4th International Conference on
Earthquake Geotechnical Engineering
June 25-28, 2007
Paper No. 1272

A MICROZONATION STUDY BASED ON LIQUEFACTION AND CYCLIC FAILURE POTENTIAL OF FINE GRAINED SOILS

H. Turan DURGUNOGLU[1] , and Huriye BILSEL [2]

ABSTRACT

Liquefaction of soils during earthquakes has been one of the most important problems in the field of geotechnical earthquake engineering. Findings from 1999 Kocaeli, Turkey and 1999 Chi-Chi, Taiwan earthquakes created a need to evaluate the liquefaction and cyclic failure potential of fine grained soils as well. This paper presents a critical review of the studies conducted by various researchers with regard to the effect of fines content and consistency limits on liquefaction susceptibility. Based on the available methods an example microzonation study for the Enkomi (Tuzla) region of the city of Famagusta, Cyprus is presented together with the foundation engineering implications toward the mitigation of the potential liquefaction hazards.

Keywords: liquefaction, cyclic failure, fine-grained soils, microzonation, Cyprus

INTRODUCTION

The liquefaction potential of sands and silty sands under strong earthquakes are well understood and had been studied extensively over the last 30 years after the pioneering studies conducted under the supervision of Prof. H. B. Seed at the UC Berkeley during late 1960's and early 1970's. On the other hand, the liquefaction type seismic hazard potential related to fine-grained soils have been ever debating controversy in the geotechnical earthquake engineering community. The early studies have covered the cyclic behavior of fine grained soils in the laboratory employing seismic triaxial and simple shear testing. However, very limited comprehensive case studies were available from the field for the behavior of fine-grained soils until the 1999 Kocaeli and Düzce earthquakes of M_w=7.2 and 7.4 of Turkey except the field data provided by Wang (1979) related to major earthquake of China.

Based on the site observations related to liquefaction induced hazards during 1999 Kocaeli earthquake of Turkey, especially in Adapazari, Golcuk, Karamursel and Izmit, it was realized that Sancio et al. (2002), Bray et al. (2004-a), the liquefaction susceptibility of fine grained soils that was observed could not be explained by well known Chinese Criteria alone developed earlier by Seed et al.(1983). Further extensive joint research studies on the prediction of liquefaction potential of local soils that have experienced liquefaction based hazards have been conducted with the cooperation of various universities from the United States and Turkey after 1999 Kocaeli earthquake. As a result of these studies new methodologies were developed to account the influence of plasticity index, in addition of clay fraction, liquid limit and natural water content. Seed et al. (2003), Bray et al. (2004-b), Bray & Sancio (2006). The estimation of factor of safety against cyclic failure for fine grained soils are also developed recently, Bouglanger & Idriss (2004)

[1] Ph.D,P.E., Emeritus Professor, Bogazici University Civil Engineering and Chairman of Zemin Etüd ve Tasarim A.S. Istanbul, Turkey, Email:durgunoglut@zetas.com.tr
[2] Ph. D., Assistant Professor, Eastern Mediterranean University Civil Engineering, Gazimagusa, Mersin 10, Turkey, Email:huriye.bilsel@emu.edu.tr

This paper presents the findings of a preliminary work on microzonation for cyclic failure potential of local soils at a new residential development area in Enkomi (Tuzla), situated in the northwest of the city of Famagusta within one km distance to the coast in Cyprus.

Seismic hazard maps prepared for Cyprus until now include the first level of zonation for ground motions based on surface geology only. These macro zonation maps prepared using surface geology to evaluate the potential for ground failure, however, do not provide reliable information for ground motions for a specific site. An attempt for improved assessments was made within the scope of a UNOPS project for the Greater City of Nicosia including geophysical testing, penetration tests and laboratory testing for obtaining a second level of zonation (Decoster M. et al., 2004). However, more detailed geotechnical investigations are required to provide a better understanding of the local site effects and local soil conditions on seismic hazards. Therefore, for geotechnical seismic hazards such as soil liquefaction, cyclic failure, slope instability are presently pending important issues for microzonation of various major cities in Cyprus especially in high seismic risk zones. Unfortunately, there are very limited records for the island related to geotechnical earthquake hazards that had occurred in the past. This is not surprising considering that the modern seismograph network operation began only recently in 1997 and understanding of such geotechnical hazards due to the earthquakes is relatively recent.

The alluvial saturated subsoil encountered in the area of Enkomi is mainly very weak silts and clays. After evaluation of the seismicity of Cyprus and the subject region, the recent methodology proposed by Bouglanger & Idriss (2004) is employed to estimate the factor of safety values against cyclic failure of encountered fine-grained soils for thirteen different locations of the microzonation study area.

SEISMICITY

Tectonics

Cyprus has a long historical record of damaging earthquakes, (Ambraseys, 1992), (Ambraseys & Adams, 1993). The principal tectonic elements of the Northeastern Mediterranean Region are shown in Figure 1 (Barka, 1992), (USGS, 1999). Cyprus is attached to or riding on the Anatolian subplate, which is moving towards the west, based on the seismicity data, consequently it is expected that active strands of the east Anatolian fault pass to the south of Cyprus.

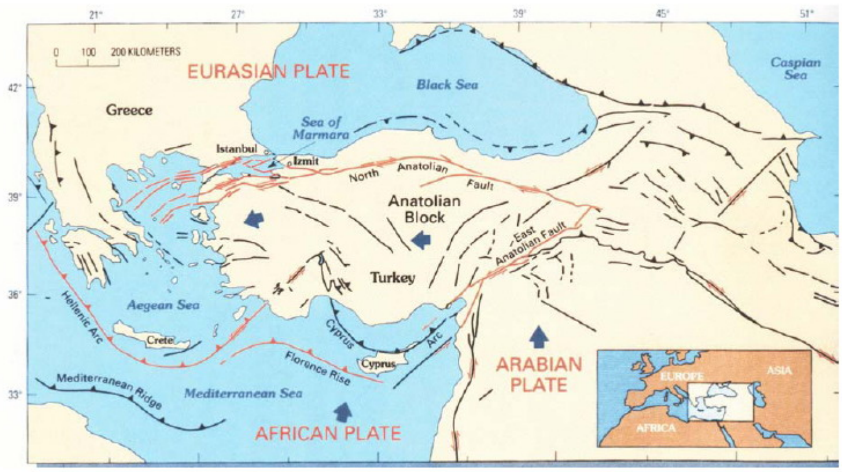

Figure 1. Map Showing the Principal Tectonic Elements of the Northeastern Mediterranean Region (from U.S. Geological Survey Circular 1193, 1999, as modified from Barka, 1992)

Damaging earthquakes in the past have taken place along both southern and eastern coastal areas of Cyprus at shallow depths.

Geological Setting
Cyprus is composed of four principal geological settings as shown in Figure 2 (Mc Callum & Robertson, 1990). These are Troodos massif, Circum-Troodos sediments, Kyneria range and the Mesaoria plain. The subject microzonation study for Enkomi-Famagusta is located at the eastern shore of Mesaoria plain.

The central plain of Mesaoria consists of middle miocene and post middle miocene calcareous marine sediments of marls and limestone outcrops, and pleistocene calcareous or non-calcareous deposits, and in some low lying areas, exits recent calcareous alluvium. Geological and hydrogeological data of alluvial deposits and the soils of the coastal strip indicate a possible potential for liquefaction.

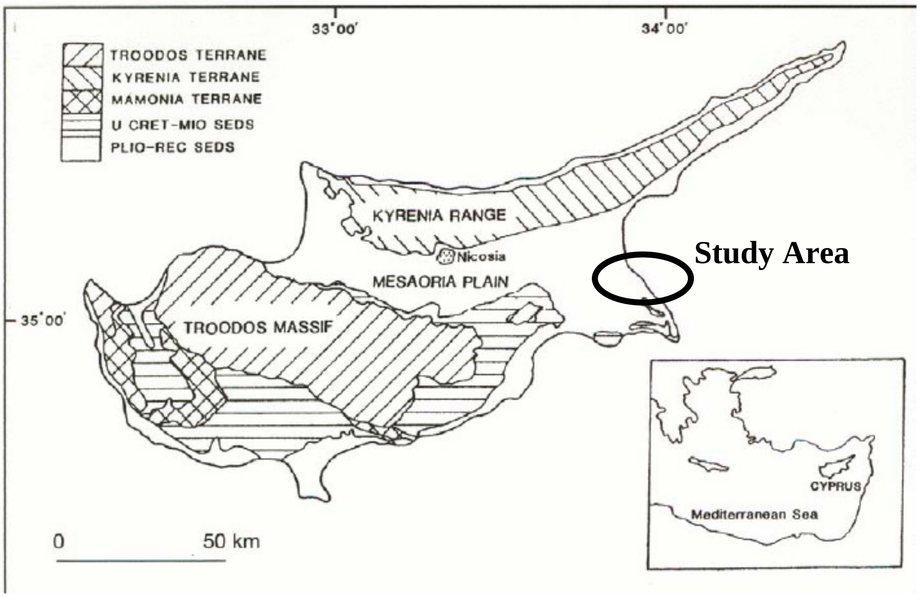

Figure 2. Generalized Geological Map of Cyprus Showing the Principal Geological Terrains after (Mc Callum & Robertson, 1990)

Crustal Faulting
Crustal faults on the island have been identified as shown in Figure 3 (USGS, 2003). Since 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 according to pertinent building codes (UBC and Turkish EQ code), the age of these faults are important. According to USGS faults Mia Milea and Main Ovgos near Nicosia are recent. In addition, south Mesaoria and Pergamos faults are considered to be active as well.

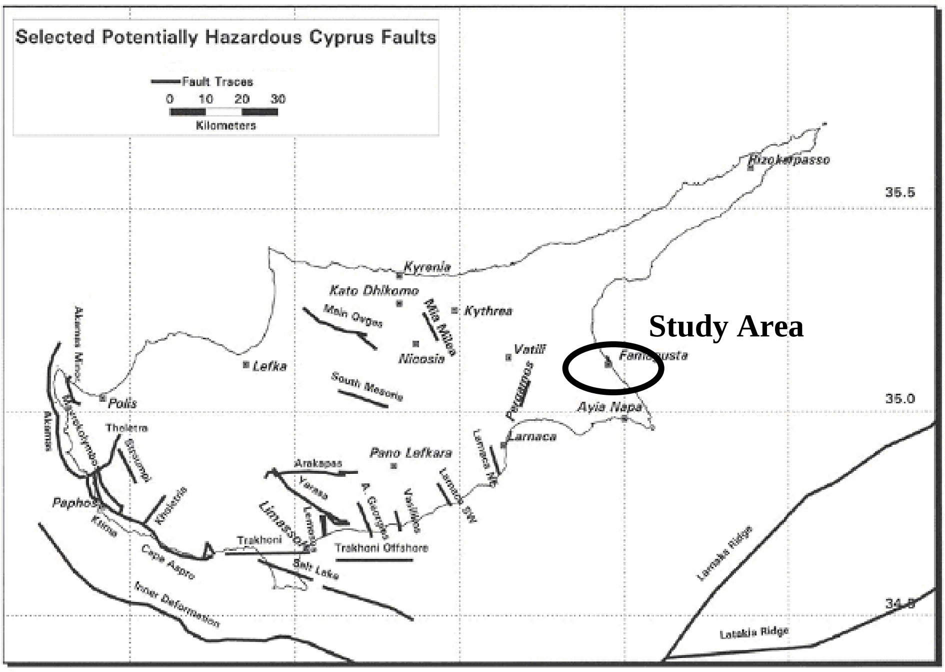

Figure 3. Faults of Cyprus of Possible Quaternary Age, (After Algermissen & Rogers, 2004)

Subduction Related Faulting

Earthquakes that have caused damage on Cyprus may be associated with various subduction structures as well. For example one or more transform faults, producing shallow earthquakes may exist that accommodate horizontal slip between sections of oceanic crust subducting at different rates or between nonconvergent oceanic and continental crust boundaries, according to evaluation of Algermissen & Rogers (2004).

Regional Seismicity

The regional seismicity of Cyprus according to USGS is given in Figure 4. It is seen that the most active areas are to the northeast in the Hellenic arc region of the western Turkey and Greece and to the southeast along the Levantine coastal area and the Dead Sea rift in Syria, Israel, and Lebanon. Southeastern Turkey is also very active through the east Anatolian Fault.

Cyprus has not been as active as these surroundings but has experienced numerous damaging major earthquakes. Much of the seismicity that occurs south of the Mesaoria plain influencing greatly the subject city of Famagusta and appears to be associated with the plate boundary.

Seismic Hazard Analysis

Probabilistic Hazard Maps showing the PGA values for Cyprus may be used in analysis if desired according to local codes. Such a study to predict PGA values for Cyprus has been performed by Algermissen & Rogers (2004) and the results are presented in Figure 5 for a firm rock site. It may be seen that PGA is about 0.23g for the city of Famagusta considered in this microzonation study.

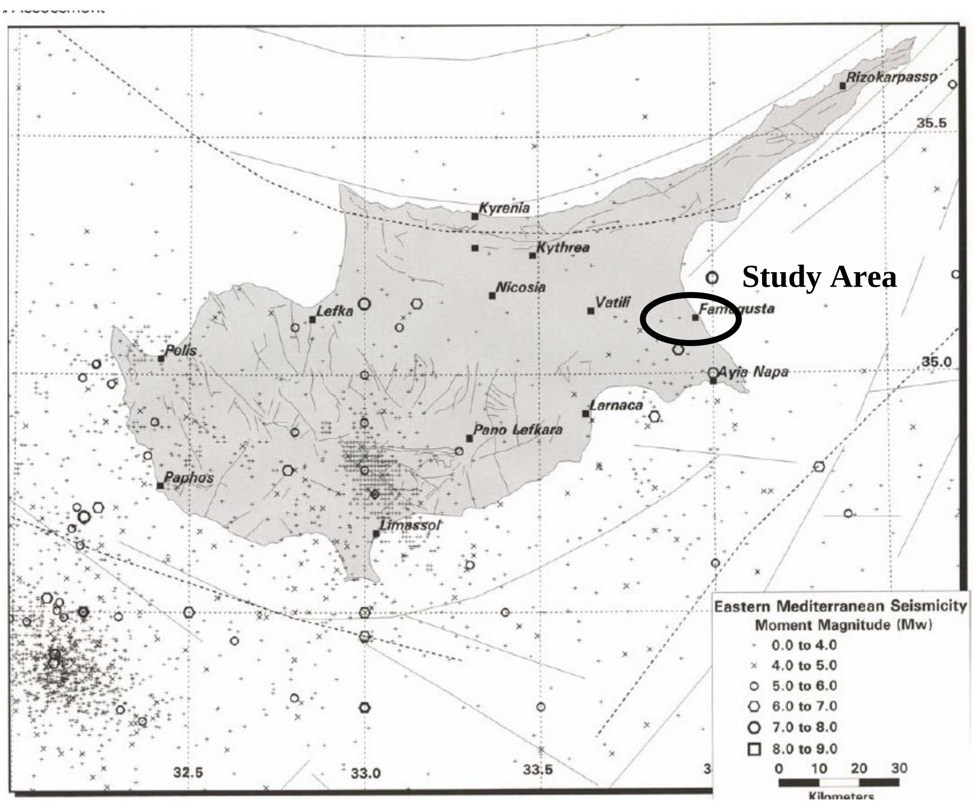

Figure 4. A Map of All Earthquakes in the Historical Record in the Immediate Vicinity of Cyprus. (After Algermissen & Rogers, 2004)

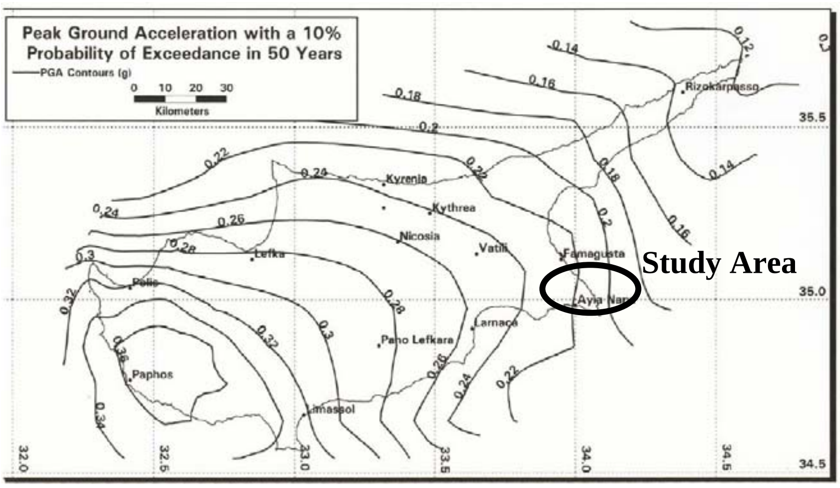

Figure 5. A Contour Map of the Probabilistic Peak Ground Acceleration (PGA) in Cyprus For 10% Probability of Exceedance in 50 years for a Firm Rock site (after Algermissen & Rogers, 2004)

LIQUEFACTION POTENTIAL BASED MICROZONATION STUDY

General

Seismic hazard maps prepared for Cyprus until now include the first level of zonation for ground motions only based on surface geology. An attempt for improved assessments was made within the scope of a UNOPS project for the Greater City of Nicosia including geophysical testing, penetration tests and laboratory testing for obtaining a second level of zonation (Decoster M. et al., 2004). However, more detailed geotechnical investigations are required to provide a better understanding of the local site effects and local soil conditions on seismic hazards. Therefore, for geotechnical seismic hazards such as soil liquefaction, cyclic failure, slope instability are presently pending important issues for microzonation for Cyprus especially in high seismic risk zones.

Study of Enkomi-Famagusta

This paper presents the findings of a preliminary work on microzonation for liquefaction of a new residential development area in Enkomi (Tuzla), situated in the northwest of the city of Famagusta within one km distance to the coast. Enkomi used to be a harbor town, dating back to 2000 B.C., also known as Alasia by the end of the 1300 B.C. an earthquake destroyed part of the city. In the 11th century the antique town was abandoned never to be used again, when the Pedios River (Kanlidere) flowing by the city filled the harbor with alluvium. The shaded area indicating the boundaries of the subject study in Figure 6 represents the alluvial beds in which building and infrastructure constructions are rapidly developing. Consequently, there is an urgent need of assessment of the potential liquefaction and cyclic failure hazard and introduction of mitigation techniques to be implemented before the design and construction of foundations.

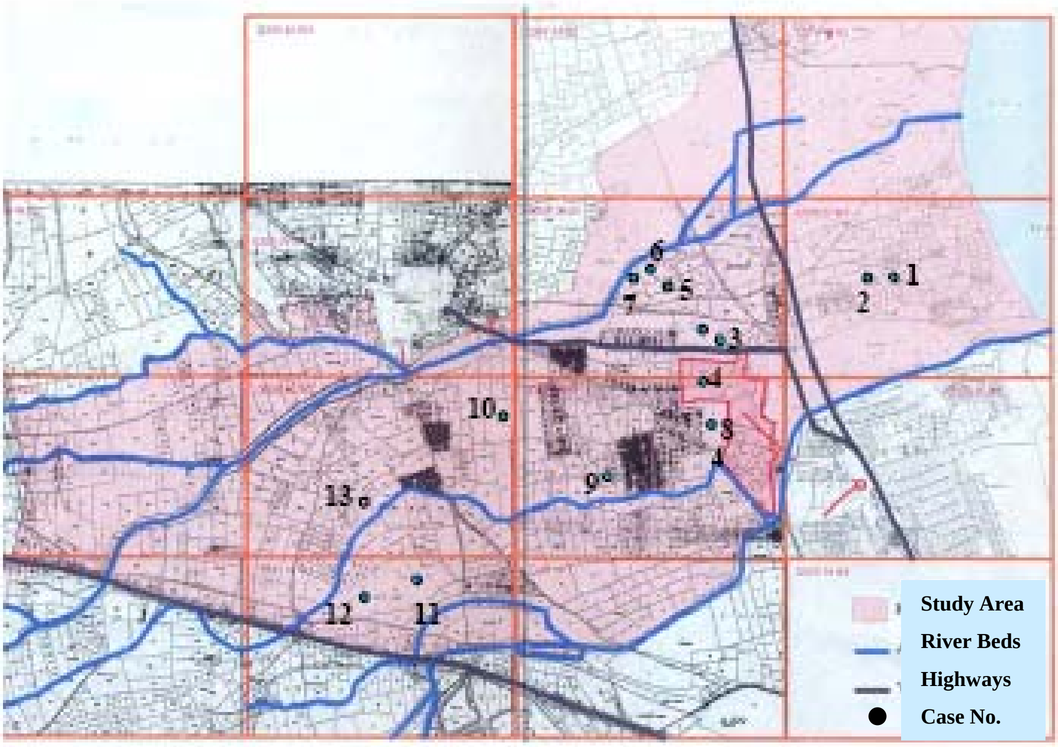

Figure 6. Microzonation Study Area for Enkomi Famagusta-Cyprus

Subsoil Conditions

In this study thirteen numbers of cases are evaluated. The locations of studied case are shown in Figure 6. Table 1 depicts the case and construction numbers, SPT-N values and laboratory parameters of consistency limits and particle size distribution for samples recovered from various depths and locations for each case. The depths of boreholes vary between 10 to 45 m. However, only upper levels with more vulnerability against liquefaction where σ_v' is low have been studied. The water table in the region is observed to fluctuate from 0.6 m in the wet season to 1.8 m depth in the dry season from the ground surface. The soil profile within the subject area consists of heterogenous layers of saturated clays and silts of low plasticity, and sands intermittently distributed within the studied depths.

Table 1. Index Properties and Factor of Safety Against Liquefaction and Cyclic Failure for Microzonation Study in Enkomi-Fagamusta, Cyprus.

Case No. Project	Depth (m)	Soil Type	SPT-N	FC (%)	<5 μm (%)	<2μm (%)	w_c (%)	LL(%)	PI(%)	s_u (kPa)	SF M_W=6.5	SF M_W=7.0	SF M_W=7.5
1	2.0-8.0	SP	9-27				22-26(24)				0.93-3.17	0.72-2.48	0.58-1.98
	12.0	ML	4				44				1.14	0.89	0.71
2	2.0-8.0	SP	22-43(35)				24-32(26)				2.96-4.19	2.32-3.28	1.84-2.62
	12.0	ML	3				40			20	1.14	0.89	0.71
	20.0	ML	3				20.5	44	16	18	1.44	1.13	0.90
3	4.0	CL	2	95	52	48	44	44	19	19	1.23	0.96	0.77
	8.5	CL-	3	75	34	26	40	36	13	17	1.09	0.85	0.68
	12.0	ML	2	70	34	26	36	36	11	17	1.14	0.89	0.71
	15.5-	ML	1-2(2)				44-52(47)				1.24-1.65	0.97-1.29	0.77-1.03
4	7.0	CL	3	60	32	23	44	27	13	13	1.11	0.87	0.69
	10.0	CL	1	60	24	17	46	28	3	40	1.09	0.86	0.68
	12.5-30	ML	1-3(2)				28-40(32)				1.15-1.80	0.90-1.41	0.72-1.12
5	3.5	CL	4				28	35	12		1.27	1.00	0.79
	7.0	ML	7	95	47	42	24				1.11	0.87	0.69
6	4.0	ML	4	92	45	30	28	33	9		1.23	0.96	0.77
	5.5	ML	12				28				1.15	0.90	0.72
	8.0-10.0	ML	4				32-36(34)				1.09	0.85-0.86	0.68
7	7.0	ML	2				44				1.11	0.87	0.69
	10.0	ML	3	95	32	24	36	41	14		1.09	0.86	0.68
8	2.0	CL	10				24				1.55	1.21	0.96
	4.0	CL	5	80	76	66	28	43	17		1.23	0.96	0.77
	6.5	SC-SM	4	34	17	15	24				0.68	0.53	0.43
	10.0	SC-SM	2	36	22	15	24				0.54	0.43	0.34
	14.0	ML	4	100	56	41	46	42	14		1.19	0.93	0.74
9	4.0	SM	17	29	10	13	24				2.07	1.62	1.29
	6.6	SM	5	47	18	20	40				0.95	0.74	0.59
	10.0	ML	4				44	50	22	40	1.09	0.86	0.68
10	4.0	SM	8	48	18	13	20				1.12	0.87	0.7
	13.0	ML	3	100	66	48	50	50	20	20	1.16	0.91	0.72
11	4.0		3	100	44	28	30				1.23	0.96	0.77
	6.0		2	90	27	18	37				1.13	0.89	0.71
	8.0		6	38	15	10	30				1.09	0.85	0.68
	10.0		5	85	30	20	40				1.09	0.86	0.68
12	4.0	MH	4	100	83	62	34	61	23		1.23	0.96	0.77
	5.0	ML-SM	2	60	22	15	32	27	5		1.17	0.92	0.73
	8.5	ML-SM	4	65	32	22	28	27	6		1.09	0.85	0.68
	13.0	MH	4	100	90	70	36	63	25		1.16	0.91	0.72
	15.0	ML	4	70	20	15	32	30			1.22	0.96	0.76
13	4.0	ML	3	100	68	50	28	50	18		1.23	0.96	0.77
	7.0		5	70	37	26	28				1.11	0.87	0.69
	8.6	ML	6				32	29	7		1.08	0.85	0.68

FC(%)=Fine Content, -5μm and -2μm(%)=Clay Fractions, LL(%)=Liquid Limit, PI(%)=Plasticity Index, s_u (kPa)=undrained shear strength, SF= safety factor against liquefaction/cyclic failure, M_w=Magnitude of Earthquake

LIQUEFACTION-CYCLIC FAILURE POTENTIAL OF FINE GRAINED SOILS

The liquefaction potential of sands and silty sand under strong earthquakes are well understood and had been studied extensively over the years. The procedures for determination of safety factor for liquefaction during strong earthquakes are developed, Youd T.L. et al. (2001). On the other hand the cyclic failure susceptibility of fine-grained soils, i.e. silts and clays are still under discussion and being developed.

The early work has been reported by Wang (1979) based on the observations of initial field case studies for liquefaction type hazards encountered during Chinese earthquakes. Later, based on these results Seed and et al. (1983) have developed what is known as "Chinese Criteria" for evaluation of liquefaction susceptibility of fine-grained soils shown in Figure 7 based on the liquid limit, LL(%), clay fraction, -5μm(%) and natural water content w_c(%).

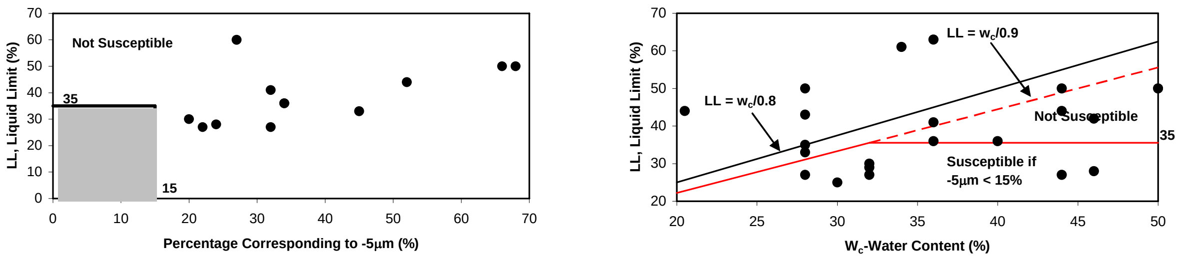

Figure 7. Chinese Criteria vs Fine Grained Soils of Enkomi

Cyclic failure of sensitive clays was studied by Youd (1998) and as a result the following criteria are developed. If the soils are classified as CL-ML having $(N_1)_{60}<5$, with sensitivity $S_r>4$, liquidity index of $I_l>0.6$ and natural water content of $w_n>0.9LL$ are called Liquefaction/Cyclic Failure Susceptible. A similar study on a soft sensitive clay located north of Istanbul, Turkey has been reported by Durgunoglu et al. (2004-a) employing systematic cyclic triaxial tests on undisturbed samples. It has been shown that even high plasticity clays of CH type can generate significant strains in a small number of cycles when a high CSR is applied on the contrary of Chinese Criteria. The main deficiency of the Chinese Criteria obviously is not considering the magnitude of the earthquake or CSR value.

In fact, Perlea (2000) have studied the effect of earthquake magnitude and epicentral distance for all kind of soils, including loose fine sands, cohesive (fine-grained) soils, sensitive clays and collapsible loess based on the field observation of liquefaction induced hazard during numerous strong earthquakes during the years of 1944 to 1989. It was shown that, any type of soil including cohesive soils and sensitive clays could be liquefied depending on the magnitude of shaking, i.e. triggered energy released during earthquakes. It was also shown that, the fine-grained soils except collapsible loess (i.e. nonplastic silts) require more released energy than in sands. It was also observed that no liquefaction (cyclic failure) of fine grained soils were observed as a consequence of earthquake with local Richter magnitude less than 7.2. This is in agreement with the findings of laboratory studies that, more time and number of cycles are necessary for fine-grained soils in comparison to sands for incremental deformations to accumulate, as a result of developed excess water pressure until the liquefaction-cyclic failure state is reached.

Andrews & Martin (2000) have developed a new criterion for the liquefaction potential of fine-grained soils based on LL(%) and clay fraction of -2μm(%) as shown in Figure 8.

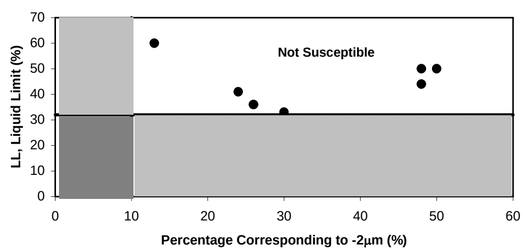

Figure 8. Andrews & Matrin (2000) Criteria vs Enkomi Soils

The influence of plasticity index on the liquefaction and/or cyclic failure of fine grained soils have been recognized after Polito (2001), Seed et al. (2003) and Bray et al. (2004-b). The Enkomi soils are evaluated using these charts based on the I_p(%), LL(%) and w_n(%) values in Figure 9, Figure 10 and Figure 11 respectively.

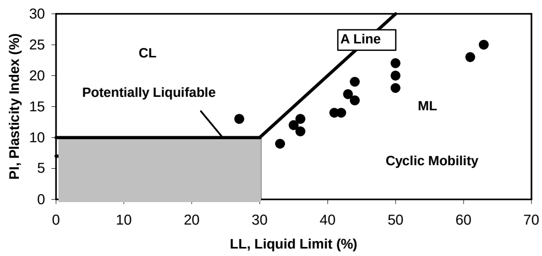

Figure 9. Polito (2001) Criteria vs. Enkomi Soils

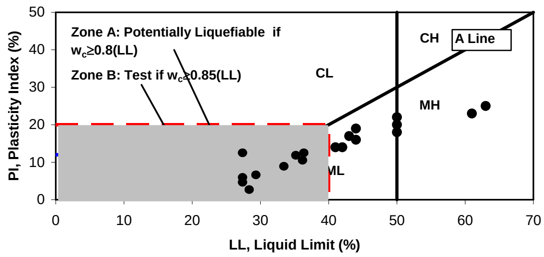

Figure 10. Seed et al. (2003) Criteria vs. Enkomi Soils

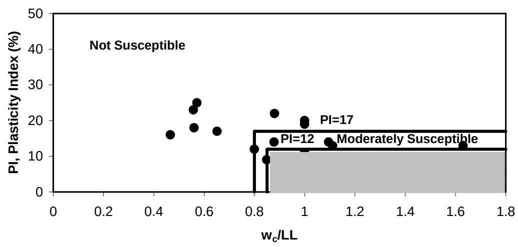

Figure 11. Bray et al. (2004-b) Criteria vs. Enkomi Soils

It is seen that, neither Chinese Criteria nor Andrews & Martin's (2000) charts account for plasticity index. From the three methods proposed utilizing PI, on the other hand neither accounts for the earthquake magnitude. Therefore, these charts should be utilized considering that there is a potential strong earthquake of M≥6.5 for the subject area.

FACTOR OF SAFETY-AGAINST CYCLIC FAILURE

A map of historical record of all earthquakes in the immediate vicinity of Cyprus given in Figure.4 indicate there were at least two major earthquake of each M_w=6.0 to 7.0 and M_w=7.0 to 8.0 with epicenters within 20 to 30 kilometers from Famagusta. Therefore, the liquefaction and cyclic failure potential of Enkomi soils are evaluated for potential future earthquake magnitudes of M_w=6.5, 7.0 and 7.5. Based on the PGA values estimated as described before a ground surface acceleration of a=0.23g are utilized in these analysis for Enkomi region. It is determined that the average ground water table in the region is very close to ground surface with a depth of h_w~1.0m.

Factor of safety-FS_l values are determined separately for sands and fine grained soils. For sands the procedure summarized by Youd et al. (2001) are utilized using corrected SPT blow counts of $(N_1)_{60}$ considering the percentage of fine contents-FC(%). On the other hand, for fine-grained soils the procedure recommended by Bouglanger & Idriss (2004) is used. For soils where plasticity index is smaller than PI=7, they are treated as sand-like material, therefore the procedure outlined above are also used utilizing SPT blowcounts and FC(%). On the other hand, for soils where PI is greater than 7, they are treated as clay-like material and CRR-Cyclic Resistance Ratio values are estimated accordingly. For CRR values, the undrained shear strength, s_u is utilized wherever the pertinent data were available as given in Table 1 and CRR is estimated using the following relationship, (Bouglanger and Idriss, 2004)

$$CRR_{M=7.5} = 0.8\frac{s_u}{\sigma_{vc}'}.K_\alpha \tag{1}$$

where σ_{vc}'=effective overburden pressure and $K_\alpha(\alpha,OCR)$ is the correction factor to represent the effects of initial static shear stress ratio $\alpha=\tau_s/\sigma_{vc}'$ developed by Seed (1983) and OCR is the over consolidation ratio of the fine-grained soils. For horizontal ground surface conditions as analyzed in Enkomi, α=0 and K_α is equal to 1.0.

Where there is no data for s_u on the other hand, the CRR value is estimated using the following empirical relation proposed by Bouglanger & Idriss (2004),

$$CRR_{M=7.5} = 0.8.S.OCR^m.K_\alpha \tag{2}$$

For homogenous low-high plasticity sedimentary clays S=0.22 and m=0.8 (Ladd, 1991) and,

$$CRR_{M=7.5} = 0.18.OCR^{0.8}.K_\alpha \tag{3}$$

For an earthquake magnitude of M other than M_w=7.5, a magnitude scaling factor, MSF is used. MSF value utilized is determined according to Idriss & Bouglanger (2004) given by:

$$MSF = 6.9.\exp\left(\frac{-M}{4}\right) - 0.058 \leq 1.8 \tag{4}$$

where $CRR_M = MSF.CRR_{M=7.5}$ and consequently factor of safety against cyclic failure is determined using

$$FS_l = \frac{CRR_M}{CSR_M} \tag{5}$$

The factor of safety values estimated for potential of cyclic failure of encountered fine-grained soils of Enkomi Region are lower than unity for earthquake magnitude of M≥7.0. It could be seen that, the Factor of Safety values are slightly above the unity even for earthquake magnitude of M=6.5, indicating that, considerable displacements are likely to occur during such an earthquake in the study area. Therefore, proper design and construction of remediation techniques should be implemented in the area below the foundations. Since the encountered soils are fine grained the densification techniques utilized for the mitigation of liquefaction for sands could not be employed.

The best practice for such soils had been the utilization of high modulus columns beneath the foundations covering the liquefiable depth. It has been shown based on the performance of improved sites during 1999 Kocaeli Earthquake of Turkey M=7.4 that, the utilization of jet grout columns using cement slurry for this purpose found to be satisfactory, Durgunoglu et al. (2004-b), Martin et al. (2004). The design methodology for the use of high modulus columns to mitigate soil liquefaction and cyclic failure has been developed by Durgunoglu (2006).

CONCLUSIONS

- Factors such as magnitude of earthquake, distance from epicenter or PGA, consistency limits, natural water content and liquidity index of fine-grained soils have major effects in predicting the cyclic failure potential. Criteria and charts without employing plasticity index alone may give misleading results.
- The plasticity index is one of the most important factor affecting the cyclic failure potential of fine-grained soils.
- The factor of safety against cyclic mobility for fine-grained soils are also controlled by undrained shear strength and stress history.
- It is seen from the estimated safety factors against cyclic failure that, Richter Magnitude of approximately 7.0 earthquake is expected to cause liquefaction type hazard for the microzonation study area of Enkomi-Famagusta.

ACKNOWLEDGEMENT

We would like to thank to Cyprus Turkish Chamber of Civil Engineers and Department of Mining, Metallurgy and Geology for their kind help in providing necessary documents related to the seismicity and the geology of the island and Famagusta. We are also thankful to Prof. J. D. Bray from UC Berkeley, Prof. I.M. Idriss and Prof. R.W. Bouglanger from Univ. of Calif. Davis, Prof. J. K. Mitchell and J.R. Martin from VPI for their kind cooperation during the joint research studies conducted on the behavior of fine-grained soils under seismic loadings. Special thanks are due to Mr. Kayhan Aykın and Ms. Emel Hacialioglu, Project Engineers of Zetas for their kind help in the preparation of the manuscript.

REFERENCES

Algermissen T. and Rogers A., "A Cyprus Earthquake Hazard Assessment: Maps of the Probabilistic Peak Ground Acceleration and Uniform-Hazard Pseudo-Absolute Acceleration Spectral Response," Seismic Hazard and Risk Assessment of Greater Nicosia Area, UNOPS, Chapter 5, 2004

Ambraseys N.N. and Adams R.D., "Seismicity of the Cyprus Region," *Terra Nova*, Vol.5, p. 85-94, 1993

Ambraseys N.N., "Reappraisal of the Seismic Activity in Cyprus: 1894-1991," *Bollettino di Geofisica Toerica ed Applicata,* Vol. 34, p. 41-80, 1992

Andrews D.C.A. and Martin G.R., "Criteria for Liquefaction of Silty Soils," *Proceedings of 12th World Conf. on Earthquake Engineering*, UpperHutt, New Zealand, NZ. Soc. For EQ Engineering, paper no. 0312

Barka A., "The North Anatolian Fault Zone," *Annales Tectonicae*, Vol. 6, p. 164-195, 1992

Bouglanger R.W and Idriss I.M., "Evaluating the Potential for Liquefaction on Cyclic Failure of Silts and Clays," *Report UCD/CGM-04/01*, University of California at Davis, Calif., 2004

Bray J.D et al., "Subsurface Characterization at Ground Failure Sites in Adapazari, Turkey,"*Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 130, No. 7, p. 673-685, 2004-a

Bray J.D et al., "Liquefaction Susceptibility of Fine-Grained Soils," *Proceedings 11th ICSD and 3th ICEGE*, UC Berkeley, Calif., Vol. 1, p. 655-662, 2004-b

Bray J.D. and Sancio R.B., "Assessment of the Liquefaction Susceptibility of Fine-Grained Soils," *Journal of Geotechnical and Geoenvironmental Engineering,* ASCE, Vol. 132, No. 9, p. 1165-1177, September 2006

Decoster M. et al., (edts.) "Seismic Hazard and Risk Assessment of Greater Nicosia Area, with support from the Bi-communal Development Programme funded by USIAD and UNDP through UNOPS", 2004

Durgunoglu H. T. et al., “Case History for Ground Improvement Against Liquefaction Carrefoursa Shopping Center-Izmit, Turkey”, *Proceedings of Satellite Conference Lessons Learned from Recent Strong Earthquakes,* August 24, Istanbul, Turkey, 2001

Durgunoglu H. T. et al., “An Integrated Approach for Characterization of Modeling of Soft Clays Under Seismic Loading; A Case Study,” *Proceedings 11th ICSD and 3th ICEGE*, UC Berkeley, Calif., p. 663-668, 2004-a

Durgunoglu H. T. et al., “Soil Improvement with Jet-Grout Columns: A Case Study from the 1999 Kocaeli Earthquake,” *Proceedings of Fifth International Conference on Case Histories in Geotechnical Engineering,”* Newyork, N.Y., April 13-17, 2004-b

Durgunoglu H. T., “Utilization of High Modulus Columns in Foundation Engineering Under Seismic Loadings,” 100th Anniversary Earthquake Conference, 8th U.S. National Conference on Earthquake Engineering, San Francisco, Calif., April 18-22, 2006

Idriss I.M. and Bouglanger R.W., “Semiemprical Procedures for Evaluating Liquefaction Potential During Earthquakes,” *Proceedings 11th ICSD and 3th ICEGE*, UC Berkeley, Calif., Vol. 1, p. 32-56, 2004

Ladd, “Stability Evaluation During Staged Construction,” *Journal of Geotechnical Engineering*, ASCE, Vol. 117, No. 4, p. 540-615, 1991

Martin et al. , “High Modulus Columns for Liquefaction Mitigation,” *Journal of Geotechnical and Geoenvironmental Engineering,* ASCE, Vol. 130, No. 6, June, 2004

Mc Callum J.D. and Robertson A.H.F., “Pulsed Uplift of the Troodos Massif-Evidence from the Plio-Pleistocene Mesaoria Basin,” *Proceedings of the Symposium Troodos 1987*, Geological Survey Department, Nicasia, Cyprus, p. 217-229, 1990

USGS, “Implications for Earthquake Risk Reduction in United States from Kocaeli, Turkey, Earthquake of August 17, 1999,” *U.S. Geological Survey Circular*, No. 1193, 1999

USGS, “Seismic Hazard Assessment Project, WSE-PS02-4008 USGS Survey Report for Phase II. Prepared for UNOPS,” Nicosia, Cyprus, p. 60, 2003

Perlea V.G., “Liquefaction of Cohesive Soils,” *Soil Dynamics and Liquefaction 2000,* Specialty Conf., Denver, ASCE Geotechnical Special Publication, No. 107, p.58-75, 2000

Polito C., “Plasticity Based Liquefaction Criteria,” *Proceedings of 4th IC on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*, Univ. of Missouri-Rolla, Rolla, Mo., Paper No. 1.33, 2001

Seed H.B., “Earthquake Resistant Design of Earth Dams,” Proceedings, Symposium on Seismic Design of Embankments and Caverns,” Pennsylvania N.Y., ASCE, p. 41-64, 1983

Seed H.B. et al., “Evaluation of Liquefaction Potential Using Field Performance Data,” *Journal of Geotechnical Engineering*, ASCE, Vol. 109, No. 3, p. 458-482, 1983

Seed H.B. et al., “Recent Advances in Soil Liquefaction Engineering: A Unified and Consistent Framework,” *EERC-2003-06*, EERC, Berkelry, Calif., 2003

Sancio R.B et al., “Correlation Between Ground Failure and Soil Conditions in Adapazarı, Turkey” *Soil Dynamics and Earthquake Engineering*, Elsevier Science Ltd, Vol. 22, p. 1093-1102, 2002

Youd T.L., “Screening Guide for Rapid Assessment of Liquefaction Hazard at Highway Bridge Sites,”*Technical Report, MCEER-98-0005, Multidisciplinary Center of Earthquake Engineering*, 1998

Youd T.L. et al., “Liquefaction Resistance of Soils: Summary Report from the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils,” *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 127, No. 10, p. 817-833, 2001

Wang W., “Some Findings in Soil Liquefaction,” Water Conservancy and Hydroelectric Power Scientific Research Institute, Beijing, China, 1979