Earthquake Performance and Characterization of Gravel-Size Earthfills in the Ports of Cephalonia, Greece, following the 2014 Earthquakes

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ABSTRACT: The sequence of two major earthquakes with moment magnitudes of 6.0 and 6.1 that hit the island of Cephalonia in Greece in 2014, resulted in significant liquefaction of gravelly soils. Two of the island's main ports, Lixouri and Argostoli, were impacted by liquefaction of gravel-size fills and experienced significant lateral displacements (up to 1.5 m). Investigations were conducted using the Dynamic Penetration Test (DPT) with energy measurements and the Multichannel Analysis of Surface Waves (MASW) technique to measure shear wave velocity (V_S). In both ports, the DPT results show relatively low N'_{120} values (<10 blows/30 cm). Liquefaction triggering analyses using the DPT indicate that liquefaction would be expected at both ports. Triggering analyses using V_s-based methods indicate that liquefaction should have occurred in Lixouri, where the accelerations were higher, but not in Argostoli where V_S values were higher than 225 m/sec. The results of this study confirm the need for a revised liquefaction triggering methodology for gravelly soils.

1 INTRODUCTION

1.1 *Seismotectonic Setting and the 2014 Cephalonia Earthquakes*

Cephalonia is part of the Hellenic Trench in the Ionian sea that represents an active plate boundary between the Mediterranean tectonic plate and the Aegean tectonic plate and is the most active seismic region in Europe. Cephalonia has a history of seismic activity with 18 earthquakes of $6.3 < M_w < 7.4$ observed since the 15th century. The Cephalonian Transform Fault (CTF) is the main seismotectonic feature of the region. Two major earthquakes occurred near the island of Cephalonia on January 26, 2014 and February 3, 2014. The first event had a moment magnitude (M_w) of 6.1, while the second event had a M_w of 6.0 and appeared to be more damaging. The mean horizontal acceleration in Lixouri was 0.6g and 0.64g for the first and second event respectively, whereas in Argostoli, 0.39g and 0.25g (Theodoulidis et al. 2016).

1.2 *Gravel Liquefaction and Port Performance during the 2014 Cephalonia Earthquakes*

No loss of life occurred during these earthquake events; however, damage was observed. This included some structural damage in residential and commercial buildings, pronounced damage in the main ports of Argostoli and Lixouri, the occurrence of landslides and rockfalls, road damage, and pervasive damage to cemeteries where the ground motions were higher (Nikolaou et al. 2014, Nikolaou et al. 2015). Of particular interest in this paper is the observed liquefaction in the port areas of the towns of Argostoli and Lixouri. Liquefaction of gravelly fills produced lateral spreads, ground cracking, and ejecta consisting of coarse-grained material. Figures 1 and 2 show evidence of liquefaction (i.e. sand and gravel ejected from the ground due to pore pressure relief) at the Lixouri and Argostoli port. Anecdotal testimonies by residents in Lixouri describe pressurized water ejected from the ground that reached nearly 1 m. Similarly, stains from water and liquefaction ejecta on the walls of the Port Authority building in Argostoli indicate that the ejecta reached 35 cm and possibly 50 cm. The grain size of ejecta in Argostoli had a maximum diameter of 3 cm, whereas in Lixouri it was even coarser in many locations. Liquefaction occurred in both Lixouri and Argostoli during both 2014 earthquake events, but the second event resulted in more evidence of liquefaction, and caused more damage to the ports due to lateral movement of the quay walls. This may be at least partially attributed to forward directivity (Garini et al. 2017).

Figure 1: Examples of gravelly soil liquefaction through pavement construction joint at the port of Lixouri following the second earthquake. Note the large particle size of the ejecta (a): 38°11'55.38"N, 20°26'20.98"E; (b): 38.199166, 20.439166.

Figure 2: (a) Evidence of gravelly soil liquefaction outside the customs building of the Port Authority of Argostoli following the second earthquake (38.17998°, 20.48996°); (b) close-up view of liquefaction ejecta on top of concrete slab (38°10'47.85"N, 20°29'24.42"E).

Along the port front, the quay walls translated, tilted and rotated outwards resulting in damage and affecting the operation of the ports. Damage was more severe at the Lixouri port compared to the Argostoli port, probably due to the higher accelerations and despite the fact that the quay walls in Argostoli are taller than at Lixouri. Horizontal displacement of the quay walls varied in each of the ports depending on the location, the height and other geometric characteristics of the quay wall that consisted of stacked concrete blocks of variable size. The maximum horizontal displacements measured were about 150 cm with longitudinal cracks parallel to the seafront observed as far as 100 m inland from the seafront (Nikolaou et al., 2014). In other places in Lixouri, the displacement was lower, commonly 10-50 cm. In Argostoli, the lateral displacements were much lower (≤16 cm). It is important to note that liquefaction boils were less pronounced (and in many cases not visible) in the vicinity of the quay walls and when visible, consisted of finer material. This is probably attributed to the lateral movement of the walls that likely alleviated any water pressures and reduced the necessity for water expulsion upwards. Examples of damage at the seafront in Lixouri and Argostoli port is shown in Figure 3.

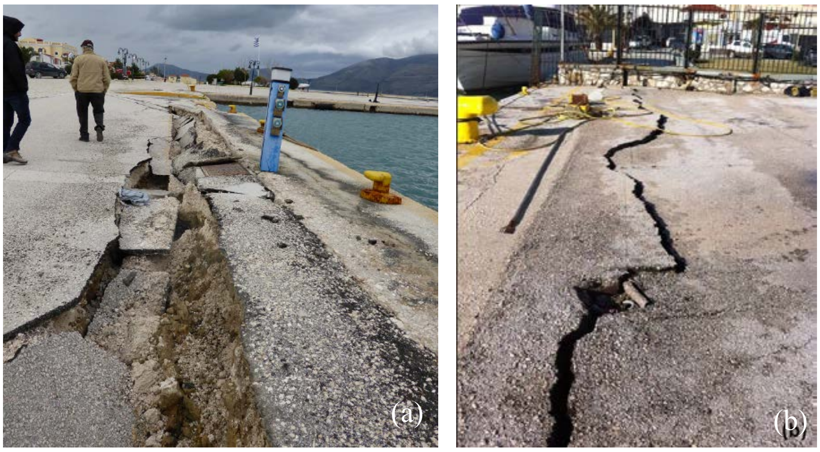

Figure 3: (a) Displacement of the quay wall in Lixouri port, across the Plaza of National Resistance following the second earthquake (GPS coordinates: 38.199444, 20.439444); (b) displacement (~16 cm) of the quay wall in Argostoli port.

2 FIELD INVESTIGATION

2.1 *Initial Geotechnical Investigation*

As part of the effort to restore the ports following the earthquake damage, a characterization of the subsurface was conducted using exploration trenches and boreholes (Geoconsult Ltd, 2016). The subsurface conditions behind the quay walls consisted of fills, underlain by native, stiff, low plasticity clays. The fills that formed the shallower layers of the ports and appear to have liquefied are not natural deposits. They were human-made fills placed following the 1953 Ionian Earthquake sequence. This series of historic earthquakes caused devastation on the island and nearly complete damage of the towns of Lixouri and Argostoli. During the recovery efforts from the 1953 earthquake, sea reclamation occurred and debris from the earthquake was used to expand the land seaward. Debris included primarily bricks, stones and finer material that originated from the collapsed masonry structures. It is in these fills that damage was concentrated in the 2014 earthquakes. Figure 4 is indicative of the physical characteristics of these fills that include coarse grained materials as well as large cobbles. The fill is also visible in Figure 3a.

2.2 *Dynamic Penetration Testing (DPT)*

Subsequently, as part of an ongoing research project, the gravelly fills at the ports were characterized using the Dynamic Penetration Test (DPT) and shear wave velocity (V_s) profiling to gain a better understanding of the nature of the material. The Dynamic Cone Penetration Test (DPT) was developed in China in the 1950s for testing gravelly soils as an alternative to Standard Penetration Testing (SPT) and Cone Penetration Testing (CPT), which can be unreliable in gravelly deposits. The DPT was used for liquefaction analyses in China following the 2008 Wenchuan earthquake (Cao et al., 2013). DPT testing was conducted in both Lixouri and Argostoli using the same cone tip described by Cao et al. (2013). The cone diameter was 74-mm with a cone angle of 60º. However, in Cephalonia, the hammer on the rig weighed 63.5-kg and had a drop height of 75 cm that produced a lower energy than the specified DPT energy. Therefore, measured DPT blow counts were scaled down by the ratio of measured SPT energy divided by the measured Chinese hammer energy to obtain N'_{120}. The SPT hammer was operated using an automatic pulley system at a rate of 15 blows per minute. The blow counts were recorded in 10 cm increments as is common with the DPT in China (Cao et al., 2013).

Figure 4: Views of debris excavated adjacent to the port seafront at the location where the maximum lateral displacement of the quay walls was registered in Lixouri. The large particles of the fill material is visible. (Geoconsult Ltd, 2016)

Energy transfer measurements were recorded for each hammer blow for four of the test locations using a pile driving analyzer (PDA) system manufactured by Pile Dynamics, Inc. (PDI). Measurements of the energy transferred from the hammer to the drill rods were recorded and the energy transfer ratio (ETR) was calculated. The energy transfer ratio (ETR) is the ratio of the energy that passes through the drill rods to the potential energy of the hammer falling from its specified drop height. This value is expressed as a percentage and typical ETR values for the DPT drill rig used in this study were in the range of 60-70% with an average value of 65%.

2.3 *Shear Wave Velocity Measurements (MASW)*

Shear wave velocity (V_s) measurements were performed using the Multichannel Analysis of Surface Waves (MASW) method, employing 16 geophones (4.5Hz), and a 4.5 kg sledgehammer as a source. Spacing of the geophones was either 1 or 3 m, depending on the testing location. Active source signals were usually stacked 8-12 times. Data analysis for the MASW measurements consisted of developing dispersion curves from active source signals using the procedure described by Park et al. (1998). The DPT data were used to develop layering for the V_s profiles based on site stratigraphy and were used to constrain the forward modeling analyses and generate more refined estimates of V_s.

3 FIELD TEST RESULTS

In this paper, the field test results at two locations, one in Lixouri and one in Argostoli, are presented and used to perform liquefaction triggering calculations with available methods. It should be mentioned that throughout the two ports, the stratigraphy is similar, i.e., it consists of human-made fills overlying the natural stiff clay deposits, but the thicknesses of the fills vary in different locations within each port.

At the Argostoli port, field test results are shown for a location next to the customs building in the Argostoli port complex. The stratigraphy consists of gravelly fill materials to a depth of 8.3 m, underlain by the stiff native layer. V_S measurements were performed using geophones at 1 m spacing at this site. The blow counts versus depth and the V_s profile are shown in Figure 5.

At the Lixouri port, field test results are presented for one location as well (Fig. 6). The DPT was completed to a depth of 6.6 m, where blow counts increased significantly (3 consecutive 10 cm layers of greater than 50 blow counts) so the test was ended. Upon removing the drill roads and cone tip from the ground, wet green/gray silty sand was observed on the rods, which was indicative of the native layer below the gravelly fills. MASW measurements were performed with geophones at 1 m spacing. The N'_{120} blow counts versus depth as well as the V_S profile are shown in Figure 7.

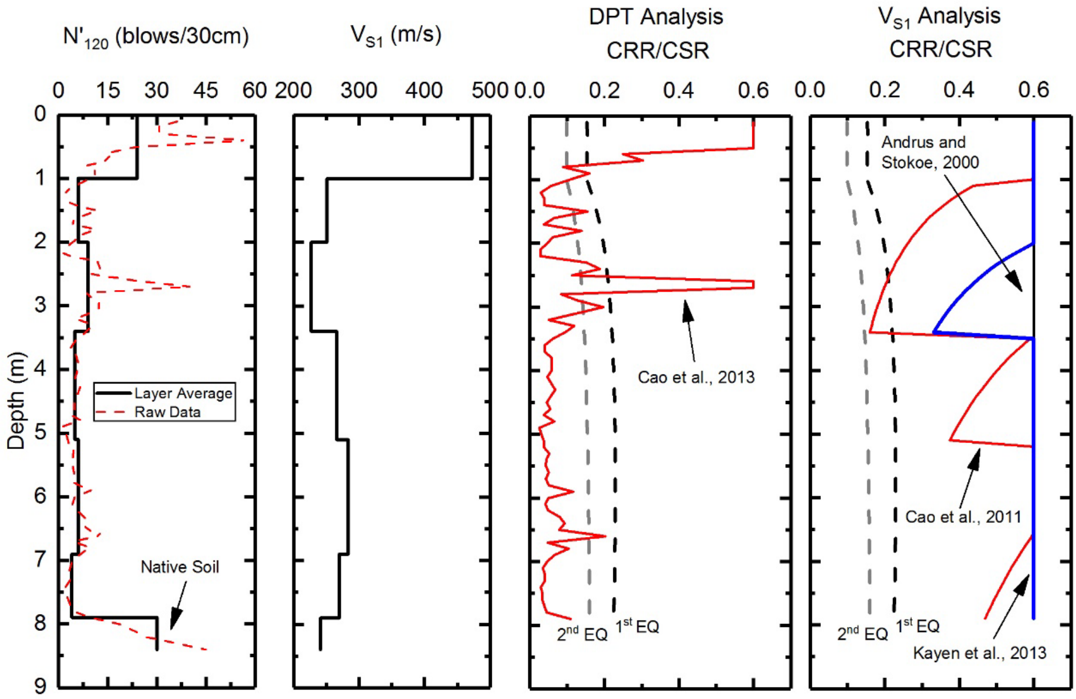

Figure 5. (a) DPT blowcount vs. depth; (b) Vs1 vs. depth, and (c) CRR/CSR ratio for DPT and (d) shear wave velocity procedures in Argostoli port.

Figure 6. (a) DPT performed in a planter box at the Lixouri Port and (b) MASW performed next to the planter box.

4 LIQUEFACTION ANALYSES

Liquefaction triggering analyses were conducted at both locations and the results are presented in this section. Liquefaction triggering analyses were conducted using the V_s-based methods proposed by Andrus and Stokoe (2000) and Kayen et al. (2013), as well as a method recently proposed by Cao et al. (2011) based on the liquefaction of gravelly soils during the 2008 Wenchuan earthquake. In addition, liquefaction triggering analyses were conducted using the DPT blowcount and the recommendations by Cao et al. (2013). It should be noted that the Kayen et al. (2013) relationship has been developed for sandy soils, but it was used in this study since it is one of few existing V_s correlations for liquefaction triggering. The Andrus and Stokoe (2000) relationship used in this study is the one developed for gravels.

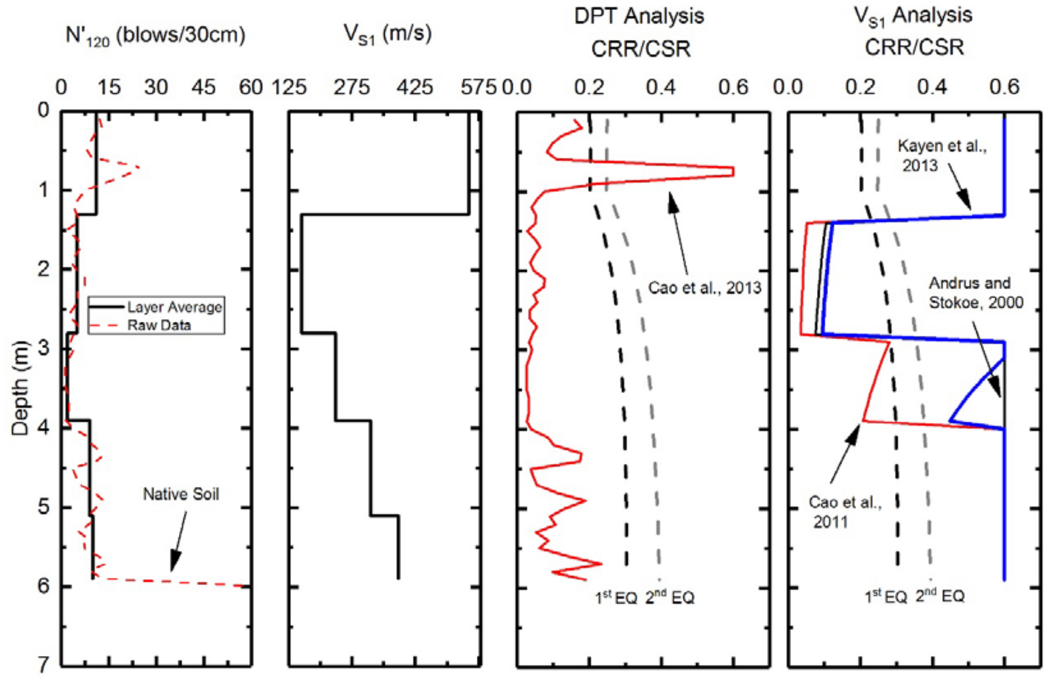

Figure 7. (a) DPT blowcount vs. depth; (b) Vs_1 vs. depth, and (c) CRR/CSR ratio for DPT and (d) shear wave velocity procedures in Lixouri port

The Cyclic Stress Ratio (CSR) was estimated using the simplified procedure described in Youd et al. (2001). Corrections for overburden stress and r_d were made as well as the Magnitude Scaling Factor (MSF). The equation used for calculating the CSR was:

$$CSR = 0.65\left(\frac{\tau_{max}}{\sigma'_{vc}}\right)/MSF \;= 0.65\left(\frac{\sigma'_{vc}}{\sigma'_{vc}}\right)\left(\frac{a_{max}}{g}\right)r_d/MSF \qquad (1)$$

where a_{max} is the maximum acceleration at the ground surface, r_d is the stress reduction coefficient, which was calculated using Equation 2 by Liao and Whitman (1986) and MSF is the Magnitude Scaling factor which was calculated using Equation 3 by Andrus and Stokoe (1997):

$$r_d = 1\text{-}0.00765^*\, z \qquad \text{for } z<9.15\text{m} \qquad (2)$$

where z is the depth in meters.

$$MSF=(M_w/7.5)^{-2.56} \qquad (3)$$

CSRs were calculated in 0.1 m increments at each test location for the 1st and 2nd Cephalonia earthquakes. The 1st earthquake had a PGA (peak ground acceleration) of 0.53g in Lixouri, while the 2nd earthquake had a PGA of 0.68g in Lixouri. In Argostoli, the 1st earthquake had a PGA of 0.40g, while the 2nd event had a PGA of 0.27g (Papathanassiou et al., 2016; Theodoulidis et al., 2016). PGA values are based on strong ground motions recordings using accelerographs installed in Argostoli (ARG2) and Lixouri (LXR1). The ARG2 accelerograph was installed by EPPO-ITSAK (Earthquake Panning and Protection Organization - Institute of Engineering Seismology and Earthquake Engineering) while the LXR1 accelerograph was installed by the National Observatory of Athens (NOA).

For the liquefaction analyses the groundwater table was assumed to be at a depth of 1 m, which is estimated based on measured elevations in the field and the sea level. The unit weight of the soil was assumed to be 20.5 kN/m^3. Liquefaction triggering was assessed at each location using both DPT and V_s relationships from Cao et al. (2011, 2013) and the V_s relationships from Andrus and Stokoe (2000) and Kayen et al. (2013). For the Cao et al. methods, the line corresponding to a 50% probability of liquefaction was used to calculate the corresponding CRR values based on either N'_{120} or V_{S1}. The CRR values based on the various relationships were then compared to the CSR values at the sites that were computed using Equation 1. The results for both the DPT and V_S analyses are shown in Figures 5 and 7.

Figure 5 shows the results of the liquefaction analysis performed for the Argostoli Port location. The plots for the DPT-based analysis and V_S-based analysis show varying results for liquefaction prediction. The DPT analysis predicts liquefaction for the 1-2 m and 3-8 m range. The V_S analysis only predicts marginal liquefaction in the 2.5-3.5 m range based on Cao et al. (2011) and no liquefaction based on both Andrus and Stokoe (2000) and Kayen et al (2013). Figure 7 shows the results of the liquefaction triggering analyses for the location at the Lixouri Port. For this location all methods predict liquefaction triggering. Specifically, the DPT method and V_S method by Cao et al. (2011, 2013) predict triggering in the 1-4 m range (with the DPT results indicating triggering possibly extending as deep as 6 m), whereas the Andrus and Stokoe (2000) and Kayen et al. (2013) relationships predict triggering in the range of 1.5-2.5 m.

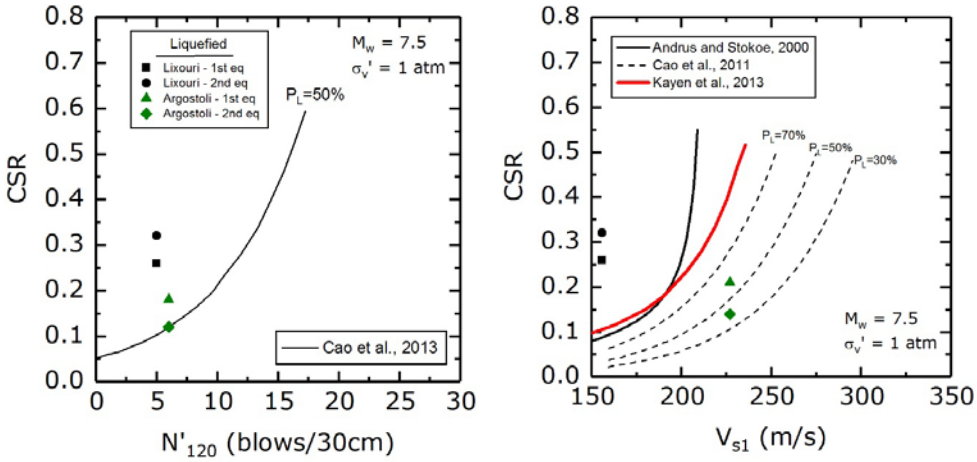

Figure 8. (a) CSR vs. DPT blowcount; (b) CSR vs. V_{S1} with data from Lixouri and Argostoli (see legend in left figure) and liquefaction triggering curves.

The critical liquefiable layers from Lixouri and Argostoli are shown as points in Figure 8 compared to DPT and Vs-based triggering curves and for both earthquakes. In terms of the DPT relationship recommended by Cao et al. (2013), it is shown that both Lixouri and Argostoli were expected to liquefy. As shown in Figure 8b, liquefaction in Lixouri was expected according to Andrus and Stokoe (2000), Cao et al. (2011) and Kayen et al. (2013). However, the observed liquefaction in Argostoli is not predicted by Andrus and Stokoe (2000) and Kayen et al. (2013) as the points fall well below (and to the right) of the liquefaction curve. The Lixouri points fall above and below the 50% probability of liquefaction curves by Cao et al. (2011). Overall, as demonstrated, liquefaction is still expected in gravelly soils with shear wave velocities as high as 226 m/sec.

5 CONCLUSIONS

The sequence of two major earthquakes with moment magnitudes of $M_w = 6.1$ and $M_w = 6.0$ that struck the island of Cephalonia in Greece on January 26th and February 3rd 2014, respectively, resulted in significant liquefaction of gravel-size fills in the ports of Argostoli and Lixouri. The geotechnical investigation presented in this paper allowed for the characterization of the gravelly fills at both ports. Specifically, the DPT was shown to be an effective field test for characterizing these challenging soil materials and consistently predicted liquefaction where it occurred in the field. The liquefaction triggering analyses performed using the V_S field data obtained with MASW testing along with existing triggering methods in the literature (i.e. Andrus and Stokoe, 2000, Kayen et al. 2013 and Cao et al. 2011 and 2013) correctly predicted that liquefaction would occur in Lixouri. However, liquefaction was not expected at the Argostoli port based on V_S measurements, highlighting the need for improved triggering correlations for gravelly soils. Fills with a

V_s as high as 226m/sec liquefied in Cephalonia.

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