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AN INVESTIGATION OF SOIL VOID RATIO EFFECT ON LIQUID LIMIT VALUES DETERMINED BY DIFFERENT TEST METHODS

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ABSTRACT

The liquid limits of different types of silts were determined under varying void ratio conditions by carrying out the cone penetrometer and the Casagrande tests. According to the results obtained from this study, the void ratio was determined to have a notable effect on the liquid limit values of soils. In terms of eliminating the void ratio effect based and operator dependent variations of results, the cone penetrometer test was assessed to be advantageous in comparison with the Casagrande test. The liquid limit values of soils were found to have various relations with the void ratio parameter depending on the soil material. Therefore, a general correlation between the liquid limit and void ratio parameters is not suggested for use. Instead, it is recommended to separately evaluate the liquid limit values for the changes in the void ratio values of different soils.

Keywords: Atterberg limits; Liquid limit; Soil classification; Soil testing; Void ratio.

1 INTRODUCTION

The liquid limit was firstly defined by Swedish chemist and agricultural scientist Albert Atterberg in 1911 [1]. The liquid limit is a water content to change a soil from plastic to liquid state. In other words, soil materials become liquids in case of having higher water content than the liquid limit. As a result of liquefaction, soil materials have highly diminished yield strength values and can no longer maintain a molded shape [2–5].

The liquid limit is relevant for a wide range of purposes in soil mechanics. For instance, liquid limit is one of the main parameters used in the soil classification. Therefore, the accuracy in determination of the liquid limit has a great importance. Within various test methods developed to determine the liquid limit values of soil materials, the Casagrande test and the cone penetrometer (or fall-cone) test are the two popular and world-widely used ones.

The Casagrande test was developed and firstly proposed by Austrian-born American civil engineer Prof. Dr. Arthur Casagrande (1902–1981) in 1932 [6, 7]. The Casagrande test is older than the cone penetrometer test which was firstly proposed to determine shear strength values of soil specimens by Swedish Geotechnical Engineer Prof. Dr. Sven Hansbo (1924–2018) in 1957 [8]. The cone penetrometer test has been accepted and become popular as an alternative of the Casagrande test method to determine the liquid limit in 1970s [9-13]. For the cone penetrometer test, there are various in use standards such as BS 1377-2, CEN ISO/TS 17892-6, CAN/BNQ 2501-092/2006 and TS 1900-1 [14–17].

The cone penetrometer and Casagrande tests have different mechanisms and methodological circumstances as given in the following materials and methods title, in detail. As summary, mechanism of the cone penetrometer test is based on a standard steel cone penetration depth in the soil and water mixture. On the other hand, the

Casagrande test is based on closing of a standard groove by the flow of the soil and water mixture put in a repeatedly dropped cup.

As an important drawback for both cone penetrometer and Casagrande tests, the effect of the void ratio of soil specimens are neglected to consider in determination of liquid limit values. There is no statement on the void ratio of specimens in relevant standards for the liquid limit tests. As the motivation for this study, the void ratio was thought to have a significant role on the liquefaction because it is an important parameter for strength and deformability properties of soil materials [18–20].

The purpose of this study is to investigate whether the void ratio has a notable effect to vary the liquid limits of soil materials, or not. For this aim, liquid limits of different soil materials were determined for varying void ratios by carrying out both Casagrande and cone penetrometer tests within this study.

2 MATERIALS AND METHODS

Soil specimens from four different locations of the Black sea region of Turkey (Giresun, Bulancak, Piraziz, Unye) were tested within this study. The soils were coded as Soil G, Soil B, Soil P and Soil U for specimens from Giresun, Bulancak, Piraziz and Unye, respectively. Soil specimens were sieved before tests to prepare them for passing the No. 200 (0.075 mm) sieve to use in the experimental study.

To calculate the void ratio of specimens, specific gravities of soils were determined in accordance with the ASTM D854-10 coded standard [21]. As the first step, the empty and dry weights of the pycnometers were measured using a scale with a sensitivity of 0.001 g. Then, the weights of the dry soil placed pycnometers were determined and recorded. To make dry soil, specimens were heated in a 105 ºC stove for a day. The distilled water was filled in 250 ml pycnometers and the specimens were soaked for 30 minutes. Afterwards, a partial vacuum was applied for 15 minutes to remove the entrapped air. After stopping the vacuum process, additional distilled water was added to fill pycnometers and the pycnometer valves were put to fix the water level to the mark. Then, the pycnometers with soil and water contents were weighed to calculate specific gravity as given in Eq. 1 [21]:

$$G_s = W_0/(W_0+(W_A-W_B)) \qquad (1)$$

where G_s is specific gravity, W_0 is weight of dry soil, W_A is weight of pycnometer filled with water and W_B is weight of pycnometer filled with water and soil. W_0 and W_B were measured within the test. Since the 250 ml pycnometers were used in this study, W_A was calculated as the sum of empty and dry weight of the pycnometer and 250 g.

The cone penetrometer test was performed in accordance with the TS 1900-1 coded standard [17]. For the aim of investigating the effect of void ratio, the standard specimen cup of the cone penetrometer test was filled with varying weights of same soil and water mixtures. The cone penetrometer test was repeated for different four water content conditions of each soil specimens (Soil G, Soil B, Soil P and Soil U).

According to the TS 1900-1 coded standard, the cone penetrometer (or fall-cone) equipment has a standardized stainless-steel cone with a weight of 80 g and an angle of 30° (Figure 1). The cone drops freely from a fixed height into soil specimens placed in the standard cup. The cone is released for 5 s and its penetration into the soil is measured. The liquid limit of the soil is determined as the water content for the cone penetration of 20 mm. For this measurement, several tests are carried out using specimens with varying water contents [17].

Figure 1. *The cone penetrometer*

In the Casagrande test, the methodology stated in the ASTM D4318-10 coded standard was followed. Soil and water mixtures were put in the Casagrande test cup and cut into two parts with the standard groove. The cup of the Casagrande test equipment was then dropped repeatedly by the motor until the groove is closed due to the flow of the soil and water mixture. The liquid limit was determined as the water content for closing the groove under impact of 25 blows. In case of having a contact length of 13 mm, the test was stopped and the groove was considered to be closed [22].

The water content was determined as the ratio of mass of water to mass of dry soil. To obtain dry soil, specimens were heated in the 105 °C stove for a day. The void ratio was calculated using the water content, specimen volume, dry density and specific gravity parameters as seen in well-known Eqs. 2–5 [23].

$$\rho_b = M_b / V \quad (2)$$

$$\rho_{dry} = \rho_b / (1+m) \quad (3)$$

$$\gamma_{dry} = \rho_{dry} . g \quad (4)$$

$$\gamma_{dry} = (G_s . \gamma_w)/(1+e) \quad (5)$$

where, M_b is mass of soil and water mix, V is volume of the specimen, ρ_b is bulk density, ρ_{dry} is dry density, m is the water content, g is the gravitational acceleration, γ_{dry} is dry unit volume weight, γ_w is unit volume weight of water, G_s is specific gravity and e is the void ratio.

Since the standard cup with the volume of 80 cm^3 was used and filled by soil specimens with top surfaces flattened using a spatula as seen in Figure 2, the volume of specimens was known and used in the void ratio calculations. To prepare specimens with different void ratios, specimens with different masses were filled in the cup to replicate tests for the same water content condition. The relation between the cone penetration and void ratio values were investigated for different water content conditions. The dry density was calculated using the bulk density of soil and water mix and water content parameters, as given in Eq. 3. In consequence of the determination of the dry density, the void ratio could be calculated as seen in Eqs. 4 and 5.

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To determine void ratios of the Casagrande test specimens, transparent glass tubes with sharpened cutter heads and an inner diameter of 5 mm were used to take specimens from the Casagrande test cup. The specimens were taken from the location of the groove before being cut (Figure 3). The mass of the thin glass tubes were 0.42 g. Heights of the specimens in tubes were measured using a vernier calliper to calculate the volume parameter. Then, masses of the tubes and specimens were measured using the scales with a sensitivity of 0.0001 g (Figure 4).

As same with the method followed in the cone penetrometer test, specimen volume, mass of soil and water mix, bulk density, water content and specific gravity parameters were used to determine the void ratios of the Casagrande test specimens.

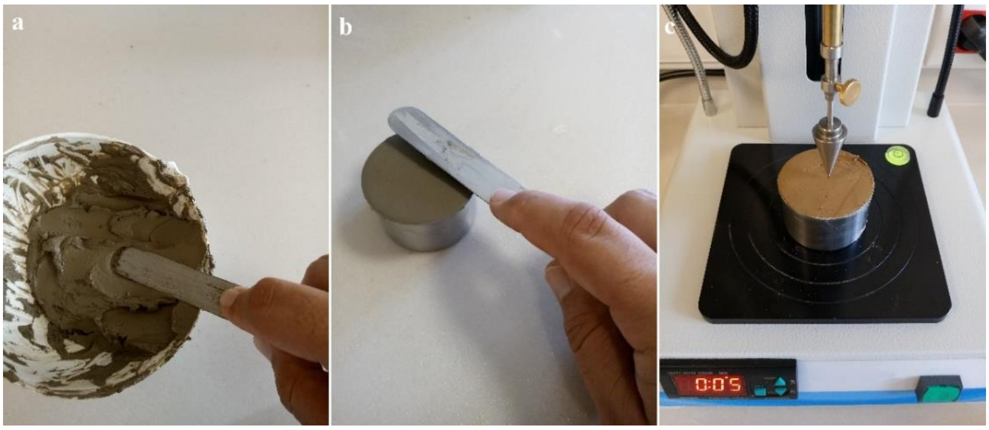

Figure 2. *a) Soil mixing, b) placing specimen in the mold and surface flattening, c) a prepared specimen under the cone penetrometer*

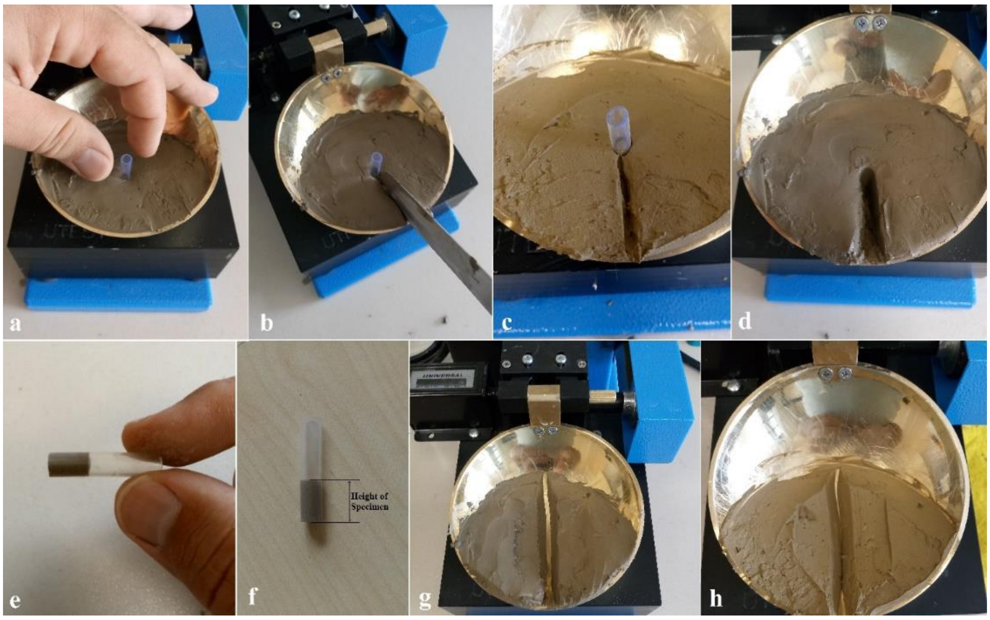

Figure 3. *a) Tube insertion into the Casagrande test specimen, b) and c) cutting the way to remove the tube, d) a specimen after removing the tube, e) and f) void ratio specimens in the glass tube, g) the groove cut, h) closure of the groove of a tested specimen*

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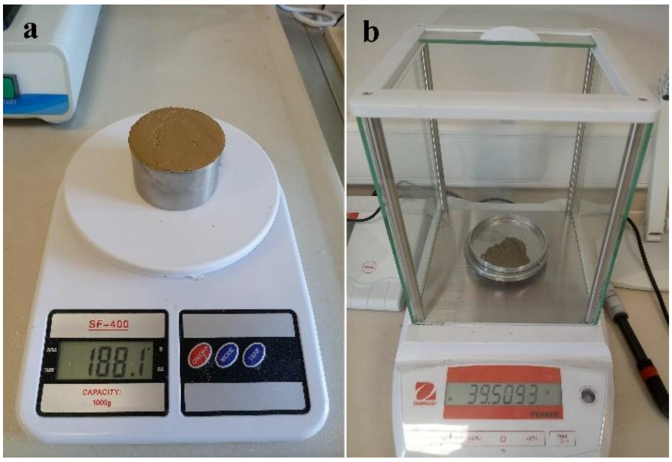

Figure 4. *Scales used in this study: a) scale with the sensitivity of 0.1 g, b) scale with the sensitivity of 0.0001 g*

3 RESULTS

The specific gravity values of soil specimens, which were determined in accordance with the results of the pycnometer test, are given in Table 1. Changes in the cone penetration depth for varying void ratios of soil specimens are given in Table 2. The void ratio values for the cone penetration depth of 20 mm were determined for different water contents using regression analyses results given in Table 3. The relations between void ratio and liquid limit values for different soil specimens tested within this study are given in Tables 4 and 5. According to the results, the liquid limit notably decreased with an increase in the void ratio of specimens tested in cone penetrometer test. Although there was a strong correlation between the two variables of the void ratio and the liquid limit of a soil type, the relation was found to vary for different soil specimens.

Table 1. *Specific gravities of soils tested*

Soil	G_s
Giresun (Soil G)	2.55
Bulancak (Soil B)	2.61
Piraziz (Soil P)	2.52
Unye (Soil U)	2.47

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Table 2. *Cone penetration (CP) values for soils tested (m: water content, e: void ratio)*

Soil G			Soil B			Soil P			Soil U		
m	e	CP (mm)	m	e	CP (mm)	m	e	CP (mm)	m	e	CP (mm)
0.25	0.74	13.0	0.24	0.79	13.2	0.31	0.93	12.2	0.30	0.87	16.0
0.25	0.93	15.4	0.24	0.90	15.4	0.31	1.08	14.1	0.30	1.02	17.3
0.25	1.15	17.9	0.24	1.04	17.8	0.31	1.25	16.8	0.30	1.21	18.5
0.32	0.89	16.3	0.28	0.81	16.3	0.37	1.00	14.5	0.33	0.92	16.9
0.32	1.05	18.0	0.28	0.92	19.1	0.37	1.14	16.7	0.33	1.05	18.0
0.32	1.24	20.5	0.28	1.08	21.4	0.37	1.26	19.0	0.33	1.29	20.4
0.37	1.08	19.6	0.31	0.90	19.0	0.42	1.13	17.3	0.38	1.04	19.7
0.37	1.20	21.3	0.31	0.99	21.5	0.42	1.28	20.1	0.38	1.26	21.9
0.37	1.33	24.2	0.31	1.13	23.6	0.42	1.37	23.0	0.38	1.40	24.2
0.41	1.15	22.9	0.35	0.97	22.5	0.49	1.32	22.8	0.44	1.19	22.0
0.41	1.25	25.7	0.35	1.05	24.8	0.49	1.41	24.9	0.44	1.31	25.3
0.41	1.37	28.1	0.35	1.16	26.7	0.49	1.49	27.6	0.44	1.43	27.1

Table 3. *Correlation data for the cone penetration (CP) and void ratio (e) relation*

Water content, soil	Equation of the regression line	R^2	Void ratio interval in tests
0.25, Soil G	CP: 11.94e + 4.214	0.990	0.74-1.15
0.32, Soil G	CP: 12.04e + 5.509	0.996	0.88-1.24
0.37, Soil G	CP: 18.45e - 0.5065	0.984	1.08-1.33
0.41, Soil G	CP: 23.52e - 3.986	0.989	1.05-1.27
0.24, Soil B	CP: 18.34e - 1.226	0.996	0.79-1.16
0.28, Soil B	CP: 18.56e + 1.547	0.974	0.81-1.08
0.31, Soil B	CP: 19.57e + 1.670	0.970	0.90-1.13
0.35, Soil B	CP: 21.81e + 1.545	0.979	0.97-1.16
0.31, Soil P	CP: 14.41e - 1.290	0.995	0.93-1.25
0.37, Soil P	CP: 17.26e - 2.832	0.986	1.00-1.26
0.42, Soil P	CP: 23.23e - 9.138	0.977	1.13-1.37
0.49, Soil P	CP: 28.09e - 14.47	0.979	1.32-1.49
0.30, Soil U	CP: 7.308e + 9.715	0.991	0.87-1.21
0.33, Soil U	CP: 9.527e + 8.081	0.998	0.92-1.29
0.38, Soil U	CP: 12.28e + 6.791	0.980	1.04-1.40
0.44, Soil U	CP: 21.25e - 3.038	0.972	1.09-1.43

Table 4. *Relation between void ratio and liquid limit (LL) values obtained from the cone penetration test*

Soil G		Soil B		Soil P		Soil U	
e	LL	e	LL	e	LL	e	LL
1.32	0.25	1.02	0.24	1.48	0.31	1.41	0.30
1.20	0.32	0.99	0.28	1.32	0.37	1.25	0.33
1.11	0.37	0.93	0.31	1.25	0.42	1.08	0.38
1.02	0.41	0.85	0.35	1.22	0.49	0.80	0.44

Table 5. *Correlation data for void ratio and liquid limit values obtained from the cone penetration test*

Soil	Equation of the regression line	R^2
Soil G	LL: -0.5273e + 0.9621	0.984
Soil B	LL: -0.6074e + 0.8705	0.959
Soil P	LL: -0.6153e + 1.196	0.881
Soil U	LL: -0.2344e + 0.6286	0.995

As similar, the void ratio has varying relations with the liquid limit values of different soil types in accordance with the results obtained from the Casagrande test. A general relation between the void ratio and Casagrande test results was found to be no existing. However, it is possible to say that the blow number in the test decreased with an increase in void ratio. In Table 6, the data of void ratio to blow numbers of the cup is given for varying water contents. The void ratio values were evaluated for the drop number of 25 using regression analyses results given in Table 7. The relations between void ratio and liquid limit values for different soil specimens used in the Casagrande test are given in Tables 8 and 9. Additionally, changes in the liquid limit values in accordance with the regression analyses for the cone penetrometer and the Casagrande tests are shown in Figure 5.

Table 6. *Blow numbers (BN) obtained from the Casagrande test (m: water content)*

Soil G			Soil B			Soil P			Soil U		
m	e	BN	m	e	BN	m	e	BN	m	e	BN
0.26	0.82	35	0.22	0.73	29	0.30	0.92	46	0.29	0.89	65
0.26	0.89	34	0.22	0.84	26	0.30	1.10	43	0.29	1.06	47
0.26	0.94	32	0.22	0.89	26	0.30	1.14	41	0.29	1.15	41
0.31	0.95	26	0.29	0.88	17	0.38	1.13	32	0.36	1.08	29
0.31	1.01	24	0.29	1.00	15	0.38	1.20	28	0.36	1.23	24
0.31	1.06	21	0.29	1.07	13	0.38	1.28	25	0.36	1.30	19
0.37	1.06	15	0.34	0.95	12	0.48	1.25	14	0.45	1.29	12
0.37	1.17	13	0.34	1.06	11	0.48	1.33	13	0.45	1.41	10
0.37	1.20	13	0.34	1.13	8	0.48	1.42	11	0.45	1.47	7

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Table 7. *Correlation data for the blow number and void ratio relation*

Water content, soil	Eq. of the regression line	R^2	Void ratio interval in tests
0.26, Soil G	BN: 55.142-24.312e	0.903	0.82-0.94
0.31, Soil G	BN: 69.023-45.055e	0.972	0.95-1.06
0.37, Soil G	BN: 31.202-15.337e	0.958	1.06-1.20
0.22, Soil B	BN: 43.521-20.150e	0.907	0.73-0.89
0.29, Soil B	BN: 35.237-20.581e	0.976	0.88-1.07
0.34, Soil B	BN: 32.371-21.056e	0.842	0.95-1.13
0.30, Soil P	BN: 65.323-20.874e	0.944	0.92-1.14
0.38, Soil P	BN: 84.236-45.458e	0.985	1.13-1.28
0.48, Soil P	BN: 36.060-17.653e	0.970	1.25-1.42
0.29, Soil U	BN: 148.203-94.069e	0.986	0.89-1.15
0.36, Soil U	BN: 76.394-43.538e	0.957	1.08-1.30
0.45, Soil U	BN: 46.067-26.190e	0.909	1.29-1.47

Table 8. *Relation between void ratio and liquid limit values obtained from the Casagrande test*

Soil G		Soil B		Soil P		Soil U	
e	LL	e	LL	e	LL	e	LL
1.24	0.26	0.92	0.22	2.17	0.30	1.31	0.29
0.98	0.31	0.50	0.29	1.30	0.38	1.18	0.36
0.41	0.37	0.35	0.34	0.63	0.48	0.80	0.45

Table 9. *Correlation data for void ratio and liquid limit values obtained from the Casagrande test*

Soil	Equation of the regression line	R^2
Soil G	LL: -0.1281e+0.4256	0.974
Soil B	LL: 0.2010e+0.4019	0.970
Soil P	LL: -0.1157e+0.5447	0.981
Soil U	LL: -0.3004e+0.6917	0.959

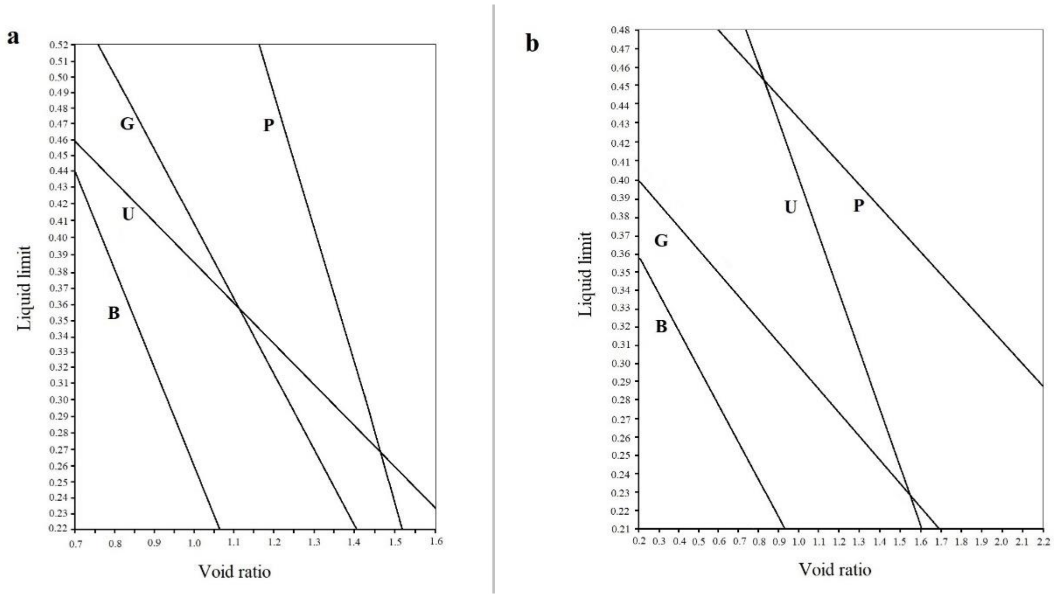

Figure 5. *Relation between void ratio and liquid limit values obtained from the Cone Penetrometer (a) and the Casagrande test (b)*

4 DISCUSSIONS

According to the results of this experimental study, the void ratio was found to have an important role on the liquid limit values of soils. Both the cone penetrometer and the Casagrande test mechanisms were assessed to be directly influenced by the void ratio parameter. Therefore, it was found there is a big lack to have no statement about the void ratio parameter in relevant standards. It was inferred that a standard void ratio should be used in the standard test methods to comparatively and accurately investigate the liquid limits of different soils.

Because the cylindrical standard specimen cup has a regular shape and a known volume, it is possible to make specimens with a target void ratio in the cone penetrometer test. To make a standard void ratio before liquid limit testing, specific gravity and water content are needed to be known and dry soil specimens should be prepared first. In opposition to the cone penetrometer test, it is not possible to make a Casagrande test specimen with a target void ratio. Instead, void ratios can be determined after preparation of the specimen used in the test. Because relations between void ratio and liquid limit parameters are different for various soils, use of a correlation for various types of soils was found to be not convenient.

Liquefaction of soils is a phenomenon whereby a soil and water mix loses its strength in response to an applied shear stress [24–26]. In case of a compact soil, strength loss is harder in comparison with the case of a loose soil having a relatively high void ratio. It is predicted that the resistance against the liquefaction of soils improves as the void ratio decreases because of the increase in the friction interface area at the particle contacts.

The internal friction angle parameter also increases with a decrease in the void ratio [27–29]. Considering the closure of the Casagrande test specimens with a groove as a mini slope instability, it is well-estimated that the compact soil specimens have a better resistance against sliding than loose soils [30–33].

With regard to the cone penetrometer test mechanism, the penetration depth depends on the compactness of a soil material. The results obtained from the cone penetrometer test depend not only on the water content but also the void ratio. In a similar manner, the famous standard penetration test (SPT) which has a very similar mechanism with that of the cone penetrometer test is applied in the field studies and gives results with strong correlations with the relative void ratio parameter [34–36].

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The plastic limit parameter is another topic for further studies. For the aim of accurate soil classifications, it should be investigated to understand whether the void ratio has a notable effect on the plastic limit values of soil specimens, or not.

5 CONCLUSION

In short, void ratio was assessed to be an important parameter for the determination of the liquid limit values using both cone penetrometer and Casagrande tests. A test method including no information on the void ratio means an important lack in terms of obtaining operator dependent results. As a result of the use of a specimen cup with a definite volume, the cone penetrometer test is advantageous in comparison with the Casagrande test, to prepare specimens with a target void ratio. Because of the change in the liquid limit values for different void ratio values, considering only one liquid limit value is not recommended for determining the liquefaction property of a soil material. As another outcome obtained from this study, there is no general relation between liquid limit and void ratio parameters to use for different soil materials. Therefore, it was found that the liquid limits of the soils cannot be correlated for different void ratios without testing.

REFERENCES

[1] ATTERBERG, A. Die Plastizität der Tone. *Internationale Mitteilungen für Bodenkunde*. 1911, 1, pp. 10–43.

[2] ANDRADE, F.A., H.A. AL-QURESHI and D. HOTZA. Measuring the plasticity of clays: A review. *Applied Clay Science*. 2011, 51, pp. 1–7, 2011. DOI: https://doi.org/10.1016/j.clay.2010.10.028

[3] SHARMA, B. and A. SRIDHARAN. Liquid and plastic limits of clays by cone method. *International Journal of Geo-Engineering*. 2018, 9:22. DOI: https://doi.org/10.1186/s40703-018-0092-0

[4] FIEGEL, G.L. and B.L. KUTTER. Liquefaction Mechanism for Layered Soils. *Journal of Geotechnical Engineering*. 1994, 120:737. DOI: https://doi.org/10.1061/(ASCE)0733-9410(1994)120:4(737)

[5] STANCHI, S., M. CATONI, M.E. D'AMICOA, G. FALSONE and E. BONIFACIO. Liquid and plastic limits of clayey, organic C-rich mountain soils: Role of organic matter and mineralogy. *Catena*. 2017, 151, pp. 238–246. DOI: https://doi.org/10.1016/j.catena.2016.12.021

[6] CASAGRANDE, A. Research on the Atterberg limits of soils. *Public Roads*. 1932, 13(3), pp. 121–136.

[7] CASAGRANDE, A. Notes on the Design of the Liquid Limit Device. *Geotechnique*. 1958, 8, pp. 84–91. DOI: https://doi.org/10.1680/geot.1958.8.2.84

[8] HANSBO, S. *A new approach to the determination of the shear strength of clay by the fall cone test*. Royal Swedish Geotechnical Institute, 1957.

[9] CLAYTON, C.R.I. and A.W. JUKES. A One Point Cone Penetrometer Liquid Limit Test? *Geotechnique*. 1978, 28, pp. 469–472. DOI: https://doi.org/10.1680/geot.1978.28.4.469

[10] SHERWOOD, P.T. and M.D. RYLEY. An investigation of a cone-penetrometer method for the determination of the liquid limit. *Géotechnique*. 1970, 20(2), pp. 203–208. DOI: https://doi.org/10.1680/geot.1970.20.2.203

[11] WASTI, Y. Liquid and Plastic limits as determined from the fall cone and the Casagrande methods. *ASTM Geotechnical Testing Journal*. 1987, 10(1), pp. 26–30. DOI: https://doi.org/10.1520/GTJ10135J

[12] WASTI, Y. and M.H. BEZIRCI. Determination of the Consistency Limits of Soils by the Fall Cone Test. *Canadian Geotechnical Journal*. 1986, 23, pp. 241-246. DOI: https://doi.org/10.1139/t86-033

[13] BS 1377:1975. *Methods of test for soils for civil engineering purposes*. London: British Standards Institution, 1975.

Vol. 66 (2020), No. 3
pp. 150–161, ISSN 1802-5420
DOI 10.35180/gse-2020-0039

[14] BS 1377-2. *Methods of test for soils for civil engineering purposes: Classification Tests*. London: British Standards Institution, 1990.

[15] CAN/BNQ 2501-092/2006. *Soils-determination of liquid limit by the Swedish fall cone penetrometer method and determination of plastic limit*. Ottawa: Standards Council of Canada, 2006.

[16] ISO 17892-6:201. *Geotechnical investigation and testing – Laboratory testing of soil – Part 6: Fall cone test*. Geneva: International Organization for Standardization, 2017.

[17] TS 1900-1. *İnşaat Mühendisliğinde Zemin Laboratuvar Deneyleri*. Ankara: Turkish Standards Institution, 2006.

[18] HENNICHE, A. and S. BELKACEMI. Numerical Simulation to Select Proper Strain Rates during CRS Consolidation Test. *Periodica Polytechnica Civil Engineering*. 2018, 62(2), pp. 404–412. DOI: https://doi.org/10.3311/PPci.9650

[19] YILMAZ, Y., A.B. KHEIRJOUY and A.P. AKGUNGOR. Investigation of the Effect of Different Saturation Methods on the Undrained Shear Strength of a Clayey Soil Compacted with Standard and Modified Proctor Energies. *Periodica Polytechnica Civil Engineering*. 2016, 60(3), pp. 323–329. DOI: https://doi.org/10.3311/PPci.8891

[20] LI, Y. Effects of particle shape and size distribution on the shear strength behavior of composite soils. *Bulletin of Engineering Geology and the Environment*. 2013, 72, pp. 371–381. DOI: https://doi.org/10.1007/s10064-013-0482-7

[21] ASTM D854-10. Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer. *2010 Annual Book of ASTM Standards*. West Conshohocken, PA: ASTM International, 2010.

[22] ASTM D4318-10. Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. *2010 Annual Book of ASTM Standards*. West Conshohocken, PA: ASTM International, 2010.

[23] ASTM D2216-19. Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass. *2019 Annual Book of ASTM Standards*. West Conshohocken, PA: ASTM International, 2019.

[24] MORADI, G., M.H. SOTOUBADI and B.R. KHATIBI. The influence of overburden pressure on liquefaction potential. *Turkish Journal of Engineering & Environmental Sciences*. 2014, 38, pp. 323–337. DOI: https://doi.org/10.3906/muh-1304-9

[25] ZHANG, W., A.T.C. GOH, Y. ZHANG, Y. CHEN and Y. XIAO. Assessment of soil liquefaction based on capacity energy concept and multivariate adaptive regression splines. *Engineering Geology*. 2015, 188, pp. 29–37. DOI: https://doi.org/10.1016/j.enggeo.2015.01.009

[26] KHEIRBEK-SAOUD, S. and J. FLEUREAU. Liquefaction and post-liquefaction behaviour of a soft natural clayey soil. *Geomechanics and Engineering*. 2012, 4(2), pp. 121–134. DOI: https://doi.org/10.12989/gae.2012.4.2.121

[27] ALIKONIS, A. Ground compaction zone of structures and structural strength of soil. *Journal of Civil Engineering and Management*. 1995, 1(2), pp. 65–70. DOI: https://doi.org/10.3846/13921525.1995.10531513

[28] SANTANA, T. and M. CANDEIAS. Effect of Void Ratio on K0 of a Sand by Means of Triaxial Stress-Path Testing. *Geotechnical and Geological Engineering*. 2018, 36, pp. 257–266. DOI: https://doi.org/10.1007/s10706-017-0324-7

[29] ZHANG, Q., S.K. UPADHYAYA, Q. LIAOA and X. LI. Determination of in-situ engineering properties of soil using an inverse solution technique and limited field tests. *Journal of Terramechanics*. 2018, 79, pp. 69–77. DOI: https://doi.org/10.1016/j.jterra.2018.07.001

[30] ZHANG, L.L., M.D. FREDLUND, D.G. FREDLUND, H. LU and G.W. WILSON. The influence of the unsaturated soil zone on 2-D and 3-D slope stability analyses. *Engineering Geology*. 2015, 193, pp. 374–383. DOI: https://doi.org/10.1016/j.enggeo.2015.05.011

[31] UKRITCHON, B. and S. KEAWSAWASVONG. A new design equation for drained stability of conical slopes in cohesive-frictional soils. *Journal of Rock Mechanics and Geotechnical Engineering*. 2018, 10(2), pp. 358–366. DOI: https://doi.org/10.1016/j.jrmge.2017.10.004

[32] DUNCAN, J.M., S.G. WRIGHT and T.L. BRANDON. *Soil Strength and Slope Stability*. New Jersey: John Wiley & Sons, 2014.

[33] ZHAI, J. and X. CAI. Strength Characteristics and Slope Stability of Expansive Soil from Pingdingshan, China. *Advances in Materials Science and Engineering*. 2018, vol. 2018, Article ID 3293619, 7 pages, DOI: https://doi.org/10.1155/2018/3293619

[34] ANBAZHAGAN, P., A. UDAY, S.S.R. MOUSTAFA and N.S.N. AL-ARIFI. Soil void ratio correlation with shear wave velocities and SPT N values for Indo-Gangetic basin. *Journal of Geological Society of India*. 2017, 89, pp. 398–406. DOI: https://doi.org/10.1007/s12594-017-0621-z

[35] BAROUNIS, N. and J. PHILPOT. Estimation of in-situ water content and void ratio using CPT for saturated sands. In: HICKS, M.A., F. PISANÒ and J. PEUCHEN, eds. *Proceedings of the 4th International Symposium on Cone Penetration Testing (CPT'18)*: 21–22 June, 2018, Delft. Delft: CRC Press, 2018, pp. 129–135.

[36] MUJTABA, H., K. FAROOQ, N. SIVAKUGAN and B.M. DAS. Evaluation of relative density and friction angle based on SPT-N values. *KSCE Journal of Civil Engineering*. 2018, 22, pp. 572–581. DOI: https://doi.org/10.1007/s12205-017-1899-5

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