27 May 2010, 4:30 pm - 6:20 pm

Assessment of Liquefaction Susceptibility of Geological Units in the Area of Gulf of Corinth, Greece

George Papathanassiou
Aristotle University of Thessaloniki, Greece

Sotiris Valkaniotis
Aristotle University of Thessaloniki, Greece

Spyros Pavlides
Aristotle University of Thessaloniki, Greece

Fifth International Conference on
Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics
and Symposium in Honor of Professor I.M. Idriss
May 24-29, 2010 • San Diego, California

ASSESMENT OF LIQUEFACTION SUSCEPTIBILITY OF GEOLOGICAL UNITS IN THE AREA OF GULF OF CORINTH, GREECE

Papathanassiou George
Aristotle University of Thessaloniki
Department of Geology
54124 – Greece

Valkaniotis Sotiris, Pavlides Spyros
Aristotle University of Thessaloniki
Department of Geology
54124 – Greece

ABSTRACT

The coastal area of Gulf of Corinth is characterized as medium to high seismicity zone since devastating earthquakes occurred during a 2500 years period. One of the most characteristic events is the 373 B.C. Eliki earthquake that triggered severe secondary effects including soil liquefaction and large scale landslides. The basic aim of this paper is the compilation of a map regarding the liquefaction susceptibility in the coastal area of Gulf of Corinth, Central Greece. In order to achieve this, we used data regarding the age and depositional process of sediments the value of peak ground acceleration (PGA) and the occurrence of historical liquefaction manifestation within the area. In particular, surficial geologic maps at 1:50.000 scale, published by the Institute of Geology and Mineral Exploration of Greece, were used as baseline layer for mapping Quaternary sediments and past liquefaction sites were delineated, based on information provided by the web site of Database of Historical Liquefaction Occurrences in the broader Aegean region, DALO (http://users.auth.gr/gpapatha/dalo.htm).

INTRODUCTION

Liquefaction is the transformation of saturated granular material from a solid state to a liquid state as a consequence of increased pore pressures that reduce the effective strength of the material (Youd, 1973). The liquefaction of a subsoil layer may induced surface disruption such as ground settlements, sand boils and lateral spreading and lead to structural damages at buildings, pipelines, bridges etc.

The generation of liquefaction manifestations is influenced by many factors such as the depositional environment of the geological unit, the depth of the water table, the density of the soil layer etc. These parameters can be evaluated based on in-situ tests and surficial geological mapping, realized by engineers and geologists, and are taken place in order to assess the liquefaction susceptibility and the potential to liquefaction in an area. The outcome of these studies can be used for mitigating the soil liquefaction-induced failures.

Areas susceptible to liquefaction can be identified through detailed geologic, geomorphic and hydrologic mapping (Witter et al. 2006) while the liquefaction potential is evaluated based on data regarding the susceptibility to liquefaction of the soil layer and the expected value of ground motion triggered by the earthquake.

Liquefaction susceptibility maps have been compiled for several regions and countries including USA, Japan, Greece, Iran, Turkey etc. In particular, maps were developed for the San Francisco Bay region (Youd and Perkins, 1987; Knudsen and others, 1997; Sowers et al., 1998; Knudsen et al., 2000; Holzer et al., 2002), for Los Angeles urban area (Tinsley et al. 1985) and for Greece (Papathanassiou et al., 2009). These maps do not predict liquefaction-related ground failures, although ground failures may accompany liquefaction and are more likely to occur in areas with higher liquefaction susceptibility (Tinsley et al., 1985)

The goal of this study was the evaluation of liquefaction susceptibility of sediments in the area of Gulf of Corinth and the compilation of a relative map. This map is based on the 1:50,000-scale mapping of geological units, historical surface evidences of liquefaction phenomena, and seismotectonic data. The study area includes the coastal zone of the Gulf of Corinth (figure 1), an intra-continental rift where the geodetically extension is estimated as high as 1 cm/yr. The main active and possibly active faults are situated at the southern Corinthian gulf with length up to 40 km. Within the study area large earthquakes occurred and triggered severe primary and secondary effects including liquefaction-induced ground failures. The resultant map can be used only as a screening guide for planning purposes since for the assessment of the liquefaction potential of the area, site-specific studies including in-situ tests and geotechnical test in the laboratory are required.

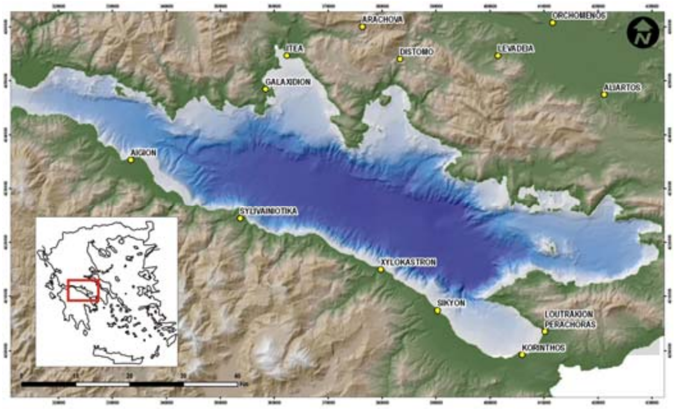

Fig. 1. Map showing the area of the Gulf of Corinth

The map that is presented in this article has been compiled in the frame of a project regarding the evaluation of liquefaction susceptibility of deposits in Greece. This project has been started five years ago and is taken place at Aristotle University of Thessaloniki, Department of Geology. Its primary goal, achieved few years ago, was the collection of data regarding historical liquefaction occurrences and the compilation of a map showing the sites where liquefaction-induced failures were reported (Papathanassiou et al. 2005). The second goal of the project was the evaluation of the liquefaction susceptibility of deposits in Greece (scale 1:500.000) that was accomplished last year and presented by Papathananassiou et al. (2009).

The following years is programmed the assesment of the liquefaction susceptibility of the geological units on a larger scale (1:50.000) by dividing Greece in several zones.

SEISMOTECTONIC OF THE AREA

The Gulf of Corinth is an excellent example of back-arc extension on continental crust, where enough surface, geological, seismological, geophysical as well as geodetic data and results, highlight the rapid extension of the region. It is a 130 km long intra-continental rift within the south Aegean subduction - back arc system. The WNW-ESE-trending Gulf of Corinth separates the northern coast of the Peloponnese from mainland Greece. To the east it is bounded by the Isthmus of Corinth through which the Corinth Canal passes into the Saronic Gulf, while the deepest point of the gulf bottom is 900m. This has resulted in a NNW-SSE and NW-SE structural grain to the area which may have had some control on the later extensional deformation (Jackson and McKenzie 1988, Skourlis and Doutsos 2003, Hinsbergen 2004). To the WNW the Gulf of Corinth narrows considerably in the region of Rio-Antirio where it is linked with its western continuation, the Gulf of Patras. In the northern part of Gulf of Corinth Rift are situated the mountain chains of Elikonas, Parnassos – Giona and part of Pindos. The older than 5 Myr Gulf of Corinth rift is a 100 - 300 km, high- strain band in central Greece that experiences N-S extension (McKenzie 1972, 1978, Le-Pichon and Angelier 1979, Angelier et al. 1982, Doutsos et al. 1988, Roberts and Jackson 1991, Armijo et al. 1996) at rates of 5-15 mm/year (Le-Pichon et al. 1995, Kahle et al. 2000, McClusky et al. 2000, Jenny et al. 2004) and a geodetically estimated extension as high as 1 cm/yr (Billiris et al., 1991).

Onshore and offshore neotectonic surveys and earthquake focal mechanism studies indicate that the Gulf of Corinth is currently undergoing approximately north-south extension. Deformation and rift uplift in the current extensional regime is accommodated by generally W-E trending normal faults (figure 2) in an en echelon arrangement (Sebrier 1977, Doutsos et al. 1988, Doutsos and Piper 1990, Poulimenos 1991, Doutsos and Poulimenos 1992, Roberts and Koukouvelas 1996, Morreti et al. 2003, Ghizzeti and Venzzani 2005, Tsodoulos et al. 2008, Zygouri et al. 2008, Valkaniotis 2009).

The typical length faults range 10 to 40 km long (Jackson et al., 1982; Doutsos and Poulimenos 1992; Roberts and Koukouvelas 1996). The main active and possibly active faults are situated at the southern Corinthian gulf (Northern Peloponnese), north dipping at high (60-80^o, rarely) to moderate angles (55^0). Fault segmentation along all faults of the Corinth gulf indicates that this is the dominant geometry in the area. The rift was developed in two phases (Ori 1989; Doutsos and Piper 1990). During the first stage the basin was shallow, controlled by listric faults, filled with shallow-fresh water sediments (1000 to 2000m). The second phase is characterized by deep-sea sedimentation, Gilbert-type deltas (1200m) and related to second generation high-angle normal faults. These results have been based only on the detailed study of sediments, while the fault geometry is a hypothesis on the basis of Jackson and McKenzie's (1983) suggestion for the geometrical evolution of normal fault systems.

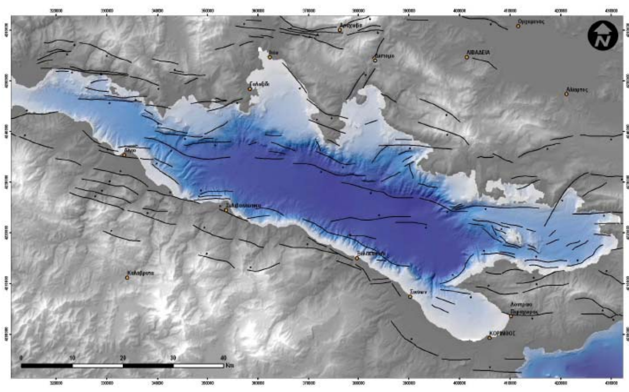

Fig. 2. Main neotectonic and active faults in the Gulf of Corinth area. (Valkaniotis, 2009).

Active deformation in the area is shown by neotectonic, morphotectonic features, and palaeoseismological investigations and by historical and instrumental earthquakes. The oldest known seismic event is the well described 373 BC earthquake by many philosophers, geographers and mathematicians, among them Aristotle and Strabo, but it is not documented until now neither by archaeological nor by geological data (Soter and Katsonopoulou 1999; Koukouvelas et al., 2001). Other known strong earthquake's of the area are the 23 AD, 1402, 1748, 1817,1861, 1888, 1889, 1965 (Ms 6.4), 1995 (M 6.3) among many other moderate and strong events.

METHODOLOGY

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 based on detailed information of a soil formation such as the grain-size characteristics and the values of Atterberg limits.

In particular, regarding the small scale approach, Youd and Perkins (1978) stated that the younger, looser and more segregated the deposit, the greater the suscpetibility and proposed the evaluation of liquefaction susceptibility by classifying the geological units based on the criteria listed on table. Moreover, they defined as very low liquefaction susceptibility the Pre-Pleistocene sediments.

Furthermore, Wakamatsu (1992) classified sedimentary deposits using geomorphological criteria in 3 categories of liquefaction susceptibility under the ground motion at the MMS intensity VIII: likely, possible and not likely. Areas classified as “not likely” liquefaction susceptibility define zones 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 classified as the highest level of liquefaction potential, i.e. liquefaction likely (TC4, 1999). At these areas, further investigation using in-situ test and quantitative parameters of subsoil layers must be performed.

In addition, another well known procedure for the characterisation of an area as liquefiable was proposed by the California Department of Conservation, Division of Mines and Geology (CDMG, 1999). According to these guidelines, a zone is considered as prone to liquefaction when is meeting the following criteria:

- evidence of historical liquefaction occurrences
- data from in-situ tests and analyses indicate that the soils are likely to liquefy

in case of lacking of the above data, a site is considered as susceptible to liquefaction when:

- area containing soils of late Holocene age, the groundwater is less 13 meters deep and the peak ground acceleration (PGA) having a 10% probability of being exceeded in 50 years is greater than 0.1g
- soils of Holocene age where the depth of groundwater table is less than 10 meters and the PGA (10% in 50 years) is greater than 0.2g
- areas containing soil deposits of latest Pleistocene age, where the PGA has a 10% probability of being exceeded in 50 years is greater or equal to 0.3g and the depth of the groundwater table is less than 6 meters

In recent years, Witter et al. (2006) developed a criteria matrix for the classification of a geological units regarding liquefaction susceptibility based on procedures proposed by previous studies (Knudsen et al., 2000). According to their study, the liquefaction susceptibility of a deposit can be evaluated by taking into account its age and depositional environment, the typical depth of the ground water and afterwards, the classification is calibrated with historical liquefaction occurrences and the borehole evaluations of liquefaction peak ground accelerations thresholds.

EVALUATING LIQUEFACTION SUSCEPTIBILITY

In our study, the evaluation of liquefaction susceptibility of the deposits has been performed based on the Youd and Perkins (1978) criteria. Initially, a suscpetibility map was compiled based on the age and depositional environment of the sediments and afterwards a calibration was realized by taking into account the distribution of historical liquefaction occurrences. In what concerns the expected value of PGA in the area, the Greek Seismic Code defines that the designed peak ground acceleration (PGA) is equal to 0.24g, having a 10% probability of being exceeded in 50 years (EAK, 2000).

Geological mapping and classification

Generally, the pre-rift sedimentary cover of the broader Peloponnese region is composed of Triassic evaporites and carbonate strata, Cretaceous limestone and Oligocene turbidities (flysh), Lower Miocene (Burdigalian) marls and limestone, middle Miocene to lower Pliocene marls, clays and Messinian evaporites and Pliocene - Quaternary recent deposits as it shown by geological, deep drilling and seismic profiles.

In particullar, outcropping along the southern coast of the Gulf are thick sequences of Pliocene lacustrine and Quaternary terrestrial sediments cut by arrays of extensional faults that have been rapidly uplifted (Ori 1989, Doutsos and Piper 1990, Poulimenos 1991, Leeder et al. 2002). The age of the early Rift opening and sediment deposition is poorly constrained and is estimated to Middle – Late Pliocene (Sauvage 1977, Kontopoulos and Doutsos 1985, Frydas 1989, Leeder et al. 2008). Syn- and post-sedimentary deformation can be demonstrated in these sequences indicating that the basin was much wider in form at earlier stages of its evolution. The most characteristic and widespread Plio-Quaternary sediments in the southern part of the Corinth Rift are conglomerate-rich Gilbert-type delta bodies with unusually large dimensions, varying in radius from 3 to 8 km and are up to 900 m thick (Ori 1989, Collier 1990, Collier and Dart 1991, Ori et al. 1991, Poulimenos et al. 1993, Ford et al. 2007, Rohais 2007). In the northern part, the most distinguished and widespread formation is Middle to Late Pleistocene series of terrestrial cohesive breccia and conglomerates, named as 'Agia Efthimia' or 'Arahova Breccia' (Celet 1962, Péchoux 1964, 1977, Sebrier 1977, Valkaniotis 2009). Neogene and Quaternary sediments are less abundant in the northern part, and are found mainly in wide river valleys, uplifted remnant plateaus, deltaic river plains and narrow coastal strips.

In order to evaluate the liquefaction susceptibility of the sediments, the criteria proposed by Youd and Perkins (1978) were applied. Initially, data provided by geologcial maps in 1:50.000 scale compiled by IGME (Geological Survey of Greece) were used as a base layer for digitizing the spatial distribution of the geological units. Afterwards, the geological units were classified into two categories based on their ages; pre-quaternary and quaternary (figure 3). This classification was realized in order to further analyze and evaluate the liquefaction susceptibility of the Quaternary sediments since pre-Pleistocene deposits are classified as very low susceptibility units (Youd, 1998).

Supplementary data were collected using topographic maps, satellite (Landsat 7 ETM+) and aerial images, and digital elevation model from SRTM data, along with field surveys. Low-land saturated coastal and fluvial sediments, wetlands and river flood-plains usually depicted as undivided Quaternary/Holocene sediments in geological maps were traced using the above combination of data: candidate areas were identified using digital elevation and geology raster data, and manually checked in Landsat 7 images and/or aerial images.

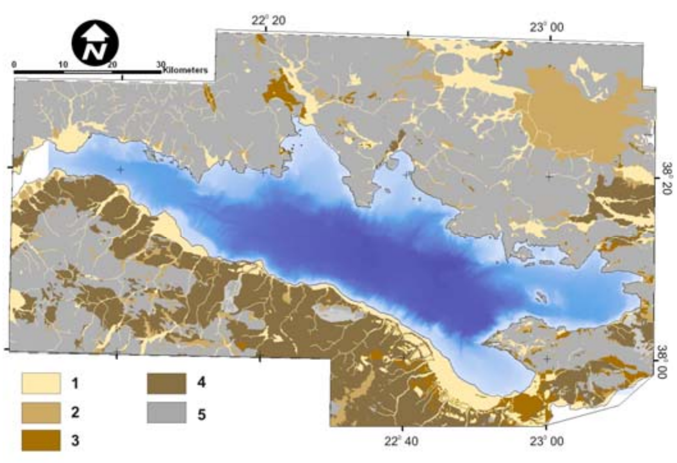

Fig. 3. Simplified geologic map of the Gulf of Corinth area. (1) Holocene unconsolidated alluvial and fluvial deposits, (2) Pleistocene – Holocene lacustrine and fan deposits, (3) Pleistocene – Holocene breccia, scree and conglomerates, (4) undifferentiated Pliocene – Pleistocene fluvioterrestrial sediments, (5) Pre-Quaternary bedrock

Historical liquefaction occurrences

Greece and particularly the area of the Gulf of Corinth are characterized by intense seismic activity. This high seismcity in conjunction with the existence of detailed historical reports, describing secondary effects, was the motivation for the evaluation of the liquefaction susceptibility of the geological units at this specific region. The distribution of deposits was examined using published geological maps, as it was previously described, and information regarding historical liquefaction occurrences was collected from Papathanassiou et al. (2005). Moreover, data regarding the coordinate of liquefied sites and a brief description of the liquefaction-induced failures were obtained by the database DALO v1.0 developed by Papathanassiou and Pavlides (2009). This database is an open-access file and can be found in the wed address of http://users.auth.gr/~gpapatha/dalo.html .

According to the information provided by the database (DALO v1.0), liquefaction phenomena were triggered by 13 earthquakes, occurred at the area of the Gulf of Corinth (figure 4). The most characteristic example and one of the oldest reports describing earthquake-induced ground deformation is provided by Strabo and refereed to the 373 B.C. Eliki earthquake destroying the towns of Eliki and Voura, while the generated sea wave destroyed ten boats. In addition, a detailed description of liquefaction manifestations generated by the 1861 Aeghio 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 Aeghio. However, as it is shown in figure, 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 observed and reported by Georgalas (1928).

In particular, the 1817 event caused the slumping of the cape Aliki east of Aeghio and the settlement of the coast at the area between the mouth of Meganitis River and the cape Aliki. For a distance of 2km about inland, the fields were covered with mud ejected from the ground (Ambraseys and Jackson, 1997). The 1858 earthquake, occurred at the eastern part of the Gulf of Corinth, generated liquefaction-induced failures at Kalamaki, where the man-made fill behind the quay slumped and cracks opened on the ground running parallel with the dock. Furthermore, as it is previously mentioned, the 1861 Aeghio earthquake is one of the most well reported events of 19^{th} century. Schmidt (1867) included into his report brief descriptions of earthquake-induced ground deformations and mapped their spatial distribution. In particular, 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 addition, at the port of Itea, north part of the Gulf, the ground in places liquefied. Furthermore, this event generated sand boils ejecting muddy material 15 minutes after the shock in the village of Kalamitsi, 85km far from the epicenter, a disproportionate distance in relation to the earthquake magnitude.

An event, occurred in the north part of the Gulf of Corinth, that triggered liquefaction phenomena at the ports of Itea and Kira, is the 1870 one. As it reported by Ambraseys and Pantelopoulos (1989) the earthquake caused the ejection of sandy material at the area of Katavothra and the slumping of the quay at Kira. At the coastal area between Kira and Itea sand craters were observed where water and sandy material ejected for 3 hours after the event. In addition, at the villages of Skliri and Larnaki sand craters with diameter up to 2 meters were also reported and at Galaxidi ground cracks and settlement of the quay caused by the shock. The 1888 earthquake induced the slumping of the ground in the district of Faneromeni and at the villages of Valimitika and Selianitika the ground open up and liquefied (Ambraseys and Jackson, 1997). A shock that affected the western part of the Gulf of Corinth is the 1889 event that caused liquefaction and slumping of the ground at Aetoliko (Ambraseys and Jackson, 1997).

Regarding the earthquakes occurred during the 20th century, it could be said that the ground failures were less severe. Five earthquakes were correlated to the generation of liquefaction phenomena, the 1909, 1928, 1965, 1981 and 1995 events, respectively. In particular, the 1909 shock triggered liquefaction of the ground at the area of Kamara and Douvia, close to the town of Aeghio (Ambraseys and Jackson, 1990) and the 1928 event induced the liquefaction-induced failures at the port area of Corinth and at Kalamaki, Lutraki and Xylokastro. Moreover, ground cracks were observed at the coastal area from Nerantzia to Rahaina River. From these cracks silty material was ejected mainly close to the rivers Zapantiou and Rahaina (Georgalas, 1928). The 1965 Eratini earthquake generated liquefaction to the northwest of the village Akrata and at the area of Eraitini (Ambraseys and Jackson, 1990) and the sequence of the 1981, three events in 10 days, caused liquefaction at the villages of Lehaeo, Mavrolimni, Psatha, Kineta and Strava. Finally, the 1995 earthquake induced liquefaction manifestation such as ground cracks with ejection of sandy material, at the coastal area between the rivers Selinountas and Vouraikos, at the delta of river Meganitis and at the coastal area of the village Abithos to the west of Aeghio. Moreover, liquefaction phenomena were observed at the coastal area of Eratini (Papatheodorou and Ferentinos, 1997)

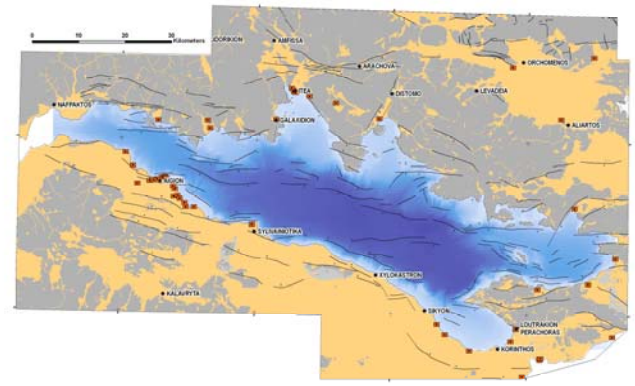

Fig. 4. Historical liquefaction occurrences at the area of Gulf of Corinth

Table 1 lists all the events that triggered liquefaction manifestations at the Gulf of Corinth. Furthermore, information regarding the liquefied site and the type of failure is also provided.

<u>Depth of ground water table</u>

The evaluation of the depth of the groundwater 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 6 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.

LIQUEFACTION SUSCEPTIBILITY MAP

As it mentionned in previous paragraph, a first delineation of liquefaction prone areas can be achieved by separating the Quaternary and Pre-Pliocene age sediments. Afterwards, taking into account the detailed distribution of Holocene and Pleistocene sediments in conjuction to the depositional environment, a liquefaction susceptibility map was compiled. In this map, four classes of susceptibility were created: low, moderate, high and very high, based solely on the criteria proposed by Youd and Perkins (1978).

In addition, on this map were plotted the sites where reports describing historical liquefaction occurrences were collected. These areas, as it is shown in figure 4, are mainly located at the coastal area close to the town of Aeghio and to the east of the Gulf of Corinth close to the city of Corinthos, while few sites were also distributed at the nortern part of Gulf.

The final liquefaction susceptibility map of the sediments at the Gulf of Corinth was compiled by taking into account the age and depositional-based classification of the deposits and the location of historical liquefaction manifestation (figure 5). In particular, the initiall grouping into classes of the susceptibility of an area was upgraded one level in case of the existence of descriptions of historical liquefaction manifestations. Thus, the coastal areas of Aeghio and Corinth that were initially classified as high susceptibility zones have been upgraded to very high susceptibility ones.

As an outcome of this project, a total of 2282 km^2 has been classified as very high susceptibiltiy zone, a zone of 1900 km^2 defined as high, a 48516 km^2 as moderate and 4255 km^2 were bounded as low susceptibilty to liquefaction area.

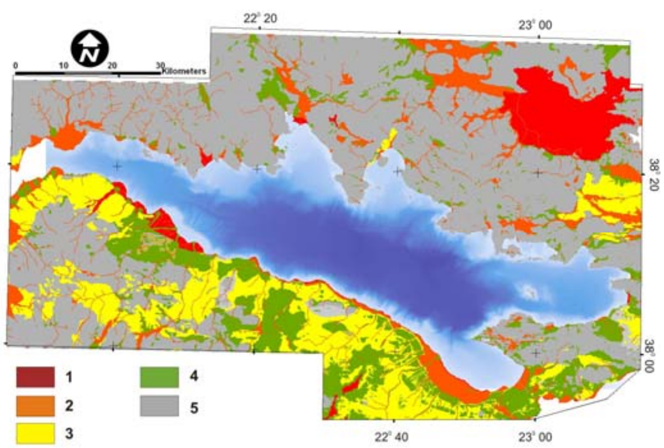

Fig. 5. Liquefaction susceptibility of the geological units at the Gulf of Corinth. 1. Very high suscpetibility, 2. High susceptibility, 3. Moderate, 4. Low susceptibility zone, 5. Bedrock

The areas defined as very high liquefaction susceptibility are mapped close to the delta of the major rivers that discharge at the southern Gulf of Corinth, around the town of Aeghio, including the coastal area of touristic mainly summer residents. Moreover, at the eastern part of the Gulf, close to the city of Corinthos, the coastal area was also delineated as very high susceptibility zone. At the same class were also grouped small size areas at the northern part of the Gulf where the town of Itea and Eratini are located. Finally, the area where lake kopais used to be existed, an area of lower risk due to the absence of urban environment was also defined as very high susceptible zone as an outcome of the application of depositional and historical based criteria.

CONCLUSIONS

The goal of this study was the evaluation of the liquefaction susceptibility of the geological units at the Gulf of Corinth, Greece. In order to achieve this, the criteria proposed by Youd and Perkins (1978) were applied. Initially, information regarding the surficial distribution of geological units was collected and maps where the sediments are classified based on their age were compiled. Furthermore, the sites where liquefaction historical manifestations had been observed, were plotted in order to correlate the reoccurrence of the failure with specific areas. The final map of susceptibility was compiled using age and depositional-based criteria and by taking into account the distribution of past liquefaction occurrences. In this map, as very high susceptibility zones are delineated the coastal area at the southern Gulf of Corinth close to the town of Aeghio and small size areas close to the towns of Itea and Eratini.

REFERENCES

Ambraseys, N.N. and J. Jackson, [1997] "Seismicity and strain in the Gulf of Corinth (Greece) since 1694". Journal of Earthquake Engineering, No 1, pp. 433-474.

Ambraseys, N. and P. Pantelopoulos, [1989] "The Fokis earthquake of 1 August 1870". J. Europ. Earthq. Eng., No 3, pp. 10-18.

Ambraseys, N.N. and J. Jackson, [1990] "Seismicity and associated strain of central Greece between 1980 and 1988". Geophys. J. Int., No 101, pp. 663-708.

Ambraseys, N.N. and C.F. Finkel, [1995]. "The seismicity of Turkey and Adjacent Areas, A historical review, 1500-1800". EREN, Instanbul. 240pp.

Angelier, J., N. Lyberis, X. Le-Pichon, E. Barrier, and P. Huchon [1982]. "The tectonic development of the Hellenic Arc and the Sea of Crete: a synthesis", Tectonophysics, No 86, pp. 159 -196.

Armijo, R., B. Meyer, G.C.P. King, A. Rigo, and D. Papanastassiou [1996]. "Quaternary evolution of the Corinth Rift and its implications for the Late Cenozoic evolution of the Aegean" Geophys . J. Int., No 126, pp. 11-53.

Athanasopoulos, G., P. Pelekis and E. Leonidou, [1999]. Effects of surface topography on seismic ground response in the Egion 15 June 1995 earthquake. Soil dyn. Earthq. Engin. No 18, pp. 135-149

Billiris, H., D. Paradissis, G. Veis, P. England, W. Featherstone, B. Parsons, P. Cross, P. Rands, M. Rayson, P. Sellers, V. Ashkenazi, M. Davison, J. Jackson and Ambraseys, N. [1991]. "Geodetic determination of tectonic deformation in central Greece from 1900 to 1988". Nature, No 350, pp. 124-129.

Celet, P. [1962]. *Contribution a l'étude géologique du Parnassse – Kiona et d'une partie des régions méridionales de la Grèce continentale*. Thèse, Faculté des Sciences de Lille, Annales Geol. Pays Hellen., No 13, 1-540.

Collier R.E.L. [1990]. “Eustatic and tectonic controls upon Quaternary coastal sedimentation in the Corinth Basin, Greece”, J. Geol. Soc. London, No 147, pp. 301–314.

Collier, R.E.L. and C.J. Dart, [1991]. “Neogene to Quaternary rifting, sedimentation and uplift in the Corinth basin, Greece”, J. Geol. Soc. London, No 148, pp. 1049-1065.

Doutsos, T., N. Kontopoulos and G. Poulimenos, [1988]. The Corinth-Patras rift as the initial stage of continental fragmentation behind an active island arc (Greece). Basin Research, No 1, pp. 177-190.

Doutsos, T. and D.J.W. Piper [1990] “Listric faulting, sedimentation and morphological evolution of the quaternary eastern Corinth rift, Greece: first stages of continental rifting”. Bull. Geol. Soc. Am., No 102, pp. 812-829.

Doutsos, T. and G. Poulimenos [1992] “Geometry and kinematics of active faults and their seismotectonic significance in the western Corinth–Patras rift (Greece)”. J. Struct. Geol., No 14, pp. 689–699.

Ford, M., E.A. Williams, F. Malatre, and S.P. Popescu [2007] “Stratigraphic architecture, sedimentology and structure of the Vouraikos Gilbert-type delta, Gulf of Corinth, Greece”. In: *Sedimentary Processes, Environments, and Basins: A Tribute to Peter Friend* Nichols, (G., Williams, E. and Paola, C. ed). Int. Assoc. Sediment. Spec Publ., No 38, pp. 49-90.

Frydas, D. [1989] “Biostratigraphische Untersuchungen Aus Dem Neogen Der Nw- UndWpeloponnes, Griechenland. N. Jb. Geol.Palont.Mon, No 1, pp. 321-344.

Georgalas G.K. [1928]. “The earthquakes that occurred in the area of Gulf of Corinth, Athens, pp. 32-103.

Ghisetti, F. and L. Vezzani [2005] “Inherited structural controls on normal fault architecture in the Gulf of Corinth (Greece)”. Tectonics, doi: 10.1029/2004TC001696.

Hinsbergen, D.J.J. [2004] “*The evolving anatomy of a collapsing orogen*” Thesis, Utrecht University. Geologica Ultraiectina, 243, 279 pp.

Jackson, J.A., J. Gagnepain, G. Houseman, G.C.P. King, P. Papadimitriou, Soufleris, C. and J. Vireux [1982]. “Seismicity, normal faulting, and the geomorphological development of the Gulf of Corinth (Greece): the Corinth earthquakes of February and March 1981”. Earth Plan. Sci. Lett.. No 57, pp. 377-397.

Jackson, J. and D. Mckenzie [1983] “Suggestion for the geometrical evolution of normal fault systems”. J. Stuct. Geol., No 5, pp. 451-482.

Jackson, J.A. and D.P. McKenzie [1988] “The relationship between plate motions and seismic tensors and the rate of active deformation in the Mediterranean and Middle East”. Geophys. J., No 93, pp. 45-73.

Jenny, S., S. Goes, D. Giardini, and H-G. Kahle [2004] “Earthquake recurrence parameters from seismic and geodetic strain rates in the eastern Mediterranean”. Geophys. J. Int., No 157, pp. 1331-1347.

Kahle, H.G., M. Cocard, Y. Peter, A. Geiger, R. Reilinger, A. Barka, and G. Veis [2000] “GPs-derived strain rate field within the boundary zones of the Eurasian, African and Arabian plates”. J. Geophys. Res., No 105, pp. 23,353-23,370

Kontopoulos, N. and T. Doutsos [1985] “Sedimentology and tectonics of the Antirion area (Western Greece)”. Bull. Geol. Soc. Italy, No 1, pp. 479-489.

Koukis, G. and Rozos D. [1982]. “Geological and geotechnical information regarding the earthquakes of February _ March 1981 in the Gulf of Corinth, Ac. Athens Κούκης, No 57, pp. 406-421. (in Greek)

Koukouvelas, I., L. Stamatopoulos, D. Katsonopoulou, S. Pavlides, [2001]. A palaeoseismological and geoarchaeological investigation of Eliki fault, Gulf of Corinth, Greece. J.Struct. Geol. No 23, pp. 531-543

Leeder, M.R., R.E. Collier, L.H. Abdul Aziz, M. Trout, G. Ferentinos, , G. Papatheodorou, and E. Lyberis. [2002]. “Tectono-sedimentary processes along an active marine/lacustrine margin: Alkyonides Gulf, E. Gulf of Corinth, Greece”. Basin Research, No 14, pp. 25-41.

Leeder, M.R., G.H. Mack, A.T. Brasier, R.R. Parrish, W. MacIntosh, E.J. Andrews, and C.E. Duermeijer [2008] “Late-Pliocene timing of Corinth (Greece) rift-margin fault migration”. Earth and Planetary Science Letters, No 274, pp.132-141.

Le-Pichon, X. and J. Angelier [1979] “The Hellenic arc and trench system a key to the neotectonic evolution of the eastern Mediterranean area”. Tectonophysics, No 60, pp. 1-42.

Le-Pichon, X., N. Chamot-Rooke, S. Lallemant, R. Noomen, and G. Veis [1995] “Geodetic determination of the kinematics of central Greece with respect to Europe: Implications for eastern Mediterranean tectonics”. J. Geophys. Res., No 100, pp. 12675-12690.

McClusky, S., et al. (2000) Global Positioning System constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus. J. Geophys. Res. 105, 5695-5719.

McKenzie, D.P. [1972] “Active tectonics of the Mediterranean region”. Geophys. J. R. Astr. Soc., No 30, pp. 109-182.

McKenzie, D. [1978] “Active tectonics of the Alpine-Himalayan belt: the Aegean Sea and surrounding regions”. Geophys. J. R.. Astr. Soc., No 55, pp. 217-254.

Moretti, I., D. Sakellariou, V. Lykousis and L. Micarelli [2003] “The Gulf of Corinth: an active half graben” J. Geodyn. No 36, pp. 323–340.

Ori, G.G. [1989] “Geologic history of the extensional basin of the Gulf of Corinth (?Miocene–Pleistocene), Greece”. Geology, No 17, pp. 918–921.

Ori, G.G., M. Roveri, and G. Nichols [1991] “Architectural patterns in large-scale Gilbert-type delta complexes, Pleistocene, Gulf of Corinth, Greece”. In: *The Three-dimensional Facies Architecture of Terrigenous Clastic Sediments and its Implications for Hydrocarbon Discovery and Recovery* (A.D. Miall and N. Tyler Eds), pp. 207–216. Concepts in Sedimentology and Paleontology, Vol. 3, Society of Economic Paleontologists and Mineralogists, Tulsa, OK.

Péchoux, P.Y. [1964] Recherches morphologiques dans la région du Parnasse – Kiona (Grèce centrale). Bull. de l’Association des Géographes Français.

Papathanassiou G., S., Pavlides B., Christaras and K., Pitilakis [2005]. “Liquefaction case histories and empirical relations of earthquake magnitude versus distance from the broader Aegean Region”. Journal of Geodynamics, No 40, pp. 257-278

Papathanassiou G. and S. Pavlides [2009]. “GIS-based DAtabase of historical Liquefaction Occurrences in broader Aegean region, DALO v1.0”, in Proc: *Earthquake Geotechnical Engineering Satellite Conference XVIIth International Conference on Soil Mechanics and Geotechnical Engineering* 2-3. 10. 2009, Alexandria, Egypt

Papathanasiou, G., S. Pavlides, S. Valkaniotis and A. Chatzipetros, [2009]. “ Towards the compilation of a liquefaction susceptibility map of Greece”. SRL, Vol. 80, No. 2, pp. 316

Papatheodorou, G., and G. Ferentinos. [1997]. “Submarine and coastal sediment failure triggered by the 1995, Ms=6.1 R Aegion earthquake, Gulf of Corinth, Greece”. Marine Geology No 137, pp. 287-304.

Péchoux, P.Y. [1977]. Nouvelles remarques sur les versants Quaternaires du secteur de Delphes. Revue de Géographie Physique et de Géologie Dynamique, No 19 , pp. 83–92.

Poulimenos, G. [1991] “Tectonic and sedimentary analysis of the western part of the Corinth rift”. Phd Thesis, University of Patras, 298p.

Roberts, S. and J. Jackson [1991] “Active normal faulting in central Greece: an overview”, in *The Geometry of Normal Faults* (Roberts, A.M., G, Yielding and B. Freeman eds.):, Geol. Soc. Sp. Pub., No 56, pp. 125-142.

Roberts, G.P. and I.K. Koukouvelas, [1996] “Structural and seismological segmentation of the Gulf of Corinth fault system: implication for models of fault growth”. Annali di Geophysica,No 39, pp. 619–646.

Rohais, S., R. Eschard, M. Ford, F. Guillocheau, and I. Moretti, [2007] “Stratigraphic architecture of the Plio-Pleistocene infill of the Corinth rift: implications for its structural evolution”. Tectonophysics, No 440, pp. 5-28.

Sauvage, J. [1977] L'apport de la Palynologie dans la connaissance du Plio-Pléistocène de la région de Corinthe (Grèce): le problème des limites et des corrélations stratigraphiques. C. R. Acad. Sci. Paris No 285, pp. 279–282 série D.

Schmidt, J., 1867. Information regarding the 26th of December 1861 earthquake, 52 pp. Athens

Sebrier, M. [1977] «Tectonique récente d’une tranversale a l’Arc Egéen. These de Docteur, Academie de Versailles, Universite de Paris XI, 100p.

Skourlis, K. and T. Doutsos, [2003]. “The Pindos fold-and-thrust belt (Greece): inversion kinematics of a passive continental margin”. International Journal of Earth Sciences, No 92 (6), pp.891–903.

Soter, S. and D. Katsonopoulou, [1999]. “Occupation horizons found in the search for the ancient Greek city of Helike”. Geoarchaeology, No 14, pp. 531-563.

Tsodoulos, I., I.K. Koukouvelas, and S. Pavlides, [2008]. «Tectonic Geomorphology of the easternmost extension of the Gulf of Corinth (Beotia, Central Greece). Tectonophysics, No 453, pp. 211 – 232.

Valkaniotis, S. [2009] “Correlation Between Neotectonic Structures and Seismicity in the broader area of Gulf of Corinth (Central Greece)”. Unpublished PhD Thesis, Aristotle University of Thessaloniki. 255p.

Zygouri, V., S. Verroios, S. Kokkalas, P. Xypolias, and I.K. Koukouvelas [2008] “Scaling properties within the Gulf of Corinth, Greece; comparison between offshore and onshore active faults”. Tectonophysics, No 453, pp. 193-210.

Table 1. Data regarding the occurrences of historical liquefaction-induced ground and structural failures

Date	Ethq	Liquefied site	Description	Reference
23/8/1817	Aeghio	Aliki Cape	local Settlement	Ambraseys and Jackson (1997)
23/8/1817	Aeghio	Meganitis river(delta)	Sand boils	Ambraseys and Jackson (1997)
23/8/1817	Aeghio	Meganitis river	local Settlement	Ambraseys and Jackson (1997)
23/8/1817	Aeghio	Sancak Burnu	local Settlement	Ambraseys and Finkel (1995)
21/2/1858	Corinthos	Kalamaki	Settlement of quay/pier	Ambraseys and Jackson (1997)
21/2/1858	Corinthos	Kalamaki	Sand boils	Schmidt (1867)
26/12/1861	Aeghio	Selinountas river	Lateral spreading	Schmidt (1867)
26/12/1861	Aeghio	Keranitis river	Lateral spreading	Schmidt (1867)
26/12/1861	Aeghio	Vuraikos river	Lateral spreading	Schmidt (1867)
26/12/1861	Aeghio	Temeni	local Settlement	Schmidt (1867)
26/12/1861	Aeghio	Diakoptitika	local Settlement	Schmidt (1867)
26/12/1861	Aeghio	Itea	Settlement of quay/pier	Ambraseys and Jackson (1997)
26/12/1861	Aeghio	Kira	local Settlement	Ambraseys and Jackson (1997)
26/12/1861	Aeghio	Kalamaki	local Settlement	Schmidt (1867)
26/12/1861	Aeghio	Kalamaki	Sand boils	Schmidt (1867)
1/8/1870	Arahova	Katavothra	ground fissures with ejection of mud	Ambraseys and Pantelopoulos (1989)
1/8/1870	Arahova	Desfina	evidense/no subscription	Ambraseys and Pantelopoulos (1989)
1/8/1870	Arahova	Itea	Settlement of quay/pier	Ambraseys and Pantelopoulos (1989)
1/8/1870	Arahova	Skala	local Settlement	Ambraseys and Pantelopoulos (1989)
1/8/1870	Arahova	Kira	Sand boils	Ambraseys and Pantelopoulos (1989)
1/8/1870	Arahova	Skliri	Sand boils	Ambraseys and Pantelopoulos (1989)
1/8/1870	Arahova	Larnaki	Sand boils	Ambraseys and Pantelopoulos (1989)
1/8/1870	Arahova	Galaxidi	Settlement of quay/pier	Ambraseys and Pantelopoulos (1989)
1/8/1870	Arahova	Thermopylae	evidense/no subscription	Ambraseys and Pantelopoulos (1989)
1/8/1870	Arahova	Itea	local Settlement	Ambraseys and Pantelopoulos (1989)
25/10/1870	Arahova	Itea	Sand boils	Ambraseys and Pantelopoulos (1989)
25/10/1870	Arahova	Larnaki	Sand boils	Ambraseys and Pantelopoulos (1989)
9/9/1888	Aeghio	Akuli	local Settlement	Ambraseys and Jackson (1997)
9/9/1888	Aeghio	Valimitika	ground fissures with ejection of mud	Ambraseys and Jackson (1997)
9/9/1888	Aeghio	Selianitika	ground fissures with ejection of mud	Ambraseys and Jackson (1997)
9/9/1888	Aeghio	Faneromeni	local Settlement	Ambraseys and Jackson (1997)
30/5/1909	Fokida	Duvia	Settlement of the coast	Ambraseys and Jackson (1997)
30/5/1909	Fokida	Kamara	evidense/no subscription	Ambraseys and Jackson (1997)
22/4/1928	Corinthos	Loutraki	Tilting of building	Georgalas (1928)
22/4/1928	Corinthos	Kalamaki	ground fissures with ejection of mud	Georgalas (1928)
22/4/1928	Corinthos	Corinthos	Settlement of the coast	Georgalas (1928)
22/4/1928	Corinthos	Rahaina river	Sand boils	Georgalas (1928)
22/4/1928	Corinthos	Neranza	ground fissures with ejection of mud	Georgalas (1928)
22/4/1928	Corinthos	Brahati	ground fissures with ejection of mud	Georgalas (1928)
17/4/1930	Corinthos	Almyri	Settlement of the coast	Ambraseys and Jackson (1990)
6/7/1965	Eratini	Akrata	evidense/no subscription	Ambraseys and Jackson (1990)
6/7/1965	Eratini	Temeni	evidense/no subscription	Ambraseys. and Jackson (1990)
6/7/1965	Eratini	Eratini	evidense/no subscription	Ambraseys and Jackson (1990)
31/12/1975	Aetolia	Aetolia	evidense/no subscription	Ambraseys (1988)
24/2/1981	Alkionides	Lehaio	evidense/no subscription	Ambraseys and Jackson (1990)
24/2/1981	Alkionides	Psatha	evidense/no subscription	Ambraseys and Jackson (1990)
24/2/1981	Alkionides	Strava	evidense/no subscription	Ambraseys and Jackson (1990)
24/2/1981	Alkionides	Maurolimni	evidense/no subscription	Ambraseys and Jackson (1990)
24/2/1981	Alkionides	Kineta	evidense/no subscription	Ambraseys and Jackson (1990)

4/3/1981	Alkionides	Kalamaki	evidense/no subscription	Koukis and Rozos (1982)
15/6/1995	Aeghio	Meganitis river	ground fissures with ejection of mud	Papatheodorou and Ferentinos (1997)
15/6/1995	Aeghio	Rizomylos	Settlement of the coast	Athanasopoulos et al. (1999)
15/6/1995	Aeghio	Selinitis river	Failure of river banks	Athanasopoulos et al. (1999)
15/6/1995	Aeghio	Nikoleika	ground fissures with ejection of mud	Athanasopoulos et al. (1999)
15/6/1995	Aeghio	Eratini	Settlement of quay/pier	Papatheodorou and Ferentinos (1997)
15/6/1995	Aeghio	Abythos	Settlement of the coast	Athanasopoulos et al. (1999)