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Reconnaissance Highlights of the 2014 Sequence of Earthquakes in Cephalonia, Greece

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ABSTRACT

Two major earthquakes hit the Cephalonia Island of Greece on January 26th and February 3rd of 2014, with moment magnitudes M_w 6.0 and 6.1. This paper will present observations from an extensive reconnaissance effort coordinated by the Geotechnical Extreme Events Reconnaissance (GEER) Association (supported by the National Science Foundation), in conjunction with Earthquake Engineering Research Institute (EERI) and Applied Technology Council (ATC). This mission brought together experts from the United States (US) and the Greek earthquake engineering community in a multidisciplinary international team.

Despite the fact that the island experienced one of the strongest sequence of ground motions ever recorded in Europe, the response of the building stock and geostructures was successful and no lives were lost. Several two and three story reinforced concrete structures within 50 meters from the strongest recording experienced peak accelerations on the order of 3 times their design values, yet exhibited minimal damage. These structures have been well documented including as-built drawings and design calculations that can be used to enhance our knowledge and approach to overstrength and ductility in seismic design of short buildings. Unlike historic earthquake reconnaissance that focuses on failures, the observations in this mission allowed us to focus on collecting data of resilient performance in addition to failures, paving the way to a new generation of reconnaissance. Damage to the ports due to extensive lateral spreading of quay walls and liquefaction, as well as damage to the cemeteries was documented.

Introduction

Two major earthquakes with moment magnitudes of $M_w = 6.0$ and $M_w = 6.1$ hit the Cephalonia Island of western Greece on January 26th and February 3rd of 2014. Cephalonia is on one of the most tectonically active geologic features of Europe in the Ionian Sea: the Hellenic Trench, with ongoing subduction of the African Plate beneath the Aegean Sea and Eurasian Plates (Fig. 1), while it is crisscrossed by various types of faults. As a result, the island has a remarkable seismic history that can be traced back to antiquity. In 1953, it was destroyed by a sequence of destructive shocks that caused more than 450 deaths. In 2014, no lives were lost and the majority of structures performed remarkably well, considering they experienced ground motions that were often multiple in magnitude of their elastic code design values. However, damage to nonstructural elements was significant enough to affect life, business operations, and economy. Ports and cemeteries also suffered significant damage.

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The reconnaissance was unique for two main reasons: First, it brought together the local, highly qualified engineering community with the US GEER/EERI/ATC group to form a multidisciplinary team of more than 70 people. Second, the resiliency of the building stock, geostructures, and communities that responded successfully to one of the highest sequence of motions ever recorded in Europe shifted our focus on collecting data of successful performance in addition to failures. The mission has produced invaluable datasets, lessons, and suggestions for future research. This paper presents highlights on: (i) ground motions; (ii) geotechnical aspects; (iii) rigid blocks; (iv) structural/nonstructural response; (v) infrastructure; (vii) economical and societal aspects.

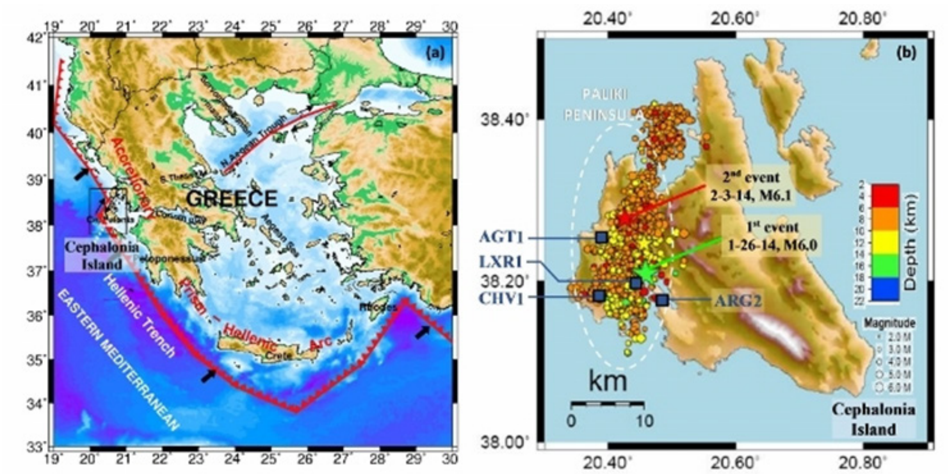


Figure 1. Cephalonia Island with the Hellenic trench tectonic feature (left; Papaoioannou et al., 2006); Epicenters of 1st (green star) and 2nd event (red star). Squares show strong motion stations

Ground Motions and Seismology

Strong motion station locations and recordings became available by the Institute of Engineering Seismology & Earthquake Engineering (EPPO-ITSAK, 2014) and the National Observatory of Athens, Institute of Geodynamics (NOA-IG, 2014). Fig. 1 shows EPPO-ITSAK stations at capital Argostoli (ARG2), and Lixouri (LXR1), Chavriata (CHV1), and Aghia Thekli (AGT1). The highest horizontal Peak Ground Acceleration (PGA) of the 1st event was 0.57g in Lixouri. The high ground motion amplitude and characteristic shape of a near-field pulse of this record agree with the station's close proximity to the epicenter, with Spectral Acceleration (SA) of 1.3g for periods of 0.5–1.0 s. In the 2nd event, PGA reached 0.68 g with PGV of 120 cm/s at this station.

Most of the damage occurred during the 2nd event in the Paliki peninsula (Fig. 1). Fig. 2 shows recorded SAs from this event and the Eurocode's (EC-8) elastic SAs. The high amplitudes could be attributed to local site effects, directivity of shaking, and the pronounced irregular topography of the island. The recorded SAs generally far exceeded code-based values, especially between 0.2–0.3 s, the periods empirically expected for 2–3 story Reinforced Concrete (RC) buildings.

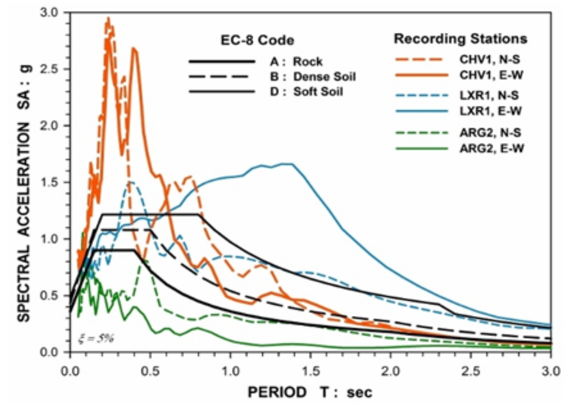


Figure 2. Acceleration spectra from the 2nd event, compared to elastic code (EC-8) spectra.

Geotechnical Aspects

Overall, the reconnaissance findings indicate that site effects played a key role in the geotechnical observations, mostly concentrated on sedimentary soils with poor mechanical properties. These include geologic units such as the Lower Pleistocene sequence and younger Holocene alluvial deposits in the Paliki peninsula which exhibited significant soil amplification.

Given the pronounced irregular features near the recording stations, topographic effects were studied by the team by conducting Horizontal to Vertical Spectral Ratios (HVSR) studies of the CHV1 recordings, where the general subsurface is characterized by 50–80 m of interchangeable layers of weathered marls, limestone, and sandstone, overlying much stiffer Pre-Pliocene bedrock. For a 70-m thick soil column of average shear wave velocity 500 m/s, the theoretical fundamental frequency is about 1.78 Hz (0.56 s), which could indicated that the HVSR peaks are 1-D site response manifestations. On the other hand, CHV1 is at a region with strong topographic relief. Thus, topographic amplification could have contributed (Asimaki et al., 2006) to the CHV1 accelerations with max PGA of 0.76g.

Additional observations include liquefaction of Holocene coarse-grained sediments, rock falls, and landslides. Widespread, repetitive liquefaction and lateral spreading were observed primarily at the main ports of Lixouri and Argostoli, within 10 km from the epicenters (Figs. 1, 3). Quay walls displaced laterally by as much as 1.5 m in Lixouri and less in Argostoli. Liquefaction manifested at ground surface on soft sedimentary sites as large displacements of pavements, and extensive coarse grained (> #4 sieve) gravel particles were observed in ejecta throughout both ports. The two other ports, Sami and Poros, were farther from the epicenters and experienced minimal damage.

Landslides and rock falls were observed at the west: More than 40 rock shallow slides and a deep-seated bedrock slump in natural slopes were recorded (Fig. 4), as well as numerous dry-stack masonry retaining walls. Two major landslides involved settlements of man-made embankments. Soil-structure interaction effects of differential deformations between pavements and structures were observed (Fig. 5). Still, the relatively mild structural damage in Lixouri's reclaimed area could be partially attributed to a layer of unsaturated fill on top of liquefied layers that acted as a "protective cap."

Figure 3. Liquefaction zones at two main ports of Lixouri and Argostoli (left). Lateral spread at Lixouri quay wall (middle); opening of joint at pier and evidence of gravel in ejecta (right).

Figure 4. Landslide and rock slope failure examples.

Figure 5. Settlements between the base of the National Bank Lixouri branch and sidewalk.

Structural and Nonstructural Aspects

Most of the island was destroyed by the strong 1953 earthquakes and new structures were built using the 1st Greek seismic code of 1959. There is a tradition of expanding homes vertically and laterally over several generations, largely due to a close-knit family structure, which results in buildings with portions built decades apart with different codes. Damage (Fig. 6) was observed in:

- RC buildings of older seismic codes with large stirrup spacing (> 300 mm), lack of confinement at beam-column joints, and poor detailing.
- RC buildings with soft stories at the ground level.
- Mixed structural systems which usually included a masonry ground floor and a RC upper floor, built in phases over the course of several years (Fig. 6).
- Old masonry buildings and churches which survived the 1953 events and had been repaired.

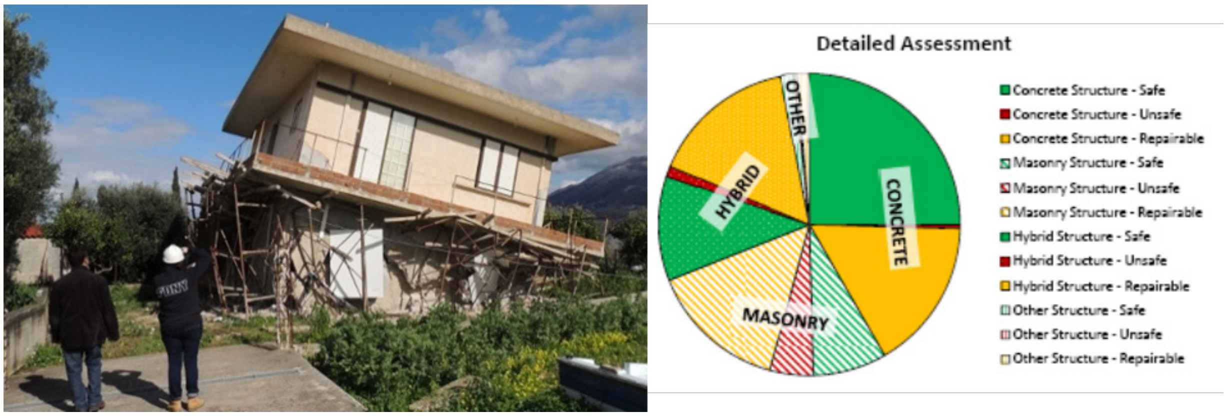
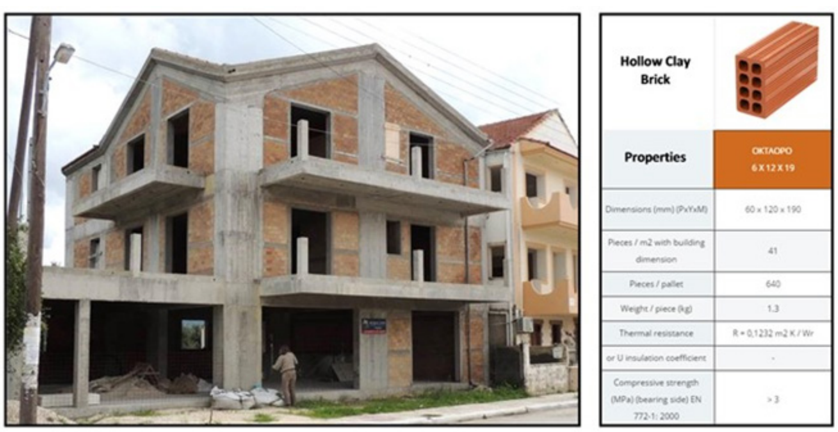


Figure 6. Mixed construction collapse (left); detailed assessment of 2,770 buildings (right).

The predominant structural type (Fig. 7) is a mix of reinforced concrete (RC), masonry infill, and wood roofs, 1–4 stories high. The infill has concrete beams around openings dowelled to the RC structure. This practice is unusual, but was resilient given the fact that in the 2nd event SAs peaked at 3 g in Chavriata and 1.5 g in Lixouri, exceeding max elastic code values by 1.25 to 2.5 (Fig. 2). Depending on the design Response Modification Factor (R) factor, the recorded SAs could have generated actual seismic loads that were higher than design by an astounding factor of 2.5–8.5 (for R of 2–3.5). Reconnaissance data have already initiated resiliency studies (Nikolaou et al., 2015).



Hollow Clay Brick	
Properties	OKTAOPO 6 X 12 X 19
Dimensions (mm) (PxYxM)	60 x 120 x 190
Pieces / m2 with building dimension	41
Pieces / pallet	640
Weight / piece (kg)	1.3
Thermal resistance	R = 0,1232 m2 K / Wr
or U insulation coefficient	-
Compressive strength (MPa) (bearing side) EN 772-1: 2000	> 3

Figure 7. Confined masonry construction (left); properties of infill clay bricks (right).

Nonstructural component deficiencies included inadequate bracing/anchorage to structure, roof tile collapse, lack of fence foundations or design for interstory drift, lack of seismic stoppers for rolling storage racks, absence of flexible joints in piping, lack of floor/wall connections of heavy furniture, bookcases and bank vaults, and unsecured objects (Fig. 8). This affected the everyday life and economy, but serious injuries or loss of life were avoided.

Figure 8. Nonstructural damage: Sliding and rotation of bank vault (left); glazing failure (right).

Rigid Blocks and Churches

In stark contrast with the overall excellent building performance, extensive damage was observed in the 18 cemeteries of the Paliki peninsula and 9 others on the island. The main cause of tomb damage was toppling on the grave marble slab. Other failure patterns included slippage, vertical separation, and/or rotation of blocks and tombstones without toppling (Fig. 9). The toppling rate was surprisingly low in the fault vicinity and concentrated in the peninsula at a rate of ~67% of objects toppling, and dropped to ~20% on the main island and zero at the east. Controlling factors were block geometry and near field directivity effects. Since cemeteries are built on a hill, topographic amplification likely contributed. Information in the GEER/EERI/ATC report can contribute to research on the highly nonlinear seismic block behavior.

Figure 9. Photos and sketches with dimensions and displacement of a rotated headstone.

Infrastructure Networks

The potable and wastewater networks suffered notable damage mainly due to the 2nd event. The Athens Water Supply & Sewerage Co. EYDAP responded rapidly with field and repair teams and provided their report for incorporation in the GEER/EERI/ATC findings. Since electronic mapping of the network was not available, EYDAP develop a GIS map of 36,191 m of water pipes based on available maps and Digital elevation models (DEMs) from satellite data. The assessment of the first day (2/6/14) is shown on Fig. 10: **Green** – normal operation; **Yellow** – significant fluctuations in pressures; **Orange** – very low pressure; and Red – zero pressure. The properties of the water pipe network are shown on Table 1. Damage was found to be concentrated to the Asbestos Cement Pipe network.

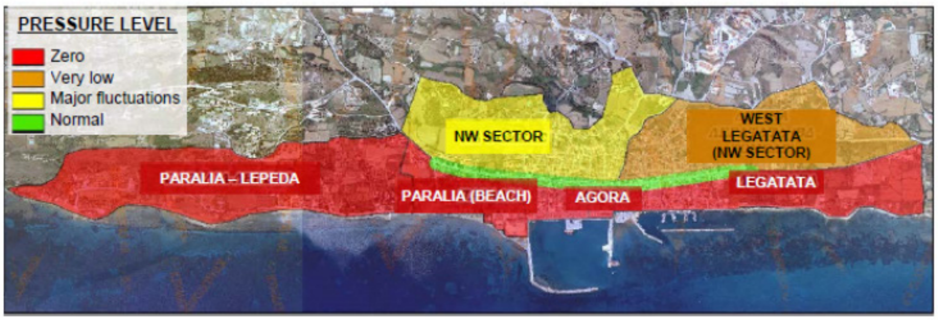


Figure 10. Rapid network assessment at the end of the first day, 2/6/14 (EYDAP, 2014).

Table 1. Potable water pipe network material

Material	Length (m)	% of Network
Plastic Pipe Network (PVC)	15,295	42.3
Asbestos Cement Pipe Network (A/C)	11,041	30.5
Polyethylene Pipe Network (PE)	9,355	25.8
Steel Pipe Network (ST)	500	1.4

Robot-operated video cameras were useful for pipeline inspection, particularly where damage was not visually evident. Over 5.6 km of wastewater pipes were inspected and telemetry systems monitored elevation, water flow, and pressure to ensure continuous operations.

Community Response

The people of Cephalonia generally handled the events stoically, as most have experienced past earthquakes, which helped minimize panic and allowed for smooth emergency response. Some facilities were temporarily evacuated. The Lixouri hospital, senior citizen housing and schools were moved to large cruise ships, public facilities or temporary settings for several weeks. While the water network was repaired, bottled water was distributed and authorities, churches and volunteers provided food to those in need with financial support from various sources. Art has always been a cultural mechanism for Greeks to cope with strenuous ordeals.

Conclusions

The GEER/EERI/ATC reconnaissance after the Cephalonia earthquakes has yielded invaluable datasets, lessons, and future research directions disproportionally larger to the size of the affected area. Thanks to an enthusiastic engagement of the local community, the experience gained spans geotechnical, structural and lifeline engineering, and extends into social studies, public policy and health. The good performance of geotechnical/structural systems was documented in detail and give an opportunity to advance our understanding on resilient behavior that could be considered in future codes. Key lessons and needs for future research based on reconnaissance include:

1. Expansion of seismographic network which is currently constrained on the eastern part of the island is needed as most seismic events have originated on the western part.
2. Geophysical testing and high-resolution Digital Elevation Models (DEM) are necessary to evaluate the evident site amplification and topography effects.
3. Damage at the ports was mostly at the quay walls, which is typical. Reconnaissance data and better site characterization can be used to develop much needed simple design methods.
4. The seismic response of gravelly fills using data from liquefaction ejecta in the main ports that included coarse grained (greater than #4 sieve) gravel particles should be studied further.
5. Potential natural base isolation of structures founded on a stiff nonliquefied soil layer (cap) overlying liquefied soil layers that filter accelerations (at the expense of larger deformations) should be researched further using data of minor structural damage in Lixouri liquefied zones.
6. The nearly elastic structural and resilient response of short RC buildings combined with detailed data and ground motions can be used to study the benefits of local construction.
7. Near-field directivity effects: The vast number of rigid blocks that toppled in the inspected cemeteries and the characteristically long period pulse recordings at Lixouri provides a unique opportunity to study the near field effects on ground motions.
8. Nonstructural data of photos, measurements, and security videos can be used to study and enhance existing practices by FEMA and Eurocode for design of nonstructural components.
9. Life safety was achieved despite high ground motions. However, the public did not realize that nonstructural damage is expected after large seismic events as per code intent. As this has been observed in other reconnaissance missions, further educational public outreach is needed.

Acknowledgments

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