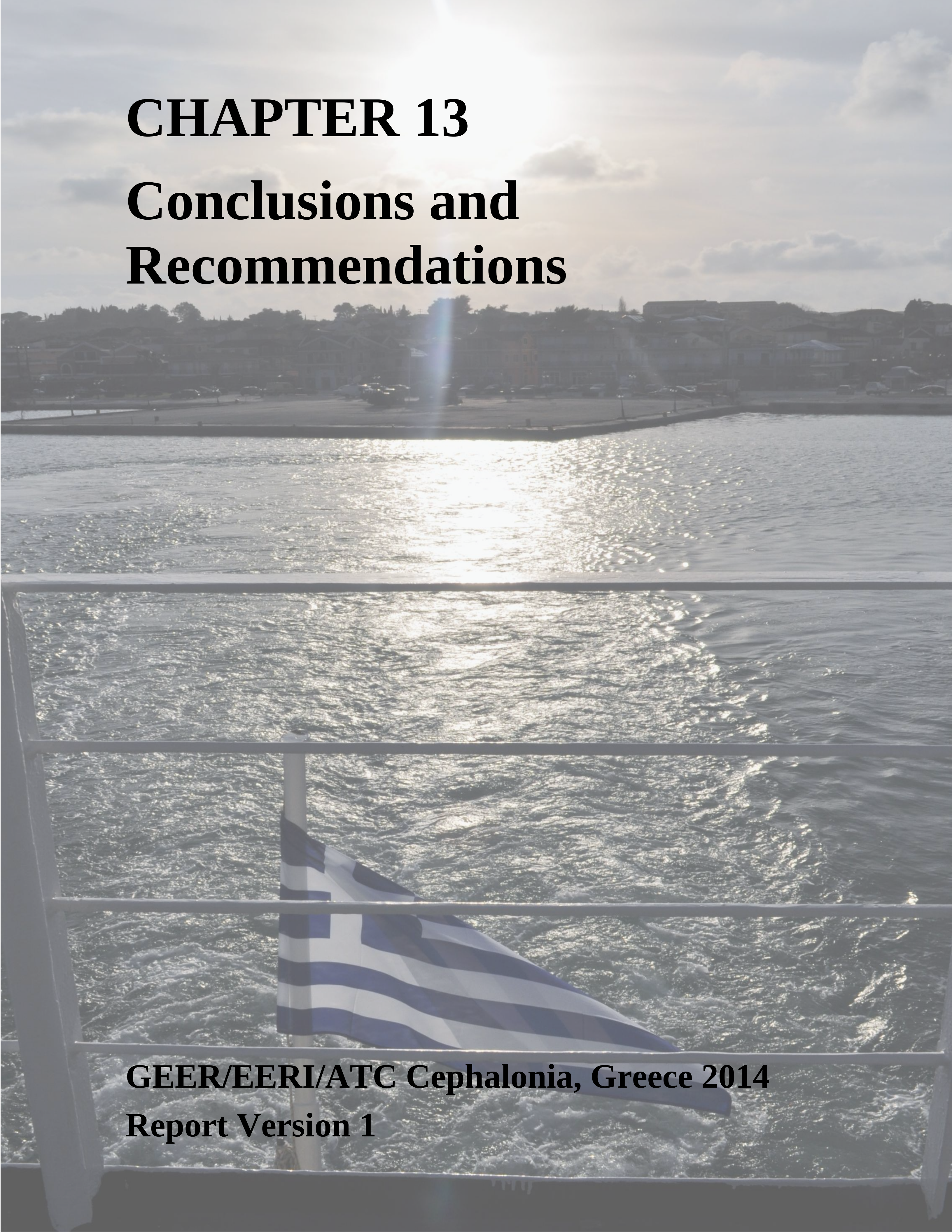

CHAPTER 13

Conclusions and Recommendations

GEER/EERI/ATC Cephalonia, Greece 2014

Report Version 1

13 Conclusions

Two major seismic events of moment magnitudes $M_w = 6.1$ and $M_w = 6.0$ struck the Greek island of Cephalonia on January 26th and February 3rd, 2014, respectively, fortunately causing no loss of life. The reconnaissance mission was unique for two reasons: First, it brought together the local and highly qualified earthquake engineering community with US-based GEER/EERI/ATC representatives, to form a multidisciplinary team of more than 60 people that documented geotechnical, structural, and nonstructural observations. Secondly, the reconnaissance approach was modified from the typical learning from failures to a new methodology that includes a focus on learning from success and resiliency of the building stock, natural geostructures, and communities, which responded well to some of the highest ground motion levels ever recorded in Europe. Data collected, including instrumentation and design documentation, can be used in combination with recorded ground motions and much-needed in-situ testing to further understand and explain the good response of most structures.

MAIN OBSERVATIONS

Seismological and Recorded Motions

Both events occurred along the so-called Cephalonia Transform Fault, a well-documented active offshore dextral strike-slip fault with a thrust component southwest of the island. Since the seismographic network that recorded the events is installed exclusively east of the causative fault, epicenters were only approximately located, while seismologists are still entertaining the possibility of a pair of closely-spaced parallel causative faults that ruptured in sequence.

Satellite data from the second event revealed a maximum ground deformation of 12 cm south-ward at the midpoint of the island's west most peninsula (Paliki), and of 7 cm northward along the east coast of the same peninsula. The highest horizontal Peak Ground Acceleration (PGA) recorded during the 1st event was 0.57 g; the exceptionally high ground motion amplitude and the characteristic shape of a near-field pulse of the record are consistent with the station's close proximity to the epicenter. The corresponding spectral acceleration (SA) was 1.3 g for periods between 0.5 and 1.0 s. At the same station, the horizontal PGA reached 0.68 g during the 2nd event, with peak velocity of about 120 cm/s. The response spectra from at least two recordings of the 2nd event far exceeded the current code design spectra for periods that affect the 2- to 3-story structures of the island.

Geotechnical Aspects

It is very likely that site effects played a key role in both events. The damage concentration on sedimentary soils with poor mechanical properties, like the Lower Pleistocene sequence and younger Holocene alluvial deposits in the Paliki peninsula, is indicative of significant soil amplification. This observation supports the need for further studies including extensive site characterization and site-specific response analyses. Given the pronounced irregular features in the immediate vicinity of several ground motion recording stations, topography likely affected the recorded ground motion.

Additional observations include liquefaction of Holocene coarse-grained sediments, rock falls, and landslides. Widespread and repetitive liquefaction and lateral spreading were documented, primarily at the Lixouri and Argostoli ports (two of the four main ports), within less than 10 km from the epicenters. On the other hand, minimal –if any- damage was observed at the ports of Sami and Poros, which are farther from the epicenters. Landslides and rock falls were also concentrated on the western part of the island, closer to the epicenters, as were retaining wall failures. As is typical, concrete walls were proven to be much more resilient than unreinforced masonry walls.

Short-span reinforced concrete bridges, by far the most common type on the island, performed well, with the exception of the Havdata bridge that suffered differential settlement at both embankments. The historic (1830) multi-span stone Debosset bridge, which was seismically retrofitted in 2005, showed no damage despite high accelerations recorded nearby. Road embankments performed well, with very few instances of severe or moderate damage that obstructed or delayed traffic. Landfills and dams also performed well without any damage.

Liquefaction manifested at the ground surface primarily as large horizontal and vertical displacements of pavements on soft sedimentary sites and in areas with widespread liquefaction, mostly in the town of Lixouri. Soil-structure interaction effects of differential settlements and lateral deformation between pavements and structures were primarily documented for pile-supported structures built on reclaimed land. Still, the relatively mild structural damage in the reclaimed part of Lixouri could be partially attributed (from a soils perspective) to the layer of unsaturated fill on top of the liquefied layers that acted as a “protective cap.”

Rigid Blocks

In stark contrast with the overall excellent performance of the building stock in the most severely shaken region, very extensive damage was observed in almost all of the 18 cemeteries of the Paliki peninsula and 9 additional cemeteries elsewhere 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. Controlling factors were the block geometry and the characteristics of the seismic excitation. Since cemeteries are often built on a hill, topographic amplification is a possible contributing factor which needs further examination, along with directivity and local soil amplification. Interestingly, rigid objects (crosses, vases, markings) located on tombs generally oriented in the EW direction, consistently toppled towards the East. Other cemeteries, in the vicinity of the damage observations exhibited different response or minor damage, even though general geologic setting and altitude were similar. The toppling rate was surprisingly low in the vicinity of the fault.

Extensive structural damage (even partial collapse), and severe nonstructural damage was also documented for the 49 inspected Greek Orthodox Churches of Cephalonia. Similar to other structures, severe damage was concentrated in the Paliki peninsula, near the epicenters. The extent of damage was found to depend on the structure's age, construction type, retrofit history, and the type of lateral force resisting system.

Structural Aspects

Overall, the building stock of the island is relatively new. Most of the island was destroyed by the strong earthquake events of 1953 and new structures were built using the 1st Greek seismic code published in 1959 due to these earthquakes. There is a common practice of building and expanding homes over the span of several generations. This building pattern is largely due to the close-knit family social structure of Cephalonia. Several generations of a single family typically live together in the same house, which they expand vertically and laterally as their families grow. This results in buildings that have portions built decades apart under different codes and structural systems.

The predominant building type is a mix of reinforced concrete, masonry infill, and wood roofs. These structures typically range from one to four stories in height. The infill masonry has concrete beams around openings that are dowelled to the concrete structure. This practice is different from confined masonry or regular infill masonry construction. Buildings of this category were found among both residential and commercial structures. These low rise reinforced concrete buildings behaved very well during the 2014 earthquakes, despite the fact that they experienced spectral accelerations more than twice their elastic design values. Further studies of these structures should be pursued, as they seem to be an economical cost for structure is on the order of 20% of the total construction cost) design approach in high seismic zones.

Infrastructure Lifelines

Lifelines -water and sewage systems- were being closely monitored and promptly repaired by the national water company (EYDAP). Only the 2nd event caused a large number of leaks in Lixouri. However most of the operational problems, like leaks and associated public health risk incidences, emerged in the days following the 2nd event, as a result of network fatigue and overflow of the sewage system.

Nonstructural components

Nonstructural component failures and installation deficiencies, like roof tile collapse, inadequate bracing and anchorage to structural elements, lack of fence foundations, lack of design to accommodate interstory drift, lack of seismic stoppers or brakes for rolling storage racks, absence of flexible joints in piping, lack of floor or wall connections of heavy office furniture, bookcases and bank vaults, not properly braced or anchored equipment, and unsecured objects on shelves, were extensive in the densely populated towns of the island (Lixouri and Argostoli). Their damage significantly affected the everyday function of the island and its economy, and could have resulted in serious injuries or loss of life if the residents were not intuitive about expecting the 2nd earthquake and for the good fortune of both major events happening when businesses were not operating. The critical facilities of the Cephalonia international airport Terminal remained closed for 3 weeks following the events and the Hospital of Lixouri was evacuated, mainly due to nonstructural damage.

Community and Government Response

The Greek government responded with rapid assessment performed immediately following the 1st and 2nd events. Some critical and essential facilities had to be evacuated temporarily and some were evacuated as a precaution due to the known history of sequential earthquakes in the island that created concerns to the residents. Examples of evacuated facilities include the

Lixouri hospital and the schools, which were moved to large cruise ships for several weeks. Although tents were made available by the army, the rainy weather made living hard and several homeless people had to also be moved to ships or chose to sleep in their cars. Water supply was interrupted in Lixouri after the 2nd event and bottled water was distributed until the network became operable. Psychological help was provided, especially to children, who experienced such a natural phenomenon for the first time. The people of Cephalonia handled the events stoically, as they have most likely experienced earthquakes in their lifetime, which helped to avoid panic and allow for emergency response to run smoothly. However, even these experienced residents, appeared to not realize the success in achieving the life-safety goal of the seismic codes by the very good structural behavior, but often complained about nonstructural damage that caused impact to their business and life.

Economical

Despite the fact that the island suffered no casualties and the majority of the building stock suffered little to no damage, the economic cost for the Greek government is significant. Rental allowances for residents whose homes were deemed unsafe for immediate re-occupancy will cost an estimated $22 million. An estimated additional amount in excess of $65 million will be required for reconstruction aid. Preliminary cost estimates bring the total cost of replacing or repairing the damaged buildings to more than $250 million. The Greek Government has appealed to European Union’s Solidarity Fund for financial aid.

LESSONS LEARNED AND FUTURE RESEARCH NEEDS

The GEER reconnaissance effort after the Cephalonia earthquakes has yielded a number of invaluable datasets, lessons learned, and future research directions disproportionally larger than the size of the affected area would have suggested. Thanks to the enthusiastic engagement of the Greek research community and local authorities and residents, the experience gained not only spans the areas of geotechnical, structural and lifeline engineering, but also extends beyond the boundaries of technical knowledge into social studies (community emergency response), public policy and public health. Above all, this event highlighted the advantages of documenting and incorporating the lessons learned from past damaging events into updated versions of seismic codes. The excellent performance of geotechnical and structural systems gave us the opportunity to also learn from the success stories, to advance our understanding on resilient infrastructure, hazard mitigation and risk reduction.

The immediate response and thorough reconnaissance by the GEER team in collaboration with Greek researchers and the local authorities was invaluable and enabled collection of time-sensitive data on structural and ground failures, such as soil ejecta in areas which suffered from liquefaction, which could have been washed away by a rainfall before the teams arrived to the sites. On the other hand, documented failures and shortcomings observed in the reconnaissance efforts revealed lessons and needs for future research, including:

1. Expansion of seismographic network: the network is constrained on the eastern part of the island, while most seismic events have originated on the western part. As a result, locating epicenters is still underway as it has to incorporate a large margin of uncertainty. Additional instrumentation in the western part would be desirable to record any future events.
2. Geophysical testing and high-resolution Digital Elevation Models (DEM): Site amplification and topography effects have likely played a role in the damage distribution and strong recorded ground motions. In-situ geophysical testing and topographic maps will be necessary to quantitatively evaluate the relative contribution of each effect.
3. Detailed displacement measurements and site characterization of affected ports and waterfront: The structural damage at Lixouri and Argostoli ports comprised primarily of rotation and translation of quay walls at the waterfront, a typical damage mechanism for waterfront structures on soft and/or liquefiable soils. However, no simple design recommendation exist to limit the deformations of this particular type of structure in the

event of strong seismic shaking. Improving our understanding on this topic would advance our capabilities to predict and limit the number of failures in the future.

4. Seismic response of gravelly fills: Liquefaction ejecta in Lixouri and Argostoli ports included numerous gravel particles. The fill materials at these locations, therefore, seem to involve a significant amount of coarse grained (greater than #4 sieve) particles, which makes their seismic response of particular interest.
5. Role of liquefied layers as natural base isolation of buildings: The minor structural damage at Lixouri could be associated with beneficial effects of structures founded on a stiff non-liquefied soil layer (cap) overlying liquefied soil layers that significantly filter accelerations at the expense, however, of increased lateral displacement. Further understanding of this effect in the context of performance based structural design, will require extensive site-specific geotechnical investigation and site-specific numerical analyses.
6. Structural effects: This event provides a unique opportunity to enhance our understanding of the nearly elastic response exhibited by the lateral load resistance mechanisms of Reinforced Concrete buildings, which had been designed in accordance with the latest Greek seismic code. Collected data in reconnaissance include detailed design calculation and construction drawings, photos after each event, and records in the immediate vicinity (within 50 m) of structures that behaved very well despite cases where recorded PGA reached 0.8 g and spectral values where more than twice the elastic design values.
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 components: The collection of information, photos, measurements, and security video footage can be used to enhance practices and simple solutions for protection of nonstructural components. Education on FEMA and Eurocode guidelines for expected deformations and loads depending on the type, weight, and location (in floor height) of nonstructural components needs to be promoted.
9. Education and outreach: The intent of the seismic code on life-safety was achieved despite the very high ground motions. However, the public did not seem to comprehend that nonstructural damage is expected after large seismic events for code-complaint structures. This appears to be the case in other earthquake-prone areas and further outreach is needed to better educate the public on their risk exposure.