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Isık Yilmaz
Atilla Bagci

Soil liquefaction susceptibility and hazard mapping in the residential area of Kütahya (Turkey)

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I. Yilmaz (✉)
Department of Geological Engineering, Faculty of Engineering, Cumhuriyet University, 58140 Sivas, Turkey
E-mail: iyilmaz@cumhuriyet.edu.tr
Tel.: +90-346-2191010
Fax: +90-346-2191171

A. Bagci
JMS Ltd. Co, Hedef Sok. No. 6/2, YücetepeAnkara, Turkey

Abstract This study presents the results of both field and laboratory tests that have been undertaken to assess liquefaction susceptibilities of the soils in Kütahya city, located in the well-known seismically active fault zone. Liquefaction potentials of the sub-surface materials at Kütahya city were estimated by using the geological aspect and geotechnical methods such as SPT method of field testing. And, the data obtained have been mapped according to susceptibility and hazard. The susceptibility map indicated "liquefable" and "marginally liquefable" areas in alluvium, and "non-liquefable" areas in Neogene unit for the magnitude of earthquake of $M = 6.5$; whereas, liquefaction hazard map produced by using of liquefaction potential index showed the severity categories from "very low" to "high." However, a large area in the study area is prone to liquefy according to liquefaction susceptibility map; the large parts of the liquefable horizon are mapped as "low" class of severity by the use of the liquefaction potential index. It can be said that hazard mapping of liquefaction for a given site is crucial than producing liquefaction susceptibility map for estimating the severity. Both the susceptibility and hazard maps should be produced and correlated with each other for planning in an engineering point of view.

Keywords Kütahya · Liquefaction · Hazard · Severity · Standard penetration test · Susceptibility

Introduction

Liquefaction is defined as the transformation of a granular material from a solid to a liquefied state as a consequence of increased pore water pressure and reduced effective stress (Marcuson 1978). Increased pore water pressure is induced by the tendency of granular materials to compact when subjected to cyclic shear deformations (Youd and Idriss 2001). Cyclic stresses as a result of earthquakes lead to the development of special soil behaviors, especially in fully saturated granular soils. As a result of liquefaction, soil loses its shear strength and thus its bearing capacity, and cannot support structures and results in settlement, tilting, or overturning of structures, and various kinds of damages to lifeline systems (Mollamahmutoglu et al. 2003).

Liquefaction susceptibility refers to the relative ease with which materials at a particular site can be liquefied during an earthquake (Youd and Perkins 1978; Youd 1991). Liquefaction susceptibility is a function of the geotechnical properties and topographic position of the unit, and is dependent on the region's expected seismicity. Factors affecting liquefaction susceptibility include sedimentation process, age of deposit, water table depth, geologic history, grain-size distribution, depth of burial, density state, proximity to a free face, and ground slope (Youd and Perkins 1978). A susceptibility map delimits zones which are more prone to liquefaction due to mechanical properties. This map is based on geological, hydrogeological, and geotechnical data. On the other hand, an opportunity map represents the return period, for each point of interest, of earthquakes (or accelerations) which are great enough to cause liquefaction. The potential is obtained by combining both maps. As Tinsley et al. (1985) indicate, a map of potential demonstrates that the probability of the occurrence of liquefaction at one point can be greater than at another due to variations in the physical properties of the surface materials (susceptibility), or to the variations in the return period as a consequence of the position of each point with regard to the considered seismogenetic sources (opportunity) (Delgado et al. 1998).

Surface and near-surface geology and geomorphological criteria are also important for liquefaction susceptibility. Surficial geologic mapping is an effective means of delineating areas prone to seismic hazards. In particular, surficial geology is the most important factor controlling the liquefaction susceptibility, according to Youd (1991).

Potential of ground failure at a given site is more important than the knowledge about the soil liquefability at a given depth. The potential for liquefaction-induced ground failure is related to the thickness of liquefied soil layers and non-liquefied soil layers (Ishihara 1985). Ground failure can occur if the thickness of the overburdened non-liquefied layer is smaller than the thickness of underlay liquefied layer. But there will be no ground failure at this site if the thickness of non-liquefied layer is greater than a threshold value, which depends on the magnitude of the peak horizontal ground acceleration. Iwasaki et al. (1982) developed the liquefaction potential index (LPI) to predict the potential of liquefaction to cause foundation damage at a site or ground failure risk.

The study area is located at the western part of Turkey between 32,100–24,900 longitudes and 24,400–38,000 latitudes, and surrounded by Bursa and Bilecik provinces in the north, Balıkesir in the north-west, Eskis ehir in the east, Manisa in the west, Usak in the South, and Afyon province in the south-east. The city of Kütahya is affected by significant seismic hazards because of its proximity to the most active seismic zones in Turkey. According to the ''Turkey Earthquake Zoning Map'' prepared by the Ministry of Public Works and Settlement, the study area takes place both in first and second degree earthquake zones (Fig. 1). The objective of this study is to prepare the liquefaction susceptibility, liquefaction potential, and risk contour

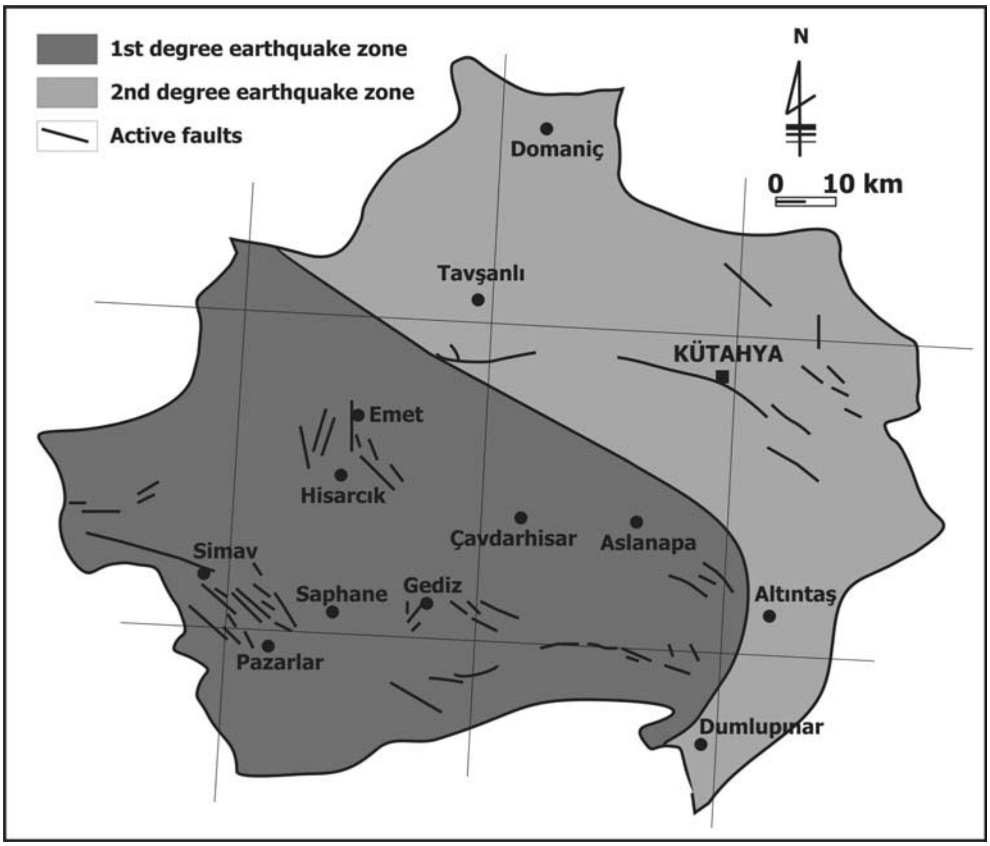

Fig. 1 Location map and earthquake zones

maps of the city of Kütahya. The investigation comprised two stages: field work and laboratory testing. Initially, geological and groundwater depth maps were produced. Thereafter, standard penetration tests (SPT) were conducted every 2 m down to 12 m. Grain-size distribution and saturated unit weight of the sample soils were determined by means of laboratory testing. Using corrected N values, and adopting an average saturated unit weight at the magnitude of earthquake of $M = 6.5$, the liquefaction susceptibility and potential hazard maps of the soils in the study area have been estimated. Finally, differences between liquefaction susceptibility and liquefaction hazard maps were discussed. It is thus hoped that this paper will serve civil and geotechnical engineers as well as engineering seismologists, architects, and urban planners in making rational decisions for selecting the appropriate design for new development projects in the city of Kütahya.

Geology and seismicity

The study area is characterized by very large Quaternary alluvium deposits and Neogene units. Quaternary deposits overlie the Neogene units with a disconformity (Fig. 2).

The Neogene is situated in the south of the study area and shows a sedimentary stratigraphy consisting of claystone, sandstone, siltstone, conglomerate, and marl. This unit underlies the alluvium, and is observed in some locations as an alternation of gravelly clay, tuff, and limestone. Grayish limestone contains thin interbeds of clay and cavities of dissolution.

Quaternary alluvium consists of varied grain sizes, and is derived from the various geological units in the vicinity. Their continuity cannot be established laterally and vertically. Alluvium in the study area is dominantly formed of sand, silt, and clay size materials. Gravels were observed rarely. Alluviums were also widespreadly outcropped in the north of the study area.

As is well known, the neotectonic framework of Turkey is outlined and characterized by major intracontinental strike-slip faults, namely the dextral North Anatolian fault zone and the sinistral East Anatolian fault zone, between which the Anatolian block moves westward relative to the Eurasian plate in the north and the Arabian plate in the south, owing to the continued convergence of these plates since the middle Miocene (McKenzie 1972; Dewey and Sengör 1979; Sengör 1980; Barka and Gülen 1988; Koçyiğit 1989) (Fig. 3).

The other striking secondary faults are the left-lateral Central Anatolian Fault Zone, the right-lateral Salt Lake Fault Zone, and the Inönü-Eskisehir and Aksehir oblique-slip normal fault zones (Koçyigit and Özacar 2003). The area of neotectonic extensional tectonic regime is effective in the southwestern part of Anatolia, partly covering the Central Anatolia region (Oral et al. 1995; Altiner et al. 1997; Reilenger 2002; Akman and Tüfekçi 2004).

Kütahya city is in the first and second seismic zones according to the seismic zoning map of Turkey (Fig. 2) (General Directorate of Disaster Affairs 1996). The

Fig. 2 Geological and documentation map of the study area

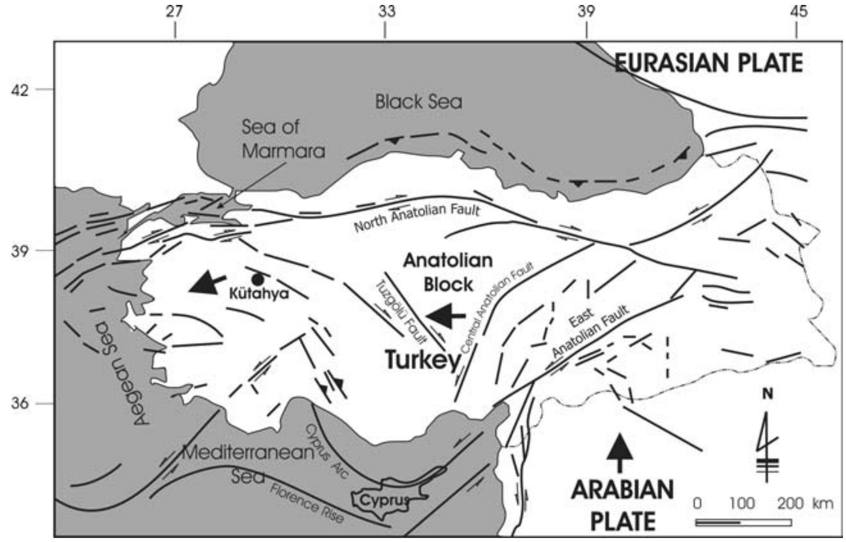

Fig. 3 Tectonic map of Turkey

region is known to be seismically active, and large earthquakes are historically known and expected.

The plot of earthquake (from 1900 to 2002) epicenters in the study area and its vicinity can be shown in Fig. 4. Magnitudes and counts of the earthquakes that occurred in the study area and vicinity have been tabulated in Table 1. Totally 83 earthquakes with magnitudes greater than 5.0 had occurred within the circle having a 150 km radius.

In 1969, Alasehir earthquake located 38.45°N and 28.50°E, with the magnitude $M_s = 6.9$ occurred, and 3,700 houses were destroyed, 53 people died, and more were injured.

The Gediz earthquake (1970) and other historical earthquakes are evidence of tectonic activity in and around the study area. The large earthquake with the magnitude $M_s = 7.1$ (28 March 1970 Gediz earthquake, at 23:02 on local time) within the Aksehir Fault zone caused widespread loss of life, and damage to buildings, roads, and lifelines. One thousand and one hundred people died and 520 people injured, and houses were damaged severely. Gediz earthquake is located approximately 39.2°N and 29.5°E. Another earthquake in Gediz with the magnitude $M_s = 5.9$ occurred (39.1°N and 29.7°E) on 19 April 1970, and 1,360 houses were severely damaged.

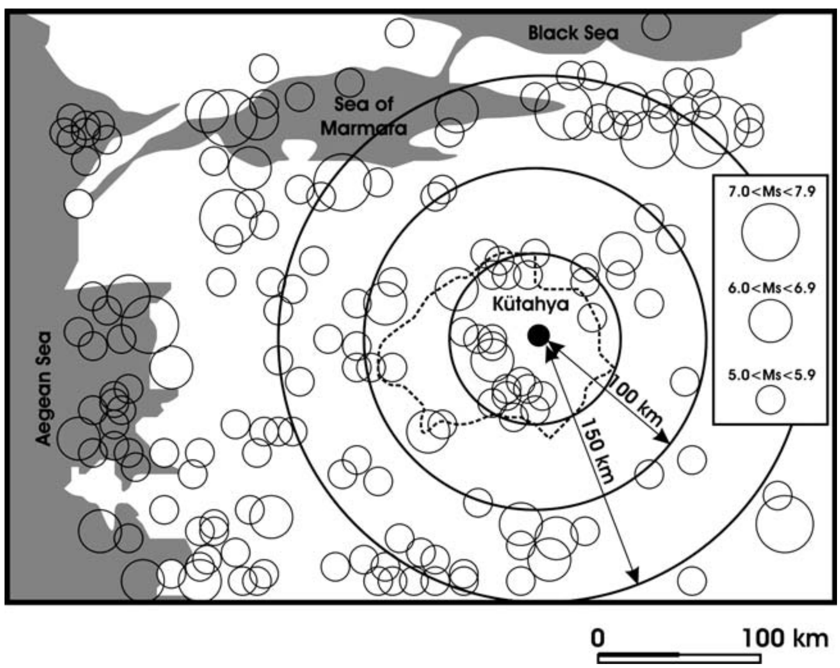

Fig. 4 Distribution of the earthquake epicentres between 1900 and 2002 (Kandilli Observatory, Turkey)

Table 1 Magnitudes and counts of the earthquakes occurred in the study area and vicinity having the magnitude greater than $M_s = 5.0$ between years 1900 and 2002

Radius from Kütahya city center	Magnitudes (M_s)	Count
50 km	$5.0 < M_s \leq 5.9$	20
	$6.0 < M_s \leq 6.9$	2
	$7.0 < M_s \leq 7.9$	–
100 km	$5.0 < M_s \leq 5.9$	34
	$6.0 < M_s \leq 6.9$	5
	$7.0 < M_s \leq 7.9$	–
150 km	$5.0 < M_s \leq 5.9$	68
	$6.0 < M_s \leq 6.9$	11
	$7.0 < M_s \leq 7.9$	4

An earthquake of magnitude 6.0 (M_d), according to Kandilli Observatory and Earthquake Research Institute of Bogaziçi University, occurred at 9:11 (7:11 GMT) local time on 3 February 2002 in the province of Afyon at the western part of Turkey. Based on the distribution of damage, site observations, and epicentral locations released by some earthquake institutes, the earthquake is called ''Çay–Eber Earthquake'' by the authors (Ulusay et al. 2002). Official estimates place the death tolls at 42 and injuries at about 325. The earthquake caused structural damages particularly in the settlements close to the epicenter such as Çay, Eber, and Sultandağı. It is estimated that about 10,000 buildings suffered light to moderate damage. In addition, a considerable number of structures collapsed and/or heavily damaged, generally resulting from poor construction and resonance phenomena. The Afyon province severely affected by the Çay–Eber earthquake is located within an area bounded by approximately 30–32°E and 38–39°N including the Kütahya city. Strong ground motion was observed (Ulusay et al. 2004). During this earthquake, in Kütahya province, 23 gal maximum ground acceleration value of 23 gal was measured (Tüzel et al. 2002), as a result of the distance from the earthquake epicenter ((100 km).

The entire Kütahya province is prone to large earthquakes ($M_w = 6.5$) and it has been postulated that there is around a 40% probability of a major earthquake affecting the region in the next 49 years (Gencoglu et al. 1990).

Hydrogeological conditions

The main drainage system is dominated by the Porsuk River, Felent, and Çandiras creeks. Porsuk creek is the most important one in the region, and originates from the near location to Agaçköy villages at the south of Kütahya. The mean monthly discharge rates of Porsuk River is 7.0–10.2 m^3/s. Felent and Çandiras creeks are secondaries having the respective approximate discharge value of 0.5 and 0.6 m^3/s.

In the study area, Quaternary alluvium is the most important formation as an aquifer. From the records of the boreholes drilled in different locations throughout the study area, it is evident that the groundwater table is generally shallow. The groundwater level is closely

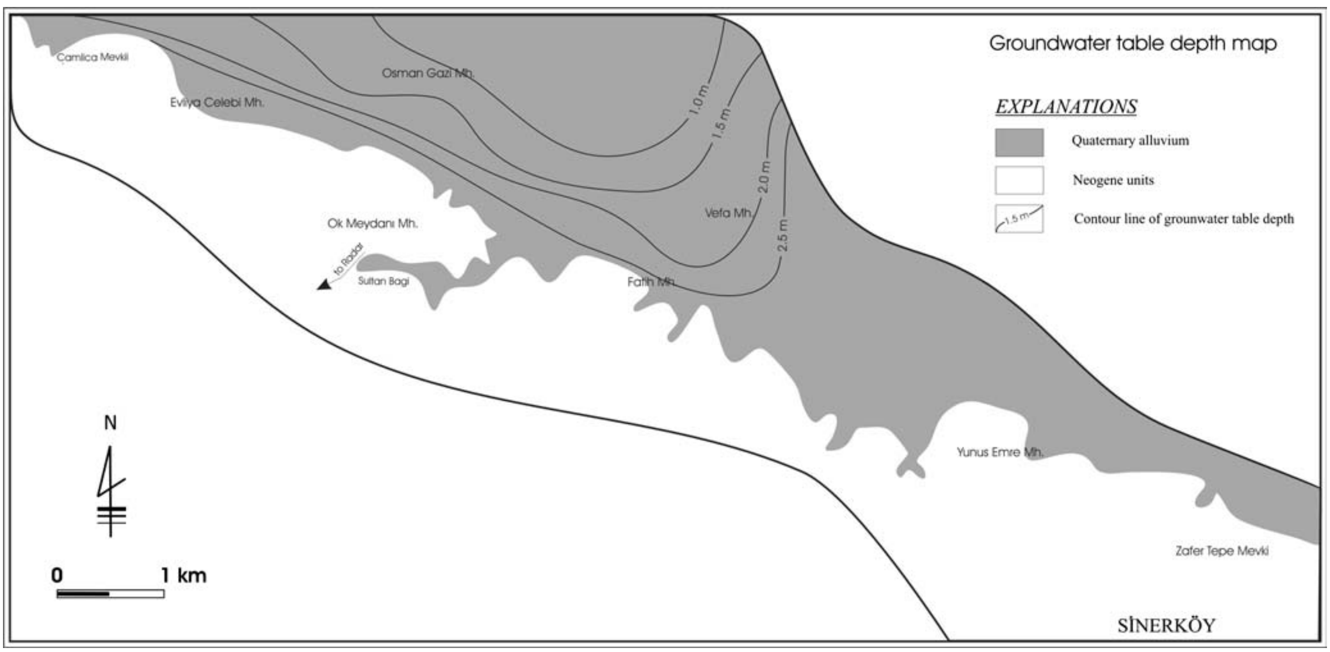

Fig. 5 Static groundwater depth map

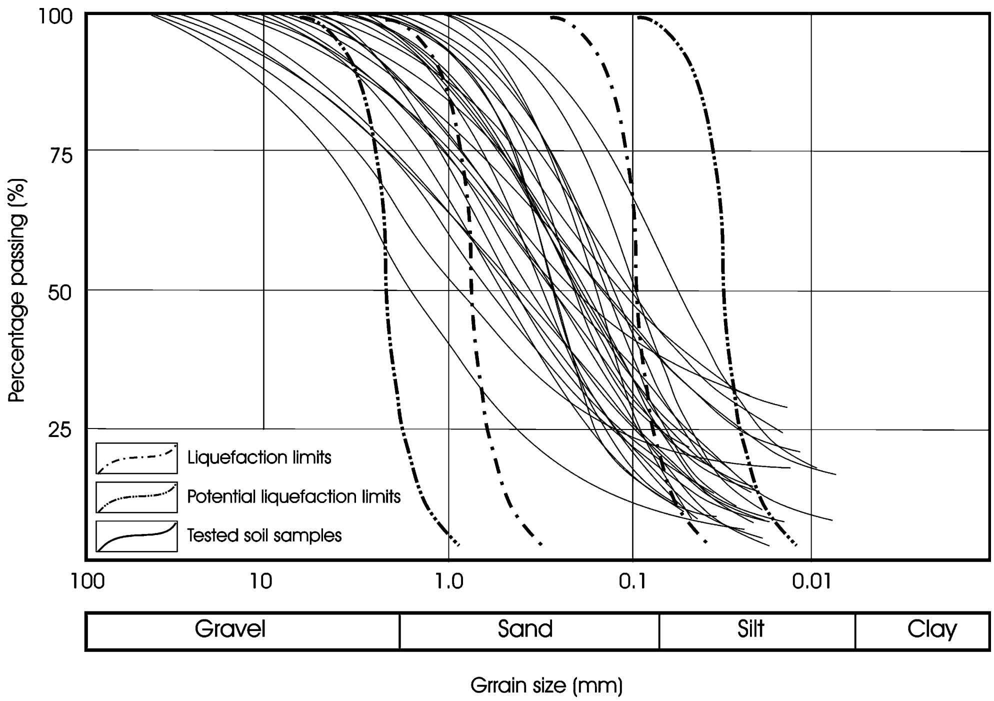

Fig. 6 Grain-size distribution of the soils

associated with the amount of precipitation and may be quite high when the monthly precipitation is high. The ground water level generally fluctuates between 1.0 and 4.0 m below the surface as seen in static groundwater depth map (Fig. 5). Measured discharge rates in the boreholes change from 3.0 to 40 l/s. In general, Neogene formations and impervious clayey and silty layers underlie the aquifer layers. The direction of the groundwater flow through the aquifer is generally toward the north in the Kütahya city. The high groundwater levels may contribute to the creation of conditions favorable to the occurrence of liquefaction during an earthquake.

Physical properties of the soils

During the field works, sampling of the soils was carried out at a number of locations, and laboratory testing was undertaken to determine the physical properties of the soils. Coarse sieve, fine sieve, and hydrometer methods were used for grain-size analyses of the soil samples. These analyses revealed that the soils are composed of 5% gravel, 70% sand, 15% silt, and 10% clay size material. Figure 6 shows the grain-size distribution curves and their position according to the well-known upper and lower bound curves for liquefaction susceptibility. It was seen that the obtained curves were in good agreement with those bounds. The D_{50} of the soil grains of 53% of the samples showed a scatter, and ranged between 0.11 and 0.3 mm, indicating that the soil is highly susceptible to liquefaction (Iwasaki 1986). Respective minimum, maximum, and mean values of D_{50} of the tested samples are 0.08, 2.1, and 0.41, respectively. All the grain-size distributions point to the SM and SC (poorly graded sand with silt and clay) group of soils. Both the high groundwater level and the grain size of the soils, in conjunction with the active seismic features of the region, result in conditions favorable to the occurrence of liquefaction.

Evaluation of liquefaction susceptibility

The loads applied to soils also occur slowly, which is why cohesionless soils have plenty of time to draw water into or out of the voids as they expand or contract. Little or no excess pore water pressures develop in these situations because the potential rate of drainage is greater than the rate of loading. Soil liquefaction can cause extensive damage, so geotechnical engineers working in seismically active areas need to be aware of the soil conditions where this phenomenon is likely occur. Differential settlements, slope failures, and tilted foundation due to the liquefaction cause damage to the buildings.

Cyclic stresses as a result of earthquakes lead to the development of special soil behavior, especially in fully saturated granular soils. As a result of liquefaction, the soil loses its shear strength and thus its bearing capacity, and cannot support structures and results in settlement, tilting, or overturning of structures, and various kinds of damages to lifeline systems (Mollamahmutoglu et al. 2003). Liquefaction susceptibility refers to the relative ease with which materials at a particular site can be liquefied during an earthquake (Youd and Perkins 1978; Youd 1991). Liquefaction susceptibility is a function of the geotechnical properties and topographic position of the unit and is dependent on the region's expected seismicity. Factors affecting liquefaction susceptibility include sedimentation process, age of deposit, water table depth, geologic history, grain-size distribution, depth of burial, density state, proximity to a free face, and ground slope (Youd and Perkins 1978). A susceptibility map delimits zones which are more prone to liquefaction due to mechanical properties. This map is based on geological, hydrogeological, and geotechnical data.

Surface and near-surface geology and geomorphological criteria are also important for liquefaction susceptibility. Surficial geologic mapping is an effective means of delineating areas prone to seismic hazards. In particular, surficial geology is the most important factor controlling the liquefaction susceptibility, according to Youd (1991).

Youd and Perkins (1978) have shown that by mapping the surface and near-surface geology, liquefaction susceptibility can be qualitatively assessed. When the surface and near-surface geological conditions were taken into consideration, it was seen that the study area's geology is prone to liquefaction, having moderate liquefaction susceptibility.

And also, if a correlation is established between past occurrences of liquefaction and geologic and geomorphological criteria, then this might be used to infer the likely area of liquefaction susceptibility. Such a study was done by Iwasaki et al. (1982) who developed the criteria. Therefore, if geologic and geomorphological criteria are considered, it should be understood that study area as discussed under the region's geology is susceptible to liquefaction.

Determination of absolute susceptibility requires site-specific geotechnical studies (Youd 1991). It is necessary to use geotechnical information in order to increase our knowledge of the susceptibility of the region. This information has been acquired through granulometric analyses and through SPT performed in 61 borings of 15 m (on average) in depth. Several techniques are available for the estimation of dynamic soil properties. Some of these have been compiled and tabulated (Table 2), with an indication for advantages and disadvantages for each type by Woods (1978) (after Teme 1990). Liquefaction potentials of such sub-surface saturated, fairly loose sandy units can be assessed by the use of field dynamic tests such as the SPT in conjunction with established methods such as those of Seed (1979). Appropriate foundation types could be selected and designed for engineering applications. According to Woods (1978), the SPT is a method that can be used in the empirical correlation with liquefaction potentials of the sub-surface materials. The studies of Seed and Lee (1966), Seed and Idriss (1971), Prakash and Gupta (1970), Finn et al. (1970), Castro and Poulos (1976), Casagrande (1976), Seed (1976), and Gupta (1979) have demonstrated that the liquefaction characteristics of a soil depend upon a larger number of factors. Although, it may not be possible at this stage of present knowledge to determine an index in terms of one single parameter, Seed and Idriss (1971, 1982), Christian and Swiger (1975), Seed et al. (1977, 1983, 1985), Tokimatsu and Yoshimi (1983), Seed and DeAlba (1986), and Youd and Idriss (2001) have shown that the SPT blow counts data, *N*, may ultimately solve this problem.

Table 2 Field techniques for measuring dynamic soil properties (Woods 1978) (after Teme 1990)

Field technique	P-wave velocity	S-wave velocity	Other measurements	Advantages	Disadvantages
Refraction	X	X	Depths and slope of layers	Reversible polarity, works from surface samples, large zone, preliminary studies	Misses low velocity zones, low strain amplitudes, properties measured are for thin zones near boundaries
Cross-hole	X	X		Known wave path, riversible polarity, works in limited space	Need two or more holes, needs to survey holes for vertically
Down-hole Up-hole	X	X		One hole only, reversible polarity, finds low velocity, works in limited space	Measures average velocities, ambient noise near surface, low strain amplitude
Surface		X	Attenuation of R wave	Works from surface	Uncertain about effective depth, needs large vibrator
SPT			Empirical correlation with liquefaction	Widely available, widely used in past	Needs "standardization"
Resonant footing			Modulus of near-surface soils	Works from surface	Limited depth of influence

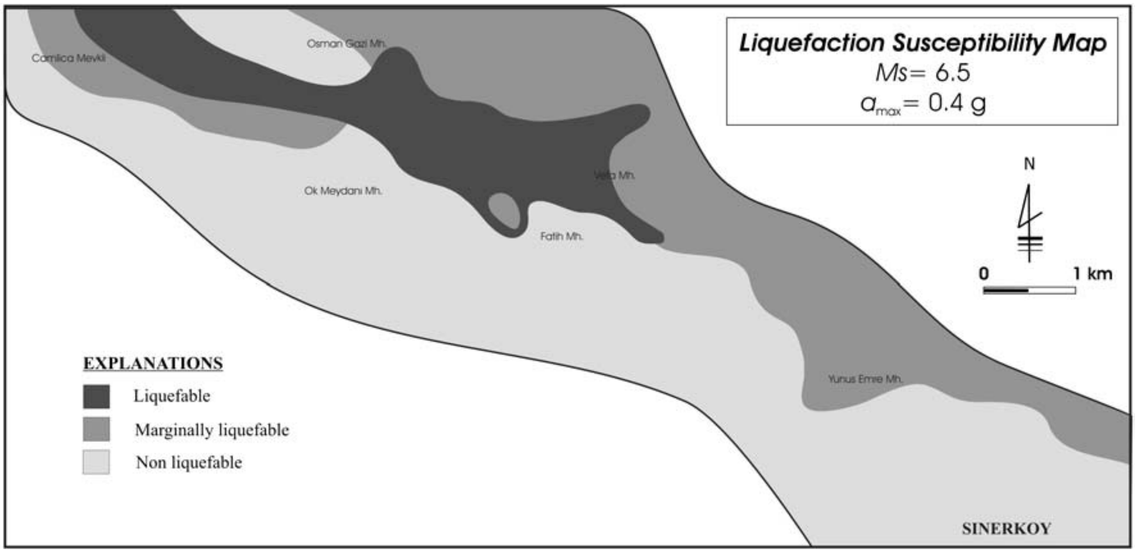

Fig. 7 Liquefaction susceptibility map

Evaluation of the cyclic stress ratio and cyclic resistance ratio

Calculation, or estimation, of two variables is required for evaluation of liquefaction resistance of soils: (1) the seismic demand on a soil layer, expressed in terms of cyclic stress ratio (CSR), and (2) the capacity of the soil to resist liquefaction, expressed in terms of cyclic resistance ratio (CRR) (Youd and Idriss 2001).

Cyclic stress ratio within a given site was calculated by using the following equation formulated by Seed and Idriss (1971):

$$\mathrm{CSR} = \frac{\tau_{\mathrm{av}}}{\sigma'_{\mathrm{vo}}} = 0.65\frac{a_{\max}}{g}\frac{\sigma_{\mathrm{o}}}{\sigma'_{\mathrm{o}}}r_{\mathrm{d}} \quad (1)$$

where $a_{\max}$ = peak horizontal acceleration at the ground surface generated by the earthquake; g = acceleration of gravity (9.81 m/sn^2); σ'_{o} and σ_{o} are total and effective vertical overburden stresses, respectively; and r_{d} = stress reduction coefficient, which can be estimated by the following equations defined by Liao and Whitman (1986):

$$r_{\mathrm{d}} = 1.0 - 0.00765z \quad \text{for } z \le 9.15\,\mathrm{m} \quad (2)$$

$$r_{\mathrm{d}} = 1.174 - 0.0267z \quad \text{for } 9.15\,\mathrm{m} < z \le 23\,\mathrm{m} \quad (3)$$

where z = depth below ground surface in meters.

A plausible method for evaluating soil liquefaction resistance is to retrieve and test undisturbed soil specimens in the laboratory. Unfortunately, in situ stress states generally cannot be re-established in the laboratory, and specimens of granular soils retrieved with typical drilling and sampling techniques, such as ground freezing, can obtain sufficiently undisturbed specimens. The cost of such procedures is generally prohibitive for all but the most critical projects. To avoid the difficulties associated with sampling and laboratory testing, field tests have become the state-of-practice for routine liquefaction investigations (Youd and Idriss 2001; Yilmaz and Yavuzer 2005).

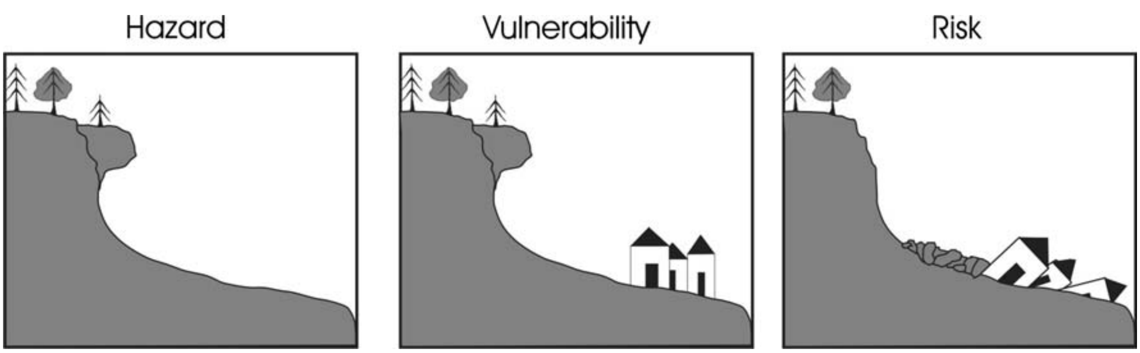

Fig. 8 Illustration of the terms hazard vulnerability and risk (Monge et al. 1998)

Standard penetration tests were conducted at 1.5 or 2.0 m intervals in the boreholes which were drilled by rotary methods, according to the test specification of ASTM D-1586 (American Society for Testing Materials 1990). Obtained raw SPT-N blow counts were corrected to obtain $(N1)_{60}$ (in Eq. 4). These corrections are overburden stress correction (C_N), correction for hammer energy during the test (C_E), correction for borehole diameter (C_B), correction for the length of rods used (C_R), and sampler correction (C_S).

$$(N1)_{60} = NC_N C_E C_B C_R C_S \tag{4}$$

In the above formula, C_E is taken as 0.7 for SPT hammer energy donut type, C_B is used as 1.0 for 65–115 mm borehole diameter, C_R is taken as 0.95 for 6–10 m rod length, and C_S is taken as 1.0 for standard sampler. Overburden correction factor of C_N is taken as 1.7 as consensussed in the NCEER Workshop (1997).

Finally, obtained $(N1)_{60}$ were corrected for fines content by using the following equation proposed by NCEER (1997).

$$N' = \alpha + \beta(N1)_{60} \tag{5}$$

where

$$\text{for FC} = 5\%;\ \alpha = 0,\ \beta = 1 \tag{6}$$

$$\text{for } 5\% < \text{FC} < 35\%;\ \alpha = e^{\left(1.76 - \frac{190}{\text{FC}^2}\right)},\ \beta = 0.99 + \frac{\text{FC}^2}{1,000} \tag{7}$$

$$\text{for FC} \geq 35\%;\quad \alpha = 5,\ \beta = 1.2 \tag{8}$$

Cyclic resistance ratio expressing the resistance of the soil to liquefaction was calculated by using the formula given by Blake (1997);

$$\text{CRR} = \frac{-0.048 - 0.004721N' + 0.0006136(N')^2 - 1.6731^{-5}(N')^3}{1 - 0.1248N' + 0.00957(N')^2 - 0.0003285(N')^3 + 3.7141^{-6}(N')^4} \tag{9}$$

In the last stage of the evaluation of the liquefaction analyses, factor of safety (FS) against liquefaction was computed by

$$\text{FS} = \frac{\text{CRR}}{\text{CSR}}\text{MSF} \tag{10}$$

MSF in Eq. 10 is the earthquake magnitude scaling factor. MSF can be calculated as suggested in NCEER (1997).

$$\text{MSF} = \frac{10^{2.24}}{M_w^{2.56}} \tag{11}$$

The procedure based on the field performance data was used in this study to evaluate liquefaction susceptibility. FS to liquefaction of the soils in the study area were estimated by using a computer model for the magnitude of earthquake of $M = 6.5$, and $a_{max} = 0.4$. The study area is in the second degree (also very near to first degree risk zone) risk zone of the earthquake zoning map of Turkey (General Directorate of Disaster Affairs 1996). The layers with factors of safety greater than 1.2, between 1.0 and 1.2, and lower than 1.0 were predicted to be non-liquefable, marginally liquefable, and liquefable, respectively. The susceptibility maps of the soils to liquefaction based on the earthquake magnitude of $M = 6.5$ can be shown in Fig. 7.

The areas mapped as having high liquefaction susceptibilities will be prone to liquefy in a future earthquake, and those areas mapped as marginally liquefable will probably liquefy, and non-liquefable areas will not. It was evaluated that the alluviums in the study area were liquefable and marginally liquefable; however Neogene sediments were non-liquefable.

Evaluation of liquefaction potential and hazard mapping

To define the liquefaction hazard, we must first clarify the term "hazard," taken as a component of natural risks, and then define the phenomenon of soil liquefaction. The definitions below are based on the international multilingual glossary of terms concerning disaster management, which was drawn up as a part of the International Decade for Natural Disaster Reduction. Figure 8 illustrates the various terms (Monge et al. 1998).

Hazard: "A threatening event, or the probability of occurrence of a potentially damaging phenomenon within a given time period and area." Hazard includes the probability of location in space, which is conditioned by permanent factors of predisposition and susceptibility, the probability of occurrence within a time interval that is conditioned by triggering factors, and the intensity of the phenomenon (Monge et al. 1998).

Vulnerability: "Degree of loss (from 0 to 100%) resulting from potentially damaging phenomenon" (Monge et al. 1998).

Risk: "Expected losses (deaths, injuries, property damage, and disruption of economic activity) due to a particular hazard for a given area and reference period. Based on a mathematical calculation, risk is the product of hazard and vulnerability.'' This academic, but generally accepted, definition of risk must be established for each hazard type, and in particular for the liquefaction phenomenon (Monge et al. 1998).

More important than the question of whether the soil at a given depth will liquefy is the potential of ground failure at a given site. Ishihara (1985) concluded that the potential for liquefaction-induced ground failure was related to the thickness of liquefied soil layers and non-liquefied soil layers. If the thickness of the overburden non-liquefied layer is smaller than the thickness of underlay liquefied layer, ground failure will occur. If the thickness of non-liquefied layer is greater than a threshold value, which depends on the magnitude of the peak horizontal ground acceleration, there will be no ground failure at this site. The meaning of the calculated factors of safety is not consistent, as some methods are more conservative than others. Iwasaki et al. (1982) developed the LPI to predict the potential of liquefaction to cause foundation damage at a site or ground failure risk. They assumed that the severity of liquefaction should be proportional to the

1. thickness of the liquefied layer;
2. proximity of the liquefied layer to the surface; and
3. amount by which the FS is less than 1.0, where FS is the ratio of the liquefaction resistance to the load imposed by the earthquake (Toprak and Holzer 2003).

Because surface effects from liquefaction at depths greater than 20 m are rarely reported, they limited the computation of LPI to depths (z) ranging from 0 to 20 m.

Different levels of intensity are associated with the liquefaction potential. These depend on the probability of occurrence of the phenomenon or its scale. The intensity of liquefaction can be defined from? the overall liquefaction index. The index LPI is defined as follows:

$$\mathrm{LPI} = \int_0^{20} F_1 w(z)\,\mathrm{d}z$$

where F_1 is an index defined as: F_1 = 1 - FS, if FS $\leq$ 1.0; and $F_1 = 0$ if FS > 1.0. $w(z)$ is a weight function of the depth, which is used to estimate the contribution of soil liquefaction at different depths to the failure of the ground. The weight function is assumed to be a linear function:

$$w(z) = 10 - 0.5z$$

where z is the depth from the ground surface in meters. Iwasaki et al. (1982) used the liquefaction evaluation method recommended in the Japanese Highway Bridge Design Code (JSHE 1990) to calculate the FS. Based on his analysis of a database of 64 liquefied sites and 23 non-liquefied sites from six earthquakes, Iwasaki et al. (1982) provided the following liquefaction risk criteria as severity categories, referred to herein as the Iwasaki criteria: IL = 0, the liquefaction failure potential is extremely low; 0 < IL ≤ 5, the liquefaction failure potential is low; 5 < IL ≤ 15, the liquefaction failure potential is high; IL > 15, the liquefaction failure potential is extremely high (Lee et al. 2003). Liquefaction hazard map prepared based on the LPI can be seen in Fig. 9.

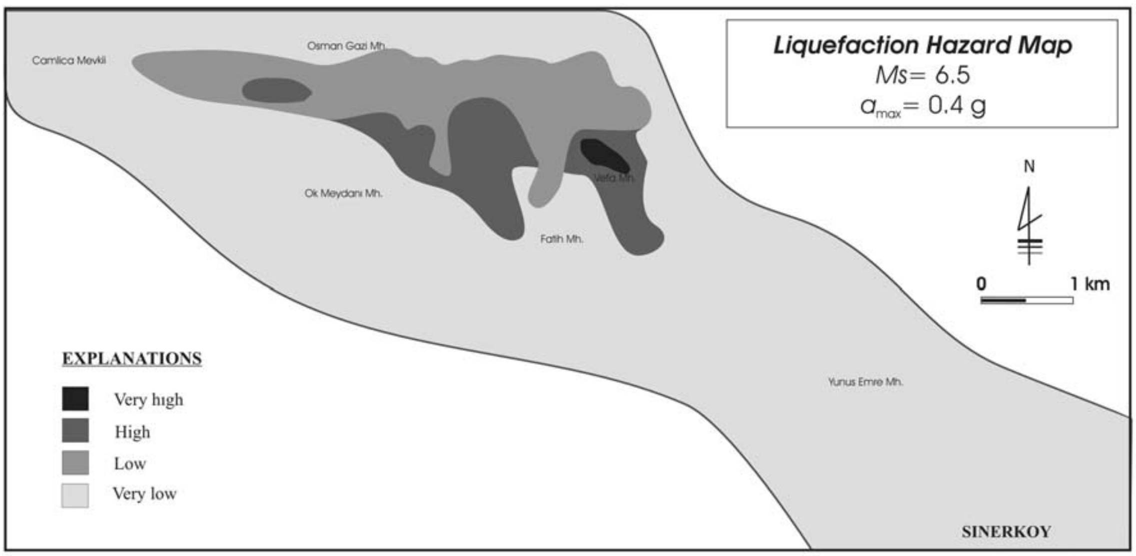

Fig. 9 Liquefaction potential hazard map

Liquefaction hazard map prepared according to the LPI showed that the large parts of the liquefable horizon was mapped as ‘‘low’’ class of severity.

Results and conclusions

Results of both field and laboratory works that have been used to assess liquefaction susceptibilities of the soils in Kütahya city located in the seismically active zone are presented in this study. Liquefaction potentials of the sub-surface materials at Kütahya city were estimated by using the geological aspect and geotechnical methods such as SPT method of field testing. And, finally the obtained data have been mapped according to susceptibility and hazard.

The susceptibility map based on the geotechnical data indicated ‘‘liquefable’’ and ‘‘marginally liquefable’’ areas in alluvium, and ‘‘non-liquefable’’ areas in Neogene unit for the magnitude of earthquake of $M=6.5$; whereas, liquefaction hazard map produced by using LPI showed the severity categories from ‘‘very low’’ to ‘‘high.’’

Grain size of the soils in conjunction with the active seismic features of the region result in conditions is favorable to the occurrence of liquefaction. The high groundwater levels may contribute to the creation of conditions favorable to the occurrence of liquefaction during an earthquake. When the surface and near-surface geological conditions were taken under consideration, it was seen that the study area's geology is prone to liquefaction.

Dynamic in situ soundings employing the SPT were carried out in the city of Kütahya and values of N (corrected) obtained were used to evaluate both the shear stress that could cause liquefaction (τ_d/σ_o') and the soil liquefaction resistance (τ_l/σ_o') that would be developed during earthquake having a magnitude of 6.5. The in situ SPT investigations were restricted to the sandy, silty strata since N values have been found to be more reliable in sands than in clay strata, as reported by Peck et al. (1974). According to the geotechnical determinations of the soils, areas mapped as liquefable and probably liquefable, will probably liquefy in a future earthquake.

In order to prevent the occurrence of possible soil liquefaction and attendant settlement of buildings, it has been recommended that a raft or deep footing of a suitable thickness (below the liquefable zone) should be used to bear both static and dynamic stress. Site response effects will be more important for any structure greater than about three storeys in height, sited on Quaternary alluvium.

Severity categories of the study area were estimated as ‘‘very low,’’ ‘‘low’’, and ‘‘high,’’ by using the LPI. ‘‘Marginally liquefable’’ and ‘‘liquefable’’ areas in liquefaction susceptibility map were classified as having ‘‘very low’’ severity and ‘‘low-high’’ severity in liquefaction hazard map, respectively. However a large area in the north of the study area is prone to liquefy according to liquefaction susceptibility map, the large parts of the liquefable horizon was mapped as ‘‘low’’ class of severity by use of the LPI. A liquefaction susceptibility mapping is sufficient only to predict that a layer can liquefy or not. It can be said that hazard mapping of liquefaction for a given site is crucial than producing liquefaction susceptibility map, for estimating the severity. Both of the susceptibility and hazard maps should be produced and correlated with each other for planning in an engineering point of view.

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