EARTHQUAKE ENVIRONMENTAL EFFECTS, BUILDING DAMAGE AND INTENSITIES OF THE NOVEMBER 17, 2015 Mw 6.4 LEFKAS EARTHQUAKE (IONIAN SEA, WESTERN GREECE)

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Abstract

On November 17, 2015, an Mw 6.4 earthquake struck Lefkas Island (Ionian Sea, Western Greece) with epicenter located 20 km southwest of Lefkas town. It caused 2 fatalities, 8 injuries, earthquake environmental effects (EEE) and damage to buildings and infrastructure. Ground cracks, slope movements and liquefaction were observed in western Lefkas. The highest intensity $VIII_{ESI\ 2007}$ was assigned to large-volume slope movements along the western coastal part of Lefkas. Damage to buildings was mainly observed in Dragano-Athani graben in southwestern Lefkas. Masonry buildings and monumental structures suffered the most, while traditional buildings with dual structural system performed well. Reinforced-concrete buildings were not affected. The highest seismic intensities $VIII_{EMS\text{-}98}$ were assigned to villages of Dragano-Athani graben. Based on historical and recent earthquake data and the field observations on the 2015 Lefkas earthquake, it is concluded that the western part of the island is the area usually affected by earthquake effects including landslides and rock falls, liquefaction phenomena, small-scale subsidence and tsunamis.

Introduction

On November 17, 2015 (09:10 local time), an earthquake struck Lefkas Island (Ionian Sea, western Greece) (Fig. 1). It was assessed as Mw 6.4 (NOA, GFZ, UPSL, INGV) or Mw 6.5 (USGS, GCMT). It was felt predominantly on the western part of Lefkas and throughout the Ionian Islands, the western continental Greece and Peloponnese. It caused 2 fatalities and 8 injuries. Based on preliminary data provided by GCMT, INGV, USGS, IPGP and NOAGI, the epicenter is located in the western offshore area of Lefkas, while according to UPSL, AUTH and GFZ the epicenter is located in the western onshore part of Lefkas. Based on the aforementioned preliminary data, the main shock is consistently located at depths of 7-15 km and the fault plane solutions demonstrate a NNE-SSW striking dextral strike-slip seismic fault with a reverse component that dips east at a high angle (Fig. 1). Western Lefkas suffered the most damage induced by the earthquake in the natural environment, the building stock and the infrastructure. Earthquake environmental effects (EEE) and building damage were mapped during our field reconnaissance in Lefkas immediately after the earthquake and are presented herein. Their distribution was considered appropriate for the application of the Environmental Seismic Intensity 2007 scale (ESI 2007) and the

European Macroseismic Scale (1998) based on the guidelines of Michetti et al. (2007) and Grünthal (1998) respectively.

Geodynamic setting

Lefkas is located in the central part of the Ionian Sea (western Greece) (Fig. 1) which is one of the most seismically active parts in the Mediterranean region with high seismicity rate and earthquake magnitudes up to 7.4 (Papazachos and Papazachou, 2003). The primary tectonic structure affecting the area is the Cephalonia Transform Fault Zone (CTFZ in Fig. 1). Seismological data indicate dextral strike-slip focal mechanisms (Scordilis et al., 1985; Louvari et al., 1999). The CTFZ is composed of two segments: the 40-km-long NE-SW striking Lefkas segment (LS in Fig. 1) located west of Lefkas and the 90-km-long NE-SW striking Cephalonia segment (CS in Fig. 1). Both dip to SE and are characterized by a dextral strike-slip motion combined with a small thrust component involved in the movement (Scordilis et al., 1985).

Lefkas comprises (a) alpine formations of Ionian and Paxoi (Pre-Apulian) geotectonic units, (b) molassic formations and (c) recent deposits unconformably lying on the previous formations (Bornovas, 1964; Lekkas et al., 2001; Rondoyanni et al., 2012) (Fig 1). The Ionian unit is composed of Triassic evaporites, Upper Triassic - Upper Cretaceous carbonate sequence and Oligocene - Lower Miocene flysch sediments, while the Paxoi unit consists of limestones covered by Miocene clastic sediments, mainly marls, sands and clays that constitute the atypical flysch sequence of the unit. The molassic formations comprise mostly marine Aquitanian-Tortonian marls, bioclastic limestones, conglomerates and sandstones (Bornovas, 1964; Lekkas et al., 2001) that are unconformably overlying the deformed Ionian formations and few outcrops of Ionian flysch turbidites (Cushing, 1985). The recent Lefkas formations are of Quaternary age and comprise lagoonal, lacustrine, alluvial and coastal deposits, scree and talus cones as well as terra rossa.

The current geodynamic setting has been established on Lefkas after the completion of tangential movements and prevails throughout Pliocene-Quaternary. It is expressed by a dense net of faults creating a complex system of independent fault blocks. These fault blocks are the neotectonic units of Lefkas town, Tsoukalades-Katouna, Agios Nikitas, Drymonas, Mega Oros - Skaroi, Vlicho-Poros, Vassiliki and Lefkata peninsula (units 1, 2, 3, 4, 5, 6, 7 and 8 respectively in Fig. 1) (Lekkas et al., 2001). They are mainly bounded by active fault zones, the most significant of which are the Frini-Apolpaena, Tsoukalades-Agios Nikitas, Drymonas, Athani, Pigadisanoi-Fraxi, Kalamitsi-Exantheia, Sivros-Nidri, Vassiliki and Syvota-Sivros fault zones (FAFZ, TANFZ, DFZ, AFZ, PFFZ, KEFZ, SNFZ, VAFZ and SSFZ in Fig. 1) (Lekkas et al., 2001).

Earthquake environmental effects induced by the 2015 Lefkas earthquake

Many secondary EEE were induced by the 2015 Lefkas earthquake in the western part of Lefkas (Fig. 1, 2a). They comprise ground cracks, slope movements and near-

surface liquefaction. Ground cracks were observed in areas comprising mainly Upper Cretaceous limestones of Paxoi unit and secondarily Miocene marls of Paxoi unit, molassic formations and Upper Triassic-Lower Jurassic limestones of Ionian unit. Their length ranged from 5 to 10 m and their width was up to 1 cm. They were observed close to active faults, in geotechnically unstable zones and along the Ionian overthrust onto Paxoi unit, causing extensive damage to road network and limited damage to adjacent structures. They were observed at various strikes ranging from N15°E to N180°E in various sites presented in Figures 1 and 2a. The induced slope movements were generated in geotechnically unstable zones (a) along steep coastal slopes of western Lefkas, (b) along steep slopes of the eastern part of Lefkata peninsula and (c) along the Ionian overthrust onto Paxoi formations (Fig. 1). These geotechnically unstable zones are defined by the presence of active and inactive tectonic structures resulting in highly tectonized, disintegrated and almost powdered geological formations with suitable geometry of beds and discontinuities and steep slopes intensifying substantially the instability conditions of the area and increasing the susceptibility to earthquake-induced slope movements. Large damage was induced by the earthquake in Vassiliki port located in the southern part of the island (Fig. 1) and included displacements and rotations of the quay seawalls, extensive longitudinal cracking of pavements and sidewalks behind seawalls and subsidence near the waterfront. These phenomena are considered as evidence of near-surface liquefaction in the area of Vassiliki port.

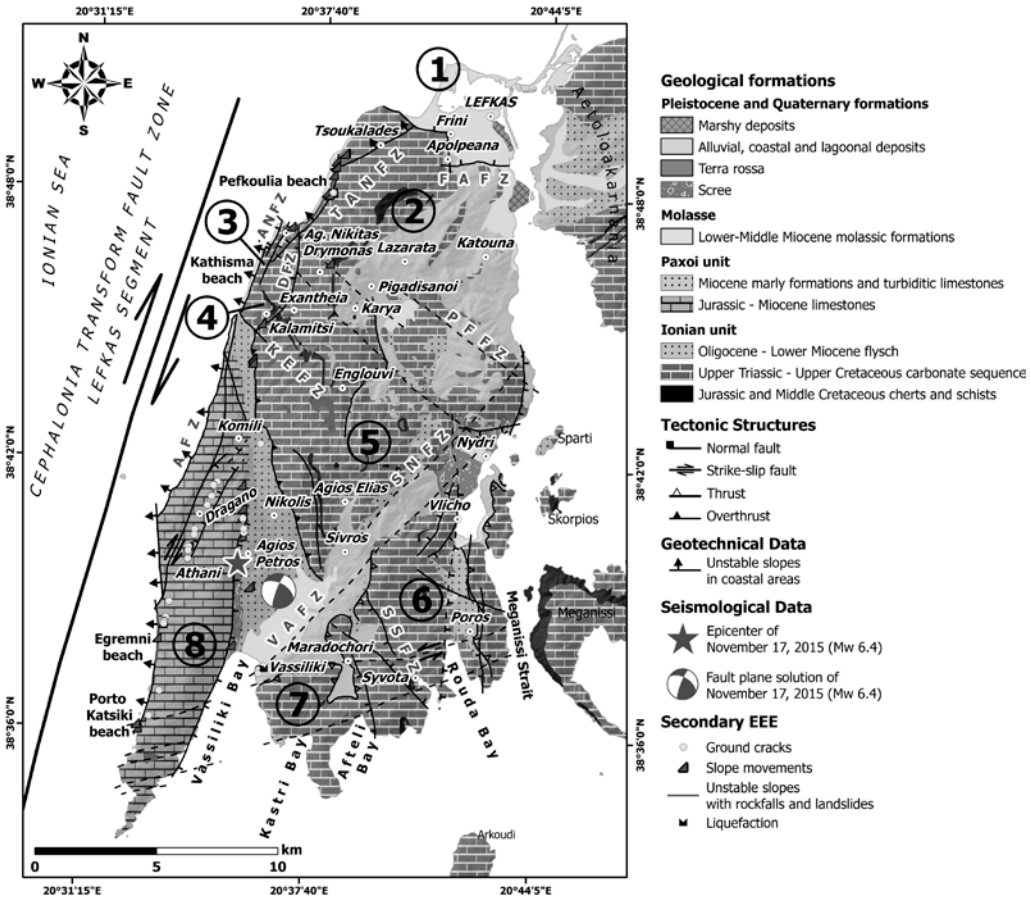

Figure 1: (a) Neotectonic map of Lefkas Island based on Lekkas et al. (2001) and Rondoyanni et al. (2012). Read abbreviations and numbers in text.

Damage induced by the 2015 Lefkas earthquake in building stock

The dominant building types in Lefkas are the following: (a) one- or two-storey stone masonry buildings, (b) one - to three-storey traditional wood buildings, (c) two-storey traditional buildings with dual structural system, (d) one- to five-storey modern reinforced concrete (RC) buildings and (e) monumental structures (Karakostas et al. 2005). Building damage was generally localized in the neotectonic structure of Lefkata peninsula. In particular, Athani, Dragano and Komili villages (Fig. 2b) suffered most damage to their building stock. Less damage was observed in the other villages of Lefkata peninsula. RC buildings constructed after the implementation of the first Greek seismic code of 1959 showed good performance since none of them collapsed.They were affected not so much by the earthquake itself but by the generation of rockfalls. On the contrary, severe damage was observed in stone masonry buildings constructed before 1959 without any seismic provisions. These buildings suffered damage including large and extensive cracks in load-bearing walls, detachment of roof tiles and plasters from masonry walls, serious failure of walls and partial structural failure of roofs and floors as well as total collapse of the building. Total collapses were observed in Athani and Dragano villages located in Dragano-Athani graben. It is significant to note that the traditional buildings with dual structural system performed well during this earthquake too. Some structures still in use in Athani and Dragano villages suffered partial collapse of the stone masonry walls of the primary load-carrying system of the ground floor, while the wooden frame of the secondary load-carrying system successfully sustained vertical loads of the upper floor and thus the structures did not collapse. As far as the monumental buildings are concerned, churches suffered severe damage like extensive cracking of masonry load-bearing walls and partial or total collapse.

Application of ESI 2007 scale and EMS-98 for the 2015 Lefkas earthquake

The total area distribution of secondary EEE has been used for assessing epicentral intensity (I_0) based on the guidelines of Michetti et al. (2007). The size of total affected area was around 81 km^2 corresponding to an intensity $VIII_{ESI\ 2007}$. $VI_{ESI\ 2007}$ intensity is assigned to all sites with observed ground cracks (Fig. 2a) based on their dimensions. Based on the volume of the earthquake-induced rockfalls and landslides, (a) intensities ranging from $VI_{ESI\ 2007}$ to $VIII_{ESI\ 2007}$ are assigned to various sites in the western coastal part of Lefkas and more specifically $VII_{ESI\ 2007}$ along the road from Tsoukalades to Agios Nikitas and $VIII_{ESI\ 2007}$ to Egremni and Porto Katsiki coastal areas, (b) $VI_{ESI\ 2007}$ to sites within the Dragano-Athani neotectonic graben, (c) intensities ranging from $V_{ESI\ 2007}$ to $VII_{ESI\ 2007}$ to various sites aligned with probably active faults forming the eastern part of Lefkata peninsula and more specifically $V_{ESI\ 2007}$ west of Vassiliki village, $VIII_{ESI\ 2007}$ to the area north of Vassiliki village, $VI\text{-}VII_{ESI\ 2007}$ to the area east of Dragano village and (d) $VI_{ESI\ 2007}$ to sites aligned with the Ionian overthust onto Paxoi unit in the central-western part of the island (Fig. 2a). Based on the abovementioned damage in Vassiliki port attributed to near-surface liquefaction, $VI_{ESI\ 2007}$ intensity is assigned to Vassiliki area (Fig. 2a).

Based on the building damage, the maximum intensity $VIII_{EMS\text{-}98}$ was assigned to Athani, Dragano and Komili villages. Intensity $VII_{EMS\text{-}98}$ is assigned to villages located in northernwestern Lefkas and $VI_{EMS\text{-}98}$ in eastern and southeastern Lefkas (Fig. 2b).

Conclusions – Discussion

The 2015 Lefkas earthquake produced secondary EEE in western Lefkas. These effects were classified as ground cracks, rockfalls, landslides and liquefaction. The induced slope movements were generated in geotechnically unstable zones defined by the presence of active and inactive tectonic structures resulting in highly tectonized geological formations and increasing the susceptibility to earthquake-induced slope movements. Ground cracking and subsidence observed in coastal areas and port facilities of the southern part of Lefkas are attributed to near-surface liquefaction.

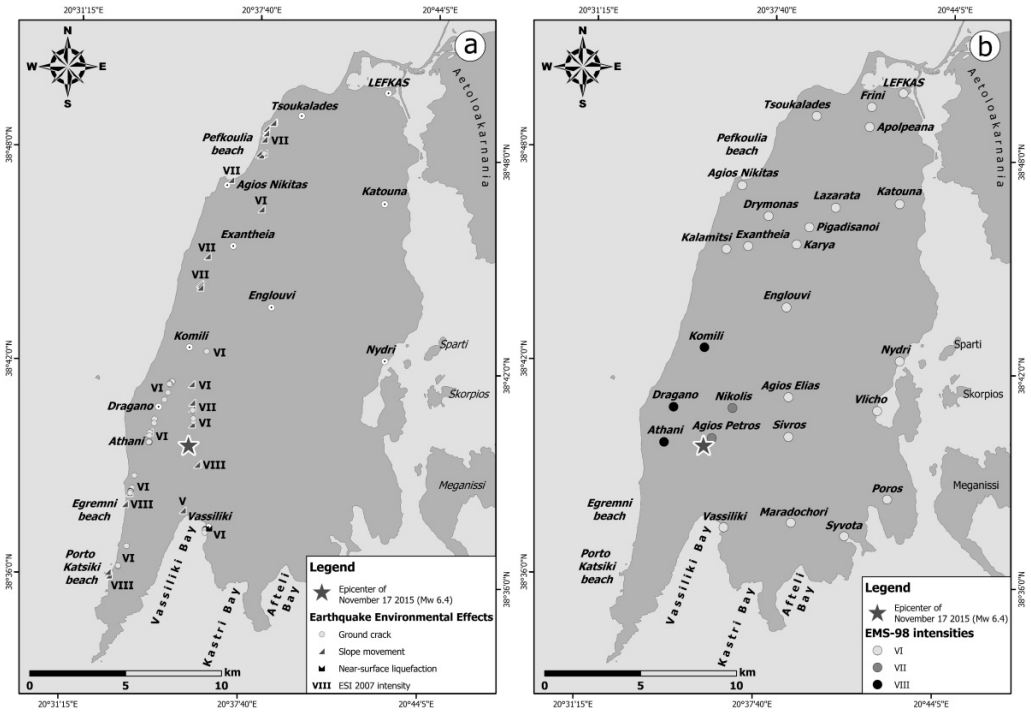

Figure 2: (a) ESI 2007 and (b) EMS-98 intensities for the 2015 Lefkas earthquake.

Damage was limited to Athani, Dragano and Komili villages located in the Lefkata peninsula. Among structures designed and constructed with no seismic provisions, the stone masonry buildings and the monumental structures suffered most damage, while the traditional buildings with dual structural system performed relatively well and suffered minor damage.

Based on historical and recent earthquake data, field observations and the assigned seismic intensities of the 2015 Lefkas earthquake, it is once again concluded that western Lefkas is the area usually affected by earthquake effects including landslides and rock falls, liquefaction, small-scale subsidence and tsunamis. Similar distribution of secondary effects were also reported and recorded after previous historical and recent earthquakes in Lefkas. More specifically, the western part of Lefkas including Agios Nikitas, Dragano and Athani areas has also suffered secondary EEE comprising subsidence during 1704, 1914, 1948 and 2003 events, slope movements mainly landslides and rockfalls during 1783, 1885, 1914, 1948 and 2003 events, ground cracking small in size and of secondary origin during 1704, 1914, 1948 and 2003 and

small-scale tsunamis during 1914 and 1948 events (Papathanassiou and Pavlides, 2007; Rondoyanni et al., 2012).

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