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ASSESSMENT OF LIQUEFACTION/CYCLIC FAILURE POTENTIAL OF ALLUVIAL DEPOSITS ON THE EASTERN COAST OF CYPRUS

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ABSTRACT

The main objective of this paper is to evaluate liquefaction potential and cyclic failure of subsoils of Tuzla area located on the eastern coast of Cyprus. The in-situ tests of cone penetration test (CPT) and standard penetration test (SPT) were used for site specific evaluation of liquefaction potential. Index properties and undrained shear strength (s_u) were used to assess cyclic failure potential of fine-grained soils. Liquefaction potential index (LPI) was evaluated based on the calculated factor of safeties for each CPT location. Sensitivity of soils was indirectly estimated from liquidity index (LI). The samples tested displayed high sensitivity values, indicating vulnerability to loss of strength and excess deformations during cyclic loading.

INTRODUCTION

Soil liquefaction has been one of the most important problems during past earthquakes in the field of geotechnical earthquake engineering. It occurs as a result of ground shaking during earthquake, manifesting itself as loss of strength and stiffness of mostly saturated sandy soils. Hence during strong ground shaking, saturated sediments behave like viscous fluid, increased pore-water pressure results in decrease in effective stress, dispersing the soil particles hence causing collapse of masses.

The 1999 Kocaeli earthquake (M_W=7.5) in Turkey, is the most recent case study, as a consequence of which more than 1200 buildings were destroyed or seriously damaged, hundreds of structures tilted and penetrated into the ground as a result of soil liquefaction and ground softening (Sancio et al., 2002). Likewise, in 1995, Kobe earthquake in Japan caused more than one hundred billion US dollars in total damage (Hamada et al., 1995).

The liquefaction potential of sands and silty sands under strong earthquakes had been studied extensively over the years and procedures for determination of safety factor for liquefaction during strong earthquakes are developed (Youd et al., 2001). One of the early works on this phenomenon has been presented by Wang (1979) based on the observations of initial field case studies for liquefaction type hazards encountered during Chinese earthquakes. Alternatively, Seed et al. (1983) have developed the “Chinese Criteria” for evaluation of liquefaction susceptibility of fine-grained soils based on the liquid limit, LL (%), clay fraction, -5μm (%) and natural water content w_c (%).

Youd (1998) studied cyclic failure of sensitive clays and concluded that if soils are classified as CL-ML having $(N_1)_{60}$<5, with sensitivity S_r>4, liquidity index of LI>0.6 and natural water content of w_c>0.9LL, then they are liquefaction/cyclic failure susceptible. Likewise, Durgunoglu et al. (2004a) employing systematic cyclic triaxial tests on a soft sensitive clay located north of Istanbul, Turkey, has reported similar results. According to Perlea (2000), any type of soil including cohesive soils and sensitive clays could liquefy depending on the magnitude of shaking, and fine-grained soils require more released energy than in sands. It is also concluded that liquefaction /cyclic failure of fine grained soils does not occur with M_w=7.2. This observation is also justified by laboratory studies observing that longer time and more number of cycles are necessary for fine-grained soils, compared to sands, until the liquefaction-cyclic failure state is reached.

Andrews & Martin (2000) have also developed a new criterion for the liquefaction potential of fine-grained soils, similar to the Chinese Criteria but clay fraction taken as -2μm (%) instead of -5μm (%). Polito (2001), Seed et al. (2003) and Bray et al. (2004b), on the other hand, studied the influence of plasticity index on the liquefaction/cyclic failure of fine grained soils, which is ignored in both Chinese Criteria and Andrews and Martin's (2000) charts. The three methods proposing to utilize PI, however, do not consider the earthquake magnitude and preferably should be utilized for earthquake magnitudes of $M_w \geq 6.5$.

This study was carried out in Tuzla area, situated in the northwest of the city of Famagusta, subject area being within one kilometer from the Famagusta Bay, Cyprus. Once known as Alasia, Tuzla used to be a harbor town, back in 2000 B.C., and was partially destroyed when hit by a devastating earthquake by the end of the 1300 B.C. As the River Pedios gradually filled the harbor with alluvium, it was abandoned in the 11th century. Nowadays, building, highway and infrastructure constructions are rapidly developing in the region, and there is a growing residential population in Tuzla, because of its nearness to Famagusta and easy access to Nicosia Road.

Historical earthquake records of the vicinity of Cyprus showed that Tuzla region is a critical area on Famagusta coast which experienced strong earthquakes of magnitudes $M_w = 6.0$ to 8.0. Consequently, there is an urgent need for the assessment of the potential liquefaction/cyclic failure. The first liquefaction assessment study and an attempt for a small scale microzonation was carried out earlier in the region by Durgunoğlu and Bilsel (2007) based on index properties and undrained shear strength of alluvial deposits.

This study incorporates a more detailed geotechnical investigation carried out to provide a better understanding of liquefaction susceptibility of local soils in Tuzla. The study includes evaluation of the soil liquefaction potential/cyclic mobility of Tuzla region over a wider area, based on SPT and CPT criteria, as well as index properties, and undrained shear strength.

SEISMICITY OF CYPRUS

Although seismograph network operations have begun in Cyprus in 1997, the long historical record of damaging earthquakes of the island is well known back to 92 BC (Ambraseys, 1993). However, details related to both onshore and offshore active faulting and earthquake occurrence are not yet well identified. Recently, scientists have been working on the tectonic record of the island for evaluation of the present day seismic hazard. The earthquake hazard assessment of Cyprus has been funded by United Nations Office for Project Services (UNOPS) and probabilistic seismic hazard maps for the island and site response of Nicosia area were evaluated, based on a revised seismic catalog for the complete historical record. The peak ground acceleration (PGA) maps with 10% chance that the calculated ground motions will be exceeded in 50 years or 250 years were developed. The regional ground motion map of Cyprus was eventually produced based on a seismotectonic model, distribution of historical seismicity, earthquake recurrence rates, assumptions of maximum earthquake magnitudes and the attenuation of strong-ground motion for certain earthquake fault types. The PGA value required for the liquefaction potential calculations of Tuzla is estimated from the maps provided as an end product of the study held by the support provided by UNOPS, Seismic Hazard and Risk Assessment of the Greater Nicosia Area, (Decoster, et al., 2004).

Regional Geology and Tectonics

Cyprus has a long historical record of damaging earthquakes, (Ambraseys, 1992; Ambraseys & Adams, 1993). Past studies on seismotectonic setting of Cyprus hypothesize that the island is either on or near the crustal plate boundary between the Anatolian Subplate and the African Plate, and 100 km west of the Arabian Plate. The principal tectonic elements of the Northeastern Mediterranean Region are shown in Fig. 1 (Barka, 1992; USGS, 1999).

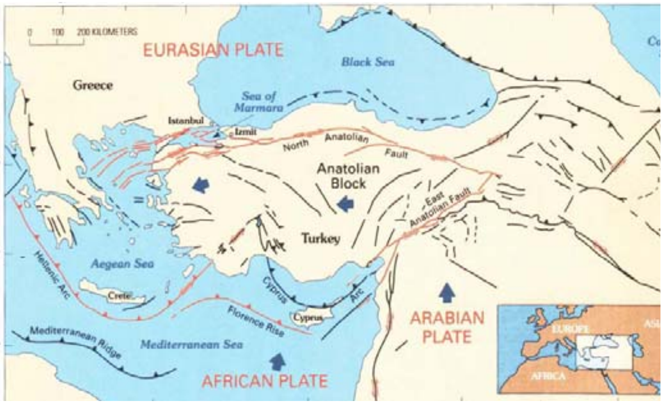


Fig 1. Map showing the principal tectonic elements of the northeastern Mediterranean region (Barka, 1992; USGS, 1999).

Studies indicate that the African Plate is moving northeastward with respect to the Eurasian Plate, while the Arabian Plate is moving northward at a faster rate. Hence the Anatolian Subplate is pushed westward by the collision of these two plates and thus Cyprus can be considered moving together with it. All these and many other tectonic elements are well known to be present in the vicinity of Cyprus. It is also known that damaging earthquakes in the past have taken place along both southern and eastern coastal areas of Cyprus at shallow depths.

Figure 2 depicts the four principal terrains of Cyprus: the Troodos Massif, the Circum-Troodos Sediments, the Kyrenian Range and the Mesaoria. The subject area in this study is located at the eastern shore of Mesaoria plain, which is a flat land consisting of Holocene alluvial deposits.

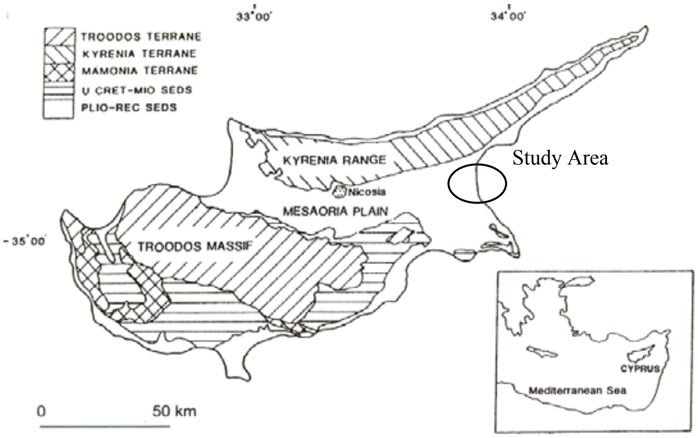


Fig. 2. Generalized geological map of Cyprus showing the principal geological terrains (McCallum and Robertson, 1990).

The ages of the crustal faults of Cyprus are not certain. However, it is believed that a potentially significant fault with tentative Holocene movement and certain Pliocene activity is bordering the southern edge of Mesaoria basin which is thought to cause cyclic mobility of deposits in the subject area. Earthquakes within the past 300 years are the dominant factor in estimating ground motion likely to occur in the next 50 years which is the life expectancy of new structures.

Regional Seismicity

Figure 3 shows the full catalog of historial earthquake records on the island. Even though Cyprus has not been as active as the surrounding regions, Turkey, Greece, Syria, Israel and Lebanon, there have been numerous damaging earthquakes in the region. Even though seismicity mainly occurred south of Mesaoria plain, several large earthquakes are located beneath Mesaoria. Therefore, based on these historical records and evidence, it is essential to do research on earthquake induced behavior of soils on the island. Tuzla in the south eastern part of Mesaoria is chosen as the study area for liquefaction potential susceptibility.

From the probabilistic hazard map for a firm rock site developed by Algermissen & Rogers (2004) the PGA for the city of Famagusta is predicted to be 0.22g-0.25g. In this study it is taken approximately as 0.25g.

BACKGROUND

Sandy soils are well known to be susceptible to liquefaction during strong earthquakes, which have been studied over the last thirty years. However, liquefaction/cyclic failure susceptibility of fine-grained soils is still under discussion.

Perlea (2000) discussed the effect of magnitude of earthquake and epicentral distance of all soil types, including loose sands, cohesive soils, sensitive clays and collapsible loess based on the field observations of liquefaction induced hazard during numerous strong earthquakes in the period of 1944 to 1989. Results have proved that, any type of soil including cohesive soils and sensitive clays could be susceptible to liquefaction depending on the magnitude of earthquake.

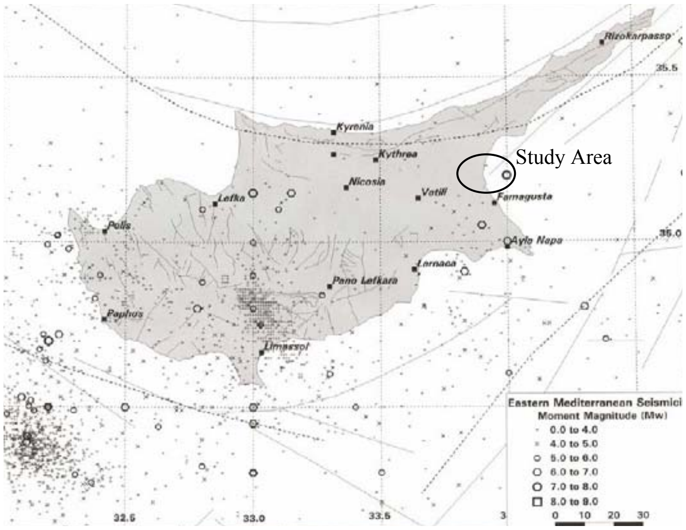


Fig. 3. A map of all earthquakes in the historical record in the immediate vicinity of Cyprus (Algermissen and Rogers, 2004).

During two major earthquakes in 1999, Kocaeli and Duzce (Turkey) earthquake and Wu Feng, Yuan Lin and Nantou Chi-Chi (Taiwan) earthquakes, significant liquefaction-type damages such as settlement and bearing capacity failure of shallow-founded structures occurred mainly in cohesive soils. According to Seed et al. (2003) cohesive soils that are highly "sensitive" were often neglected in terms of their susceptibility to liquefaction. However, these types of soils are vulnerable to major strength loss if sheared or remolded. Additionally, it was recommended that the Modified Chinese Criteria be relegated to history, because, "percent clay fines" is less important than the overall contribution of the fines to plasticity.

Recently, Bray et al. (2004) have generated new criteria to evaluate liquefaction susceptibility of fine-grained soils. Cyclic triaxial tests were carried out on the undisturbed samples, silty and clayey soils of Adapazari, Turkey. The results of cyclic tests showed that the Chinese Criteria are not reliable for determining the liquefaction susceptibility of fine-grained soils. Soils that are observed to have liquefied in Adapazari during Kocaeli earthquake did not typically meet the clay-size criterion of the Chinese Criteria. As a consequence, results demonstrated that the condition based on the amount of particles is a miss-indicator of liquefaction susceptibility.

A study on a soft sensitive clay located north of Istanbul, Turkey by Durgunoglu et al. (2004a), utilizing cyclic triaxial tests on undisturbed samples conclude that, even high plasticity clays of CH type can generate significant strains in a small number of cycles when a high cyclic stress ratio (CSR) is applied contrary to Chinese Criteria. The main deficiency of the Chinese Criteria evidently is that the magnitude of earthquake or CSR value is not considered.

Boulanger and Idriss (2006) have presented new liquefaction susceptibility criteria for saturated silts and clays based on the mechanics of their stress-strain behavior. As a result, an improved guidance for selecting engineering procedures for estimating potential strains and strength loss during seismic loading is provided. Monotonic and cyclic undrained loading tests were carried out and the results for silts and clays showed that there is a transition over a fairly narrow range of plasticity indices (PI), from soils behaving more fundamentally like sands (sand-like behavior) to soils behaving more fundamentally like clays (clay-like behavior). Fine-grained soils exhibit clay-like behavior if they have PI ≥ 7.

Boulanger and Idriss (2006) recommended that, for fine-grained soils that behave more fundamentally like clays, the cyclic and monotonic undrained shear strengths are closely related and show relatively unique stress-strain normalized behaviors. Cyclic strengths can then be determined based on information from in-situ testing, laboratory testing and empirical correlations that are similar to established procedures (Boulanger and Idriss, 2004) for evaluating the monotonic undrained shear strengths of such deposits.

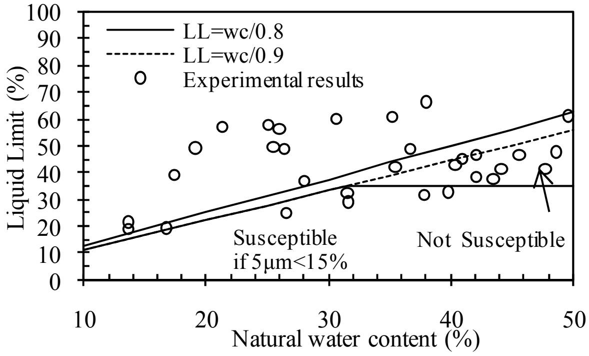
More recently, Boulanger and Idriss (2007) have predicted procedures for assessing the potential for cyclic softening in saturated silts and clays during earthquake. The recommended procedures are applicable for fine-grained soils that behave more fundamentally like clay. The procedures were presented in a form that is similar to that used in semi-empirical liquefaction procedures. The application of these procedures and the associated liquefaction susceptibility criteria were demonstrated for the Carrefour Shopping Center case study from the 1999 Kocaeli Earthquake, Turkey. The results show that, cyclic softening in clay-like fine-grained soils occurred as a result of sensitivity, the specific site conditions (e.g., presence of a slope or building foundation), and the earthquake ground motion. Boulanger and Idriss (2007) state that, normally consolidated or lightly consolidated, sensitive clays and silts may have relatively low cyclic strengths and may lose significant strength if the earthquake-induced strains are large enough. Otherwise, clays and silts with higher OCR have much greater cyclic strengths and lower susceptibility, such that even very strong shaking might not necessarily present a major problem.

Liquefaction Assessment of Fine-Grained Soils of Tuzla by Index Properties

In this study Atterberg limits, percentage of clay fractions (<5 µm and <2 µm), and natural water content are used to evaluate liquefaction potential of fine-grained soils, based on the following criteria.

Chinese Criteria. Wang (1979) and Seed and Idriss (1982) have evaluated the Modified Chinese Criteria which is the criteria most widely used to identify potentially liquefiable soils. According to these criteria, fine-grained soils (cohesive) are considered to be potentially liquefiable provided less than 15% “clay” fines (based on the Chinese definition of “clay” sizes as less than 0.005 mm) exits, liquid Limit less than or equal to 35%, and the natural in-situ water content greater than or equal to 90% of liquid limit.

Based on Chinese criteria for Tuzla soils, only a few points are on the liquefaction susceptible zone, based on liquid limit versus natural water content relationship as depicted in Fig. 4.



.Fig. 4.Chinese Criteria applied to fine-grained soils of Tuzla, based on liquid limit versus natural water content

Andrews and Martin (2000) Criteria. Parameters of liquid limit (%) and clay fractions, -2µm (%) based on Andrews and Martin (2000) criteria are plotted for Tuzla soils as in Fig. 5. None of the points are liquefiable according to Andrews and Martin (2000) criteria. However, for some points further study is recommended.

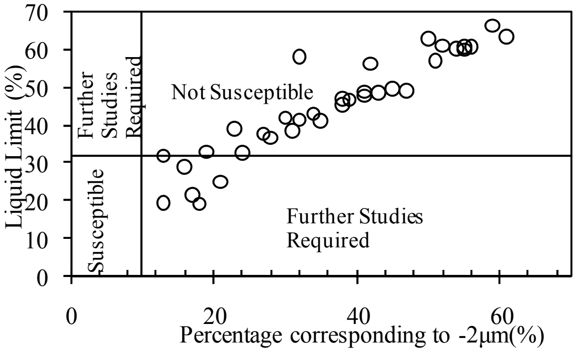


Fig.5. Andrews and Martin (2000) criteria for Tuzla soils.

Polito (2001) Criteria. The influence of plasticity index on the liquefaction of fine-grained soils developed by Polito (2001) was implemented for the study area. Liquefiable points of Tuzla region according to Polito (2001) criteria are shown in Fig. 6.

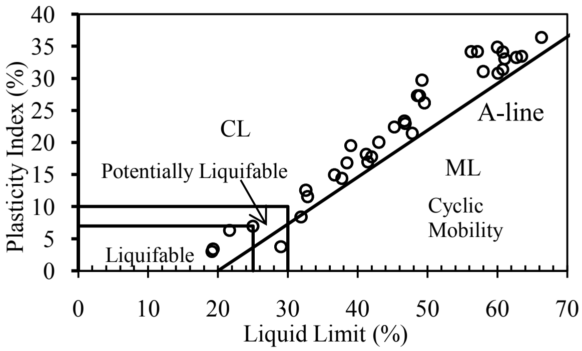


Fig.6. Polito (2001) criteria for the study area.

Seed et al. (2003) Criteria. Seed et al. (2003) criteria give more critical points than the other four methods. The soils in Zone A are potentially susceptible to "classic" cyclically induced soil liquefaction. Soils within Zone B fall into a transition range; they may in some cases be susceptible to liquefaction, especially in cases where their in-situ water content is greater than about 85% of their liquid limit. However, those soils tend to be more ductile and may not "liquefy" in the classic sense. Soils in Zone C are usually not susceptible to "classic" cyclically-induced soil liquefaction, but they may be "sensitive" and vulnerable to strength loss.

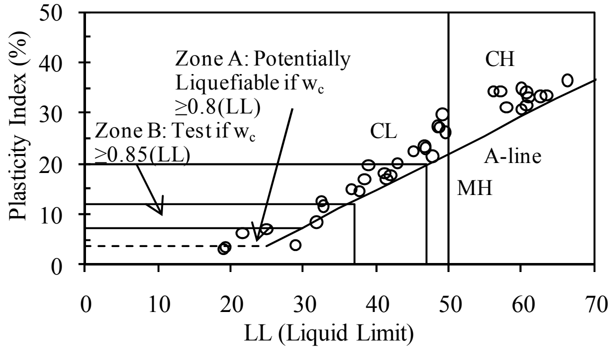


Fig.7. Fine-grained soils based on Seed et al. (2003) for Tuzla soils.

Bray et al. (2004) Criteria. These results indicate that, liquid limit, plasticity index and water content based criteria are good indicators of liquefaction susceptibility. It is also concluded that, the criterion based on the amount of particles smaller than 2 µm or 5 µm, is not a correct approach for evaluation of liquefiable soils. These results indicate that, liquid limit, plasticity index and water content based criteria are good indicators of the soil's response and thus liquefaction susceptibility.

In-situ Test Results

Soil liquefaction potential of Tuzla area was also evaluated by in-situ tests of standard penetration test (SPT) and cone penetration test (CPT). During this study, 10 CPT soundings were installed and 5 soil borings closely spaced to CPT locations were drilled in Tuzla to further investigate the subsurface conditions.

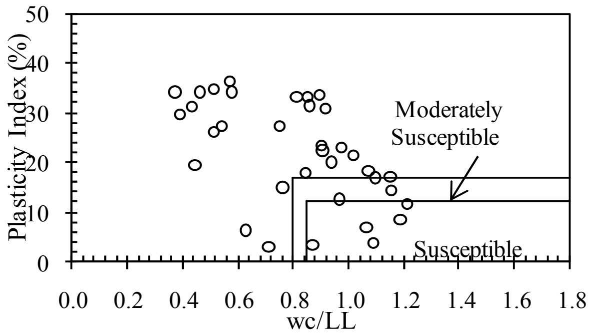


Fig.8. Bray et al. (2004) criteria vs. Tuzla soils.

Standard Penetration Test. Factor of safety ($FS_{7.5}$) against liquefaction for earthquake magnitude of 7.5 was determined based on CSR and $CRR_{7.5}$ values. For different earthquake magnitudes FS was determined by using magnitude scaling factor (MSF) from a range of recommended values given by Youd et al. (2001). For this study, factor of safety values were estimated for earthquake magnitudes of M_w = 6.5, 7.0, 7.5. Calculated CSR, CRR and factor of safeties only for M_w= 7.5 are summarized in Table 1. The FS values are mostly below 1.0, indicating a high liquefaction potential in the region.

Table 1. Calculated factor of safeties against liquefaction based on SPT results.

BH	Depth (m)	$(N_1)_{60}$	$(N_1)_{60CS}$	$CRR_{7.5}$	CSR	$FS_{7.5}$
1	3.0	58	65	0.44	0.34	1.3
	9.0	4	9	0.11	0.32	0.3
2	3.0	6	12	0.13	0.34	0.4
	7.5	2	7	0.09	0.33	0.3
3	3.0	9	15	0.16	0.34	0.5
	8.0	2	7	0.09	0.32	0.3
	8.9	13	20	0.22	0.32	0.7
4	3.0	5	11	0.12	0.34	0.4
	7.0	31	41	0.16	0.33	0.5
5	3.0	12	20	0.21	0.34	0.6
	7.5	3	8	0.10	0.33	0.3

Cone Penetration Test. The site investigation included 10 cone penetration test (CPT) profiles. Tip resistances (q_c) were normalized and CRR$_{7.5}$ values were calculated. CSR, CRR and FS parameters were calculated for the whole profile of 10 boreholes for earthquake magnitudes of 6.5, 7.0 and 7.5 The FS values for each profile is utilized to predict the liquefaction potential index (LPI) given in the following section.

CPT-Based Liquefaction Potential Index

Calculated FS values were used to evaluate liquefaction potential index (LPI). For Tuzla area, LPI was calculated to represent the liquefaction potential for each profile at a single location. LPI was developed for three different earthquake scenarios (M_w = 6.5, 7.0, 7.5 and a_{max} = 0.25g). Results are presented in Table 2 for M_w = 7.5 scenario only. Liquefaction potential classifications were classed according to Sonmez (2003).

Table 2. CPT-based liquefaction potential index values with liquefaction potential classes estimated for each borehole with respect to M_w = 7.5 earthquake scenario. a_{max} = 0.25g).

Borehole	LPI	Liquefaction Potential Classification
	M_w = 7.5	
1	8.4	High
2	1.4	Low
3	3.8	Moderate
4	2.2	Moderate
5	1.4	Low
6	0.0	Non-liquefiable
7	2.5	Moderate
8	0.9	Low
9	0.5	Low
10	0.1	Low

Undrained Shear Strength- based Liquefaction Potential Assessment

Based on undrained shear strength (s_u), factor of safeties (FS) against liquefaction were calculated based on the procedure recommended by Boulanger & Idriss (2004). For horizontal ground surface conditions, as analyzed in the studied area, α=0 and K_α is equal to 1.0. CRR$_{7.5}$ was determined for K_α=1.0 and CSR values were calculated for PGA of 0.25g. The results are listed in Table 3.The liquefaction potential of Tuzla soils were evaluated by means of factor of safety against liquefaction for potential future earthquake magnitudes of 6.5, 7.0 and 7.5. Table 3 listed values of cyclic stress ratio (CSR), cyclic resistance ratio (CRR) and factor of safeties (FS) against liquefaction for earthquake magnitude of 7.5.

Table 3. Calculated factor of safeties against liquefaction based on undrained shear strength.

BH	Depth	s_u (kPa)	CSR	CRR$_{7.5}$	FS$_{7.5}$
1	12.0-12.5	25	0.30	0.19	0.6
2	11.5-12.0	13	0.30	0.10	0.3
3	6.0-6.5	37	0.19	0.57	3.0
4	4.5-5.0	20	0.23	0.40	1.8
5	5.0-5.5	45	0.21	0.83	3.9
	14.0-14.5	11	0.28	0.07	0.3

Sensitivity

Sensitivity of Tuzla soils given in Table 4 were calculated by the ratio of the undrained shear strength (undisturbed) to remolded shear strength. Remolded shear strength values were estimated from liquidity index (LI).

As it is known quick clay is clay that turns into viscous fluid on remolding condition. Undisturbed quick clay resembles a water-saturated gel. When a mass of quick clay undergoes sufficient stress, it instantly turns into a viscous fluid which is a process of liquefaction. Quick clay is vulnerable to earthquake vibrations.

As could be seen from the Table 4, sensitivity values of Tuzla clays are high (S_r>4-8), meaning they are defenseless to cyclic loading and they may develop excess deformations and loose strength during earthquakes.

Table 4. Sensitivity values of Tuzla clays.

BH	Depth (m)	LI (%)	s_{uUN} (kPa)	s_{uRE} (kPa)	Sensitivity
1	12.0-12.5	0.81	25	2.8	8.9
2	11.5-12	1.04	13	1.5	8.7
3	6.0-6.5	1.4	37	0.7	52
4	4.5-5.0	0.87	20	2.3	8.5
5	5.0-5.5	0.95	45	1.8	25
	14-14.5	0.8	11	2.9	3.7

CONCLUSIONS

In this case study of factor of safety (FS) against liquefaction was determined from the results of CPT and SPT soundings, and undrained shear strength (s_u) of alluvial soils of Tuzla. For sandy soils the procedure summarized by Youd et al. (2001) was applied using normalized CPT tip resistance of (q_{c1N}) and corrected SPT blow counts, $(N_1)_{60}$, and considering the percentage of fine contents, FC (%). In fine-grained soils, however the procedure recommended by Boulanger and Idriss (2004) was used and FS was determined based on s_u values obtained from unconsolidated undrained triaxial test. The FS values obtained indicate a high potential for liquefaction/cyclic mobility in the region.

The soft clays in the study area have high sensitivity and in very sensitive soils, the cyclic disturbance can cause a significant loss in shear strength. Consequently, both ground settlements and lateral spreads which are the pervasive type of liquefaction-induced ground deformations may take place after a strong earthquake ($M_w \geq 6.5$) in Tuzla. However, currently, the estimations of liquefaction-induced ground deformations are less successful than the evaluations of liquefaction potential. In particular, no reliable CPT or SPT-based methods are available to estimate ground settlements and lateral displacements.

Cyclic failure potential of fine-grained soils, silts and clays, were further studied based on index-properties of liquid limit, plasticity index, clay fraction, and natural water content $\boldsymbol{w_c}$(%). Five criteria were applied to the study area based on these parameters. Results demonstrated that Seed et al. (2003) criteria are the most appropriate within the studied criteria. Also liquid limit, plasticity index and w_c/LL classifications are concluded to be better indicators than the particle size distribution, in assessing liquefaction or cyclic failure susceptibility of fine-grained soils.

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