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Article in Canadian Geotechnical Journal · February 2010

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Shear strength of remolded soils at consistency limits

Kamil Kayabali and Osman Oguz Tufenkci

Abstract: The undrained shear strength of remolded soils is of concern in certain geotechnical engineering applications. Several methods for determining this parameter exist, including the laboratory vane test. This study proposes a new method to estimate the undrained shear strength, particularly at the plastic and liquid limits. For 30 inorganic soil samples of different plasticity levels, we determined the Atterberg limits, then performed a series of reverse extrusion tests at different water contents. The plastic and liquid limits are derived from the linear relationship between the logarithm of the extrusion pressure and water content. The tests show that the average undrained shear strength determined from the extrusion pressures at the plastic limit is about 180 kPa, whereas the average undrained shear strength at the liquid limit is 2.3 kPa. We show that the undrained shear strength of remolded soils at any water content can be estimated from the Atterberg limits alone. Although the laboratory vane test provides a reasonable undrained shear strength value at the plastic limit, it overestimates the undrained shear strength at the liquid limit and thus, care must be taken when the laboratory vane test is used to determine undrained shear strengths at water contents near the liquid limit.

Key words: soil consistency limits, undrained shear strength, remolded soil, reverse extrusion, laboratory vane.

Résumé : La résistance au cisaillement non drainé de sols remaniés est une préoccupation dans certaines applications géotechniques. Plusieurs méthodes existent pour déterminer ce paramètre, incluant l’essai scissométrique en laboratoire. Cette étude propose une nouvelle méthode pour estimer la résistance au cisaillement non drainé, particulièrement aux limites plastiques et liquides. Nous avons déterminé les limites d’Atterberg de 30 échantillons de sol inorganique avec des niveaux de plasticité différents. Ensuite, une série d’essais d’extrusion inverse ont été effectués à des teneurs en eau variables. Les limites plastiques et liquides sont dérivées de la relation linéaire entre le logarithme de la pression d’extrusion et la teneur en eau. Les essais montrent que la résistance au cisaillement non drainé moyenne déterminée à partir des pressions d’extrusion à la limite plastique est de 180 kPa, alors que la résistance au cisaillement non drainé à la limite liquide est de 2,3 kPa. Nous démontrons que la résistance au cisaillement non drainé d’un sol remanié peu importe la teneur en eau peut être estimée à l’aide des limites d’Atterberg seulement. Même si l’essai scissométrique en laboratoire permet d’obtenir une valeur raisonnable de la résistance au cisaillement non drainé àla limite plastique, cet essai surestime la résistance au cisaillement non drainé à la limite liquide. Ainsi, il faut être prudent lorsque l’essai scissométrique en laboratoire est utilisé pour déterminer des résistances au cisaillement non drainé à des teneurs en eau près de la limite liquide.

Mots-clés : limites de consistance du sol, résistance au cisaillement non drainé, sol remanié, extrusion inverse, scissomètre de laboratoire.

[Traduit par la Rédaction]

Introduction

The undrained shear strength of remolded soils is of great concern in geotechnical engineering, such as submarine soil investigations of offshore structures, studies of glacial soils, and pile design. For instance, pile installation causes disturbances in the soil adjacent to the pile. The undrained and remolded strength profile of soft clay deposits is often required for the design of offshore foundation systems (Yafrate and DeJong 2005). Bozozuk (1972) showed that when relative movements and excess pore pressures in soils subjected to pile penetration are large, skin friction decreases to the remolded strength. Glacial deposits and quick clays often require the determination of the remolded strength, particularly in mass movement investigations (e.g., Kvalstad et al. 2005). Powell and Lunne (2005) showed that the sleeve friction stress from an electrical cone penetration test (CPT) is a function of the remolded shear strength of the soil, which is important because the cone remolds the soil in its vicinity during penetration.

Engineers often make important design decisions based upon inadequate and (or) poor quality soil strength data. In such cases, the engineer may wish to evaluate the remolded soil strength as a lower bound value. Therefore, the objective of this study is to present a new approach for determining the undrained shear strength of remolded saturated inorganic soils of various levels of plasticity using the reverse extrusion technique.

Received 19 March 2008. Accepted 6 August 2009. Published on the NRC Research Press Web site at cgj.nrc.ca on 17 February 2010.

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Background on undrained strength at consistency limits

In fine soils, soil strength decreases as the water content increases. Because of this, both the percussion cup and the bead-rolling tests for determining the liquid and plastic limits of soils, respectively, are interpreted as undrained strength states. If the consistency limits can be defined on the basis of strength, then what values of strength should be adopted to be reasonably consistent with the Atterberg limits?

As early as 1939, Casagrande related shear strength to the liquid limit of a soil (Sharma and Bora 2003). Casagrande suggested that an average value of the shear strength of soils at the liquid limit was 2.65 kN/m^2, taking into account the large spread of liquid limit values depending on the apparatus used for tests. A number of papers exist related to this topic. Wroth and Wood (1978) and Sharma and Bora (2003) provide excellent summaries of the relevant literature. Table 1 presents undrained shear strengths at the liquid limit based upon the literature. The data reveals that, although the undrained shear strength at the liquid limit ranges from 0.5 to 4.0 kN/m^2, most researchers have concluded that the undrained shear strength of remolded soils at the liquid limit is around 1.6 to 1.7 kN/m^2.

A review of the literature shows that the undrained shear strength of remolded soils at the plastic limit covers a large range, from 20 to 320 kN/m^2 (Table 2). It appears that the strength criterion for the plastic limit is invalid; however, as in the case of the liquid limit, most researchers have proposed that the undrained shear strength of remolded soils at the plastic limit is around 110–170 kN/m^2, mostly towards the lower bound.

Based upon the common view that the undrained shear strengths of remolded soils at the plastic and liquid limits are 170 and 1.7 kN/m^2, respectively, the ratio between these two strengths is about 100 (e.g., Skempton and Northey 1953; Wroth and Wood 1978; Belviso et al. 1985; Sharma and Bora 2003; Lee and Freeman 2007). For some Swedish clays, Whyte (1982) suggested that this ratio was approximately 70; Karlsson (1977) indicated that this ratio was between 50 and 100.

Soil tests used to establish consistency limits are essentially strength tests. Through these tests, the undrained shear strength of soils is determined, either directly or indirectly. The undrained shear strength of remolded soils provides a rational basis for index tests to establish liquid and plastic limits (Medhat and Whyte 1986). We intend to establish a relationship between consistency limits and undrained shear strength.

Extrusion

Extrusion is a mechanical process by which a block of metal, plastic, food or soil (mostly for brick making) is reduced in cross section by forcing it to flow through a die orifice under pressure. The two basic types of extrusion are direct and reverse extrusion (Fig. 1). Direct extrusion of materials involves placing a billet in a container and driving it through a die using a ram. A dummy block, or pressure plate, is placed at the end of the ram, in contact with the billet. In reverse extrusion, a hollow ram carries the die, while the other end of the container is closed with a plate. In reverse extrusion (Fig. 1*b*), the billet (A) is rigidly contained in the chamber. When the soil reaches the shear zone (B), it distorts and leaves the die as a soil worm (C). The material is stressed to its yield limit and it is not possible to transmit more pressure from the billet to the die face through this yielding plastic zone (Whyte 1982). There is no relative motion between the wall of the container and the billet in reverse extrusion. Thus, the friction forces are lower and the force required for extrusion is less than for direct extrusion.

The first use of the extrusion technique in soil mechanics was by Timar (1974), who attempted to determine both plastic and liquid limits using direct extrusion tests, but had difficulties with the interpretation of results due to the influence of friction as the billet is forced along the container towards the die. Whyte (1982) utilized the reverse extrusion technique to establish a relationship between soil plasticity and undrained shear strength.

In Fig. 2, extrusion pressure is plotted against punch travel for direct and reverse extrusion. Extrusion pressure is defined as the extrusion force divided by the cross-sectional area of the billet. The rapid rise in pressure during the initial punch travel is due mainly to the initial compression of the billet intended to fill the extrusion container. For direct extrusion, the material begins to flow through the die at the maximum pressure. As the billet extrudes through the die, the pressure required to maintain flow progressively decreases with decreasing length of the billet in the container. For reverse extrusion there is no relative motion between the billet and the container wall. Thus, the extrusion pressure is approximately constant with increasing ram travel and represents the stress required to deform the material through the die (Dieter 1988).

The extrusion ratio of the initial cross-sectional area of the billet (A_0) to the final cross-sectional area after extrusion (A_f) is $R = A_0/A_f$. Extrusion pressure is directly related to the natural logarithm of the extrusion ratio; therefore, the extrusion force may be expressed as (Dieter 1988)

$$[1] \quad P = kA_0 \ln A_0/A_f$$

where k is the the "extrusion constant", an overall constant that accounts for flow stress, friction, and inhomogeneous deformation.

Whyte (1982) proposed the following form as a best-fit result based on a series of reverse extrusion tests on a low-plasticity clay with varying area ratios:

$$[2] \quad P = c_u(1.6 + 4.3 \ln R)$$

where P is the extrusion pressure and c_u is the undrained shear strength of the remolded soil.

Medhat and Whyte (1986) suggested a slightly different form after carrying out a series of tests on Flixton clay

$$[3] \quad P = c_u(0.5 + 5.8 \ln R)$$

Experimental analyses

Atterberg limit tests

The soil data used in this study were taken from 30 inor-

Table 1. Undrained shear strengths (c_u) at liquid limit.

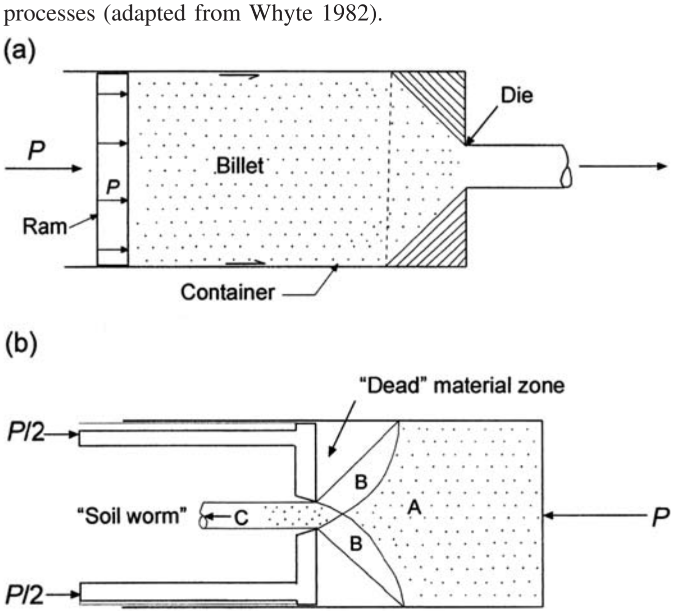
Source	c_u (kN/m^2) Range	Average	Remarks
BS 1377 (BSI 1948)	—	1.6	Quoted by Whyte (1982)
Skempton and Northey (1953)	0.7–1.75	—	Soils with very different PI values
Norman (1958)	0.8–1.6	—	Apparatus used conforms to British Standards Institute standards
Seed et al. (1964)	2.5	—	Quoted by Whyte (1982)
Youssef et al. (1965)	1.3–2.4	1.7	Utilized laboratory vane tests
Skopek and Ter-Stepanian (1975)	1–3	—	Quoted by Wroth and Wood (1978)
Karlsson (1977)	0.5–4.0	—	Quoted by Whyte (1982)
Wroth and Wood (1978)	—	1.7	Adopted as the best estimate
ASTM D4318-00 (ASTM 2001)	1.1–2.3	—	Quoted by Wroth and Wood (1978)
Swedish cone	—	1.7	Quoted by Whyte (1982)
Whyte (1982)	—	1.6	Upon literature review
Federico (1983)	1.7–2.8	—	Quoted by Sharma and Bora (2003)
Wood (1985)	—	1.7	Quoted by Sharma and Bora (2003)
Medhat and Whyte (1986)	—	1.6	Upon literature review
Sharma and Bora (2003)	—	1.7	Adopted as the best estimate

Table 2. Undrained shear strengths (c_u) at plastic limit.

Source	c_u (kN/m^2) Range	Average	Remarks
BS 1377 (BSI 1948)	—	110	Quoted by Whyte (1982)
Skempton and Northey (1953)	85–125	110	Quoted by Whyte (1982)
Dennehy (1978)	30–320	115,* 104†	Quoted by Whyte (1982)
Arrowsmith (1978)	20–220	110	Quoted by Whyte (1982)
Whyte (1982)	25–280	130	Cited as oral communication with Arrowsmith
Wroth and Wood (1978)	—	170	Adopted as the best estimate
Medhat and Whyte (1986)	—	110	Upon literature review
Sharma and Bora (2003)	—	170	Cone penetration method

*Arithmetic.
†Geometric.

Fig. 1. Schematic illustration of (*a*) direct and (*b*) reverse extrusion processes (adapted from Whyte 1982).

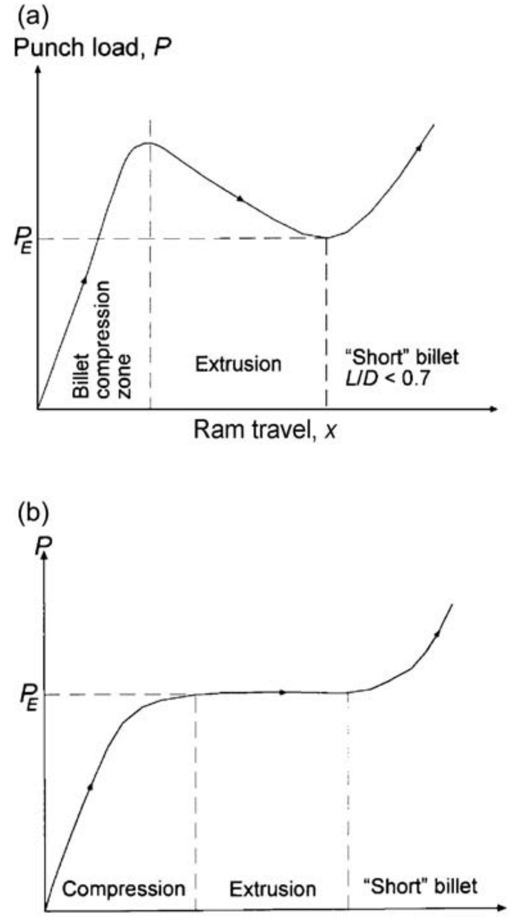


ganic soil samples. Atterberg limit tests were performed in accordance with the ASTM D4318 standard (ASTM 2001). Fifteen of the soil samples (group A) were analyzed in eight different soil mechanics laboratories by several different operators in each laboratory. Each soil sample in this group has 22 pairs of plastic and liquid limit tests. The remaining 15 soil samples (group B) were analyzed in a single laboratory, again by different operators. Each soil sample in this group was subject to 15 plastic and liquid limit tests. The results of these Atterberg limit tests are listed in Table 3.

Reverse extrusion tests

The oven-dried soil samples were first sieved through the No. 40 sieve. Then, each soil sample was mixed with water to bring the sample to a consistency between the liquid and plastic limit and was thoroughly mixed until a homogeneous mixture was obtained. The mixture was then placed into the extrusion container of 38 mm diameter such that the sample length was twice the diameter. The container and the ram, which had a die orifice of 6 mm, were assembled into the unconfined compression test instrument. The mixture inside the container was compressed under the ram pressure and the resulting stress values were plotted as a function of the

Fig. 2. Load–travel diagrams for (*a*) direct and (*b*) reverse extrusions (adapted from Whyte 1982).



ram travel as shown in Fig. 3. This process was repeated four to six times on each soil sample at different water contents. The flat portion of the curves in Fig. 3 was considered as the extrusion pressure for the relevant water content. Extrusion pressure versus water content graphs were plotted for each of the 30 samples as shown in Fig. 4. The semi-logarithmic plot of extrusion pressure versus water content resulted in a linear fit. The extrusion pressure corresponding to the average liquid limit obtained from the conventional Casagrande cup method (ASTM 2001) was marked on the extrusion pressure – water content plot for each soil sample. Similarly, the extrusion pressure corresponding to the average plastic limit value obtained from the conventional bead rolling test (ASTM 2001) was determined.

The extrusion pressures corresponding to the mean liquid limit values determined by the common test technique for all 30 soil samples are plotted in Fig. 5. Most results plot between extrusion pressures of 31 and 45 kPa. The representative extrusion pressure corresponding to the water content at the liquid limit of tested soils is found to be 40 kPa, which is the average of the extrusion pressures within this range.

Similar to the procedure outlined above, the extrusion pressures corresponding to the mean plastic limit values were determined and are shown in Fig. 6. Most extrusion pressures corresponding to the plastic limit values plot between 2000 and 4000 kPa. The average extrusion pressure in this interval was computed to be about 3100 kPa.

The apparatus used in the experiments has an extrusion ratio (R) of 40. By using this value in eqs. [2] and [3], along with an extrusion pressure (P) of 3100 kPa at the plastic limit, the undrained shear strength (c_u) at the plastic limit is found to be 177 and 142 kPa, respectively. As eq. [2] is based on more detailed research, the former number is preferred and is rounded to 180 kPa. Similarly, by using an extrusion ratio of 40 in eqs. [2] and [3] along with an extrusion pressure (P) of 40 kPa at the liquid limit, the undrained shear strength (c_u) at the liquid limit is found to be 2.3 and 1.8 kPa, respectively. The former value of 2.3 kPa is preferred for the same reason as stated above and is set as the undrained strength at the liquid limit.

Laboratory vane tests

The laboratory vane test is an important tool for investigating the undrained shear strength of both intact and remolded fine-grained soils. Because the main purpose of this study is to use a different method to determine the undrained shear strength of fine-grained soils at the liquid and plastic limits, we conducted a series of laboratory vane tests to compare with our extrusion test results. In this regard, our laboratory vane data serve as a complementary study as well as a comparison tool.

Five to seven laboratory vane tests were conducted on the group B soil samples only. As in the case of the reverse extrusion tests, the soil samples were first oven-dried and then passed through a No. 40 sieve. The tests were run at water contents between the plastic and liquid limits using a Wykeham Farrance model WF2350 testing apparatus. The starting water content was close to the plastic limit of the tested soil. Each sample tested was progressively wetted after each laboratory vane test until the soil gained the "very soft" consistency. An appropriate spring was selected depending upon the consistency of the tested soil such that the shear failure occured between 20° and 90° stress. The test results are presented in Table 4.

The undrained shear strengths (c_u) versus water contents (w) obtained from the laboratory vane tests are shown in Fig. 7. As was observed from the reverse extrusion tests, there is a linear relationship between the logarithm of the undrained shear strength and water content. From the graphs of c_u versus w, the undrained shear strengths corresponding to the water contents at the plastic and liquid limits were determined and are listed in Table 5. These data reveal that, after excluding extreme values, a rough average of the undrained shear strength is 180 kPa at the plastic limit and is about 5 kPa for the liquid limit. This evaluation of limited data shows that, although the undrained shear strengths at the plastic limit estimated from the laboratory vane tests vary in an acceptable range, the undrained shear strengths at the liquid limit are overestimated when compared with our extrusion tests.

Conclusions

We derive the following conclusions from this study:

(1) The reverse extrusion test offers great potential in deter-

Table 3. Results of conventional consistency limit tests on soil samples.

Sample No.	Plastic limit (%) Min.	Max.	Mean	Standard deviation	Liquid limit (%) Min.	Max.	Mean	Standard deviation	USCS name
A-01	24.1	30.3	27.3	1.7	62.5	83.9	73.8	5.7	CH
A-02	18.2	25.7	21.1	2.0	51.3	63.6	57.3	3.2	CH
A-03	16.0	28.5	25.4	2.8	49.0	60.4	53.4	2.9	CH
A-04	14.7	26.5	20.7	2.6	46.3	60.2	52.3	4.1	CH
A-05	18.4	31.0	24.5	3.3	42.0	58.2	48.9	3.8	CL
A-06	13.8	33.0	19.6	4.3	42.4	53.5	47.1	3.0	CL
A-07	12.0	27.1	17.7	3.8	34.3	42.7	38.2	2.7	CL
A-08	17.2	25.1	20.4	2.1	45.0	52.0	48.4	2.4	CL
A-09	12.1	20.1	16.7	1.8	27.8	36.2	31.6	2.5	CL
A-10	26.6	40.4	31.5	3.3	53.4	70.6	62.4	4.7	MH
A-11	26.1	37.7	31.4	3.2	53.6	74.2	64.3	5.6	CH
A-12	27.2	43.0	33.7	3.6	63.8	90.0	75.8	7.3	CH
A-13	15.1	22.9	19.5	1.9	33.1	45.2	37.5	2.9	CL
A-14	15.0	22.3	18.8	1.9	33.2	46.4	38.9	3.2	CL
A-15	13.6	31.0	19.6	3.2	35.4	55.1	39.1	4.5	CL
B-01	36.0	46.0	40.7	3.1	71.0	98.0	83.6	9.5	MH
B-02	45.0	51.0	46.9	1.9	66.0	81.0	77.3	4.6	MH
B-03	27.0	44.0	31.8	5.8	55.0	71.0	62.4	5.1	MH
B-04	30.0	44.0	39.1	3.4	62.0	91.0	79.7	7.4	MH
B-05	20.0	26.0	23.5	2.0	44.0	48.0	46.1	1.2	CL
B-06	20.0	25.0	22.3	1.2	33.0	40.0	37.2	2.6	CL
B-07	33.0	37.0	35.3	1.3	77.0	91.0	81.7	4.6	MH
B-08	33.0	49.0	39.2	3.6	62.0	71.0	64.2	2.4	MH
B-09	25.5	32.0	29.7	1.7	37.7	46.5	44.3	2.7	ML
B-10	20.0	30.0	24.2	3.1	45.0	47.0	45.7	0.7	CL
B-11	21.0	30.0	23.3	3.0	56.0	60.0	57.1	1.2	CH
B-12	22.0	29.0	25.1	2.0	43.0	48.0	46.4	1.5	CL
B-13	15.6	25.5	23.0	3.1	43.8	46.2	44.7	0.6	CL
B-14	15.0	20.7	18.1	1.8	22.9	31.5	26.4	2.7	CL
B-15	18.0	26.0	22.7	2.6	31.0	40.0	37.5	2.4	ML

Note: USCS, Unified Soil Classification System (ASTM 2006); CH, fat clay; CL, lean clay; MH, silts of high plasticity; ML, silts of low plasticity.

Fig. 3. Extrusion pressure curves of sample No. A-11 at different water contents (w).

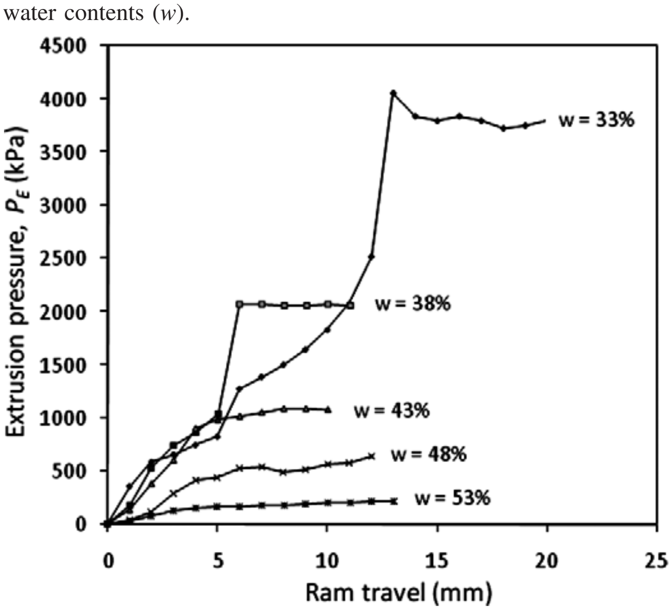


Fig. 4. Plot showing method of obtaining the extrusion pressures corresponding to the average plastic limit (PL), $P_{E(PL)}$, and liquid limit (LL), $P_{E(LL)}$, values from the conventional method for soil sample A-11.

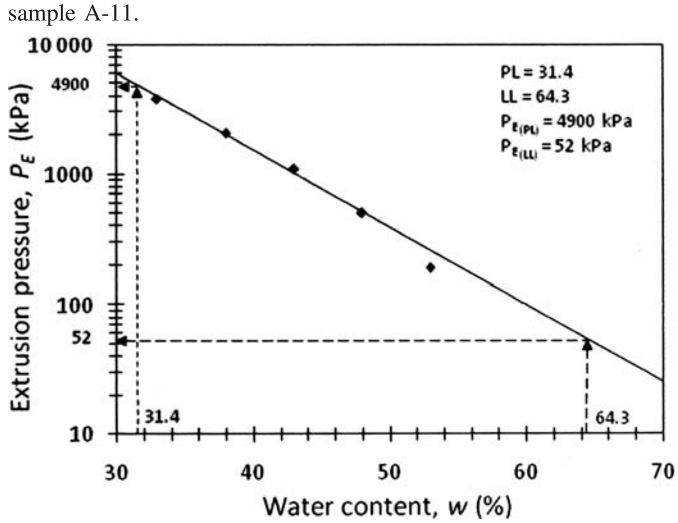


Fig. 5. Histogram of the extrusion pressures at the liquid limits.

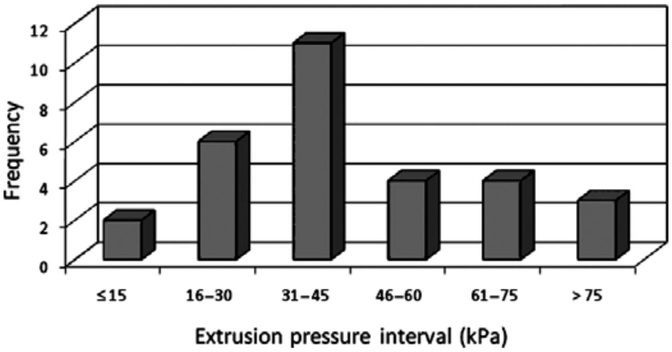
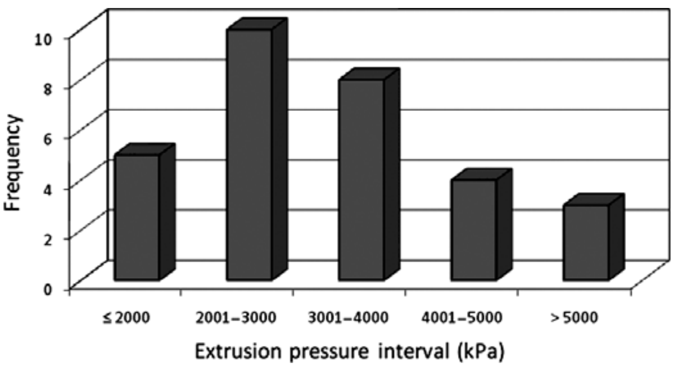


Fig. 6. Histogram of the extrusion pressures at the plastic limits.



mining the undrained shear strength of remolded soils at varying water contents.

(2) Using the reverse extrusion technique, the average undrained shear strength of soils at the liquid limit was found to be 2.3 kPa.

(3) Similarly, the average undrained shear strength of soils at the plastic limit water content was found to be about 180 kPa.

(4) The logarithm of the extrusion pressure and the water content have a linear relationship. Once the plastic and liquid limits of soils are known, the undrained shear strength of remolded soils can be estimated for any water content from this information.

(5) As the reverse extrusion test provides relatively consistent results, it may also be applied to natural soils.

(6) Although the laboratory vane test gives similar results to the extrusion test for undrained shear strength at the plastic limit, the undrained shear strength at the liquid limit is overestimated. Care must be taken for soft to very soft soils close to the liquid limit for which the laboratory vane was devised.

It should be kept in mind that, as it is virtually impossible to conduct an extrusion test at the liquid state of a soil, the extrusion pressures corresponding to the liquid limits are all extrapolations of the log-linear extrusion pressure versus water content curve to the liquid limit. The proposed undrained shear strengths at the plastic and liquid limits involve some degree of uncertainties introduced by the testing method as well as the empirical relationship used for conversion. Further refinements can be made upon use of a larger body of data.

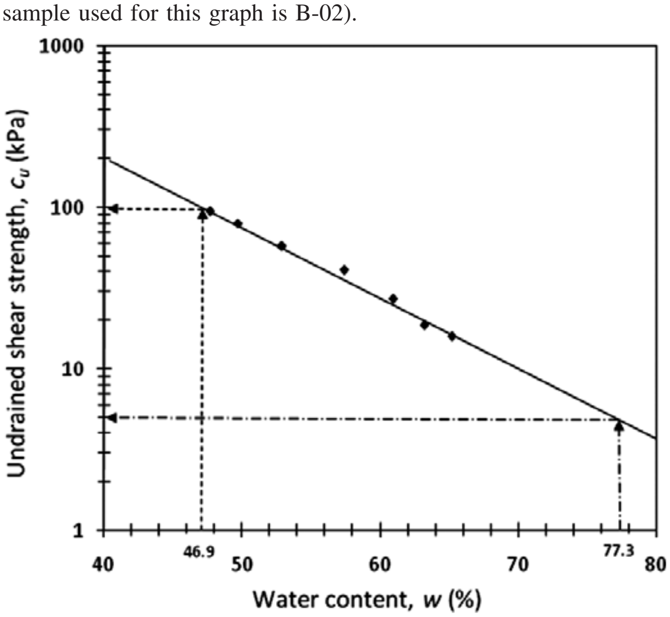
Table 4. Results of laboratory vane tests.

Sample No.	w (%)	c_u (kPa)
B-01	39.7	50
	46.7	42
	60.0	12
	63.1	9.5
	72.3	5.0
B-02	47.6	95
	49.7	80
	52.9	57
	57.3	41
	60.9	27
	63.1	19
	65.1	16
B-03	35.3	144
	38.2	80
	47.8	25
	50.5	15
	52.9	14
	49.7	19
B-04	45.7	122
	52.2	99
	66.3	27
	58.0	83
	74.5	19
	79.2	14
B-05	26.2	99
	29.5	59
	31.7	28
	33.7	15
	35.4	14
	38.1	6.8
B-06	25.8	47
	27.7	23
	30.5	8.8
	31.5	7.2
	23.0	87
	28.5	23
	23.0	99
B-07	63.9	51
	70.3	25
	76.1	15
	66.0	38
	71.0	23
B-08	53.0	41
	60.0	11
	55.2	29
	63.6	6.8
	57.3	20
B-09	40.3	15
	42.7	5.9
	37.8	20
	31.5	89
	36.0	32
B-10	28.6	57
	33.4	24
	29.7	34
	35.6	13
	30.2	31

Table 4 (*concluded*).

Sample No.	w (%)	c_u (kPa)
B-11	33.8	43
	35.6	41
	37.7	31
	40.7	23
	40.5	17
B-12	30.9	86
	34.3	51
	36.8	37
	38.3	28
	39.6	22
	41.7	19
B-13	31.2	80
	34.6	43
	34.9	37
	39.9	19
	40.3	12
B-14	19.4	83
	21.3	50
	24.1	6.6
	25.3	9.9
	26.3	5.9
B-15	28.0	89
	30.5	78
	33.6	14
	35.1	11
	36.2	8.6

Fig. 7. Determination of undrained shear strengths at the plastic and liquid limits using the laboratory vane test results (the soil sample used for this graph is B-02).



Acknowledgments

The contributions of data from numerous Atterberg limit tests from privately owned soil test laboratories are gratefully appreciated. Dr. M. Mollamahmutoglu from the Civil Engineering Department of Gazi University kindly provided access to their soil mechanics laboratory and made the laboratory vane apparatus available.

Table 5. Undrained shear strengths for fifteen samples from laboratory-vane tests corresponding to the plastic and liquid limit test results from the conventional methods.

	Plastic limit		Liquid limit	
Sample No.	PL (%)	c_u (kPa)	LL (%)	c_u (kPa)
B-01	40.7	68	83.6	1.8
B-02	46.9	100	77.3	4.3
B-03	31.8	170	62.4	4.2
B-04	39.1	190	79.7	12.0
B-05	23.5	190	46.1	1.2
B-06	22.3	125	37.2	1.3
B-07	35.3	530	81.7	9.0
B-08	39.2	400	64.2	6.0
B-09	29.7	130	44.3	3.8
B-10	24.2	115	45.7	1.9
B-11	23.3	260	57.1	1.2
B-12	25.1	210	46.4	8.0
B-13	23.0	340	44.7	6.3
B-14	18.1	220	26.4	5.8
B-15	22.7	200	37.5	6.0

References

Arrowsmith, E.J. 1978. Roadwork fills — a material engineer's viewpoint. *In* Proceedings of the Clay Fills Conference, 14–15 November 1978. Institution of Civil Engineers, London. pp. 25–36.

ASTM. 2001. Standard test methods for liquid limit, plastic limit and plasticity index of soils. ASTM standard D4318-00. American Society for Testing and Materials (ASTM), West Conshohocken, Pa.

ASTM. 2006. Standard practice for classification of soils for engineering purposes (Unified Soil Classification System). ASTM standard D2487. American Society for Testing and Materials (ASTM), West Conshohocken, Pa.

Belviso, R., Ciampoli, S., Cotecchia, V., and Federico, A. 1985. Use of the cone penetrometer to determine consistency limits. Ground Engineering, **18**(5): 21–22.

Bozozuk, M. 1972. Downdrag measurements on a 160-ft floating pipe test pile in marine clay. Canadian Geotechnical Journal, **9**(2): 127–136. doi:10.1139/t72-014.

BSI. 1948. Methods of test for soils suitable for civil engineering purposes. BSI standard BS 1377. British Standard Institution, London.

Dennehy, J.P. 1978. The remoulded undrained shear strength of cohesive soils and its influence on the suitability of embankment fill. *In* Proceedings of the Clay Fills Conference, London, UK, 14–15 November 1978. Institution of Civil Engineers, London. pp. 87–94.

Dieter, G.E. 1988. Mechanical metallurgy. McGraw-Hill, London.

Federico, A. 1983. Relationships (c_u–w) and (c_u–s) for remolded clayey soils at high water content. Rivista Italiana di Geotecnica, **17**(1): 38–41.

Karlsson, R. 1977. Consistency limits. *In* A manual for the performance and interpretation of laboratory investigations, Part 6. Swedish Council for Building Research, Stockholm. pp. 131–136.

Kvalstad, T.J., Farrokh, N., Kaynia, A.M., Mokkelbost, K.H., and Byrn, P. 2005. Soil conditions and slope stability in the Ormen

Large area. Marine and Petroleum Geology, **22**(1–2): 299–310. doi:10.1016/j.marpetgeo.2004.10.021.

Lee, L.T., and Freeman, R.B. 2007. An alternative test method for assessing consistency limits. Geotechnical Testing Journal, **30**(4): 1–8.

Medhat, F., and Whyte, I.L. 1986. An appraisal of soil index tests. *In* Engineering Geology Special Publication, 1986. Geological Society, London. Vol. 2, pp. 317–323. doi:10.1144/GSL.1986.002.01.55

Norman, L.E.J. 1958. A comparison of values of liquid limit determined with apparatus having bases of different hardness. Géotechnique, **8**: 79–85.

Powell, J.J.M., and Lunne, T. 2005. Use of CPTU data in clays/fine grained soils. Studia Geotechnica et Mechanica, **27**(3–4): 29–66.

Seed, H.B., Woodward, R.J., and Lundgren, R. 1964. Fundamental aspects of the Atterberg limits. Journal of Soil Mechanics Foundation Division, ASCE, **90**(SM6): 7–105.

Sharma, B., and Bora, P.K. 2003. Plastic limit, liquid limit and undrained shear strength of soil – reappraisal. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, **129**(8): 774–777. doi:10.1061/(ASCE)1090-0241(2003)129:8(774).

Skempton, A.W., and Northey, R.D. 1953. The sensitivity of clays. Géotechnique, **3**: 30–53.

Skopek, J., and Ter-Stepanian, G. 1975. Comparison of liquid limit values determined according to Casagrande and Vasilev. Géotechnique, **25**(1): 135–136.

Timar, A. 1974. Testing the plastic properties of cohesive and intermediate-type soils by extrusion. Acta Technica ASH. **76**(3–4): 355–370.

Whyte, I.L. 1982. Soil plasticity and strength – a new approach using extrusion. Ground Engineering, **15**(1): 16–24.

Wood, D.M. 1985. Index properties and consolidation history. *In* Proceedings of the 11th International Conference on Soil Mechanics and Foundation Engineering, San Francisco, Calif., 12–16 August 1985. A.A. Balkema, Rotterdam, the Netherlands. Vol. 2, pp. 703–706.

Wroth, C.P., and Wood, D.M. 1978. The correlation of index properties with some basic engineering properties of soils. Canadian Geotechnical Journal, **15**(2): 137–145. doi:10.1139/t78-014.

Yafrate, N.J., and DeJong, J.T. 2005. Considerations in evaluating the remoulded undrained shear strength from full flow penetrometer cycling. *In* Frontiers in Offshore Geotechnics, Proceedings of the First International Symposium on Offshore Geotechnics, Perth, Australia, 19–21 September 2005. *Edited by* S. Gourvenec and M. Cassidy. Taylor and Francis Group, London. pp. 991–997.

Youssef, M.F., El Ramli, A.H., and El Demery, M. 1965. Relationships between shear strength, consolidation, liquid limit and plastic limit for remolded clays. *In* Proceedings of the 6th International Conference on Soil Mechanics and Foundation Engineering, Montréal, Que., 8–15 September 1965. University of Toronto Press, Toronto, Ont. Vol. 1, pp. 126–129.

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