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The M6.5, Nov 17th 2015, Lefkada earthquake Reconnaissance Report

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1. The event

The earthquake occurred at 09:10am (07:10 GMT/UTC) November 17, 2015, with an estimated magnitude M_w=6.5 according to USGS [1] (M_L=6.0 according to ITSAK [2]) at a depth of 11.1 km. The source was located [3] on several segments of a known dextral fault zone 130km long and 30km deep, running parallel to the west shore of the island (Fig. 1.1). It is of particular interest that the earthquake occurred at the southern part of that fault occurred 12 years after the August 2003, M6.2 Lefkas, that ruptured the northern part of the same fault so it was a rather expected event.

Furthermore, there is ample historical evidence (Table 1) of over a dozen earthquake-induced destructions in Lefkada during the past four centuries (Papazachos &Papazachos 1997). Available information suggests that 4 to 5 events above M 6¼ are released percentury. This is also true for the past century, during which five strong events took place (1914, 1948a, 1948b, 1978, 2003).

The losses induced by the earthquake were relatively low compared to its intensity: two lives were lost (one from boulder impact which is rather unusual for Greece), less than 10 injured, a handful of old masonry buildings collapsed and a large number of masonry and RC buildings were damaged. For the latter most of the damage was limited to non-structural elements, such as infill walls and roof tiles.

On the other hand, geotechnical damage was much more pronounced since extensive rockfalls and landslides occurred on the southwest part of the island and along the coastal zone from Porto Katsiki to Ag. Nikitas. Quay walls in the port of Vassiliki suffered considerable displacements while large cracks and settlements on the road network were extensive.

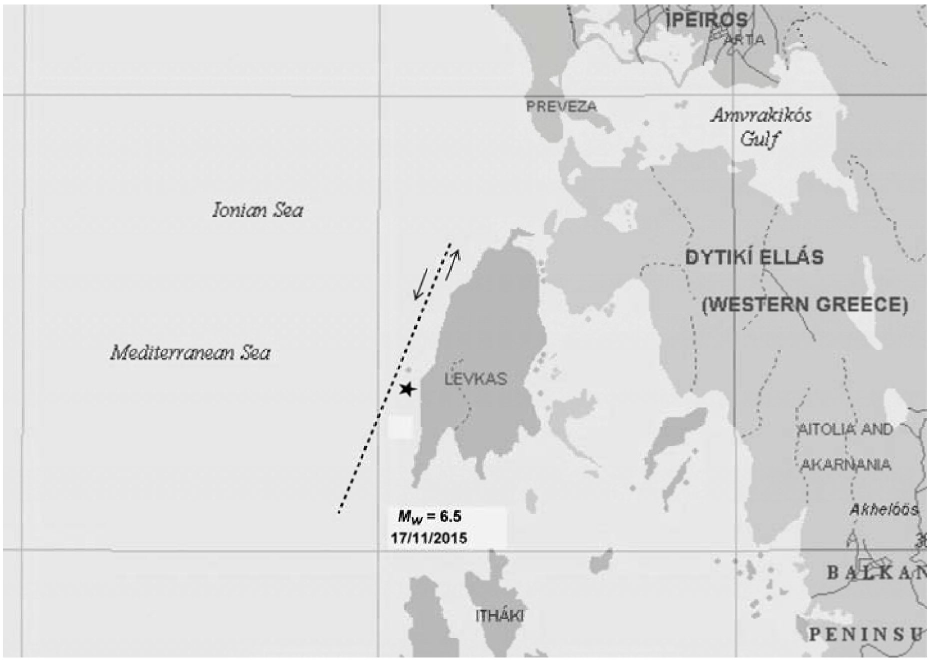

Fig. 1.1 Rough map of region showing fault and epicenter.

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TABLE 1: Destructive earthquakes in Lefkada after 1577 A.D. [4]

Location / Year	Magnitude	Maximum Intensity	Losses
Lefkada 2015	6.5	VII	2 dead, several collapsed buildings, serious damages in masonry structures and in the ports of the Vassiliki; Extended rock falls and landslides.
Lefkada 2003	6.4	IX	No lives lost, 50 injured, one collapse, 5 R/C buildings damaged beyond repair, serious damages in masonry structures and in the ports of the capital and Lygia; Falling of rocks
Lefkada 1973	5.8	VII	Serious damages in the town of Lefkada
Vasiliki 1948	6.5	IX	11 dead, 244 collapses, serious damage in Vassiliki, Kalamitsi, Ag. Petros, Eglouvi; falling of rocks
Komilio 1914	6.3	IX	16 dead, destruction of 18 villages, subsidence of Nydri port, rock falls, settlement at Kalamitsi
Lefkada 1869	6.4	X	15 dead, destruction of villages Amaxiki and Tsoukalades
Lefkada 1825	6.5	X	58 dead, destruction of the capital and several villages
Lefkada 1820	6.4	IX	Extensive damage in the capital, ground settlement in the central square
Lefkada 1815	6.3	VIII	20 dead, destruction throughout the island
Athani 1783	6.7	X	10 dead, 862 collapses throughout the island, destruction of the village Athani, extensive damage in 10 other villages
Lefkada 1769	6.7	IX	7 dead, 497 collapses out of a total of 826 houses in the capital
Lefkada 1723	6.7	VIII	Significant damage in the island, especially in the capital
Athani 1722	6.4	VIII	Extensive collapses in Athani, Damiliani, Agios Petros, Agia Marina; serious damage in the castles of Agia Mavra and Aepetron
Lefkada 1704	6.3	IX	34 dead, massive collapses in the city of Lefkada and at Fryni
Katouna 1630	6.7	IX	Collapses in the city of Lefkada and at Katouna; Falling of rocks and trees, cracks in the ground, notably in the south part of the island
Lefkada 1625	6.6	IX	Massive collapses of masonry structures in the city
Lefkada 1613	6.4	VIII	Destruction of houses, palaces and minarets in the city of Lefkada, collapses throughout the island
Lefkada 1612	6.5	VIII	Damage in 4 villages
Lefkada 1577	6.2	VIII	Damage to the city walls

2. Strong motion data

The event was one of the strongest reported in the the area. According to the preliminary report published by EPPO-ITSAK [2] the value of peak ground acceleration (PGA) was 0.36 g recorded at the village of Vassiliki (VAS 2 station) and 0.1 g at the city of Lefkada (LEF 2 station). The records at the Vassiliki station corrsepond to response spectra with values that exceed those of the design spectra of both the Greek Code 2000 (GSC-2000) and the Eurocode 8 (EC8) as presented in Fig.2. In this Figure, the response spectra of the earthquake on directions N-S and E-W are plotted along those of GSC-2000 and EC8. For the latter, the reference peak ground acceleration is a_{gR}=0.36g, the importance factor is considered as γ_I = 1, the behaviour factor is taken q=1 and the ground type is assumed to be C, which is the common type of soil for most structures in the island.

The horizontal broken line corresponds to the equivalent response spectrum of the 1959 Seismic Code - the first seismic regulations in Greece. A large number of structures in Lefkada were designed following that code based exclusively on pseudo-dynamic considerations. A constant distribution of the lateral load with a value of (ε W) was considered, where ε is the seismic coefficient of the 1959 code and W is the gravity load of the structure. The equivalent demand in the realm of modern codes would be a constant response spectrum with R_d = 1.75 (q × ε), 1.75 being an empirical conversion factor between modern and

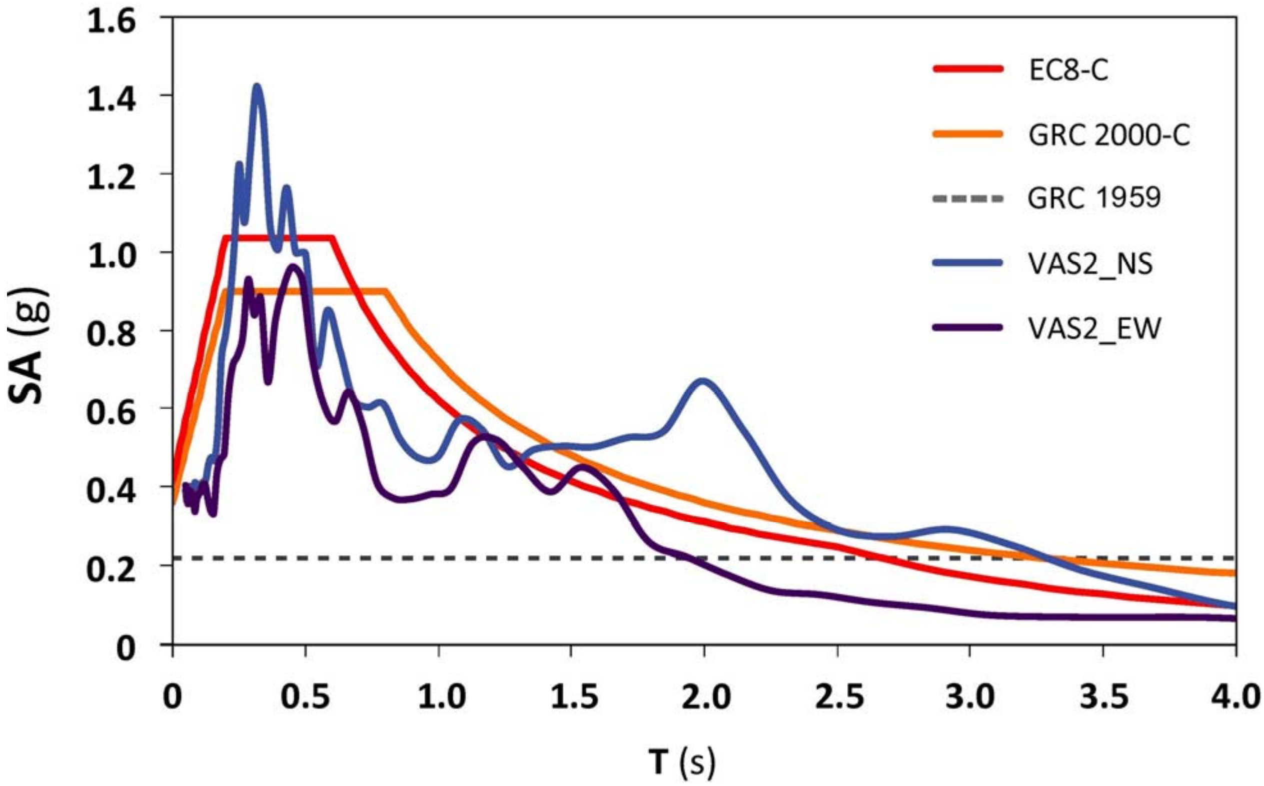

Fig. 2.1 Response spectra of the 17/11/2015 Lefkada Earthquake

old codes, relating reinforced concrete provisions based on allowable stresses and ultimate strength concepts. Should a value of 1.50 be adopted for the behaviour factor (a reasonable approximation for the older generation of RC structures in Greece built without capacity design considerations) and factor ε taken at 0.08 (wgich is the lowest specified by the 1959 code for the region), then R_d = 0.21.

From the response spectra of Fig. 2 it is obvious that the spectral values in terms of acceleration were higher than the requirements of the current codes at the periods between 0.2 to 0.5s which are critical for the majority of the buildings in the island. The spectral acceleration at the VAS 2 station reaches the value of 1.4g at 0.4s however this is lower than the peak spectral value of the devasting 2003 earthquake which reached the 2.2g at 0.5s [4].

3. Landslides

As has been already mentioned, the dominant type of the earthquake-induced failures was rockfalls and landslides that affected the southwest part of the island. The most severe slope failures took place along the coastline from Porto Katsiki to Ag. Nikitas and especially the Egremnoi beach (Figs 3.1a, b).

Also extensive rockfalls triggered by the earthquake took place along the road from Vassiliki to Agios Petros with displaced rocks of a size up to 3m (Figs 3.2a, b). At some places the mitigation measures consisting of retaining or restraining structures (retaining walls and rock curtains) failed due to the impact (Figs 3.2c, d). Overall the mitigation measures over the road network can be considered as effective preventing a larger catastrophe.


Fig 3.1a, b Debris slide and rockfalls along the the coast of Egremnoi

Fig 3.2a, b, c, d Earthquake-induced landslides along the road from Vassiliki to Agios Petros.

4. Damage to the port and waterfront area of Vasiliki

The earthquake induced damages to the waterfront area of Vassiliki. The recently constructed pier and quay wall experienced displacement that possibly leaded to road cracks and small settlements at the

Fig 4.1a, b Road cracks at the waterfront area of the port of Vassiliki.

waterfront area. We found no visible evidence of liquefaction however careful studies should determine if liquefaction actually took place.

Fig 4.2a, b, c , d Displacement of new quay wall - cracks at the waterfront area of the port of Vassiliki.

5. Damage to the road network

The extensive cracks at the southwest part of the island's road network were a major damage in terms of cost and can be attributed to slope movement or fill settlement (Figs. 5.1 a, b, c, d and 5.2 a, b, c).

Fig 5.1 a, b, c , d Asphalt cracks due to slope movement (a, b,c) or fill settlement (d).

Fig 5.2 a, b, c Asphalt cracks due to slope movement.

6. Building Damage

In the villages of the southwestern part of the island, near the epicenter, several old masonry buildings sustained serious damage (Figs 6.1, 6.2). Characteristic is the collapse of the Agia Paraskevi church at Athani a historical structure built in the 18th century (Figs 6.3a,b). However most of these old buildings avoided collapse. A possible explanation is that the actual strength of traditional structures in the area (built using an ingenious combination of masonry and wood) is unusually high due to local design traditions (low weight, overstrength) [4]. Also it should be mentioned that geotechnical failures such as settlements may have contributed to some of the failures.

New reinforced concrete structures experienced minimal damage usually concentrated at the columns' head of the top floor under the roof (Figs 6.4a,b, 6.4, 6.6). The uplift and dislocation of roof tiles was widely observed along with cracks on masonry infillwalls (Figs 6.7a,b,c,d). The latter is a proof of the high, earthquake induced, vertical accelerations at the epicenter area.

It should be mentioned that structures at the northeastern part of the island, including those in the town of Lefkada, presented minimal or no damage.

Fig 6.1 Damaged old masonry building at Vassiliki.

Fig 6.2 Horizontal cracks around the openings of a masonry structure.

Fig 6.3a, b The Church of Agia Paraskevi at Athani before and after the collapse, respectively.

Fig 6.4a, b Cracks at the column' s head of the top floor under the roof and at the balcony parapet of the RC school building at Vassiliki.

Fig 6.5. Detachment of an infill wall from the surrounding RC frame at a two-storey building in Vassiliki.

Fig 6.6. Horizontal and vertical cracks on the infill walls of a building at Athani.

Fig 6.7a, b,c,d . Uplift & dislocation of roof tiles of residential buildings at Dragano (a) and Athani (b,c,d).

Acknowledgements

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