Geo-engineering mapping with respect to liquefaction susceptibility of the region of Thrace, North-eastern Greece

Papathanassiou G (1), Valkaniotis S (2) Pavlides Sp (3)

(1) Department of Geology, Aristotle University of Thessaloniki, gpapatha@auth.gr
(2) Department of Geology, Aristotle University of Thessaloniki, svalkan@geo.auth.gr
(3) Department of Geology, Aristotle University of Thessaloniki, pavlides@geo.auth.gr

Keywords: Liquefaction susceptibility, Thrace, Greece, engineering geology

Introduction

The region of Thrace is located at the north-eastern part of Greece; an area that plays a significant role regarding the status of energy in Greece due to the fact that two of the major pipelines, of natural gas and oil, will pass through this area. Consequently, the avoidance of an earthquake-induced damage to these lifelines is a major task for the country.

The region of Thrace is characterized as low seismicity area due to the limited information regarding historical and instrumental seismicity. However, the fact that large tectonic structures that were mapped during geological surveys are classified as active indicates that the occurrence of a big earthquake must not be excluded. In addition, the fact that two of the largest rivers in Greece traverse the region and deposit material susceptible to liquefaction increases the possibility of a liquefaction-induced ground failure.

Liquefaction is the transformation of saturated, unconsolidated 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 ground failures such as ground settlements, sand boils and lateral spreading and lead to structural damages at buildings, pipelines, bridges etc.

In order to prevent and/or to minimize the effectiveness of soil liquefaction, investigations regarding the susceptibility and the potential of liquefaction are taken place. 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, 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). 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 main goal of this paper is to present a preliminary map of liquefaction-prone zones in the region of Thrace, North-Eastern Greece. The susceptibility map was developed based on the 1:50,000 scale geological maps of the region and the existing correlation of geological units with the susceptibility to liquefaction.

Materials and Methods

The criteria proposed by Wakamatsu (1992) and the guidelines published by the California Department of Conservation, Division of Mines and Geology (CDMG, 1999) were used in order to evaluate the liquefaction susceptibility of deposits in the area of Thrace.

Wakamatsu (1992) classified sedimentary deposits using geomorphological criteria in 3 categories of liquefaction susceptibility under the ground motion at the MMS intensity VIII (Table 1): 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.

Table 1. Susceptibility of detailed geomorphological units to liquefaction subjected to ground motion of the MMS intensity VIII (Wakamatsu, 1992)

Geomorphological conditions		Liquefaction potential
Classification	**Specific conditions**	
Valley plain	Valley plain consisting of gravel or cobble	Not likely
	Valley plain consisting of sandy soil	Possible
Alluvial fan	Vertical gradient of more than 0.5%	Not likely
	Vertical gradient of less than 0.5%	Possible
Natural levee	Top of natural levee	Possible
	Edge of natural levee	Likely
Back marsh		Possible
Abandoned river channel		Likely
Former pond		Likely
Marsh and swamp		Possible
Dry river bed	Dry river bed consisting of gravel	Not likely
	Dry river bed consisting of sandy soil	Likely
Delta		Possible
Bar	Sand bar	Possible
	Gravel bar	Not likely
Sand dune	Top of dune	Not likely
	Lower slope of dune	Likely
Beach	Beach	Not likely
	Artificial beach	Likely
Interlevee lowland		Likely
Reclaimed land by drainage		Possible
Reclaimed land		Likely
Spring		Likely
Fill	Fill on boundary zone between sand and lowland	Likely
	Fill adjoining cliff	Likely
	Fill on marsh or swamp	Likely
	Fill on reclaimed land by drainage	Likely
	Other type fill	possible

According to the criteria listed in Table 1, 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).

Moreover, the geological units of Thrace were correlated to liquefaction susceptibility based on their age; it is well established that the susceptibility of a soil layer reduces with its age since cementation and density increase with age. In order to compile a liquefaction susceptibility map based on aging, the guidelines of CDMG (1999) were employed.

According to CDMG (1999) an area is characterized as Liquefaction zone when meeting one or more of 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

Though, these factors are reliable for the evaluation of susceptibility, they may not be themselves uniquely define liquefaction potential at a site.

Geological Mapping and Characterization

In order to evaluate the liquefaction susceptibility based on the above recommendations, we used data provided mainly by geologic maps published by IGME as a base layer. Afterwards, the geological units were classified into two categories based on their ages, pre-quaternary and quaternary (figure 1). This separation was made in order to further analyze and evaluate the liquefaction susceptibility of the deposits of Quaternary sediments since pre-Pleistocene deposits are classified as very low susceptibility units (Youd, 1998).

Evaluation of geological units was made using mainly geologic maps in 1:50.000 scale by IGME (Geological Survey of Greece). Supplementary data and coverage of areas with unpublished map sheets 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 (if provided).

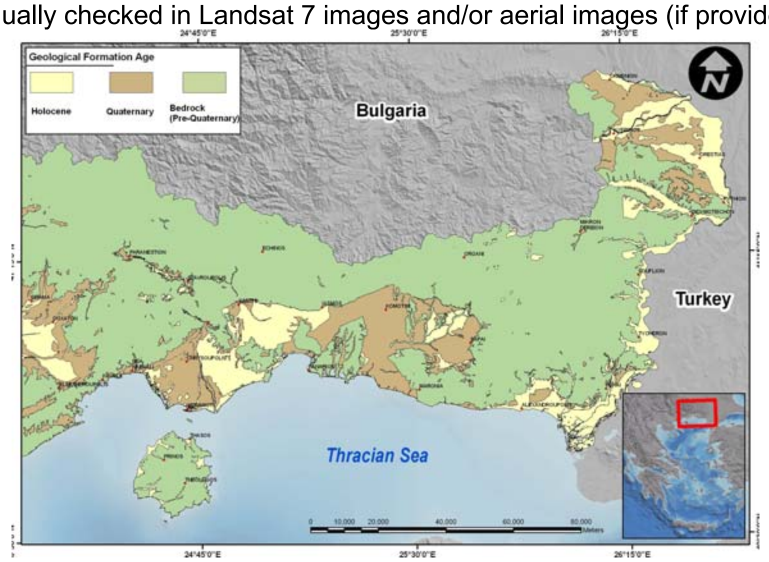

Figure 1. Map showing the distribution of the quaternary and pre-quaternary geological formations.

Seismotectonics Characteristics

The region of Thrace is considered as a low seismicity area according to the historical seismicity and the instrumental seismicity data in Greece for the years after 1911 (Kiratzi et al. 2005). According to Papazachos et al. (2007) only three earthquakes with magnitude M>5.5, the 1752, 1756 and 1784 events, occurred at the area that is examined in this study. In particular, the earthquake of 1752 (M 7.4) caused damages to Edirne (Ambraseys and Finkel, 1987) while the houses at the towns of Havsa and Haskoy and the villages of Zerna, Kozkoy, Ferecik were totally destroyed (Kiratzi et al. 2005). The event of 1784 (M 6.7) induced the collapse of 500 buildings in the area of Komotini. Though, the limited number of earthquakes in the region of Thrace, the occurrence of similar events could trigger soil liquefaction, since the lowest bound of an earthquake-induced liquefaction magnitude is smaller than the above ones (Papadopoulos and Lefkopoulos, 1993; Papathanassiou et al., 2005). In what concerns the expected value of PGA in Thrace, the Greek Seismic Code defines that the designed peak ground acceleration (PGA) is equal to 0.16g, having a 10% probability of being exceeded in 50 years (EAK, 2000).

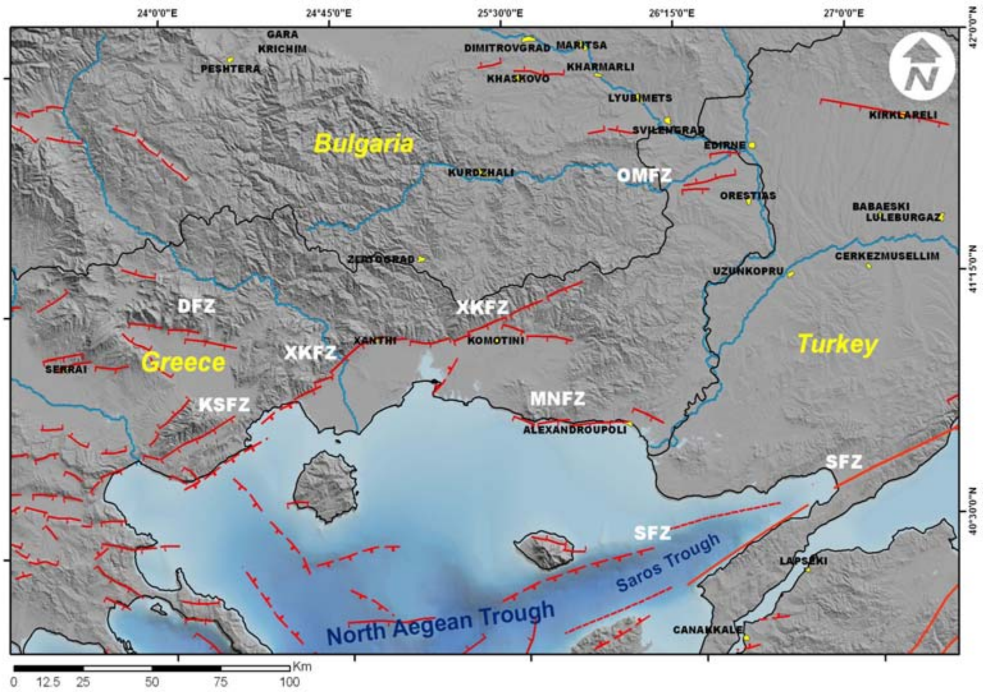

Figure 2. Main active and possible active faults (shown in red line) in the broad area of Thrace. Fault data from Pavlides et al. (2007). OMFZ – Orestias-Mikri Doxipara Fault Zone, XKFZ – Xanthi-Komotini FZ, DFZ – Drama FZ, KSFZ – Kavala-Strimonas FZ, MNFZ – Maronia-Makri FZ, SFZ – Saros FZ.

Additionally, tectonic structures capable to trigger big events are present in the broad area and active faults have been mapped and documented during field surveys. Active faults in the area have a general W-E orientation according to the present N-S extensional stress regime (Koukouvelas I.K., Aydin, A., 2002; Pavlides et al 2006). They are mostly normal-oblique faults in the mainland, with strike-slip faulting off-shore along the North Aegean Trough. As it is shown in figure 2, the major faults are the large Kavala-Strymonas (KSFZ) and Xanthi-Komotini (XKFZ) Fault Zones. Those two fault zones seem to connect, creating an impressive active fault zone reaching 200 km in length. Known active fault zones are also the Drama Fault Zone (DFZ), the Maronia-Makri Fault Zone (MNFZ) and the Orestias-Mikri Doxipara Fault Zone (OMFZ). Another important tectonic structure is the Saros Fault Zone (SFZ), the westernmost extension of the North Anatolia Fault, which can produce significantly large earthquake although it is situated outside the area of Thrace.

Evidence of past liquefaction phenomena indicates a possible high liquefaction hazard because liquefaction tends to recur at the same site, providing site conditions have not changed (Youd, 1984). Historical occurrences of earthquake-induced liquefaction have been reported in many places in Greece (Papathanassiou et al. 2005). However, at the region of Thrace only once an historical liquefaction occurrence was reported; liquefaction manifestations in the city of Dedeagac (today known as Alexandroupolis) were triggered by the event of 1912 Murefte, Turkey (Ambraseys and Finkle, 1987). Though, the fact that the existence of a description of liquefaction-induced ground failure triggered by past earthquake indicates a possibility of future liquefaction, the lack of evidence does not provide a proof for classifying a site as non liquefiable (Youd, 1998).

Evaluation of the Depth of the Groundwater Table

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 Maps

Liquefaction is the transformation of saturated, unconsolidated 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 process of liquefaction may or may not lead to ground deformation or related surface manifestations, including lateral spreading, ground settlement, bearing capacity failure, sand boils, and ground cracking.

Liquefaction susceptibility map can be developed using information provided by geologic, geomorphologic and hydrologic investigations. Liquefaction hazard maps have been compiled based on this approach at many region in the world and especially the western part of USA; for the Monterey-Santa Cruz area (Dupré and Tinsley, 1980; and Dupré, 1990), the greater Los Angeles urban area (Tinsley et al., 1985), and the San Francisco Bay region (Youd and Perkins, 1987; Knudsen et al., 1997; Sowers et al., 1998; Knudsen and others, 2000; Holzer et al., 2002). The liquefaction susceptibility map does 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). Hence, the information provided by a liquefaction susceptibility map should be used only as a screening guide for planning purposes since for site-specific conditions a detailed geotechnical investigation must be performed for the evaluation of liquefaction potential of a soil element.

In this study, liquefaction susceptibility maps for the region of Thrace were developed using the recommendations for delineating seismic hazard zones of the California Division of Mines and Geology (CDMG, 1999) and the geomorphological criteria that are listed in Table 1, proposed by Wakamatsu (1992).

For the application of CDMG (1999) criteria, the Holocene sediments were classified in one group due to the fact that the separation into late Holocene age and Holocene deposits, respectively could not be establish in this scale. Therefore, taking into account the guidelines of CDMG (1999) and the fact that the value of PGA at the region of Thrace is expected to be 0.16g (EAK, 2000) we concluded that the zones where Holocene sediments were mapped (figure 1), are considered as liquefaction-prone areas.

Furthermore, the geomorphological characteristics of the surface materials that were mapped in the same area were identified and classified according to the criteria published by Wakamatasu (1992). In figure 3, is shown the liquefaction susceptibility map that was compiled using these depositional criteria that are listed in Table 1. From the 4138.63 Km^2 of the area covered by Quaternary sediments, 277.16Km^2 are delineated as likely to liquefaction zone; 3561.38Km^2 are bounded as possible to liquefaction zone while the rest of the area (300.09Km^2) as non likely to liquefaction.

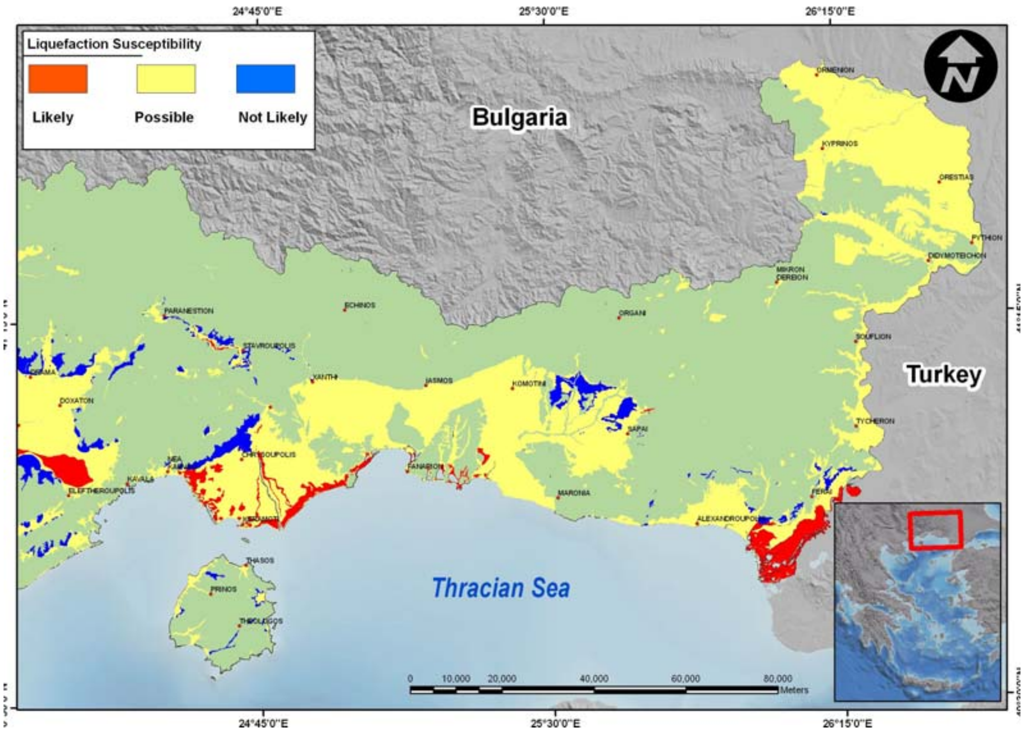

Figure 3. Liquefaction susceptibility map of the region of Thrace based on the criteria published by Wakamatsu (1992).

The areas defined as likely to liquefaction are mapped close to the delta of the two major rivers, Nestos and Evros, which traverse the region of Thrace, including the coastal area of Keramoti. Furthermore, two of the urban areas of the region, the cities of Komotini and Alexandroupolis are located in areas characterized as possible to liquefaction. Thus, it is necessary for the evaluation of liquefaction potential and the quantification of the liquefaction hazard to analyzed data from in-situ tests performed in these two cities.

Results and Discussion

The goal of this study was the identification of areas where liquefiable units exist at the region of Thrace using geological and geomorphological data. This map can be used as a screening guide of liquefaction hazard for planning purposes since areas where liquefaction occurrences pose a substantial hazard are delineated.

The liquefaction susceptibility maps were compiled using geological maps with reference to criteria published by Wakamatsu (1992) and CDMG (1999). In these maps, zones where geological units susceptible to liquefaction during earthquakes exist are delineated. The geological units that were mapped by previous field surveys were classified into three categories of liquefaction susceptibility regarding their depositional environment (Wakamatsu, 1992) while the areas where Holocene sediments are mapped, are classified as liquefaction-prone areas (CDMG, 1999).

This study resulted that a total of 277.168 Km^2 at the region of Thrace are bounded as likely to liquefaction while 3561.38 Km^2 are considered as possible to liquefaction. The rest of the area covered by Quaternary sediments, 300.09 Km^2, is considered as not likely to liquefaction-induced ground failures. Particularly, two cities of the region, Komotini and Alexandroupoli are situated at possible to liquefaction areas while the port of Keramoti is located at a likely to liquefaction zone. However, in order to evaluate the severity of liquefaction-induced failures is necessary to collect and process data regarding the geotechnical characteristics of the liquefiable soil layers.

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