% for LEF2. The sample from Nydri is classified as non-plastic sand while the values of LL and PI for the Vassiliki's sample are 25% and 2%, respectively. The results from grain size analyses of these samples show that their distributions curves are within the suggested range of possibility of liquefaction, therefore these layers seem to be susceptible to liquefaction in terms of their grain size.

According to our liquefaction analysis for the town of Lefkada, the silty sandy soil which lies beneath the artificial fills in the waterfront is evaluated as susceptible to liquefy layer. The ejected material, which had been collected during the field investigations, probably came from this layer. In addition, the artificial fill, which has also low values of Fs, can be considered as potentially liquefiable layer. Moreover, this evaluation indicates that at the center of the town there is no possibility of liquefaction occurrence for these specific conditions (Ms = 6.4 and $a = 0.42$ g).

Finally, a preliminary map of liquefaction potential index is proposed, based on data from 13 boreholes inside the town of Lefkada. The similarity between the distributions of the predicted areas of high potential to liquefaction with those in which ground failures had been triggered by the 2003 Lefkada earthquake indicates that LPI may be a useful tool for future seismic hazards studies.

Acknowledgements

The authors would like to thank the two anonymous reviewers for their comments. Funding of this research was provided by the National Observatory of Athens and the Aristotle University of Thessaloniki. The authors of this paper would like to thank also Prof. R. Ulusay and Ass. Prof. H. Sonmez (Ankara, Turkey) for their comments about the liquefaction potential index and for their permission for the use of the software SLIQUE. Some figures were prepared with GMT. We thank also Dr. G. Stavrakakis for his support and Dr. E. Sokos for his comments.

References

Ambraseys, N.N., 1988. Engineering seismology. Int. J. Earthq. Eng. Struct. Dyn. 17, 1 – 105.

Ambraseys, N., Jackson, J.A., 1998. Faulting associated with historical and recent earthquakes in the Eastern Mediterranean region. Geophys. J. Int. 133, 390 – 406.

Andizei, M., Baldi, P., Casula, G., Galvani, A., Mantovani, E., Pesci, A., Riguzzi, F., Serpelloni, E., 2001. Insights into present-day crustal motion in the central Mediterranean area from GPS surveys. Geophys. J. Int. 146 (1), 98 – 110.

Andrews, D.C., Martin, G.R., 2000. Criteria for liquefaction of silty sands. 12th World Conference on Earthquake Engineering, Auckland, New Zealand.

Barbiani, D.G., Barbiani, B.A., 1864. Memoires sur les tremblements de terre dans l'ile de Zante, Presented by A.Perrey in Academic Imperiale des Sciences, pp. 1–112. Dijon.

Bornovas, J., 1964. Géologie de l'île de Lefkade. Geol. Geophys. Res. (Special Publication by Greek Geological Survey) V.10 (1) (Athens).

Critikos, N.A., 1916. L'ile de Leucade et sismes du 23 et du 27 Novembre 1914. Ann. De l'observ. D' Athenes 7, 62 – 81.

Cushing, M., 1985. Evoluation structurale de la marge nord-ouest hellenique dans l'ile de Lefkada et ses environs (Greece nord-occidentale), PhD thesis, Univ. de Paris-Sud (XI), Centre d' Orsay.

EAK, 2000. Greek seismic code, Earthquake planning and Protection Organization, Athens-Greece, 72 pp and 7 Appendixes (in Greek).

EERI, 2003. Preliminary observations on the August 14, 2003, Lefkada Island (Westren Greece) earthquake, Spectral Earthquake report, Nov. 2003.

Galanopoulos, G.A., 1955. Seismic geography of Greece. Ann. Géol. de Pays Helleniques 6, 83 – 121.

Galanopoulos, G.A., 1981. The damaging shocks and the earthquake potential of Greece. Ann. Geol. Pays Hell. 30, 648 – 724.

Iwasaki, T., Tokida, K., Tatsuoka, F., Watanabe, S., Yasuda, S., Sato, H., 1982. Microzonation for soil liquefaction potential using simplified methods. Proc. 3rd International Conference on Microzonation vol. 3, pp. 1319 – 1330. Seattle.

ITSAK, 2003. A Preliminary Report on Earthquake Consequences of the August 14, Event M = 6.4. Thessaloniki-Greece, 61 pp. (in Greek).

Karakostas, V.G., Papadimitriou, E.E., Papazachos, C.B., 2004. Properties of the 2003 Lefkada, Ionian Islands, Greece, earthquake seismic sequence and seismicity triggering. Bull. Seismol. Soc. Am. 94 (5), 1976 – 1981.

KEDE, 2004. Results of Geotechnical Investigations at the Port of Lefkas for the Evaluation of Damages Triggered by the Earthquake of 14-08-2003, Athens, June 2004. (in Greek).

Kramer, S.L., 1996. Geotechnical Earthquake Engineering. New Jersey, Prentice Hall, pp. 348 – 355.

Le Pichon, X., Chamot-Rooke, N., Lallemant, S., 1995. Geodetic deformation of the kinematics of central Greece with respect to Europe: implications for eastern Mediterranean tectonics. J. Geophys. Res. 100 (B7), 12675 – 12690.

Liao, S., Whitman, R.V., 1986. Overbuden correction factor for SPT in sand. J. Geotech. Eng., ASCE 114 (4), 389 – 411.

Louvari, E., Kiratzi, A.A., Papazachos, B.C., 1999. The Cephalonia Transform Fault and its extension to western Lefkada Island (Greece). Tectonophysics 308, 223 – 236.

Mercier, J., Sorel, D., Simeakis, K., 1987. Changes in the state of stress in the overriding plate of a subduction zone: the Aegean Arc from the Pliocene to the Present. Ann. Tecton. I (1), 20 – 39.

Newspaper «Anthropistis», 4, No 161, 27/07/1948 and 13, No 597, 16/5/1957 (in Greek).

Newspaper «Ethniki psichi», No 58, 9/5/1948 (in Greek).

Newspaper «Kiriks», 5, No 25, 13/5/1948 (in Greek).

Papadimitriou, E., 2002. Mode of strong earthquake recurrence in the Central Ionian Islands (Greece): possible triggering due to Coulomb Stress changes generated by the occurrence of previous strong shocks. Bull. Seismol. Soc. Am. 92 (8), 3293 – 3308.

Papadopoulos, G.A., Lefkopoulos, G., 1993. Magnitude–distance relations for liquefaction in soil from earthquakes. Bull. Seism. Soc. Am. 83 (3), 925 – 938.

Papadopoulos, A.G., Karastathis, V., Ganas, A., Pavlides, Sp., Fokaefs, A., Orfanogiannaki, K., 2003. The Lefkada, Ionian Sea (Greece), shock (Mw 6.2) of 14 August 2003: evidence for the characteristic earthquake from seismicity and ground failures. Earth Planets Space 55, 713 – 718.

Papathanassiou, G., Pavlides, S., Christaras, B., Pitilakis, K., 2004. Liquefaction phenomena in the Aegean broader area and empirical relations of magnitude versus distance. Proc., 5th Int. Symp. On Eastern Med. Geology vol. 2, pp. 942 – 946. Thessaloniki 14–20 April, Greece.

Papazachos, B.C., 1990. Seismicity of the Aegean and surrounding area. Tectonophysics 178, 287 – 308.

Papazachos, C., Kiratzi, A., 1996. A detailed study of the active crustal deformation in the Aegean and surrounding area. Tectonophysics 253, 129 – 152.

Papazachos, B.C., Papazachou, K., 1997. The Earthquakes of Greece. Ziti Publ, Thessaloniki. 356 pp.

Papazachos, B.C., Comninakis, P.E., Karakaisis, G.F., Karakostas, B.G., Papaioannou, Ch.A., Papazachos, C.B., Scordilis, E.M., 2000. A Catalogue of Earthquakes in Greece and Surrounding Area for the Period 550BC–1999 1. Publ. Geoph. Lab, Univ. of Thessaloniki. 333 pp.

Pavlides, S., Caputo, R., 2004. Earthquakes versus Active Fault's length-displacement: qualitative and quantitative relationships from the Aegean (Greece and Surrounding region). Tectonophysics 380, 159 – 188.

Pavlides, S., Papathanassiou, G., Ganas, A., Papadopoulos, G.A., Ioannides, K., Stamoulis, K., Papachristodoulou, C., Keramydas, D., 2003. The 14th August 2003 Lefkada (Ionian Sea) Earthquake (Mw = 6.3), Preliminary Field Observations, Intern. Conf. "The South Aegean Active Volcanic Arc: Present Knowledge and Future Perspectives" 17–20 Sept, 2003 Milos, Abs.

Pavlides, S., Papadopoulos, G.A., Ganas, A., Papathanassiou, G., Karastathis, V., Keramydas, D., Fokaefs, A., 2004. The 14 August 2003 Lefkada (Ionian Sea) earthquake. 5th Int. Symp. On Eastern Med. Geology vol. 2, pp. 942 – 946. Thessaloniki 14–20 April, Greece.

Rondoyannis, G.P., 1995. The seismicity of Lefkada (1469–1971). Society of Lefkada's studys, H., (in Greek).

Rondoyanni-Tsiambaou, Th., 1997. Les seismes et l'environnement géologique de l'île de Lefkade, Grèce: Passe et Futur.. In: Marinos, et al., (Eds.), Engineering Geology and the Environment. Balkema, pp. 1469–1474.

Seed, H.B., Idriss, I.M., 1971. Simplified Procedure for evaluation Soil liquefaction potential. J. Soil Mech. Found. Div., ASCE 97 SM9, 1249–1273.

Seed, H., Tokimatsu, K., Harder, L.F., Chung, R.F., 1985. Influence of SPT procedures in Soil liquefaction resistance evaluations. J. Geotech. Eng. Div., ASCE 111 (12), 1425–1445.

Sonmez, H., 2003. Modification of the liquefaction potential index and liquefaction susceptibility mapping for a liquefaction-prone area (Inegol, Turkey). Environ. Geol. 44, 862–871.

Sorel, D., 1976. L'evolution de la Grece nord-occidentale depuis le Miocene, dans le cadre geodynamique de l'arc egeen. PhD thesis, Univ. d'Orsay.

Stamatelos, J.N., 1870. The thirteen mentioned destruction of Leukada, from 1612 till 1869. Efimeris of Philomathon, Athens, pp. 726. 24 January (in Greek).

Taymaz, T., Jackson, J., McKenzie, D., 1991. Active Tectonics of the north and central Aegean Sea. Geophys. J. Int. 106, 433–490.

Toprak, S., Holzer, T., 2003. Liquefaction potential index: field assessment. J. Geotech. Geoenviron. Eng., ASCE, 315–322.

Tosun, H., Ulusay, R., 1997. Engineering geological characterization and evaluation of liquefaction susceptibility of foundation soils at a dam site, southwest Turkey. Environ. Eng. Geosci. 3 (3), 389–409.

Tsuchida, H., 1971. Estimation of liquefaction potential of sandy soils. Proc. 3rd Joint Meeting, US–Japan, UNJR.

Ulusay, R., Kuru, T., 2004. 1998 Adana-Ceyhan (Turkey) earthquake and a preliminary Microzonation based on liquefaction potential for Ceyhan town. Nat. Hazards 32, 59–88.

Youd, T.L., Perkins, D.M., 1978. Mapping of Liquefaction induced Ground Failure Potential. J. Geotech. Eng. Div, ASCE 104 (GT4), 433–446.

Youd, T.L., Idriss, I.M., Andrus, R.D., Arango, I., Castro, G., Christian, J.T., Dobry, R., Finn, W.D.L., Harder, L.F., Hynes, M.E., Ishihara, K., Koester, J.P., Liao, S.S.C., Marcurson III, W.F., Marti, G.R., Mitchell, J.K., Moriwaki, Y., Power, M.S., Robertson, P.K., Seed, R.B., Stokoe II, K.H., 2001. Liquefaction resistance of soils: summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils. J. Geotech. Geoenviron. Eng., 817–833.

Wells, D.L., Coppersmith, J.K., 1994. New empirical Relationship among Magnitude, Rupture Length, Rupture Width, Rupture Area, and Surface Displacement. Bull. Seismol. Soc. Am. 84, 974–1002.