Liquefaction –induced ground surface disruption. Case study from 2003 Lefkas (Greece) earthquake

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Abstract

A strong earthquake (Mw=6.2, Ms=6.4) offshore the island of Lefkada occurred on August 14, 2003. The maximum intensity has been evaluated as Io=VIII (EMS) at Lefkas 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, as the focal mechanism has shown. The area affected by the shock falls in zone IV of the Greek seismic code (EAK, 2000), with design acceleration 0.36g, 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 Lefkas town. The value of PGA was a_g=0.42g having a period of about 0.5sec. 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.

In what concerns liquefaction repeatability, sand boils and ground fissures with ejection of mud occurred at the seaside of the town of Lefkas, and in the villages of Nydri and Basiliki as it happened in past events e.g. 1704, 1914 (Ms=6.3) and 1948 (Ms=6.5). Few hours after the main shock field observations were taken place. During these investigations ejected samples from 4 locations were collected with a view to examine their grading characteristics, which include grain size distribution, liquid limit and plasticity index. These samples were collected from vent fractures and sand boils in the town of Lefkas (Lef1, Lef2) and in the villages of Nydri and Basiliki. The results of grain size analyses of the samples are compared with the proposed curves by Tsuchida (1971) for soils at uniform grading. 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. Furthermore, the criteria suggested by Ishihara (1985), to assess the potential for ground surface disruption, were evaluated using borehole data from field investigations. The data from sites with surface disruption are correctly predicted by Ishihara's (1985) bound with the exceptions of two sites in which no ground-surface disruption was observed or reported.

Keywords: sand boils, liquefaction potential, Lefkas earthquake, surface disruption

Introduction

A strong earthquake (Mw=6.2, Ms=6.4) occurred offshore the island of Lefkada on August 14, 2003. The maximum intensity has been evaluated as Io=VIII at Lefkas municipality, while VI to VII intensities were evaluated at many other villages of the island (Fig.1). All intensities were assessed in both the EMS (European Macroseismic Scale) and MM scales. Earthquakes of such a magnitude are very frequent in the Greek area, especially in the Ionian Islands, which show the highest seismicity in the Mediterranean region. The area affected by the shock falls in zone IV of the Greek seismic code (EAK, 2000), with design acceleration 0.36g, the highest of Greece. The largest value of peak horizontal ground acceleration (PGA) was 0.42g and it was recorded in the center of Lefkas town. Due to the offshore seismic fault, no typical co-seismic ruptures were found. It is difficult to determine which the causative fault of Lefkas earthquake was. Other evidence such as bathymetry, coast morphology (sinuosity close to 1), and aftershock distribution indicate that it was an offshore, very close to northwestern coast of the island, active fault, part of the island neotectonic fault system.

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. Rock falls, ground settlement and lateral spreading caused several damages to the road network and to port facilities. In the town of

Lefkas and in the villages of Nydri and Basiliki sand boils and ground fissures were observed along the waterfront.

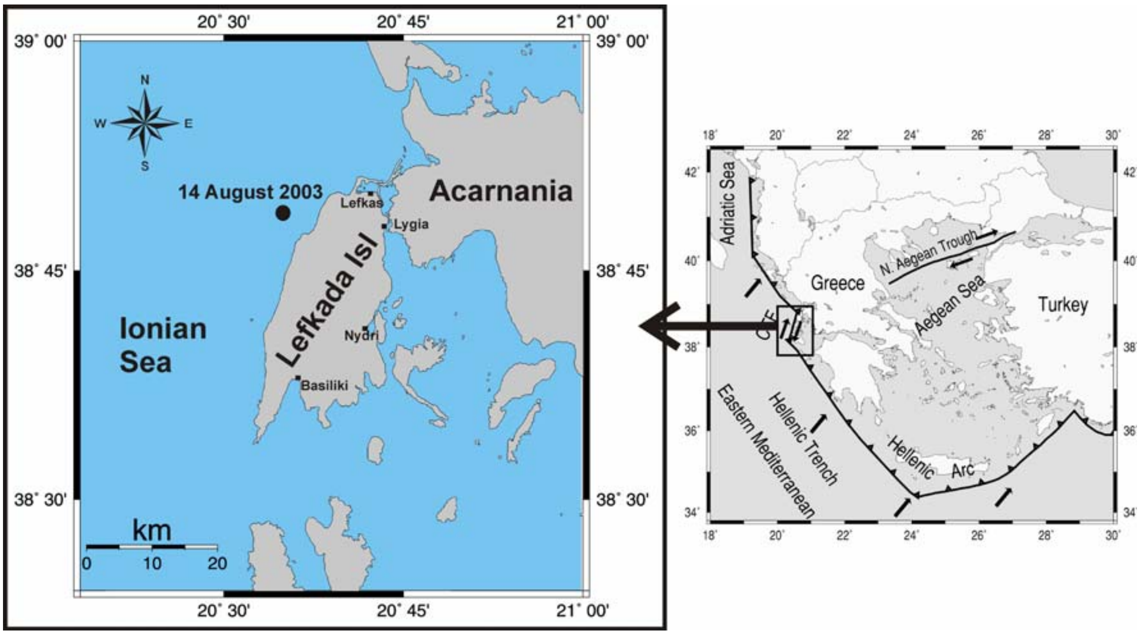

***Figure 1**. Left: Map of Lefkada island showing the epicenter (solid circle) of the 14 August 2003 earthquake. Right: Main seismotectonic properties of the Aegean and surrounding region. (Papadimitriou 2002.) The study area is indicated by the square.*

Historical seismicity

In what concerns liquefaction repeatability at least 5 earthquakes induced phenomena similar to those that were observed during the latest shock. The 17 March 1820 shock caused settlement of the central square of Lefkas town while the 24 May 1911 earthquake induced ground fissures, parallel to the coast, with length of 150m and width of 5cm (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 Lefkas town, slope failures in 3km 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 150m and width of 12 cm in the waterfront of Lefkas town. Also a vertical displacement of 12 cm was evident in the same area. In the beach of Pefkoulia, a ground crater of 3m and depth of 1m was reported (Rondoyannis, 1995). The ground failures triggered by these four events were concentrated in the northern part of the island. The 22 April 1948 earthquake caused ground failures in the Basiliki town which is situated in the southern part of the island. Ground cracks with length of 40m length and width of 5cm were observed in the coastal zone of Basiliki (Galanopoulos, 1955).

Liquefaction occurrences

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 evidence of liquefaction occurrence, like sand boils and ground fissures with ejection of mud-water mixture, was reported. In the town of Lefkas, the liquefaction occurrence (sand boils and vent fractures) was observed mainly in the waterfront area and caused damages to pavements and sidewalks behind seawalls. According to eyewitnesses, muddy water was ejected at a height of 50cm from cracks in a pavement surface near the waterfront, indicating high excess pore pressure generating during earthquake shaking. Furthermore, the asphalt pavement was covered by a thin sand silty layer which was ejected from the ground fissures.

In Nydri the consequences of liquefaction were less severe. Ground cracking with horizontal displacement of few cm towards the sea and vertical subsidence of 3cm of the pavement behind the seawall was observed. In the village of Basiliki the main shock induced major problems to the port facilities. The new pier of the village was laterally shifted and overturned. At the old pier only ground cracks were triggered. Their width ranged between 3 and 7cm. In addition, a vertical subsidence of approximately 2cm was observed. Inside the village there was no clear evidence of liquefaction. On the contrary, at the river mouth of a torrent, 400m western of the village, sand craters and vent fractures were observed. Finally, in Lygia no typical examples of soil liquefaction were observed, although 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 3cm approximately was observed.

In order to assess the liquefaction hazard in these sites, we examined initially the evaluation of liquefaction susceptibility. The criteria, by which this susceptibility can be judged, include historical, geological, compositional and geotechnical data (Kramer, 1996). The liquefaction and associated ground failures triggered by the earthquake, appeared to be concentrated in areas formed by recent coastal, alluvial and fluvial deposits, which according to Youd and Perkins (1978) are classified as high susceptible to liquefaction sedimentary deposits.

In addition, samples from sand boils and mixtures of mud and water ejected from fissures, which were observed in the waterfront of Lefkas town and in the villages of Nydri and Basiliki, were collected in order to determine their grading characteristics which include grain size distribution, liquid limit and plasticity index (Table 1). Moreover, liquefaction susceptibility of the samples, containing more than 35% fines, was evaluated based on the criteria proposed by Andrews and Martin (2000). According to these criteria, the soils from Lef1, Lef2 and Basiliki are evaluated as susceptible to liquefaction.

***Table 1**. Grading characteristics of the ejected samples*

Site	Fines content	Clay content	Liquid Limit	Plasticity index
Lef1	60%	5.11%	25%	3%
Lef2	45%	4.98%	24.5%	1.6%
Basiliki	55%	10%	25.2%	2.1%
Nydri	1.93%	-	NP	NP

Afterwards, the results of grain size analyses of the samples are compared with the proposed curves by Tsuchida (1971) for soils at uniform grading as shown in Figure 2. Their grain size distributions curves are within the suggested range of possibility of liquefaction, therefore these soils seem to be susceptible to liquefaction in terms of their grain size. Although, these preliminary results indicate the appearance of subsoil layers susceptible to liquefaction; they are not adequate to estimate the possibility of ground disruption triggered by the earthquake.

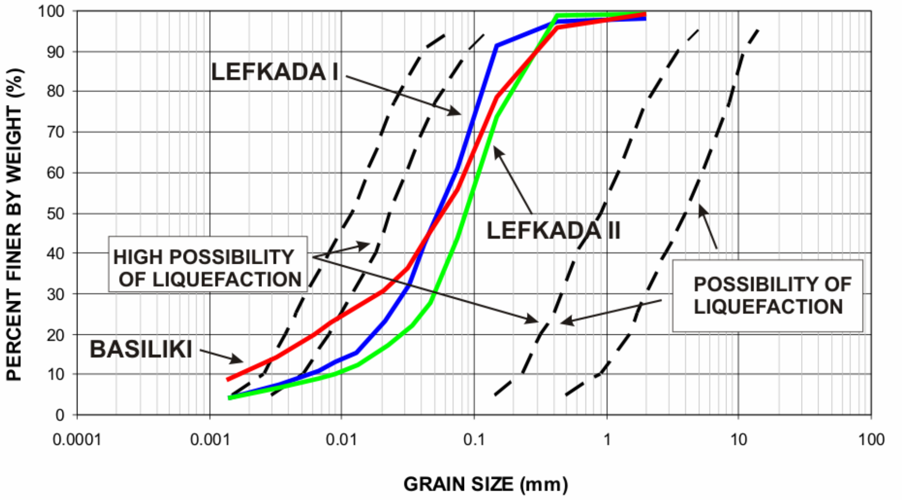

***Figure 2**. Comparison between the grain size distribution curves of the ejected samples and boundaries of possible liquefied soils.*

Assessment of liquefaction induced ground surface disruption

In 1985 Ishihara presented preliminary empirical criteria to assess the potential for ground surface disruption at liquefaction sites. His method is based on thickness of the potentially liquefiable layer (H_2) and the thickness of the non-liquefiable crust (H_1) at a given site. Ishihara's definitions of the liquefiable and non-liquefiable layers are shown in Figure 3. When a non-liquefiable layer is trapped between two liquefiable layers, that layer might liquefy due to migration of excess pore pressures from the liquefiable layers into it (Ishihara 1985; Martin et al, 1991). Hence, the appearance of a susceptible for liquefaction layer indicated by a borehole log does not mean that this condition leads to some form of ground failure.

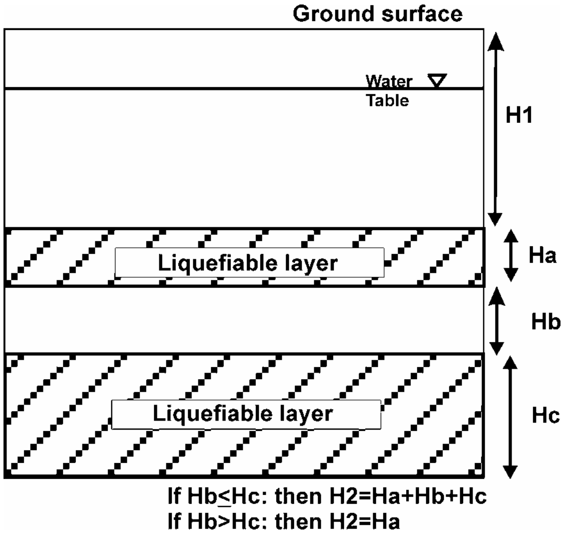

***Figure 3**. Definitions of the surface unliquefiable layer and the underlying liquefiable layer (Ishihara, 1985)*

In order to test Ishihara's criteria, assessment of liquefaction potential was carried out in boreholes data from sites where structural damages were triggered by the 2003, Lefkas earthquake; with or without surface liquefaction occurrences. 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. The most basic procedure to assess the liquefaction potential of a soil layer is the simplified procedure proposed by Seed and Idriss (1971) and Seed et al. (1985). In this process, the cyclic resistance ratio CRR is compared with the earthquake induced cyclic stress ratio CSR at that depth for a specified design earthquake. The modifications suggested by Youd et al. (2001) were taken into consideration while the SPT-N values were normalized using the overburden correction (C_n) proposed by Liao and Withman (1986). The value of C_n was limited to a maximum value of 1.7 suggested by Youd et al. (2001). Furthermore, an energy ratio (ER) of 60% was used 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 value is calculated by the equation:

$CSR = 0.65(a_{max}/g)(\sigma_{vo}/\sigma_{vo}')r_d$

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

The seismic parameters that were employed in this assessment, for the town of Lefkas, were the same with those that had been recorded by the permanent network of ITSAK during the main shock at the center of the city in the 2003 earthquake (Ms=6.4 and a_{max}=0.4g). The PGA values in the villages of Lygia, Basiliki and Nydri were estimated using the attenuation relationships proposed by Skarlatoudis et al. (2004), for shallow earthquakes in Greece, for "rock" conditions. Afterwards, the soil amplification ratios were calculated using the relationship proposed by Midorikawa (1987):

$A_k = 68\ V_s^{-0.6}$.

Because the records of shear wave velocity data were not available, values of V_s were empirical estimated by the correlation proposed by Iyisan (1996):

$V_s = 55N^{0.516}$

Thus, the PGA values that have been used for the evaluation of liquefaction potential in Lygia, Basiliki and Nydri were 0.4, 0.25 and 0.45g respectively.

The layers with factor of safety against liquefaction, Fs, less than 1.2 and SPT-N values less than 20 have been evaluated to estimate the potential of liquefaction induced ground surface disruption.

In Figure 4, two simplified borehole logs are shown, illustrating the variation of soil types and SPT-N values with depth at the seafront in the town of Lefkas.

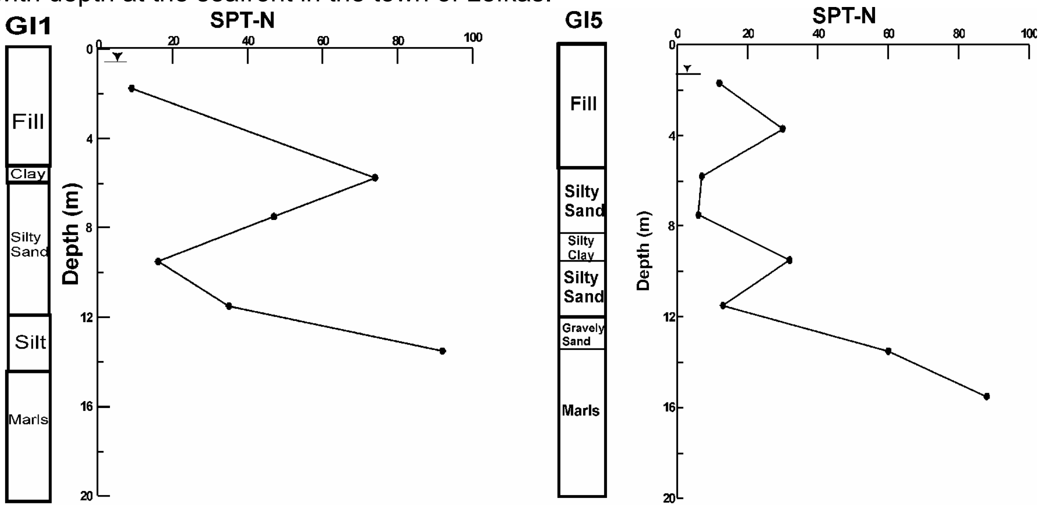

Figure 4. *Borings from Lefkas town illustrating SPT-N values with depth*

The soil elements of these boreholes were examined and the results of this evaluation are listed in Table 2. The borings with layers which do not satisfy the above criteria and thus are not susceptible to liquefaction under these specific conditions (Ms, a_{max}, depth of groundwater), do not have values in the columns of H_1 and H_2 respectively.

Table 2. *Thickness of non-liquefiable H1 and liquefiable H2 layer per borehole according to the criteria proposed by Ishihara (1985)*

Site	Borehole ID	Depth of groundwater (m)	H_1 (m)	H_2 (m)
Lefkas town	GL1	0.6	0.6	3.9
	GL2	0.6	0.6	2.7
	GL3	0.6	5.2	2.1
	GL4	1	6.5	5.5
	GL5	1.2	5.7	2.6
	GL11	2.5	-	-
	GL12	1	-	-
	GL13	1.6	-	-
	GX1	3.1	-	-
	GX2	3	-	-
	GX4	1	-	-
	GX5	0.8	0.8	6.7
	H1	1.3	8	4
Basiliki	GL6	2	-	-
	GL7	1.7	2.8	2.3
Lygia	GL8	1.5	1.5	1.25
	GL9	1.5	1.8	1.6
Nydri	N1	0.5	3.3	8.1

As it can be observed in table 2, at the town of Lefkas the surface disruption sites are correctly predicted by Ishihara's (1985) bound with the exceptions of two sites, GL4 and H1 boreholes, where no ground-surface disruption was observed or reported (Fig. 5 and 6a). In what concerns the GL4 borehole, due to the thick non-liquefiable cap layer, the liquefiable material probably found an exit to ground surface few meters SSW of the borehole in the vicinity of GL3 (see Figure 5). The result for the H1 borehole is considered as an occasional inconsistency, which may be expected in any field tests. The boreholes GX5, GL1 and GL2 were drilled in the seafront of the city which was severely disturbed by liquefaction effects.

Figure 6b,c,d shows layer thickness data from the borings in the villages of Lygia, Basiliki and Nydri respectively. All the data in this plot lie above the Ishihara's (1985) bounds. Although, clear evidences of liquefaction were not observed in all these sites (e.g. Lygia), the reported ground disruption could be predicted by this methodology.

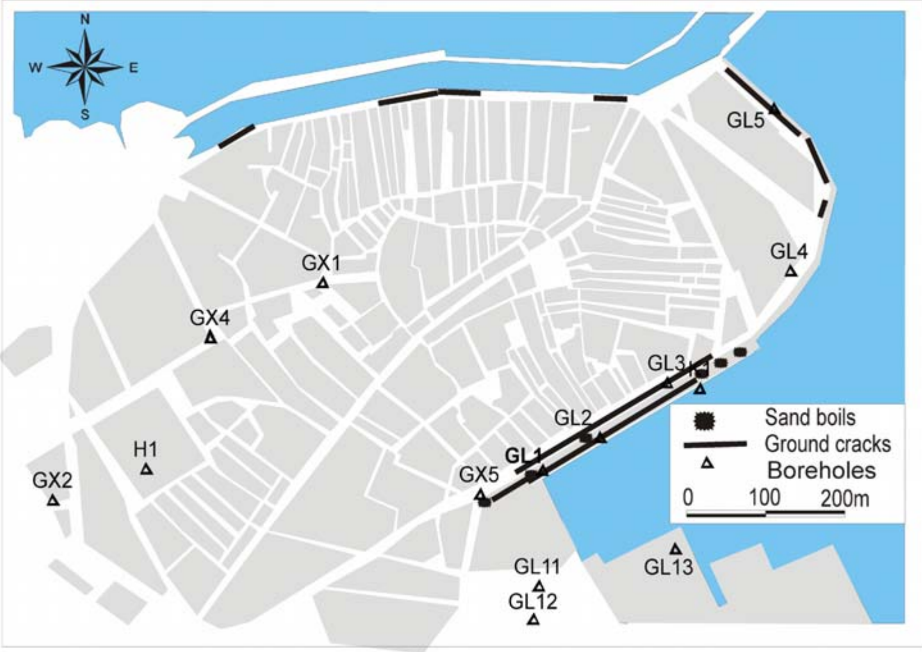

Figure 5. Liquefaction occurrences and boreholes in the town of Lefkas

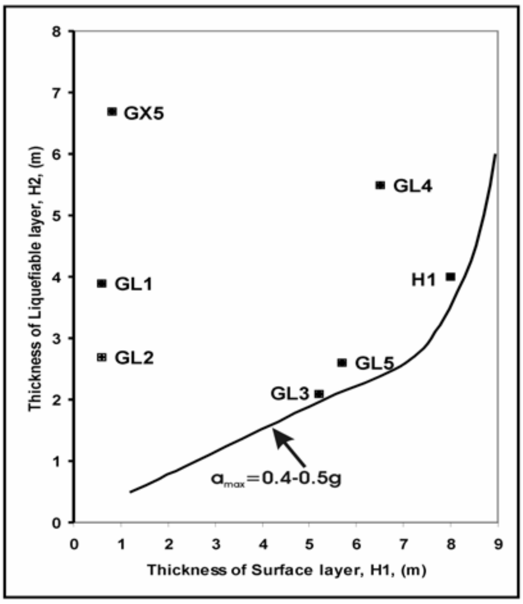

***Figure 6a**. Boundary curve proposed by Ishihara, 1985 for the effect of thickness of unliquefuable surface layer for surface disruption in the town of Lefkas*

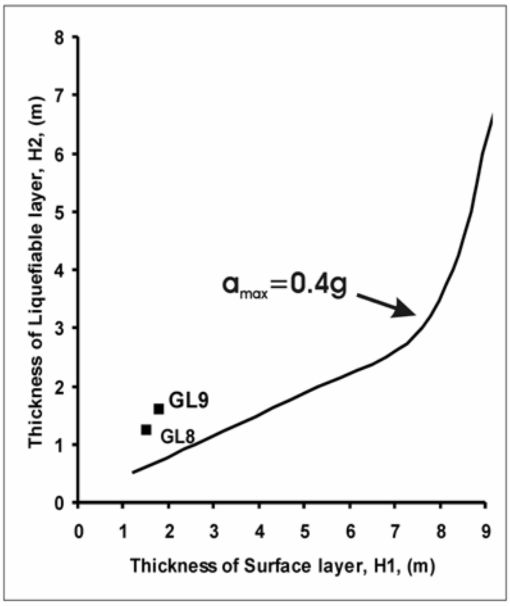

***Figure 6b**. Boundary curve proposed by Ishihara, 1985 for the effect of thickness of unliquefuable surface layer for surface disruption in the village of Lygia (GL8, GL9)*

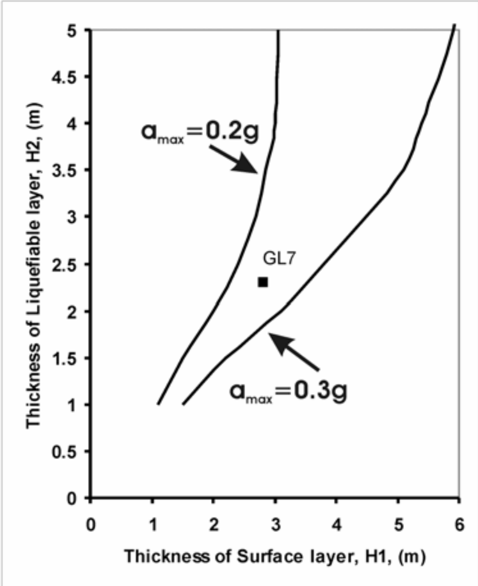

***Figure 6c**. Boundary curve proposed by Ishihara, 1985 for the effect of thickness of unliquefuable surface layer for surface disruption in the village of Basiliki (GL7)*

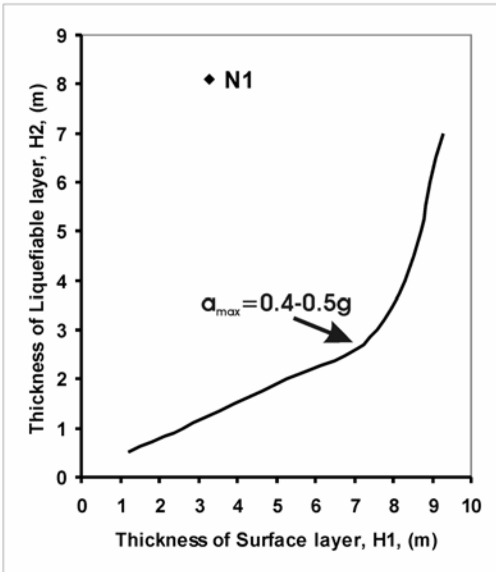

***Figure 6d**. Boundary curve proposed by Ishihara, 1985 for the effect of thickness of unliquefuable surface layer for surface disruption in the village of Nydri (N1)*

Conclusions

An earthquake Ms=6.4 occurred offshore of Lefkas Island on 13 August, 2003 causing ground failures and structural damages to port facilities. The maximum PGA was recorded at the center of the city of Lefkas having a value of 0.42g. Furthermore, the maximum intensity was reported in the same area, Io=VIII (EMS), while VI to VII intensities were evaluated at many other villages of the island. As the focal mechanism has shown the causative fault was an offshore NNE-SSW oriented strike-slip right-lateral. The island suffered extensive ground failures during almost all the known earthquakes, either to its northern part, like the present event, or to its southern.

At least five past earthquakes induced liquefaction phenomena in the same sites as the last one did. Sand boils and ground fissures with ejection of mud-water mixture were reported in the vicinity of port facilities in the town of Lefkas and in the villages of Nydri and Basiliki. Samples from these ejected soils were collected in order to identify their grading characteristics. The grain size distribution curves of the liquefied soils from these sites lie within the boundaries of possible for liquefaction soils proposed by Tsuchida (1971).

In addition, SPT-N values from borings were assessed in order to test the criteria suggested by Ishihara (1985). The good agreement between the predicted liquefiable sites and observed liquefaction induced ground surface disruption indicates the usefulness of this method in preliminary seismic hazard studies. However, the fact that it is based on limited data resulting to a limitation in the validity of the assessment.

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