Learning from Earthquakes

Preliminary Observations on the August 14, 2003, Lefkada Island (Western Greece) Earthquake

Following the earthquake, EERI members and their colleagues from three institutions in Greece went into the field. Teams from the Institute of Engineering Seismology and Earthquake Engineering (ITSAK), the National Technical University of Athens (NTUA), and the University of Athens (UoA) participated in this reconnaissance study.

A few hours after the earthquake and during the subsequent three weeks, teams of experts (seismologists and civil engineers of the research staff of ITSAK) visited the meizoseismal area. ITSAK teams consisted of engineering seismologists B. Margaris, C. Papaioannou, and N. Theodulidis; geophysicist A. Savvaidis; geotechnical engineers A. Anastasiadis, N. Klimis, and K. Makra; and structural engineers M. Demosthenous, C. Karakostas, V. Lekidis, T. Makarios, T. Salonikios, and S. Sous.

NTUA and UoA formed one team consisting of P. Carydis of the Laboratory for Earthquake Engineering of NTUA and E. Lekkas, S. Lozios, E. Skourtsos, and G. Danamos of the Laboratory for Tectonics and Geological Mapping of UoA.

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Introduction

On August 14, 2003 at 08:15 local time (05:15 GMT) a magnitude 6.4 earthquake struck close to the island of Lefkada in Western Greece (Figures 1 and 2). The earthquake was strongly felt in other Ionian Islands (Kephalonia, Zakynthos, Ithaki, etc.) and in a large area on the mainland of Greece. The shock was also felt as far away as Athens (Δ=280 km). The epicenter was located in the Ionian Sea, about 30 km east-northeast of the town of Lefkada. Within the next 12 hours, three major aftershocks were felt.

A peak ground acceleration of a_g= 0.42g was recorded at the accelerograph installed in Lefkada, close to the epicenter. Despite the very strong ground motion recorded in Lefkada, only one reinforced concrete building collapse was reported. There were no deaths, and only a small number of injuries. Moderate damage was observed in villages of the central and western part of the island as well as in the town of Lefkada.

The primary and secondary road network of the island was damaged by landslides and rock falls. A number of ports were moderately to heavily affected by the strong ground motion (settlements, horizontal displacements, lateral spreading, liquefaction, loss of shear strength). The area affected by the mainshock falls in Zone IV of the Greek seismic code (EAK 2000), with a design acceleration of a_g=0.36g, the highest for Greece.

Lefkada is third in size among the Ionian Islands at 302.5 km^2. The island is only 50 m from the mainland of Greece, and is connected by a pontoon bridge. According to the 2001 national census, there are 22,506 permanent residents on the island. The capital is the homonymous town of Lefkada.

Tourism is highly developed on the island of Lefkada and it swarms with thousands of visitors during the summer months. The earthquake happened during the culmination of the tourist season. At the time of the main event, Lefkada had an estimated combined population of about 80,000 residents and tourists.

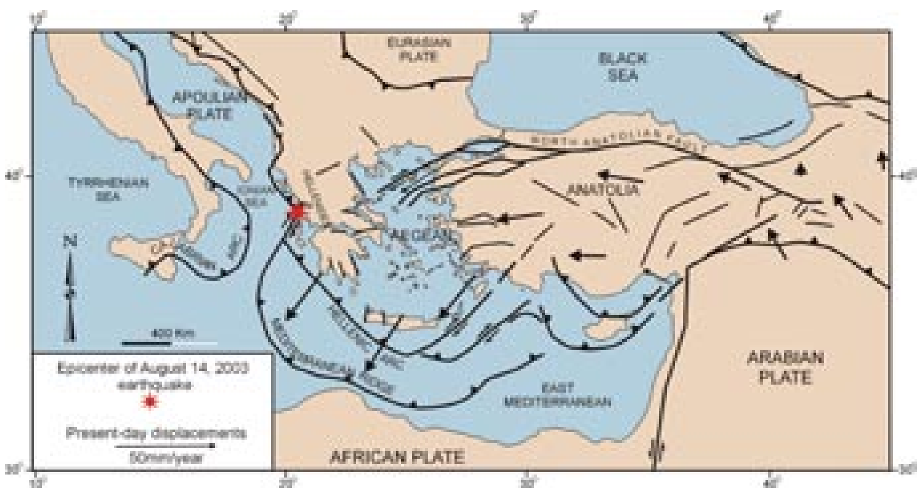

Figure 1. *Location and tectonic setting of the August 14, 2003, Lefkada earthquake.*

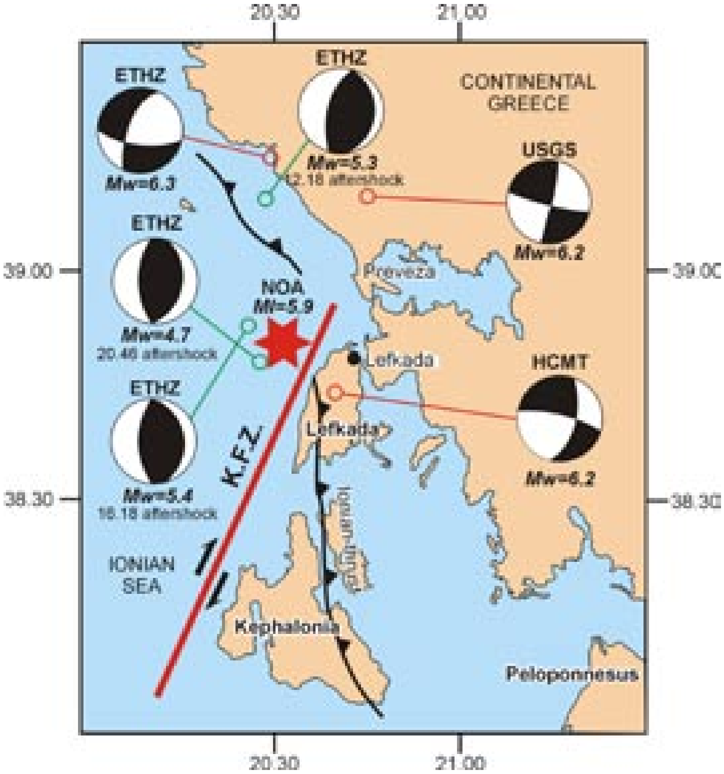

Figure 2. Location map and fault plane solutions of the main shock and the largest aftershocks of the Lefkada earthquake.

The Seismotectonic Setting

The tectonic setting of the wider area is determined by the continental collision between northwestern Greece in the east and the Apoulian platform in the west, as well as by the subduction of the African plate under the Aegean microplate along the active Hellenic Arc in the southwest (figure 1). The Ionian Islands are situated in a transitional zone between the northwestern end of this active subsidence and the continental collision in the north. This transitional zone is characterized by a high crustal deformation as revealed by the high seismicity of this zone, which is the highest in the Aegean.

The main tectonic structure of this transitional area is the Kephalonia Fault Zone (KFZ), which represents the active boundary between the SW-moving Aegean microplate and the Apulian platform (figure 2). It is an offshore fault system to the west of the island of Kephalonia, an area with a deep bathymetric trough, striking at N20E, with water depths of more than 3000m. From marine geophysical data it has been suggested that this trough represents a transform fault that demarcates the northwestern end of the Hellenic Subduction Zone. This has been reinforced by earthquake focal mechanisms, microseismic studies, and geodetic measurements that have shown that the KFZ is a right-lateral transform fault (figure 1).

Microseismic studies and GPS measurements (Yannick et al. 1998; Louvari et al. 1999) have shown that the horizontal movement continues in the sea area west of Kephalonia and Lefkada (figure 2). This north segment of the KFZ was named the Lefkada segment and is characterized by dextral strike-slip motion with a thrust component. It strikes in a north-northeast direction, dips to the east-southeast, and has a length of ~ 40 km. This fault length corresponds to an earthquake magnitude ~ 6.8, which is equivalent to the magnitude of the largest event that struck Lefkada during the last four centuries. The typical focal mechanism for an earthquake has strike =14º, dip= 65º, rake =167º.

Repeated GPS measurements carried out between the northern Ionian Islands and Crete have shown rates of crustal motion of the Aegean reaching 35 mm per year, oriented SW relative to southern Italy (figure 1).

Lefkada is 70% mountainous, with the highest peak being Stavrota (1182 m) in the center of the island. The western side of the island is very steep, with rather narrow sandy beaches, and the sea deepens rapidly. On the eastern side there are large flat areas and the sea is shallow with many islets. Inland there are narrow plateaus, fertile valleys, and deep ravines with opulent vegetation.

The main tectonic structure of the island is an emplacement of carbonate rocks of the Ionian Unit over the Pre-Apulian Unit, along a major N-S thrust fault (figure 3). Many neotectonic active faults, striking to the NNE-SSW or E-W direction,

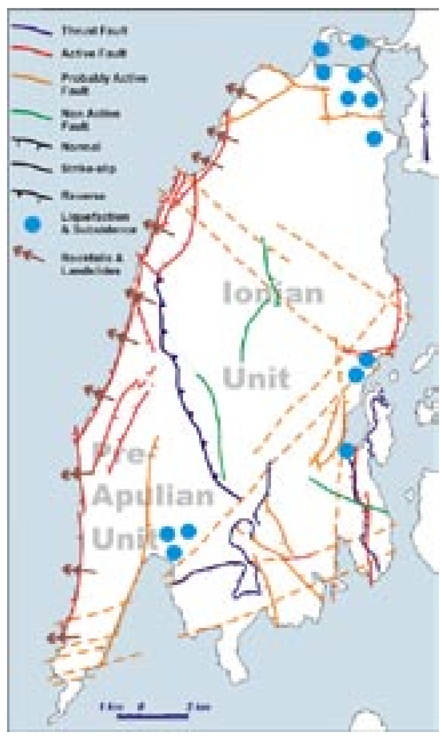

Figure 3. Alpine and neotectonic structure and natural hazard map of Lefkada Island (Lekkas et al. 2001).

cross-cut the island. They represent mainly normal or strike-slip faults. All the alpine rocks are highly fractured and deformed, especially along the active faults and the major neotectonic and alpine structures. The poor quality rocks and the steep slopes result in landslides and rock falls, which cause frequent damage to roads and the respective infrastructural works (Lekkas et al. 2001).

Table 1. The source parameters of the Lefkada main shock determined by various agencies.

Agency	M	Hypocenter Coordinates	Focal Depth	Strike/Dip/Slip (fault plane)	Reference
USGS NEIC	6.2	39.179 N 20.742 E	21 km	NP1 104°/82°/6° NP2 13°/84°/172°	neic.usgs.gov/neis/FM/neic_xlaf-q.html
Harvard	6.2	38.730 N 20.670 E	15 km	NP1 17°/60°/-175° NP2 285°/86°/-30°	seismology.Harvard.edu
EMSC	6.3	39.160 N 20.510 E	10 km		emsc-csem.org/cgi-bin/ALERT_alertfile.sh?J2329&INFO
AUT-GL[1]	6.4	38.862 N 20.735 E	10 km		lemnos.geo.auth.gr/the_seisnet
NOA-IG[2]	6.4	38.810 N 20.560 E	5 km		gein.noa.gr/services

1. *Aristotle University of Thessaloniki - Geophysical Lab.*
2. *Institute of Geodynamics – National Observatory of Athens.*

Seismological and Strong-Motion Data

Seismological Data. The area of the three islands (Lefkada, Kephalonia, and Zakynthos) from north to south (figure 4) has the highest shallow seismicity in all of Greece and in the whole western Eurasia area (Papazachos 1990; Papazachos and Papazachos 1997). Papazachos and Papaioannou (2000) separated the seismic activity in the islands into three seismogenic sources, Lefkada's being characterized by high seismic activity with maximum magnitude M=7.1 and dominated by a strike-slip fault. The typical fault plane solution for this seismogenic source has been proposed by Papazachos et al. (1998): the parameters of the two nodal planes are NP1: 11/60/165 and NP2: 109/77/31.

Table 1 summarizes the results for the source parameters of the main shock determined by various institutions. The fault plane solutions of these agencies indicate that the recent Lefkada earthquake was generated by a right-lateral strike slip fault trending NNE-SSW. This is in agreement with the typical mechanism proposed by Papazachos et al. (1998). Since 1612, 16 strong (**M**≥6.0) earthquakes have been related to this fault; the previous two strongest ones during the instrumental period were in 1914 (**M**=6.3) and 1948 (**M**=6.5) and caused great damage (Papazachos and Papazachou, 1997).

The aftershock sequence was active during the first 24 hours, but diminished quickly over the following days. Within 12 hours of the main shock, there were three major aftershocks: the first was Mw = 5.3 (ETHZ), the second Mw = 5.4 and the third Mw = 4.7. Surprisingly, the fault plane solutions of these major aftershocks, as provided by ETHZ, correspond to thrust faults, which differs from the strike-slip solution of the main shock (figure 2).

Recorded Accelerograms and Response Spectra. Near the capital city, low-resolution digital accelerographs (Kinemetrics QDR-11 bits) had been installed by ITSAK, seven of which recorded the main shock. The triggering threshold of the network instruments is 2%g, and all stations in the broader area were found in operation. The station VAS1 was filled by noise and did not record the earthquake. On August 15, six digital high-resolution accelerographs (Guralp CMG-DM24 with CMG-5 accelerometers) were deployed on the island both to capture site effects within the town of Lefkada and to increase the number of instruments monitoring aftershock activity. On September 1, three more digital accelerographs were added to the temporary strong-motion array (see figure 3).

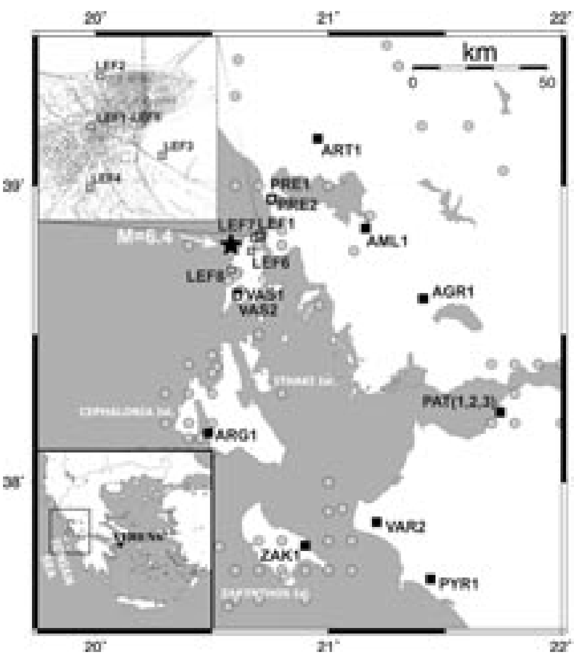

Figure 4. Permanent and temporary strong motion array of ITSAK deployed in the broader epicentral area (black squares: permanent network; gray squares: temporary array deployed after August 15, 2003. Lefkada mainshock is denoted by star. Earthquakes with M≥6 are denoted with gray circles. The upper left inset shows the special array deployed within the town of Lefkada.

Figure 5 shows the components of the accelerograms of the mainshock, with the highest peak ground acceleration recorded at the seven instruments of the permanent array of ITSAK (LEF1, PRE1, AMF1, AGR1, ARG1, ZAK1 and VAR2). Source-to-station epicentral distances range from about 10km to 115km. The largest peak horizontal ground acceleration (PGA) recorded at the LEF1 station was 0.42g, having a period of about 0.5sec. The duration of strong ground motion was estimated at 18 seconds.

Table 2 compares data on a number of earthquakes in Greece: Thessaloniki 20/6/1978; Corinthos 24/2/1981; Kalamata 13/9/1986; Kozani 13/9/1995; and Aigion 15/6/1995. A characteristic parameter of seismic motion included is the ratio of peak ground velocity to peak ground acceleration. This ratio is a crude index of strong-motion frequency content and local soil conditions. According to Seed et al. (1976), values of this ratio up to 66±7 cm/s/g are indicative of rock soil conditions,

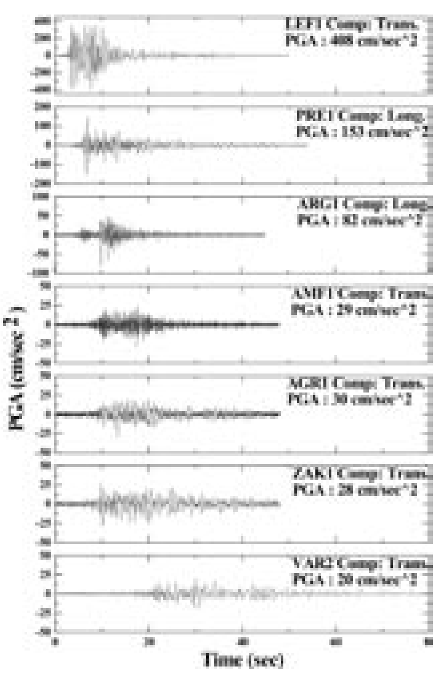

Figure 5. *Horizontal components with the highest PGA of the recorded accelerograms of the Lefkada mainshock.*

Table 2. Seismological and strong ground motion data on recent, damaging earthquakes in Greece.

Place	Date	M	R Km	a_g g	v_g Cm/s	d_g cm	v_g/a_g cm/s/g	BD* sec	EPA** g	SCZ*** Zone- g
Thessaloniki	20-6-78	6.5	29	0.15	16.7	3.4	111	6	0.13	II - 0.16
Corinthos	24-2-81	6.6	30	0.29	24.6	6.7	85	11	0.24	III- 0.24
Kalamata	13-9-86	6.0	12	0.27	32.3	7.2	120	4	0.28	III- 0.24
Kozani	13-5-95	6.6	19	0.21	8.8	1.5	42	7	0.14	I - 0.12
Aigion	15-6-95	6.4	18	0.54	51.7	7.5	96	6	0.43	III- 0.24
Lefkada	14-8-03	6.4	10	0.42	31.7	4.6	77	18	0.42	IV-0.36

(*): Bracketed duration, time span between the first and last peak with $a_g \geq 0.05g$
(**): Effective Peak Acceleration according to FEMA (1985)
(***): Seismic Code Zone - Proposed effective acceleration

and values up to 114±18 cm/s/g indicate stiff soil conditions. The recording station LEF1, where the strongest peak ground acceleration was observed, falls between the two soil conditions.

Response spectra for 5% damping of the horizontal components of Lefkada main shock are given in figure 6. The acceleration response spectra of the LEF1 station exhibited amplitudes Sa>0.9g for a period range of 0.2 sec to 0.7 sec and reveal a peak of about 1.7g around 0.5 sec. For the LEF1 station, the fundamental period was estimated around 0.5sec using strong-motion excitation (Dimitriou et al. 1999). This fact gives evidence of the influence of local conditions on strong ground motion. However, source effects (e.g., directivity) should not be completely excluded, since the energy radiation pattern is not yet clear.

Figure 7 shows a comparison of the response spectra of the Lefkada 2003 record (black lines) and the Bingöl, Turkey, 2003 (**www.deprem.gov.tr**) record (gray lines). Only the two horizontal components were considered. Even though the two earthquakes were on strike-slip faults and had the same magnitude, and their records were obtained in the near field, the damage to structures following the Bingöl quake was more extensive. This may be attributed to the frequency content of the ground motion in relation to the built environment and structural type.

In November of 1973, a magnitude M=5.8 earthquake struck close to the epicenter of the August 2003 quake, with a recorded peak ground acceleration of 0.49g (Theodulidis et al. 2003). Despite the high values of both earthquake recordings at Lefkada, damage was less than expected.

Geotechnical Effects

Site effects in the town of Lefkada: Damage surveys in the town did not indicate locations of building damage concentration that could be directly associated with the effect of local geology on earthquake ground motion. This might be attributed to quasi-uniformity of the underlying soil conditions or to building types.

Based on the average weighted value of shear-wave velocity for the upper 30m (V_{S30}) ranging between 230 and 250 m/sec, Eurocode 8 (2002) places the subsoil of Lefkada in soil category C (dense to medium density sandy, gravelly, or stiff clay of a few tens to hundreds of meters thick with $180<V_{S30}<360$ m/sec, $15<N_{SPT}<50$ and $70<C_u$(kPa)<250), or in soil category E in cases where the underlying soil layers have relatively high shear-wave velocity values ($V_s \geq 800$m/sec). The soil structure beneath the town is classified as category C according

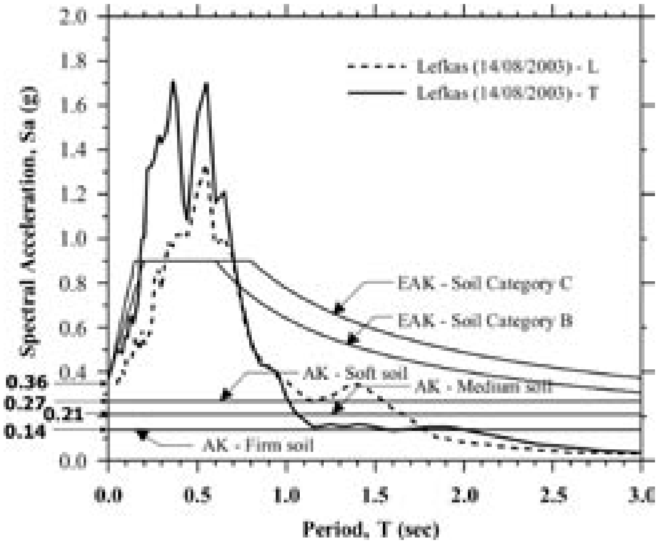

***Figure 6.** Elastic response spectra of the Lefkada mainshock (D=5%), recorded at the town of Lefkada, in comparison with the elastic design spectra of the old (AK) and recent (EAK-2000) Greek seismic codes, for different soil categories.*

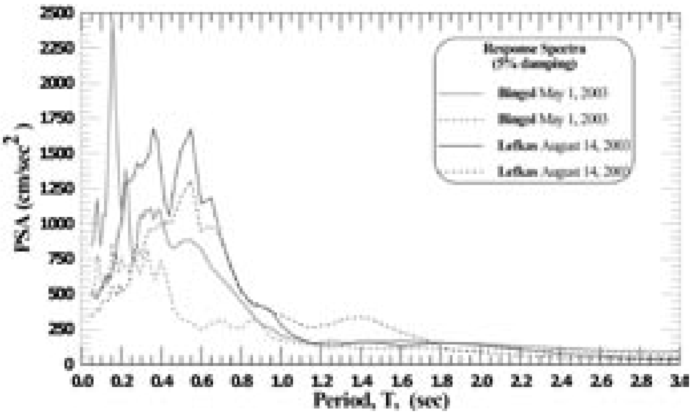

***Figure 7.** Comparison of the response spectra of the Lefkada August 14, 2003, and Bingöl, Turkey, May 1, 2003, records caused by strike-slip faults and obtained in the near field.*

***Figure 8.** Geological and geotechnical effects of the Lefkada earthquake.*

to the Greek Seismic Code (EAK 2000 (figure 6). In case where layers of loose fine sandy silts susceptible to liquefaction or densification are present, the sires are classified as soil category X (soils in need of special study)

Near the water, ground settlement and lateral spread were observed to a limited extent were directly related to liquefaction phenomena. Their effect (described in detail later in this report) was more pronounced on seawalls, pavement, and fills behind these structures than on buildings.

Damage surveys in the areas of Asprogerakata, Spanohori, Lazarata, Kavallos, Pinakohori, and Karya villages reveal building damage concentration that may be related to specific surface and subsurface topographic features. The rough alignment of the damage coincides almost with the fault strike, a factor that may also influence the damage pattern (figure 8).

Ground fissures: The main shock created a large number of fissures that caused minor damage to roads, open recreational spaces, tourist facilities, and light construction. The main fissures occurred at alluvial and coastal formations, located along the eastern coastal zone near Nydri village between Aspropotamos and Lagadi torrent, along the northern and northeastern coastal zone near the town of Lefkada and Lygia village, and near Vassiliki village along the southwestern coastal zone at the river mouth of Karouhas torrent).

***Figure 9.** Many retaining walls leaned towards the external side; the adjacent parts of the roads subsided, and cracks appeared on the pavement (NTUA-UoA team).*

Figure 10. *Ground subsidence of the fill material of about 30 cm (NTUA-UoA team).*

The length of the fissures varied from a few tens of cm to tens of m, their width was from a few mm to 10 cm, and their visible depth reached 30 cm. A systematic study of the trends of the fissures showed that there were two prevailing sets, one parallel to the coast and one normal to it. In addition, the pattern was similar at the cracks located in the river deposits; however, the primary set ran parallel to the riverbed and the secondary ran normal to it. The fissures and cracks had no genetic relationship with the fault deformation, but they were a by-product of the seismic movement. Their occurrence is exclusively controlled by the differential compaction of the loose formations, the lateral instability of the ground masses at the coastal or riverside area, and the differential seismic response of the various unconsolidated phases of the formations (figures 9 and 10). Most of them are also connected to liquefaction phenomena and represent lateral spreads and extensional failures.

Figure 11. *In the town of Lefkada, distorted pavement and sidewalks due to ground settlement and lateral spread (ITSAK team).*

Soil liquefaction: Ground settlement and lateral spreading had serious consequences for port and marine structures (docks, seawalls, and breakwaters) in the north, east, and south parts of the island, namely at the town of Lefkada and at Lygia, Nydri, and Vasiliki villages (figures 11 and 12). These phenomena were related to local ground conditions as well as to the depth of the water table. They consisted of recent formations of coastal, alluvial, and fluvial deposits, where the depth of the water table was very high, almost 0.7 m below the ground surface. The ejection of quicksand occurred through craters and fissures. It was also reported that boreholes and drainage tubes served as funnels for the upward movement of the quicksand. The ejection resulted mainly in fine material deposits of sand and silt. In other cases, no surficial outflow was noticed, but the liquefied material caused loss of support of the overlying formations, which in turn were deformed.

In the town of Lefkada, damage included uplifted, sunken or cracked concrete slabs, and distorted pavement and sidewalks (figure 11). Shallow subsurface materials at these sites probably consisted of uncompacted, miscellaneous fill. Local residents reported that muddy water was ejected from cracks in pavement surfaces. Observed ground cracking with lateral spreading, as well as silty-sandy boils along the waterfront in the town of Lefkada and in Nydri village, were the primary surface evidences of liquefaction, indicating high excess pore pressure generation during earthquake shaking.

Densification of loose surface soil layers and of poorly compacted fills behind seawall facilities caused settlements and lateral spreading towards the free face. The horizontal and vertical displacements varied between sites, but they were in the range of 10-25 cm. Figure 13 shows ground settlement near the coastline. Lateral spreading was prevented due to the seawall, but an up-lift of the ground just behind the seawall tilted the lampposts.

In some buildings near the coastal

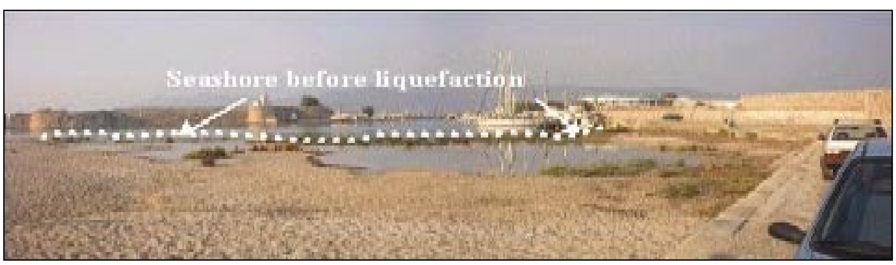

Figure 12. *Area near the castle of Lefkada where soil liquefaction, lateral spreading, and ground settlement occurred (ITSAK team).*

Figure 13. *Part of the seawall has been laterally shifted and overturned (ITSAK team).*

area, observed damage indicates a differential settlement between adjacent buildings of 5-10 cm. However, those buildings did not suffer any severe damage due to their relatively small mass, their “flexible” wooden frame, and, in cases of RC structures, their foundation type (mat foundation, tie or foundation beams). Figure 14 shows a plan view of two adjacent buildings with a common pipeline system that had a differential settlement of about 5 cm.

Coastline changes: The shock was accompanied by a coastline change (figure 15) in the northern part of Nydri, at the river mouth of the Aspropotamos torrent. The coastline retreat of 1 m to 20 m damaged some minor human construction and tourist and beach sport facilities. The most striking change took place at the coast of Kambos, where the sea progressed inland for about 20 m, covering an area more than 50 m wide. The coastline changes were due to (1) rearrangement of the packing in the Holocene formations (mainly sands, gravel, and cobbles with silt and clay intercalations) because of seismic shaking, (2) small-scale submarine landslides with simultaneous loss of lateral support, or (3) liquefaction.

Landslides and rockfalls: The earthquake triggered landslides and rockfalls. The very steep morphology of the region is the result of the active tectonics and the rock mass that is highly fractured and deformed, representing in most cases a tectonic breccia or fault gouge material. The slides were mainly observed at the central and northern part of the island, as well as in the steep western coastal zone along the road joining the town of Lefkada with Tsoukalades, Agios Nikitas, Kathisma, Kalamitsi, Chortata, Dragano, Komilio. The vast majority of slides on the island road network can be categorized as rock falls, rock sliding (plane and wedge), and soil type sliding with scree deposits (rock fragments) accumulated as cone deposits at slope toes, with volume ranging from several cm^3 to some (5 to 10) m^3. Landslides were detected on both natural and cut slopes, as well as on downstream road embankment slopes. The most important slope failures were seen in limestones (thick bedded and thin bedded interpolated by thin layers of marly

Figure 14. *Plan view of two adjacent buildings with a common pipeline system that had a differential settlement of about 5 cm (ITSAK team). (Photo taken after repairing.)*

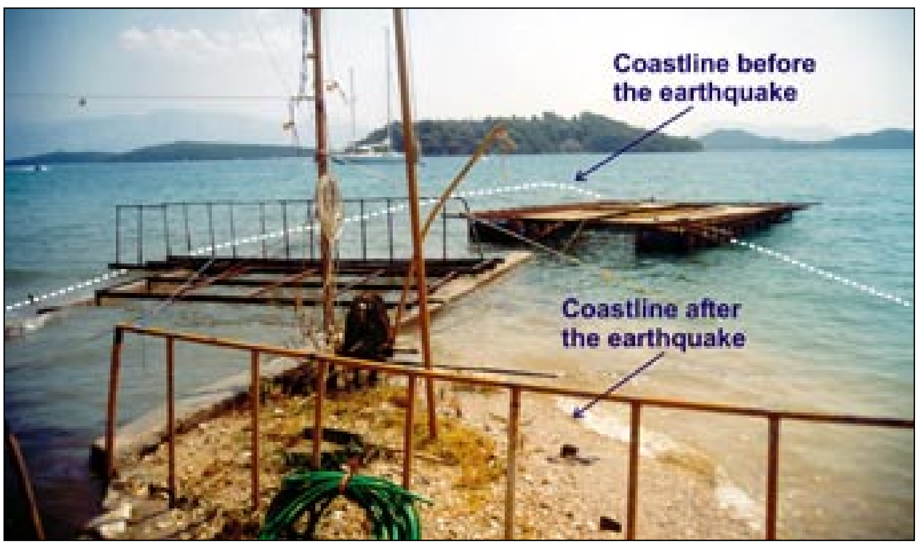

Figure 15. *Coastline changes at Nydri beach (NTUA-UoA team).*

***Figure 16**. Rockfalls due to detachment and possible overturn at the Agios Nikitas (left); Cars were buried under landslides near the same beach (right) (ITSAK team).*

schists) located on steep cut slopes (horizontal:vertical ≈ 2:1 to 3:1) and with heights ranging from 20 to 50 m, without any trench or other preventive countermeasures. There were also a considerable number of failures of embankment slopes, especially when lack of com-paction was obvious.

Some of the slope failures took place along beaches suitable for swimming and sunbathing, but they did not cause any casualties, thanks to the early morning hour of the main shock. Figure 16 shows rockfalls and scree deposits due to overturn, detachment, and sliding at Agios Nikitas Beach.

Tsunami: A very small tsunami, no more than 0.5 m, hit in Vlychos Bay south of Nydri (Figure 8) and caused minor damage to boats and coastline construction.

Damage to lifeline systems: Soil liquefaction, ground settlements, lateral spreading, landslides, and rockfalls caused some damage to lifeline systems on the island. Just after the earthquake, there was a four-hour interruption in power, and consequently also in the central pump station of the water supply system in the town of Lefkada. Damage to the wastewater system, which impeded the transfer of waste from the town center to the central waste-processing unit, was reported at one point due to local soil failure. No damage was reported to the conventional telecommunication network, but local residents reported that the cellular telecommunication network had problems due to overloading.

Structures

Buildings on Lefkada Island can be classified in four broad categories as shown in the chart below, according to their load-bearing system.

Strong ground motion compared to seismic code provisions: The

Category	Description	Remarks
A	One- or two story stone masonry buildings	Buildings more than 50 years old, with load-bearing system of stone masonry. They incorporate some empirical lateral load-bearing systems, which are in general insufficient. Masonry consists of stones with weak lime (and rarely cement or clay) mortar.
B	Buildings of special typology with dual structural system	A traditional structural typology met mainly in the old town district of Lefkada. The main load-bearing system consists of stone masonry on the ground level, complemented by a secondary (redundant) wood structural frame, designed to be activated only in case the masonry fails (e.g. during an earthquake). On the upper floors, the load-bearing system consists of wood frames with brick infill. Mostly two-story (and in some cases three-story) buildings. The dual bearing system, combined with the relatively low mass of the upper stories, exhibits a remarkably reduced vulnerability to earthquake actions. Due to poor soil conditions (and a high underground water level), the masonry walls are founded either on extended footings made up of horizontally placed tree trunks or on vertical wood piles.
C	Modern R/C buildings with one to five stories	The majority of houses and office and hotel buildings, up to five stories high (in the town of Lefkada). Load-bearing system with cast-in-place reinforced concrete. Walls with hollow bricks used as infill. Various types of foundations, ranging from spread footings to mat foundations. Due to poor soil conditions, concrete piles used in many foundations.
D	Middle-age and later-era monuments	Buildings of architectural heritage, with no special seismic provisions. Mostly churches and some castles along the entrance from the mainland to the island.

first Greek Seismic Code (AK) was issued in 1959 and revised in 1984. A major new revision took place in 1992 (EAK 1992), and upgraded versions were published in 2000 and 2003. Until 1992, design was based on maximum allowable stresses, and thereafter on ultimate strength. Significant progress has been made in Greece, especially during the last 20 years, in improving both codes and practices.

According to the 1959 Greek Seismic Code, the base shear seismic design coefficient for Lefkada was ε = 0.08, 0.12 and 0.16, for firm, medium, and soft soils, respectively. This coefficient was constant, independent of the building's period, and applied uniformly to all buildings. Since the 1959 Code was based on the allowable-stress design method, the coefficient has been modified to correspond to ultimate strength design, leading to values of ε' = 0.14, 0.21 and 0.27 (Anagnostopoulos et al. 1986).

For seismic zone IV (Lefkada's), seismic codes from 1992 onwards establish a ground acceleration coefficient of α=0.36 and typical design spectra (with a spectral magnification factor β_o=2.5). In figure 6, the response spectra of the Lefkada main shock are compared with the elastic design spectra of the new seismic code (EAK) provisions (for soil types B-medium and C-soft). In the same figure, the pre-1992 provisions (AK) are also plotted.

It is obvious that low-rise buildings with relatively small mass and fundamental period ($T<0.15\div0.20$sec), which comprise the majority of the building stock in Lefkada, were not heavily stressed, due to the particular shape of the response spectrum of the main shock. The ductility demands imposed on buildings in this specific range were not too high, thus explaining the limited damage observed. Taller buildings were in general built according to modern code provisions, thus possessing high resistance to seismic actions. Moreover, the existing buildings possess a substantial amount of reserve strength (depending mainly on their redundancy and on the overstrength of individual structural members) as well as possible additional energy dissipation mechanisms. Experience in this and previous seismic events suggests that seismic protection of Greek urban areas relies also on several alternative factors (such as infill walls, regular configuration of the structural system, proper material, and construction quality) (Bertero 1988).

Damage in the meisoseismal area: The main shock caused most damage on the island of Lefkada. Also minor damage was reported in the nearby prefectures of Thesprotia and Aitoloakarnania as well as in the neighboring island of Kephalonia. The town of Lefkada had the most damaged buildings and churches. Most damage was concentrated in the old town district, while minor damage was reported to the more modern Neapoli and Bei districts.

17a▲ *17b▼*

Figures 17a, b, and c. *The traditional earthquake-resistant system of Lefkada. The undamged structure in Fig. 17a was built at the end of the 19th century. In Fig. 17b the wooden columns and beams (w) with wooden corners (c) are visible. In Fig. 17c the special earthquake system is shown under construction (NTUA-UoA team).*

17c▼

Figure 18. *Partial collapse of masonry wall in a category B building (ITSAK team).*

Less severe damage was reported in villages throughout the rest of the island.

For a proper explanation of the distribution and intensity of damage in relation to the recorded acceleration at the town of Lefkada, an extensive vulnerability study is needed, complemented with a soil response study. A preliminary estimation of the intensity for the main event in the old town of Lefkada is between VII and VIII on the modified Mercalli scale. The inspection of 3165 buildings on the island resulted in 1544 "green," 1495 "yellow," and 126 "red" tags. The classification of damage is briefly described as follows (Lekidis et al. 1999):

"Green": Original seismic capacity has not been decreased, the buildings are immediately usable and entry is unlimited.

Figures 20a and b. *In a building with a market and mezzanine on the ground floor: insufficient stirrups with poor detailing (a). In the mezzanine: damaged columns on the surface between phases of concrete and the lower part of the arches, formed with brickwalls (b) (NTUA-UoA team).*

20a *20b*

"Yellow": Buildings in this category have decreased seismic capacity and should be repaired. Usage is not permitted on a continuous base.

"Red": Buildings in this category are unsafe and entry is prohibited. Decision for demolition will be made on the basis of more thorough inspection.

Damage according to structural system: Traditional stone masonry buildings (category A), usually with one or two stories, constitute a small percentage of the building stock on Lefkada Island. Observed damage to such buildings (partial collapse of stone walls) can be attributed mainly to lack of sufficient seismic resistance, as well as to their poor condition (old age, inadequate maintenance). A significant percentage of such buildings is found in villages outside the town of Lefkada.

Traditional buildings with the special dual structural system (category B) behaved in a rather satisfactory way, given the intensity of the main event (ITSAK 2003). In this composite system, a wooden frame has special carved corners (figure 17) that strengthen beam-to-column joints, and wooden stiffening walls with x-braces. In the plane of these stiffening walls, various masonry materials may be added in order to increase the stiffeners and the energy absorbing capacity of the whole system. On the ground floor, the wooden frame comes in contact with the external masonry wall, with which it is well connected. The carved corners are also put in the lower part of the columns that are fixed to the foundation. In some cases, there was partial collapse of masonry walls (figure 18), but the structural stability of the building was ensured by the activation of the secondary (redundant) wood frame on the ground floor level.

In the upper floors, the load-bearing wood frames suffered no damage, but cracking to the brick infills was observed. These cracks were difficult to notice at first, since the external walls at the upper stories are typically clad with zinc sheets (for rain protection). Damage could be observed only on the interior face of the walls, which are usually plastered with lime. Due to the use of extended wood footings or piles described above, and the small weight of these buildings, no foun-

Figure 19. *Collapse of R/C building in the town of Lefkada. On the right side, there are no brickwalls on the ground floor, where the building collapsed. The remaining part on the left side has partitions down to the foundation (NTUA-UoA team).*

Figures 21a and b. *A four-story building with a mezzanine was heavily damaged in the ground floor columns. The columns seem to have swollen in the center due to unsufficient transverse reinforcement (NTUA-UoA team).*

dation settling was observed, despite the poor soil conditions in the old district of the town of Lefkada, where the majority of such building types are found. The severe or total damage to a limited number of buildings of this type can be attributed to old age and poor maintenance. Common to all types of buildings was the detachment of tiles from roofs.

A total collapse occurred in a three-story R/C building (category C) with short columns on the ground floor at the front and thick brick infill walls at the back. The building was poorly designed with inadequate stirrups at the columns (figure 19).

Other serious damage to R/C buildings was due to the following conditions, some of which are shown in figures 20 and 21:

- Severe damage to poorly designed columns and walls in buildings with soft stories at ground level.
- Damage to vertical structural elements at ground floor levels due to non-symmetrical distribution of infill walls.
- Flexure-shear failure of poorly designed columns.
- Failure of short columns that were originally not designed to act as such (e.g., noncontinuous infill walls on either side due to openings).
- Failures at beam-column joints due to unpredicted local action of the infill walls.
- Shear failure of R/C shear walls due to inadequate web reinforcement.
- Flexural cracking at R/C beam ends. It should be noted, however, that this type of failure has a beneficial contribution to the overall building stability since the formation of plastic hinges at columns is avoided.
- Cracking of infill walls (diagonal shear cracks, detachment of the wall from the surrounding frames, out-of-plane collapses).
- A uniform foundation settlement was observed in several buildings at the seafront in the town of Lefkada. Since no differential settlements were involved, no imminent danger to the structural safety of the buildings was present.
- A systematic oxidation of steel reinforcement was observed at the base of ground floor columns, due to the high underground water level. In some cases, the oxidation was very severe, a serious vulnerability factor for structural safety.

Middle-age and later era monuments (category D) also suffered serious damage. It was reported that more than 40 churches all over the island (with the majority in the town of Lefkada) have been put out of service until restoration measures are taken. The churches are typically built with stone masonry walls and have a rectangular floor plan and a wooden roof. Serious damage was observed at the perimeter walls (figure 22) as well as at the corners of adjoining walls (figure 26). No collapses of bell towers were reported,

Figure 22. *Churches built of stone masonry suffered heavy damage. In various parts of Lefkada, the tiles at the center of roofs moved. This might be explained by the vertical flexibility of the roof at its center (NTUA-UoA team).*

Figure 23. *Cracking of masonry walls of Agios Minas church (town of Lefkada) (ITSAK team).*

but most towers were recently built (with R/C or steel elements), indicating collapse of the original ones during past earthquakes. The castle of Agia Mavra, at the entrance of the town of Lefkada from the mainland, suffered no damage to its exterior walls. At its interior, partial collapse of some building ruins as well as some permanent displacements of stone parapets and decorative elements were observed.

Emergency Management

The emergency response was rapid and well-managed, although the event did not cause heavy damage to structures and, therefore, few casualties (only 50 injuries). The demand for search and rescue resources was minimal, and the medical system was able to treat the injured within hours of the strong shaking. Because of the extensive landslides and rockfalls, human losses would have been heavier had the earthquake struck two to three hours later when the roads and the beaches were filled.

Emergency response to the disaster was underway immediately after the earthquake, supported by all levels of local and governmental authorities, with the collaboration of the private sector and the affected population. Sixty-four civil engineers from the Greek Ministry for the Environment, Physical Planning, and Public Works formed 32 inspection teams to proceed with visual assessments of buildings, providing the basis for determining which structures required more thorough examination. The inspection was performed in two stages — a rapid one and a more detailed one — and was completed about 20 days after the main shock for all buildings of the island.

The readiness and competence of responders can be attributed to a number of factors. One of these is the Greek Civil Protection system, which has specialized teams to respond to earthquakes and natural hazards. Because Lefkada Island has experienced several destructive earthquakes in the past, much has been learned.

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