SCENARIO LIQUEFACTION HAZARD MAP OF THE GULF OF CORINTH

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ABSTRACT

The occurrence of liquefaction phenomena and the generation of relative failures are crucial issues that should be taken into account regarding the safety of manmade environment (e.g. structures, lifelines). The earthquakes of Christchurch 2011 (New Zealand) and Emilia Romagna 2012 (northern Italy) demonstrated the severity and the extent of the failures than can be caused by the triggering of liquefaction. Taken into account the seismotectonic regime and the historical seismicity of the Gulf of Corinth, it is clear that the evaluation of the liquefaction hazard and the computation of the probability of surface manifestations, in order to minimize or avoid the consequences generated by the triggering of liquefaction, are very important.

One of the most well documented earthquakes that occurred in this area is the 1861 M6.7 earthquake. We perform forward calculations to simulate the generated ground motion of this event and we use the estimated values of acceleration to compute the liquefaction hazard within the affected by this earthquake coastal area of the Gulf of Corinth. For the latter we apply a new approach that is based on complementary cumulative frequency distributions of the liquefaction potential index (LPI) for surficial geologic units. A map of liquefaction probabilities for the Gulf of Corinth, for a 1861 event scenario, is compiled. The computed value of probability exceeds the 50% at the epicentral area of the 1861 event and is in agreement with the reports of extensive liquefaction phenomena. For such a scenario, liquefaction phenomena are expected to be triggered (calculated probabilities varies from 5 to 50 %) along the coastal areas of the northern and southern part of the Gulf of Corinth.

INTRODUCTION

The Gulf of Corinth is among the best studied regions in Greece. It is an asymmetric graben extending for more than 100 km in length, bounded by a number of segmented normal faults along its southern and northern side. The extension rate in the Gulf of Corinth is the fastest in Greece and is about 14 mm/yr in its western part and 8 mm/yr in its eastern part. The rich record of seismic activity, with frequent strong (Mw>6) events reflects the rapid extension rates. One of the most destructive and well-reported events is the 26 December 1861 M6.4-6.7 Aigio earthquake. This event induced widespread surface liquefaction such as lateral spreading phenomena and sand craters at the low lying coastal plain of the mountain streams of Selinountas, Keranitis, Vuraikos and Puntas.

The aim of this research is twofold: simulate the ground motion generated by the earthquake and develop a map showing the probability of surface manifestations of liquefaction. To simulate the expected ground motions for this event, the source characteristics are postulated on the basis of the characteristics of the macroseismic observations and the present knowledge on the seismotectonics of the region, as well as published attenuation relationships. Regarding the probability of the surface manifestations of liquefaction, it is achieved by applying a methodology, widely used in USA, which is based on complementary cumulative frequency distributions of the liquefaction potential index

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(LPI) for surficial geologic units. In addition, the liquefaction susceptibility of geological units was assessed using data provided by the geological map published by the Institute of Geology and Mineral Exploration of Greece and the liquefaction-induced surface manifestations provided by the web site of Database of Historical Liquefaction Occurrences (DALO) in the broader Aegean region. This information was used as baseline layer for mapping Quaternary sediments and past liquefaction sites, respectively.

LIQUEFACTION CASE HISTORIES

Liquefaction is known to occur repeatedly in the same site, thus maps showing the localities of past liquefaction may be considered as a preliminary tool for the delineation of likely to liquefaction zones in future earthquakes (Youd, 1984). A recently characteristic example of re-liquefaction is the Cephalonia 2014 earthquakes that triggered repeated liquefaction in the same sites in one-week period (Valkaniotis et al., 2014)

Regarding the study area, liquefaction phenomena were triggered by 13 earthquakes at several locations, as it is described by Papathanassiou et al. (2005). Most of these sites are located at the coastal area close to the town of Aigio and to the east of the Gulf of Corinth close to the city of Korinthos, while few sites were also distributed at the northern part of Gulf. In particular, information regarding historical liquefaction occurrences including a brief description of the liquefaction-induced failures was obtained by the database DALO v1.0 developed by Papathanassiou and Pavlides (2011).

The most characteristic example, and one of the oldest reports describing earthquake-induced ground deformation, is provided by Strabo and refers to the 373 B.C. Eliki earthquake that caused the sunk of the towns of Eliki and Voura, and the occurrence of a sea-wave that destroyed ten boats. In addition, a detailed description of liquefaction manifestations generated by the 1861 Aigio earthquake and a map of their distribution was provided by Schmidt (1867). These two reports described liquefaction manifestations that were observed at the central and western part of the Gulf of Corinth, close to the town of Aigio. Furthermore, as it is shown in figure 1, liquefaction phenomena were also triggered at the eastern part of the Gulf, by the event of 1928, close to the city of Corinth and have been reported by Georgalas (1928). More recently, the 2008 NW Peloponnesus earthquake triggered liquefaction-induced ground disruption in the coastal area of Kato Achaia, located at the western part of the Gulf of Corinth (Pavlides et al., 2013).

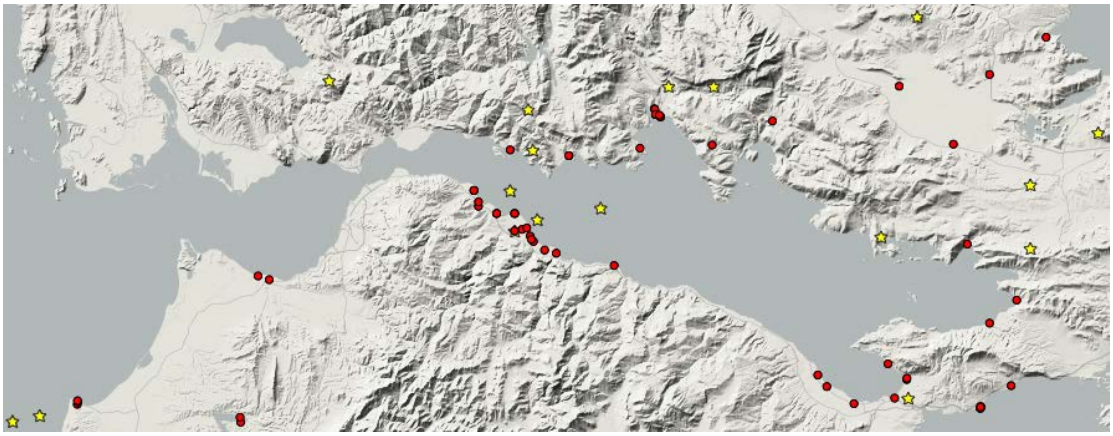

Figure 1. Map showing the spatial distribution of historical liquefaction occurrences (circles) at the Gulf of Corinth and the epicentres of the triggering earthquake (star). Image from http://gpapatha.weebly.com/DALO.html

ASSESING LIQUEFACTION SUSCEPTIBILITY

The assessment of liquefaction susceptibility of sediments is considered as the first step towards the evaluation of liquefaction hazard. The susceptibility to liquefaction of a geological unit can be evaluated based on its depositional environment; the depositional process affect the liquefaction susceptibility of sediments since fine and coarse grained soils sorted by fluvial or wave actions are more susceptible than unsorted sediments (Youd, 1998). In particular, liquefaction susceptibility can be defined based on small scale information and/or data provided by in-situ tests. The former assessment is achieved by collecting data regarding the depositional environment, the age of sediments, the value of peak ground acceleration and the depth of ground water table and the latter is based on quantitative data processing of a soil formation such as grain-size analyses and evaluation of Atterberg limits.

The most applied methodologies regarding the regional scale assessment of liquefaction susceptibility have been proposed by Youd and Perkins (1978), Wakamatsu (1992), the California Department of Conservation, Division of Mines and Geology (CDMG, 1999) and recently by Witter et al. (2006). The selection of one of the above approaches depends on the amount and type of collected data and mainly depends on the scale of geological maps. In case of having a simplified geological map at large scale, it is proposed to use the CDMG (1999) since the only geological-based criterion for the assessment of liquefaction susceptibility deals with the age of deposits.

In this study, we were able to apply the Youd and Perkins (1978) and Wakamatsu (1992) methods because we could use data provided by geological maps in 1:50.000 scale compiled by IGME (Institute of Geology and Mineral Exploration of Greece) where information regarding age and depositional process of sediments has been defined (fig. 2). These data were used as a base layer for digitizing the spatial distribution of the geological units.

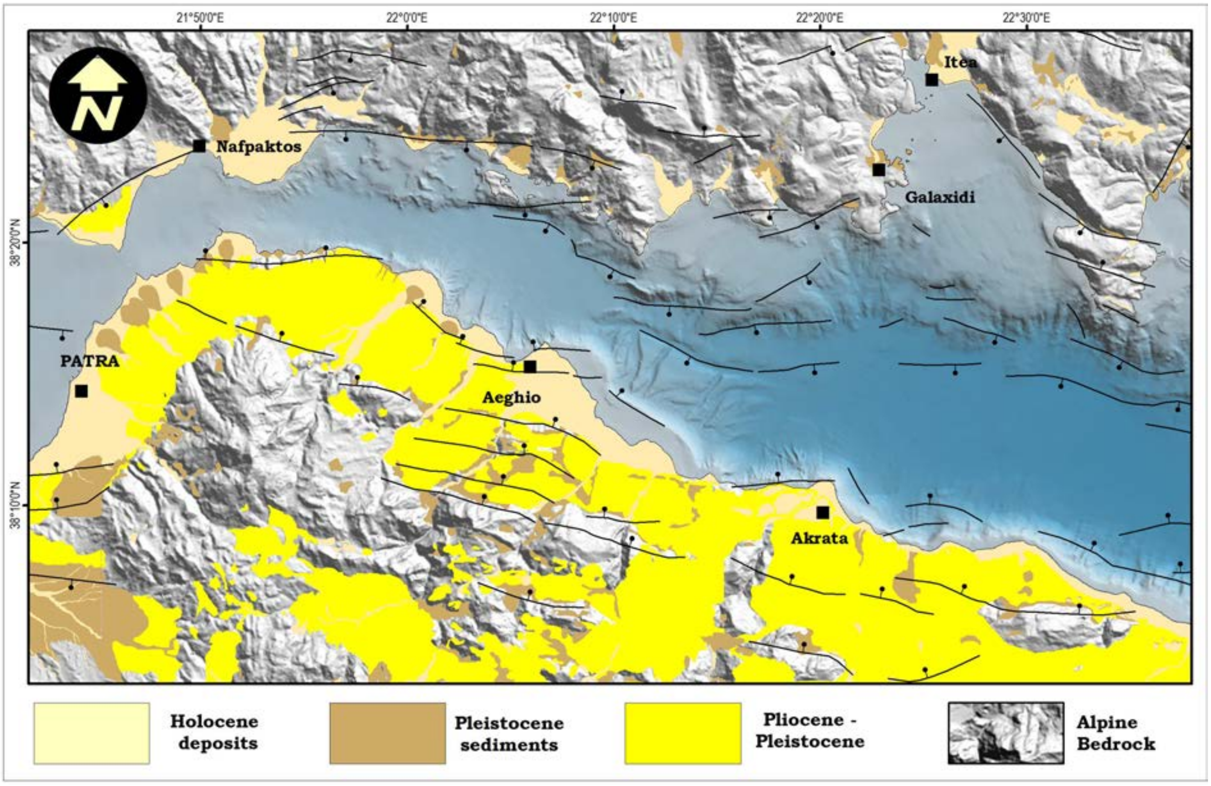

Figure 2. Simplified geological map of the Gulf of Corinth

The basic concept of the former approach is based on the statement that the younger, looser and more segregated the deposit, the greater the susceptibility; the liquefaction susceptibility can be achieved by classifying the geological units based on depositional criteria. Moreover, they defined as very low liquefaction susceptibility the Pre-Pleistocene sediments. Thus, in order to apply the criteria proposed by Youd and Perkins (1978), we initially grouped the Quaternary sediments, since pre-Pleistocene deposits are classified as very low susceptibility units, and then we further analyzed and assessed their liquefaction susceptibility based on the proposed by the researchers' classification. The outcome of this approach is shown in figure 3.

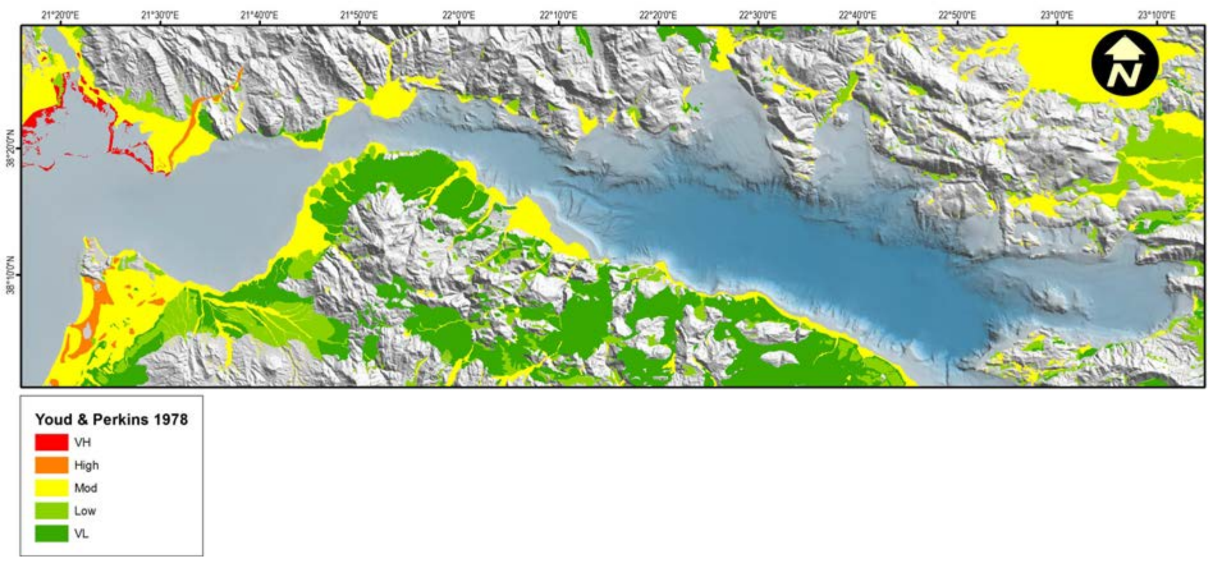

Figure 3. Liquefaction susceptibility map compiled based on Youd and Perkins (1978) classification. VH very high, Mod Moderate, VL very low

The second approach was proposed by Wakamatsu (1992) and geomorphological criteria are taken into account for the classification of sedimentary deposits. The proposed three categories of liquefaction susceptibility, under the ground motion at the MMS intensity VIII, are likely, possible and not likely. The zones that are classified as “not likely” define areas where liquefaction-induced failures are not expected. On the contrary, zones where geomorphological units such as natural levee, former river channel, sandy dry river channel and artificial fill were mapped, are classified as the highest level of liquefaction susceptibility, i.e. liquefaction likely (TC4, 1999). At these areas, further investigation using in-situ test and quantitative parameters of subsoil layers must be performed (fig. 4).

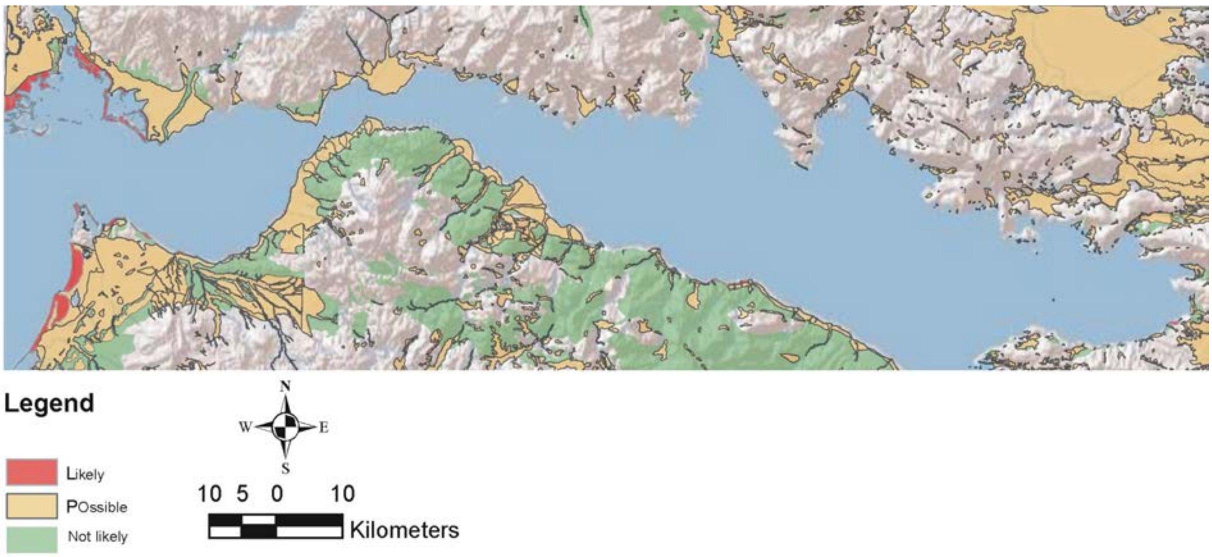

Figure 4. Liquefaction susceptibility map compiled based on geomorphological criteria proposed by Wakamatsu (1992).

The evaluation of the depth of the groundwater in both approaches is a crucial issue for the estimation of liquefaction potential since soil layer can be liquefied only when it is saturated. In this study, we assumed that the groundwater table depth is less than 3 meters thus; the degree of liquefaction susceptibility is characterized as high according to Youd and Perkins (1978). This assumption was based on the fact that the groundwater level at many sites fluctuates seasonally and consequently; unsaturated deposits during one season can become saturated the next one and capable for liquefaction. Therefore, it was decided to be conservative regarding the groundwater table at this scale liquefaction susceptibility map. Areas that are characterized as liquefiable should be further investigated in detail using groundwater measurements.

STRONG GROUND MOTION SIMULATION OF THE 1861 AIGIO EARTHQUAKE

The 1861 Aigio earthquake is one of the most well reported event of 19th century. The M 6.7 magnitude earthquake occurred at 06:30 UTC and strongly affected a narrow zone, parallel to the shore of the Gulf of Corinth, between the Meganista river in the west and Erasino river in the east. Few minutes later, a second strong shock followed inducing secondary effects (Ambraseys and Jackson, 1997). A surface expression of a 13 km normal fault has been reported for this event, having an E-W strike, and extending from Gardena village in the west up to Erasinos river (Papazachos and Papazachou, 2003). A detailed description and map of the earthquake-induced geological failures is provided by Schmidt (1867).

Regarding the liquefaction manifestations, Ambraseys and Jackson (1997) stated that at the low lying coastal plain of the mountain streams of Selinountas, Keranitis, Vuraikos and Puntas liquefaction-induced ground deformations such as lateral spreading phenomena and sand craters with diameter up to 2 meters and one meter high were observed. In particular, from Temeni to Diakoptitika, a long strip of the coast slumped into the sea and the ground was cracked inland all the way to the foot of the hills where the whole plain between the streams of Meganitis and Puntas sunk and settled. In addition, at the port of Itea, north part of the Gulf, the ground in places liquefied. Furthermore, this event generated mud volcano sandy material a few minutes after the earthquake and continued to do so for 15 minutes after the shock in the village of Kalamitsi, 85 km away from the epicentre, a disproportionate distance in relation to the earthquake magnitude.

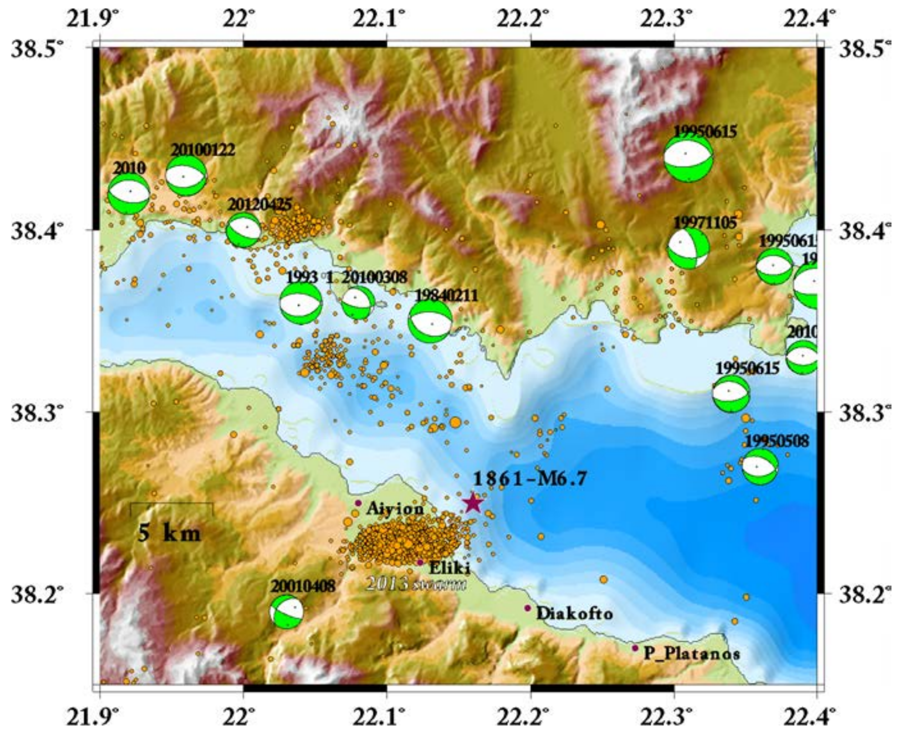

Figure 5. The postulated epicenter of the 1861 earthquake offshore in the Gulf of Corinth. The focal mechanisms of modern strong (M>4.0) earthquakes are plotted with the dates shown next to beach-balls. The seismicity shown between Aigio and Eliki corresponds to the June-Sept 2013 swarm which burst in the region.

The epicentre of the 1861 earthquake is postulated to be offshore in the Gulf of Corinth (Papazachos and Papazachou, 2003). Figure 5 shows instrumental seismicity in the broader region as well as the focal mechanisms of the strongest events (Kiratzi and Louvari, 2003). Earthquake mechanisms indicate that the dominant mode of the deformation is related to normal faulting along mainly E-W striking planes. Previous studies support the existence of steep normal faults bounding the south coast of the Gulf of Corinth, which flatten at depth to form a low-angle detachment fault (Rigo et al., 1999). A noticeable feature of the seismicity is the June-September 2013 swarm, which occurred between the towns of Aigio and Eliki. The large number of events included in this swarm and the frequent occurrence of multiplets is significant for the study of Eliki fault, as this swarm is clearly related to it. Earthquake swarms have occurred in this region in the past, as for example the swarm that occurred near Agios Ioannis in April 2001 (focal mechanism of 20100408 M4.3, in Fig. 5), between the Pyrgaki and Keritinis faults. These two swarms are mainly connected with newly formed secondary structures.

To calculate the distribution of ground accelerations in the broader epicentral region of the 1861 earthquake, forward calculations were performed (Kaverina and Dreger, 2000) and the results were also compared to the ground motions expected from empirical scaling relations applicable to the Aegean region (Skarlatoudis et al. 2007). For this processing we assumed that the 1861 earthquake was the result of the rupture of a normal fault which strikes 277º, dips 50º to the north and has a rake angle equal to -103º. This assumption is based on the focal mechanisms of the modern events, which were all determined by waveform modelling. The assumed focal mechanism is in accordance with the observation from geomorphology (e.g. De Martini et al. 2004; Stewart, 1996). The forward calculations were performed at phantom points over a grid wide enough to cover the broader region. The distribution of the peak ground acceleration (in %g), shown in Figure 6, shows that the region most affected is mainly off-shore and the ground motions on-land clearly depict the narrow zone that most damage and other phenomena were observed.

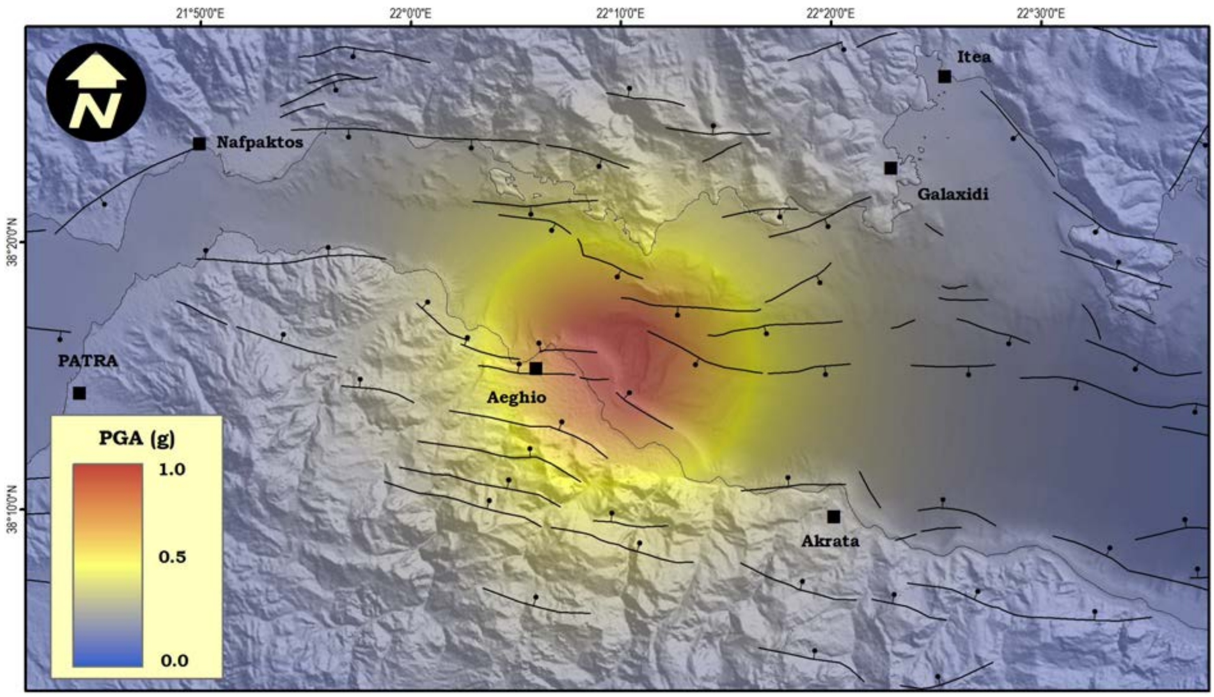

Figure 6. Simulation of the spatial distribution of the PGA generated by the 1861 event

PREDICTING THE PROBABILITY OF LIQUEFACTION HAZARD AT REGIONAL SCALE

In order to compute the liquefaction hazard of a soil element, quantitative analysis should take place. Initially, the factor of safety against liquefaction of a soil layer should be computed using the most-applied approach, *the simplified procedure* proposed by Seed and Idriss (1985) and modified by several researchers up to date. Nowadays, we could state that most of the studies, dealing with liquefaction, use either the proposed by Seed et al. (2003) or Boulanger and Idriss (2004) approaches, respectively. However, having applied these procedures we can only compute the behaviour of a single soil layer or stratum. In order to evaluate the liquefaction potential on the top of the soil column, at the surface, we have to apply another approach, proposed by Iwasaki (1978). We can compute the liquefaction potential index, a single value that characterizes the performance of the whole soil column that can be employed in GIS environment and thus, develop urban scale maps. The basic requirement for applying the above methods is to collect data provided by in-situ tests (SPT or CPT). Therefore, it is mainly applied on urban-scale maps and not in regional one since it is almost impossible to find reliable data for the latter.

Therefore, regional scale liquefaction studies were mainly focused on the assessment of liquefaction susceptibility using well-known approaches e.g. Youd and Perkins (1978), since a method correlating the liquefaction susceptibility with the magnitude and PGA in a quantitative manner was not available. Recently, Holzer et al. (2011) proposed a method for computing the probability of liquefaction occurrences on a regional scale and particularly, a method for developing liquefaction probability curves that would enable surficial geologic maps to be transformed into liquefaction hazard maps. According to Holzer et al. (2011), the probability of surface manifestation of liquefaction for each surficial geologic unit is computed for a specific earthquake magnitude, PGA and water table conditions. The proposed methodology was developed using a scenario of earthquake magnitude M 7, however it can also be used for other magnitudes by scaling the seismic demand by the magnitude scaling factor (MSF) as it was defined by Youd et al. (2001). The probability of liquefaction surface evidence (p) is computed using the regression (1):

$$p=\frac{a}{1+\left(\frac{\frac{PGA}{MSF}}{b}\right)^{c}} \qquad (1)$$

where PGA: peak ground acceleration, a, b and c : constants for geological units, MSF: magnitude scaling factor

COMPUTATION OF LIQUEFACTION HAZARD AT THE GULF OF CORINTH

We decided to apply this methodology for the first time in Greece and particularly in the area of Gulf of Corinth where liquefaction surface evidences are commonly triggered by earthquakes and reliable geological maps of 1:50000 exist. Initially, the geological maps were digitized on ArcGIS and the surface geologic units were classified based on the categories proposed by Holzer et al. (2011). For each geologic unit, constants a, b and c were assigned and relevant raster files were produced. It should be pointed out that the pre-Holocene sediments were not taken into account in this evaluation of liquefaction probability.

The same procedure, creation of the relevant raster file, was followed for the distribution of ground motion using the simulated values of acceleration for the 1861 seismic scenario while the water table depth was assigned as 1.5 m following the recommendation of Holzer et al (2011).

As an outcome of this study, a map of liquefaction probabilities for the Gulf of Corinth for a scenario using the seismic parameters of 1861 event is compiled. As it is shown in figure 7, the computed value of probability exceeds the 50% at the epicentral area of the 1861 event and is in agreement with the report of Schmidt (1867) describing extensive liquefaction phenomena. In addition, at the coastal area both at the northern and southern part of the Gulf of Corinth, liquefaction phenomena may be triggered since the calculated probabilities varied from 5 to 50 %.

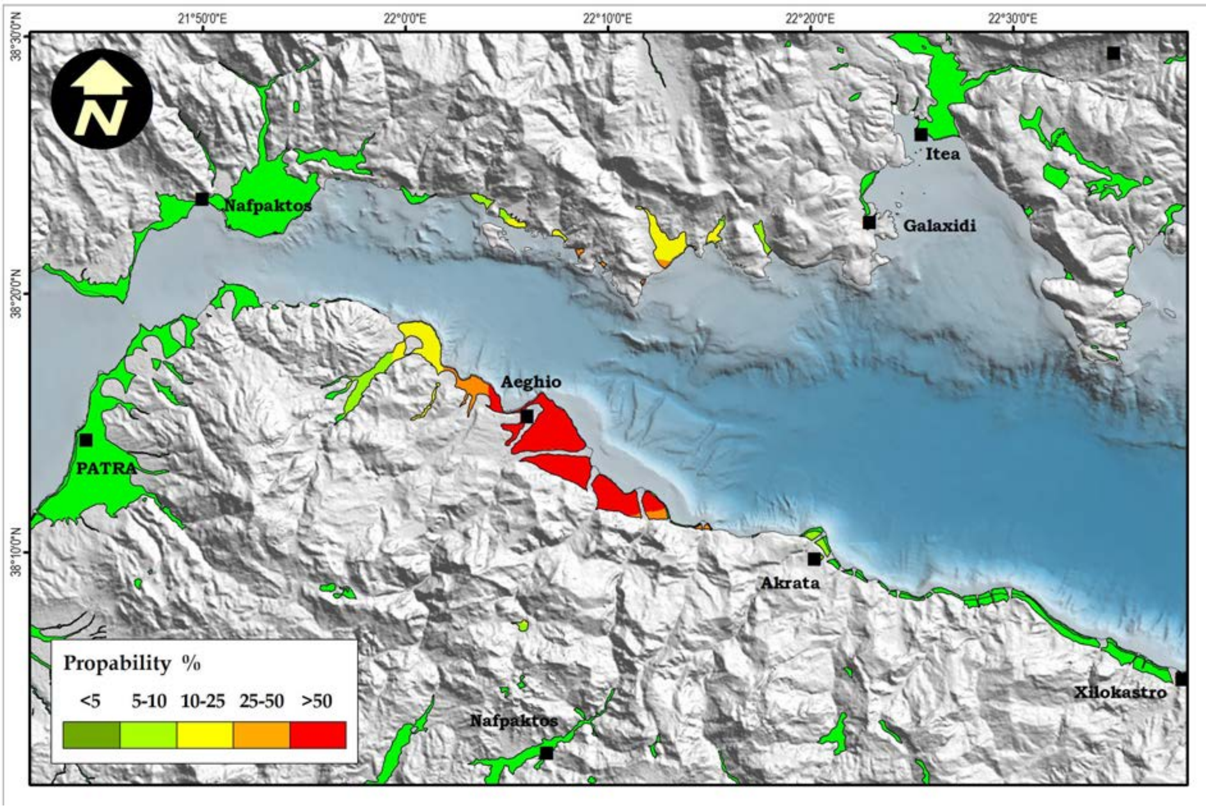

Figure 7. Map of liquefaction probabilities for the Gulf of Corinth for a scenario using the seismic parameters of 1861 event (M 6.7) and a shallow water table (depth 1,5 m)

AKNOWLEDGEMENTS

This research has been co-financed by the European Union (European Social Fund – ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF) - Research Funding Program: Thales “Investing in knowledge society through the European Social Fund”.

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