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INTERACTION BETWEEN GROUNDWATER AND EARTHQUAKES: SEISMIC SITE CHARACTERIZATION AND COASTAL LIQUEFACTION POTENTIAL IN CEPHALONIA (IONIAN SEA) FROM AN UPDATED DATASET

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Abstract
The subject of this work is the investigation of the interaction between groundwater and seismic waves, resulting in liquefaction of the soil, a particularly dangerous phenomenon. Therefore, estimates of liquefaction potential can significantly contribute to the prevention of such effects and consequently to reduction of the seismic risk. The study area is Cephalonia Island, the most earthquake prone region of Europe. A dataset consisting of seismic ambient noise, accelerograms and datasheet from geotechnical boreholes, obtained after the 2014 earthquake crisis, has been analysed using a series of methodologies. Ambient noise analysis provided amplification functions, Vs30 models and synthetic time histories for numerous sites across the 2014 epicentral area. These were used for the seismic site characterization across the western part of the island and the estimation of the liquefaction potential in the coastal areas of Argostoli and Lixouri, where liquefaction phenomena were observed after the occurrence of the two strongest earthquakes in 2014. The results of the analyses are found to be compliant with the overall arrangement of the 2014 secondary earthquake effects, implying for strong site effects and interaction with the groundwater.

Introduction
Soil liquefaction, the result of groundwater and earthquakes interaction, is one of the most hazardous secondary seismic effects. Delimitation of the areas and the grade that these are prone to liquefaction are critical issues contributing to the reduction of seismic risk by predicting the possible due damage. The subject of this work is the investigation of the potential of a liquefaction phenomenon to occur in the island of Cephalonia by the interaction between groundwater and ground excitations during a strong earthquake.

Cephalonia is located in the Ionian Sea, at the northern edge of the Hellenic Arc, a region with high seismicity rates and complicated tectonics, dominated by the prominent Cephalonia Transform Fault Zone (CTFZ). The area of Cephalonia is considered to be the most seismically prone area of Europe and the Greek territory; according to the Hellenic national seismic code (EAK 2000, 2003) the region is classified to the highest seismic hazard zone (III), for which earthquake acceleration PGA = 0.36g is predicted.

On 26/01/2014 and 03/02/2014 two strong earthquakes with magnitude \( M_w 6.1 \) and \( M_w 6.0 \) hit the western part of Cephalonia (Figure 1), developing excessively high ground accelerations (e.g. Theodoulidis et al., 2015). Despite the surprisingly high PGA (Peak Ground Acceleration) recorded by local accelerometric instruments, that largely exceeded the seismic code provisions (Kassaras et al., 2017), structural damage was low thanks to the structural characteristics of the constructions of the island (Karantoni et al., 2017).
The 2014 Cephalonia main-shocks induced severe environmental effects, the main types of which were liquefaction and slope failures, widespread at the western and central part of the island (Papathanassiou et al., 2016), whereas similar phenomena at coastal areas in Cephalonia were triggered by historical earthquakes (Ambraseys, 2009). These effects, and in particular the documented liquefaction at several coastal regions caused a prominent part of the registered damage on the island due to the 2014 earthquakes. The aforementioned motivated our study towards the investigation of liquefaction potential at certain coastal sites in Cephalonia, employing a new dataset obtained in the aftermath of the 2014 earthquake series comprising geotechnical data, earthquake waveforms and free-field ambient noise measurements.

Figure 14. Map containing focal mechanisms. Black and white quadrants represent compression and dilatation, respectively. The size of the beachballs is proportional to the earthquakes magnitude. Red stars represent the two major earthquakes of 2014 (26/01/2014, $M_w 6.1$ and 03/02/2014, $M_w 6.0$).

Geotechnical Setting
Cephalonia is characterized by complex geological structure and intense morphology. The carbonate formations of the Alpine basement, which occupy a large of the island, appear largely karstified, hence leading to a limited surface hydrographic network, the main units of which are in free hydraulic communication with the sea over several kilometres. The geological structure of the island is consisted of limestones, Neogene deposits and molassic sediments, as well as Quaternary deposits (coherent and loose). Moreover, the subsoil formations are divided into three geotechnical units according to their physical and mechanical characteristics (Lekkas et al., 2001; KEDE, 2016): (a) Reclaim ground, (b) Sand and gravel and (c) Clay and marl.
Method and Data

Methods

Figure 16. Flow chart of the methodology used in this study.

The methods applied in this work and their description are outlined below:

- **The HVSR method**: Site response was assessed by applying the HVSR, ‘so-called’ Nakamura’s technique (Nakamura, 1989). The method is based on the Horizontal-to-Vertical Spectral Ratio of earthquake or ambient noise recordings (HVSR) at a site, using a three component seismograph. The method has been proven to reliably approximate soil response and because of its low cost, its easy and quick implementation, it has been
popular, widely used in substitution of costly and time consuming geophysical surveys and geotechnical boreholes. We applied the Geopsy tools (SESAME, 2004; 2005) to calculate HVSR curves.

- **The stochastic ground-motion simulation method**: The method has been proposed by Beresnev and Atkinson (1997; 1998), is broadly used to determine ground motions in areas where strong motion data are insufficient. The EXSIM algorithm (Boore, 2003) that takes into consideration the geometry and mechanics of the fault was applied.

- **Inversion of HVSR curves**: The method is based on a Monte Carlo approach for inverting HVSR curves towards retrieving 1D viscoelastic models. It was implemented by the use of the ModelHVSR algorithm (Herak, 2008).

- **Soil liquefaction potential**: In order to estimate the soil liquefaction potential we applied the method based on the Factor of Safety (FS) (e.g. Seed et al., 1985; Youd et al., 2001). For the calculation of the FS we applied the method of Idriss and Boulanger (2008), which compares the correlation of the CSR (Cyclic Stress Ratio) caused by the earthquake with the CRR (Cyclic Resistance Ratio), a measure of a soil's liquefaction resistance. The Liquefaction Potential Index (LPI), proposed by Iwasaki et al., 1978) for the representation of the liquefaction potential within a vertical multi-layer soil column, was adopted. The advantage of LPI is that it quantifies the liquefaction potential, providing a unique value for the whole soil column, instead of many factors of safety (one for each layer) and consequently calculates the spatial probability of liquefaction (Papathanassiou, 2008). To assess the liquefaction potential we used the LiqIT software (GeoLogismiki, 2006), which enables LPI estimation from the combination of observations (i.e. SPT, CPT and Vs).

**Data**

Seismic ambient noise data were recorded between 13th May and 16th May 2014, in 80 locations of Cephalonia, in Paliki and the western part of Argostoli peninsulas during a field work conducted by the Seismological Laboratory of the National and Kapodistrian University of Athens (Kassaras et al., 2017). For the approximation of the geotechnical conditions prevailing on the island we used a large number of geotechnical borehole data, provided by the Department of Geotechnical Engineering and Geology of KEDE (KEDE, 2016) for the purposes of this work. Part of the data is the outcome of recent boreholes conducted after the 2014 seismic crisis. The geotechnical profile of the study area is described taking into account the geological map of Cephalonia (IGME, scale 1: 50,000), the neotectonic map of Cephalonia-Ithaca (National and Kapodistrian University of Athens, scale 1: 100,000), the published work of Lekkas et al. (2001) and the recent geotechnical research of KEDE (2016). Strong motion data regarding the two mainshocks of 26th January and 3rd February 2014 were considered after Theodoulidis et al. (2015).
Results

Stochastic ground motion simulation and soil characterization

The site conditions were approximated by the peak frequencies and the amplification ratios of the HVSR curves derived by the analysis of the ambient noise recording. Strong ground motion was simulated at 51 sites in western Cephalonia for two earthquake scenarios using the stochastic EXSIM algorithm (Boore, 2003) in terms of Peak Ground Acceleration (PGA). The earthquake scenarios concern the January and February 2014 Cephalonia mainshocks, while HVSR curves were employed as the site amplification function in the stochastic model. The results of the simulation, presented in Figure 5, are consistent with the effects observed during the two earthquakes (e.g., Kassaras et al., 2017).

We determined the velocity structure of the subsurface by fitting the observed HVSR at each site obtained from microtremors with a theoretical model. In this study, we considered the Model HVSR code (Herak, 2008) which is based on the hypothesis that ambient noise is composed of body-waves. The routine randomly perturbs an initial visco-elastic model within a user defined vector length, visco-elastic parameters and number of iterations. Each layer is defined by thickness, shear wave velocity (Vs), density and the frequency dependent Q-factor.
Thereafter, soils were classified in accordance to EC-8 (Eurocode 8, 2004) using the Vs30 approach, i.e. the average Vs in the upper 30 m of the soil column (Figure 6). Must be noted that the Vs30 approach does not take into account any small layers and that could affect the results.

![Soil Class](image)

**Figure 19. Soil class to each position according to Eurocode 8.**

**Liquefaction Potential**

Liquefaction phenomena during the 2014 earthquakes were mainly triggered in reclaimed grounds at the waterfront areas of Argostoli and Lixouri, inducing structural damages to quays, sidewalks and piers (Papathanassiou et al., 2016). Based on the values obtained by borehole SPT measurements, the liquefaction potential of the soil column up to 20 m from the surface was determined at the coastal areas of Argostoli and Lixouri by applying the LiqIT software (GeoLogismiki, 2006) (Figure 7). Results are assorted into two categories. The calculations for the first category are based on the recorded PGA values from permanent and temporary accelerometers during the 2014 earthquakes. For the second category, we used the simulated PGA values in the neighbourhood of boreholes for which SPT data were available. Comparing the results of these two categories, we conclude that an increase of PGA leads to a corresponding increase of CSR and consequently to an increased liquefaction potential. This is expected, as the CSR index depends on the maximum acceleration of the soil. Comparing thus the results of the two cases we can detect which layers will be liquefied in case of a larger earthquake in the area that will produce higher PGA values.
Moreover, following a similar procedure we investigate the soil liquefaction susceptibility with respect to the depth of the Ground Water Table (GWT) in the areas of Argostoli and Lixouri. Figure 8 presents the locations where changes in the liquefaction potential are observed by varying the depth of the GWT. Red and blue dots in Figure 8 denote positions that a rise of the GWT level produces increase of liquefaction potential and a decrease of the level of the GWT reduces the liquefaction potential, respectively; yellow dots indicate locations where decrease of the GWT level ceases the liquefaction potential, while increase causes liquefaction to more layers than before. In conclusion, apart from the PGA, the level of the GWT, which is a typical seasonal effect, also affects the liquefaction potential.
Figure 21. Variation of liquefaction potential, based on the Ground Water Table (GWT): A) $M_w = 6.1$ and PGA = 0.39 g (Argostoli) and B) $M_w = 6.0$ and PGA = 0.26 g (Argostoli); $M_w = 5.9$ and PGA = 0.68 g (Lixouri).

Finally, Figure 9 presents the observed liquefaction phenomena during the 2014 earthquakes which are consistent with the results of the study, confirming the validity of the employed data and the applied methods.

Figure 22. Liquefaction potential for each of our six scenarios and the actual liquefaction phenomena of 2014 earthquakes.

**Conclusion**

The most important outcomes are summarized as following:

- Most of the soil columns were classified as B or C category according to the EC8, referring to healthy conditions, however several of them are found to be prone to liquefaction; this is due to the occurrence of poor health layer(s) in the column susceptible to liquefaction.
• Variations of the PGA affect the soil liquefaction potential, since increase of PGA leads to increase of the CSR of the layer.
• The effect of GWT level variation is important, in terms of its interaction with susceptible layers existing within the soil column.
• The observed liquefaction phenomena during the 2014 earthquakes are consistent with the results of the study (Figure 9), confirming the validity of the employed data and the applied methods.

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