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Evaluation of Undrained Shear Strength of Fine-Grained Soils in Consideration of Soil Plasticity

İnce Taneli Zeminlerin Drenajsız Kesme Dayanımının Zemin Plastikliği Açısından Değerlendirilmesi

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ABSTRACT

Undrained shear strength (s_u) is one of the key geotechnical parameters for both natural and remolded soils. While it is basically a function of water content, it is also related to soil plasticity. There has been a long-lasting debate as to whether the s_u at the plastic and liquid limits are constant and whether the ratio of the s_u at the plastic limit to the s_u at the liquid limit is mostly fixed to 100. While this view is embraced by a great majority of researchers, some proclaim that the range of both the s_u at the plastic limit (PL) and the s_u at the liquid limit (LL) is rather wide; therefore, constant values of the s_u cannot be assigned for either the PL or the LL. Accordingly, the view that there is a constant ratio between the two shear strengths is invalid. The scope of this investigation is to reassess this problem using the laboratory vane shear test (VST) along with a new supplementary tool, the mud-press machine (MPM). Sixty remolded soil samples were employed as the study material. The variation of soil strength at both the plastic and liquid limit is investigated using the VST and MPM methods. While the VST method does not portray a distinctive relationship between the s_u and the two Atterberg limits, the newly introduced MPM method clearly shows that there is a meaningful relationship between the extrusion force, which is considered akin to the undrained shear strength, at the Atterberg limits and the two consistency limits, particularly the liquid limit. Concerning the constant ratio between the two shear strengths, namely the one at the plastic limit to the one at the liquid limit, it was found that this ratio is a constant, but it increases with the increase in soil plasticity.

Keywords: Undrained shear strength, soil plasticity, vane shear test, mud press method, remolded soils.

ÖZ

Drenajsız kesme dayanımı (s_u) doğal ve yoğrulmuş zeminlerin ikisi için de önemli jeoteknik parametrelerden biridir. Temelde su içeriğinin bir fonksiyonu olmakla birlikte, zemin plastikliği ile de ilişkilidir. Plastik limitte ve likit limitteki drenajsız kesme dayanımının sabit ve plastik limitteki s_u'nun likit limitteki s_u'ya oranının çoğunlukla 100 civarında olduğuna dair görüşler halen tartışılmaktadır. Çoğu araştırmacılar bu görüşe katılmakla birlikte, bazı araştırmacılar da gerek plastik limitteki (PL) ve gerekse likit limitteki (LL) drenajsız kesme dayanımının geniş bir aralıkta saçılım gösterdiğini ve bu nedenle PL ve LL için sabit bir s_u değerinin olmayacağını belirtmektedirler. Buna göre, iki kesme dayanımı arasındaki sabit oran fikri de geçersizdir. Bu çalışmanın amacı, bahsedilen problemin laboratuvar kanatlı kesme deneyi (VST) ile birlikte çamur sıkıştırma düzeneği (MPM) adı verilen yeni bir düzenek kullanılarak yeniden değerlendirilmesidir. Çalışmada 60 adet yoğrulmuş zemin numunesi kullanılmıştır. VST ve MPM yöntemleri kullanılarak plastik limit ile likit limitteki zemin dayanımının değişimi incelenmiştir. VST yöntemi su ile Atterberg limitleri arasında belirgin bir özellik sergilememekle birlikte, bu çalışmada takdim edilen MPM yöntemi drenajsız kesme dayanımı ile yakın ilişkili olduğu düşünülen ekstrüzyon kuvveti ile Atterberg limitleri ve özellikle de likit lim-

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it arasında belirgin bir ilişkinin olduğunu göstermiştir. Plastik limittteki drenajsız kesme dayanımının likit limitteki kesme dayanımına oranının da irdelendiği çalışmada bu oranın belli bir zemin için sabit olduğu fakat artan zemin plastikliği ile birlikte oranın da arttığı gözlenmiştir.

Anahtar Kelimeler: *Drenajsız kesme dayanımı, zemin plastikliği, kanatlı kesme deneyi, çamur sıkıştırma yöntemi, yoğrulmuş zeminler.*

INTRODUCTION

One of the most common index properties of fine-grained soils is the undrained shear strength (s_u), which differs for natural and remolded states. The undrained shear strength of remolded soils is important in many applications, including submarine investigations of offshore structures, pile design and studies of glacial soils (Bozozuk, 1972; Kvalstad et al., 2005; Yafrate and DeJong, 2005; Kayabali and Tufenkci, 2010; O'Kelly, 2013). The sleeve friction in a cone penetration test is also a function of remolded strength (Powell and Lunne, 2005). When the quality of the soil-strength data is inadequate or poor, geotechnical engineers may wish to evaluate the s_u as a lower bound value in making important design decisions (Wood, 1990; Sharma and Bora, 2003; Kayabali and Tufenkci, 2010; O'Kelly, 2013).

The major factor affecting the s_u is the moisture content. The variation of the s_u with the water content has been well-documented in the geotechnical literature. A brief summary of such studies was provided by Nagaraj et al. (2012).

Numerous researchers attempted to relate the undrained strength of remolded fine-grained soils to the Atterberg limits. There has been an ongoing debate regarding the s_u at the Atterberg limits resulting in two distinctive views. One claims that the undrained shear strengths at the plastic limit and liquid limit are fixed, and the ratio of the former to the latter is about 100. Another claims that the range of the variation of the s_u at both the liquid and plastic limits is extremely large, and an assertion cannot be made that the s_u has a unique value at either the LL or PL.

The earliest assignment of the undrained shear strength to a consistency limit was done in 1939 by Casagrande (Sharma and Bora, 2003), who suggested that the s_u at the LL is 2.65 kPa. Skempton and Northey (1953) reported that the s_u at the liquid limit ranged from 0.75 kPa to 1.75 kPa. Wroth and Wood (1978) proposed a mean value of 1.7 kPa for the s_u at the LL and further assumed that the s_u at the PL is 100 times higher than what it is at the LL. This 100-fold variation in the undrained shear strength has also been verified by other researchers (e.g., Belviso et al., 1985; Sharma and Bora, 2003; Lee and Freeman, 2007). A summary of the proposed s_u values at the liquid limit is provided in Table 1. A great majority of researchers found that the s_u at the LL ranges from 1–2 kPa.

Regarding the s_u at PL, most researchers have proposed that it is around 110-170 kPa and mostly towards the lower bound, as shown in Table 2.

In contrast to the first view, which was summarized in Table 1, some researchers argue that there is not a theoretical basis for a fixed ratio of undrained strength for the Casagrande PL and LL (e.g., O'Kelly, 2013). The variation of the undrained strength ratio may be attributed to clay-mineral activity in the soil (Wood, 1990; O'Kelly, 2013). It is asserted that the mechanisms controlling the undrained shear strength and liquid limit for kaolinitic soils are different from that of montmorillonitic soils (Sridharan et al., 1999; Nagaraj et al., 2012). Nagaraj et al. (2012) stated that published data from various literature sources clearly show that the variation of the undrained shear strength at the liquid limit is observed to be nearly 60 times (from as low as 0.2 kPa to as high as 12 kPa) and that at the plastic limit is more than 17 times (from 35 kPa to 600 kPa), hence no unique value of undrained shear strength can be assigned either at the liquid limit or plastic limit of soils.

The authors' perception is that both claims are right in a sense and that the variations of the

Table 1. Undrained shear strengths (s_u) at liquid limit (adapted from Kayabali and Tufenkci, 2010 and Nagaraj et al., 2012).

Çizelge 1. Likit limitteki drenasız kesme dayanımları (s_u) (Kayabalı ve Tüfenkçi, 2010 ile Nagaraj vd., 2012'den alınmıştır).

Source	s_u range (kPa)	Average (kPa)	Remarks
Casagrande		2.65	Quoted by Sharma and Bora (2003)
British Standards	0.8 – 1.6		
Skempton and Northey (1953)	0.7 – 1.75		Soils with very different PI values
Norman (1958)	0.8 – 1.6		
Seed et al. (1964)	2.5		Quoted by Whyte (1982)
Youssef et al. (1965)	1.3 – 2.4	1.7	
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	
ASTM	1.1 – 2.3		Quoted by Wroth and Wood (1978)
Swedish cone		1.7	Quoted by Whyte (1982)
Whyte (1982)		1.6	
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	
Sharma and Bora (2003)		1.7	
Houlsby (1982)	2.75 – 5.24		Quoted by Nagaraj et al. (2012)
Wasti and Bezirci (1986)	0.5 – 5.6		Quoted by Nagaraj et al. (2012)
Locat and Demers (1988)	0.2 – 2.0		Quoted by Nagaraj et al. (2012)
Sridharan and Prakash (1998)	0.66 – 1.35		Quoted by Nagaraj et al. (2012)
Kayabali and Tufenkci (2010)	1.2 – 12.0		

ratio of undrained shear strength at the plastic limit to the one at the liquid limit or the large range of undrained shear strengths at either the PL or LL are thought to emanate from soil plasticity. The scope of this investigation is to evaluate the undrained shear strengths at two Atterberg limits using the VST technique along with a newly introduced method called the mud press method.

MATERIALS

The nature of this investigation requires the use of soils with a wide range of plasticity, which would require visiting a number of sites to collect soil samples if the investigation were based on natural soils. Considering the practical difficulty of such a procedure and the length of time to be spent, the use of artificially prepared soil samples was chosen. To accomplish this, a

Table 2. Undrained shear strengths (s_u) at plastic limit (compiled by Kayabali and Tufenkci, 2010).
Çizelge 2. Plastik limitteki drenasız kesme dayanımları (s_u) (Kayabalı ve Tüfenkçi, 2010 tarafından derlenmiştir).

Source	s_u range (kPa)	Average (kPa)	Remarks
British Standards (BS 1377, 1948)		110	Quoted by Whyte (1982)
Skempton and Northey (1953)	85 -125	110	Quoted by Whyte (1982)
Dennehy (1978)	30 - 320	115 (arithmetic) 104 (geometric)	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

bulk soil sample was mixed with fine sand and commercial powdered bentonite at varying dry-mass ratios. The final product of this procedure is 60 soil samples with liquid limits ranging from about 30 to 120, which covers the plasticity range of most soils on earth.

The other materials employed in this investigation included testing tools such as a fall-cone device for measuring the liquid limit, a roll-plate device for determining the plastic limit, a miniature vane shear apparatus for testing the s_u and a mud press machine (MPM) for determining a parameter similar to the s_u. The use of those devices is explained in the following subsection.

METHODS

The liquid limits of the soil samples were determined by following the guidelines of the BS 1377 standard (British Standards Institution, 1990). The mass and the apex angle of the cone are 80 g and 30°, respectively. A sufficient number of (5–8) water contents were tried to obtain a linear plot between the cone penetration depth and the water content. The reason for choosing the fall-cone method to determine the liquid limit is its superiority to the conventional Casagrande cup method, which involves a high degree of uncertainty (e.g., Belviso et al., 1985; Prakash and Sridharan, 2003). The plastic limit tests were carried out in accordance with the ASTM D-4318 standard (American Society for Testing Materials, 2001). The tests were repeated at least five times, and the average value was assigned as the plastic limit after dropping the lowest and the highest extremes.

The tool used to determine the undrained shear strength of remolded fine-grained soils is the laboratory miniature vane shear device, which is a Wykeham Farrance model WF2350. The guidelines of the ASTM D4648 (ASTM, 2000) were followed for this test. The starting water content for the remolded samples to be tested using the laboratory VST is somewhat smaller than the liquid limit. The soil specimen is wetted at this water content and mixed homogeneously prior to shearing. The proceeding VST tests are carried out by adding a small amount of dry soil specimen to the previous wet mixture and remixing the new specimen, presumably at a slightly lower water content. The laboratory VST has four torque springs for different levels of soil stiffness. The appropriate spring was selected for each test so that shear failure takes place between 20°–90° of the sample rotation. The vane shear test was repeated at least five times for each soil sample at water contents in a range from slightly lower than the liquid limit to near the plastic limit to obtain a linear curve on a semi-logarithmic graph as shown in Figure 1, from which the y-intercept (i.e., log[a]) and

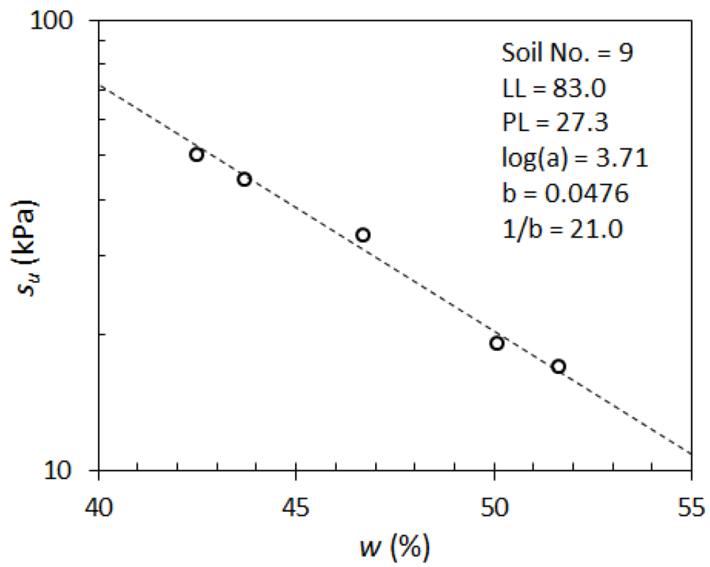

Figure 1. A sample plot for the results of the laboratory vane shear test.
Şekil 1. Laboratuvar kanatlı kesme deneyi sonuçları için örnek bir diyagram.

the slope of the curve (i.e., b) are determined. Because the slope values involve small decimals, they are represented by their inverse values (b^{-1}) for practical purposes.

A supplementary device called the mud press machine (MPM) (Figure 2) is introduced in support of the investigated topic. It consists mainly of a loadcell, a loading piston and a container. The container's diameter is 30 mm and has 28 holes, equally spaced at the bottom, each having a diameter of 2.5 mm. The sample preparation was done such that the pulverized soil samples were mixed at a water content slightly lower than the liquid limit. The soil specimen is placed in the container with the upper surface flattened. The piston is brought into contact with the specimen by using the loading arm. The loading is rendered manually until the wet specimen fails. The soil worms extruding from the bottom make a shape like spaghetti. The machine records the load as the test progresses. The load steadily increases as the test is in progress, and the load becomes constant at the time of failure, which is manifested by a flat curve on the load versus the time graph on the screen. The test is repeated at different water contents in the plastic range. A typical plot for the results of the MPM is presented in Figure 3, from which the extrusion forces at failure (which correspond to the y-intercept of the flat portion of the curve) are determined and plotted against the testing water content. The data pairs for this test are plotted on a semi-logarithmic graph, yielding a linear curve (Figure 4). Then, the slope (the b value) and the y-intercept (log[a]) of the curve are determined. The slope parameter (b) was taken as its inverse for the very same reason that it was done in the VST method.

TEST RESULTS

The results of the Atterberg limits tests are presented in Table 3. Also included in Table 3 are the coefficients of the semi-logarithmic plots of both the VST and MPM methods for 60 soil samples.

As a first step towards determining the undrained shear strengths at the consistency limits, the s_u values at the liquid limits were computed using the log(a) and b^{-1} coefficients given in Table 3 for 60 soils. Then, a plot was constructed illustrating the relationship between the s_u at the liquid limit versus the liquid limit itself (Figure 5). While the plot is not very promising, it can be interpreted that the s_u is high for low-plastic soils, or vice versa. Similarly, the log(a)

Figure 2. A view of the mud press machine and its components.
Şekil 2. Çamur sıkma makinası ve bileşenlerinden bir görünüm.

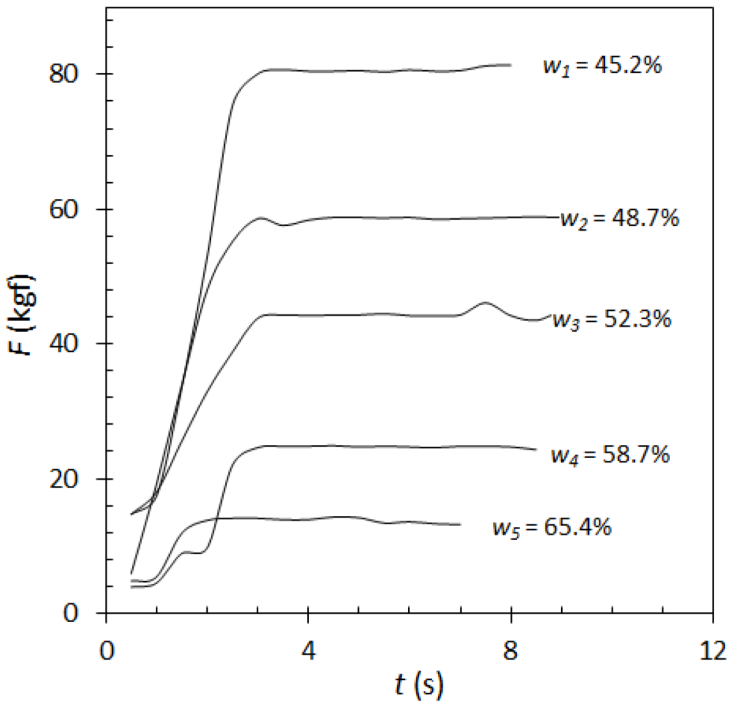

Figure 3. Plot of the results of the mud press method for various water contents.
Şekil 3. Çamur sıkma yöntemi için değişik su içeriği sonuçlarına göre çizilmiş bir diyagram.

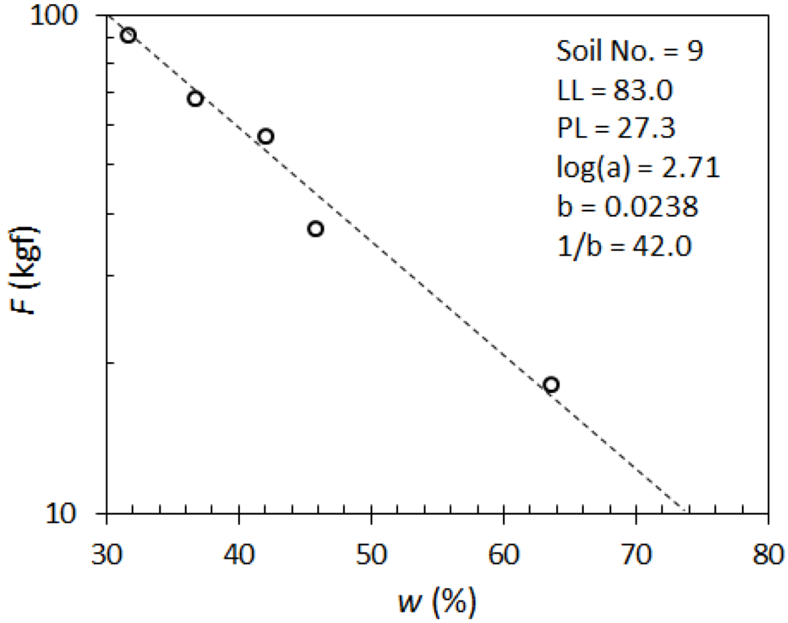

Figure 4. Extrusion force at failure versus the water content for a soil sample.
Şekil 4. Bir zemin numunesi için yenilme anındaki ekstrüzyon kuvveti ile su içeriği ilişkisi.

and b^{-1} coefficients were used to compute the s_u values at the plastic limit for 60 soils. Another plot was constructed to illustrate the relationship between the undrained shear strength at the plastic limit and the plastic limit itself (Figure 6). Neither of these plots indicates a distinctive relationship between the two correlated parameters. The best interpretation for this plot would be the one similar to Figure 5; that is, the undrained shear strength at the plastic limit appears to decrease with the increasing soil plasticity; however, it is rather a vague conclusion.

The mud press machine was employed as a supplementary tool to support the investigated topic. Similarly to what was done for the VST method, the extrusion force at the liquid limits (F_{LL}) and plastic limits (F_{PL}) were computed for 60 soils using the coefficients given in Table 3. Figure 7 shows the relationship between the extrusion force at the liquid limits versus the liquid limit itself. The quality of the correlation is remarkably good, having a regression coefficient (R^2) of 0.81. It indicates that there is a strong relationship between the extrusion force at the liquid limit and the soil plasticity and that the extrusion force at failure decreases exponentially as the plasticity increases. A similar relationship was also sought between the extrusion force at the plastic limit and the soil plasticity. Figure 8 illustrates the computed extrusion forces at the plastic limit versus the plastic limit itself for 60 soil samples. Although it does not portray a relationship as strong as the correlation in Figure 7, it still offers a moderately good relationship (R^2 = 0.54) between the extrusion force at the plastic limit and the soil plasticity. Figure 8 also indicates that the extrusion force at the plastic limit is a peculiar value and that it decreases with the increasing plastic limit.

Upon the observation that the MPM technique yields meaningful results for the targeted topic, the debatable issue of whether the ratio of the undrained shear strength at the plastic limit to the undrained shear strength at the liquid limit is constant and whether it is around 100 deserves to be addressed. Figure 9 was constructed for this purpose. The vertical axis of this plot indicates the ratio of the extrusion force at the plastic limit to the extrusion force at the liquid limit. The horizontal axis was selected to include the liquid limit, which is a better indication of soil plasticity in comparison with the plasticity index and the plastic limit. Figure 9 shows that there is a distinctive relationship between the ratio of the

Table 3. The results of the Atterberg limits, vane shear and mud press tests.
Çizelge 3. Atterberg limitleri, kanatlı kesme ve çamur presi deney sonuçları.

No.	LL	PL	a_{VST}	b^{-1}_{VST}	a_{MPM}	b^{-1}_{MPM}
1	117	28.9	2.5	40	2.59	47.3
2	116	26.0	3.06	23	2.62	49.5
3	106	28.6	3.55	25.2	2.53	50.5
4	105	29.1	3.22	23	2.57	49.6
5	102	27.8	3	25	2.59	46
6	95	28.1	3.6	17.5	2.71	42
7	93	26.5	3.88	17	2.75	38.6
8	93	28.2	3.22	23	2.68	41.1
9	83	27.3	3.71	21	2.71	42
10	84	26.7	3.7	16.5	2.74	41
11	80	26.4	2.86	38.5	2.73	37
12	75	26.4	3.7	16.5	2.83	35
13	70	25.9	2.66	38	2.99	30.2
14	69	24.4	3.93	14.5	3.05	27.5
15	62	26.0	4.42	12.4	3.17	26.6
16	63	24.4	3.9	14.7	2.97	30.4
17	59	25.5	5.44	10.8	3.34	22.8
18	58	25.4	3.9	14.7	3.14	23.8
19	55	24.9	4.83	10.6	3.13	25.5
20	55	25.3	3.89	14.8	3.29	23.1
21	52	26.3	5.27	10.4	3.35	21.9
22	53	23.6	4.06	13.6	3.35	21.7
23	54	25.8	3.61	15.5	3.16	24
24	52	23.8	4.3	12.2	3.45	19.1
25	50	25.0	3.44	17.4	3.48	18.8
26	50	24.7	4.75	9.1	3.46	18.8
27	50	25.1	3.84	15.2	3.52	18.1
28	49	23.5	7.36	5.6	3.54	18.3
29	48	25.8	4.78	9	3.56	18
30	45	23.0	4.87	8.7	3.31	20.2

Table 3. Contiuned.
Çizelge 3. Devam ediyor.

No.	LL	PL	a_{VST}	b^{-1}_{VST}	a_{MPM}	b^{-1}_{MPM}
31	45	22.8	4.08	13	3.22	20.9
32	44	23.2	4.84	8.8	3.35	19.7
33	46	22.9	3.96	11.2	3.52	17.2
34	45	23.4	4.3	10	3.18	20.8
35	44	21.8	3.88	11.7	3.27	19.3
36	44	21.0	4.04	11.3	3.26	19.6
37	45	20.7	4.1	10.5	3.36	18.3
38	41	21.0	3.83	11.5	3.37	17.1
39	42	21.6	5.07	7.5	3.35	18.1
40	42	21.3	3.91	11	3.51	16.7
41	42	20.0	4.1	10	3.4	17.3
42	39	19.5	3.69	12.4	3.39	17.4
43	40	19.1	4.26	9.3	3.3	18
44	40	22.3	4.1	10	3.38	16.8
45	38	19.5	7.95	3.7	3.34	16.7
46	37	19.1	4	10	3.48	15.1
47	37	17.8	4.15	9.3	3.5	14.9
48	37	18.9	4.8	7.5	3.5	14.8
49	35	18.3	5.18	6.6	3.3	16.4
50	35	18.0	5.5	6	3.42	15
51	35	18.6	4.26	8.4	3.28	16.5
52	34	18.1	4.94	6.8	3.31	16
53	33	17.3	5.06	6.2	3.5	13.9
54	33	17.2	4.88	6.6	3.72	12
55	32	16.9	4	9	4.29	9.3
56	32	18.1	5.06	6.2	3.39	13.7
57	31	16.4	4.77	6.5	3.43	13.6
58	32	16.5	4.86	6.3	3.44	13.7
59	29	16.9	4.9	6.2	3.32	14.5
60	31	15.4	4.6	7.2	3.94	10.6

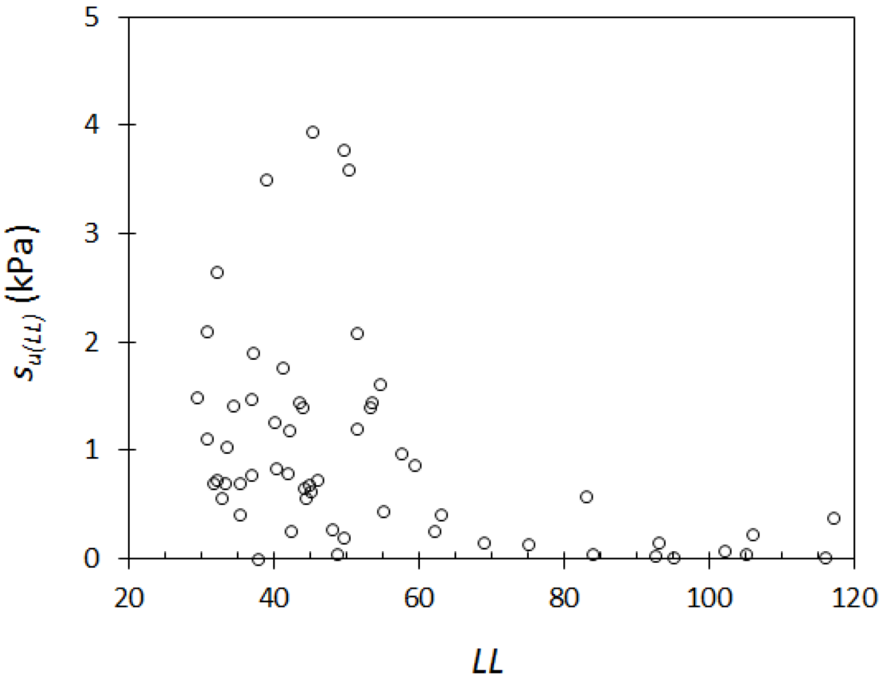

Figure 5. Computed undrained shear strengths at the liquid limit versus the liquid limit for 60 soils.
Şekil 5. 60 zemin numunesi için likit limitte hesaplama yoluyla bulunan drenajsız kesme dayanımı ile likit limit ilişkisi.

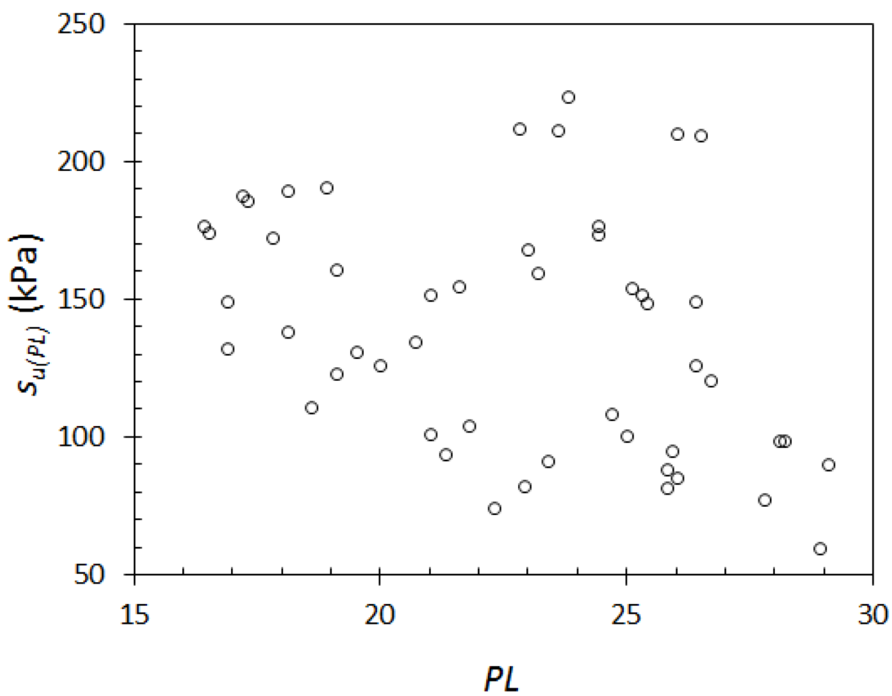

Figure 6. Computed undrained shear strengths at the plastic limit versus the plastic limit for 60 soils.
Şekil 6. 60 zemin numunesi için plastik limitte hesaplama yoluyla bulunan drenajsız kesme dayanımı ile plastik limit ilişkisi.

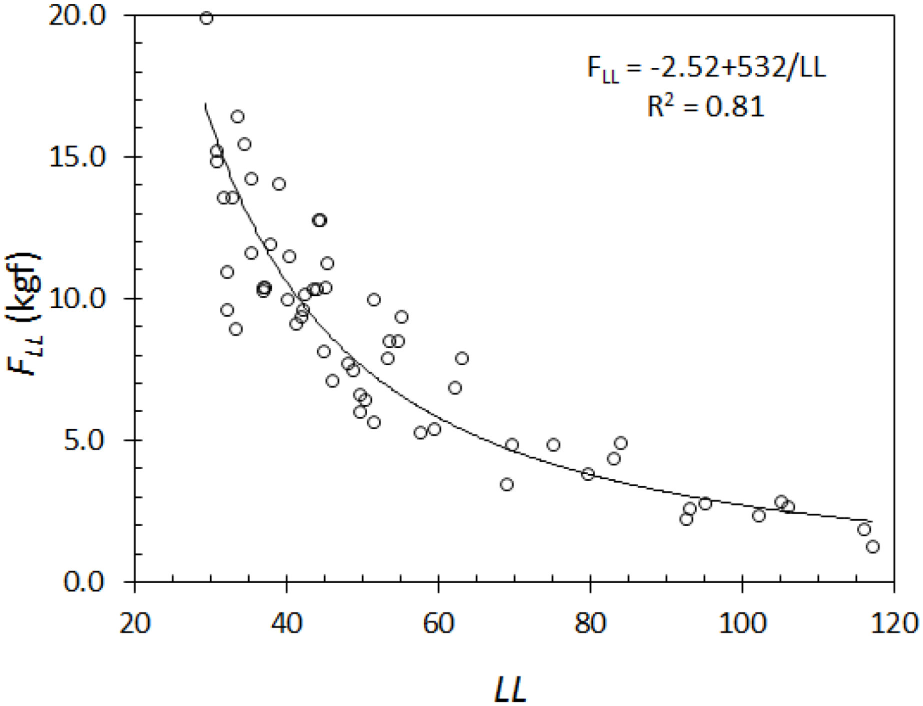

Figure 7. Computed extrusion forces at the liquid limit versus the liquid limit for 60 soils.
Şekil 7. 60 zemin için likit limitte hesaplama yoluyla bulunan extrüzyon kuvveti ile likit limit arasındaki ilişki.

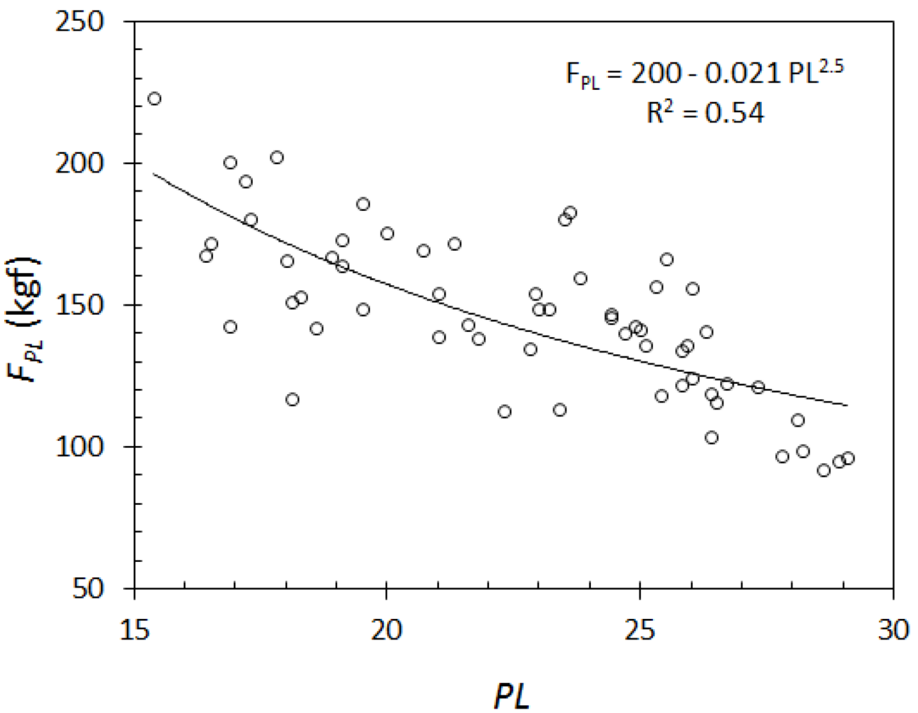

Figure 8. Computed extrusion forces at the plastic limit versus the plastic limit for 60 soils.
Şekil 8. 60 zemin için plastik limitte hesaplama yoluyla bulunan extrüzyon kuvveti ile plastik limit arasındaki ilişki.

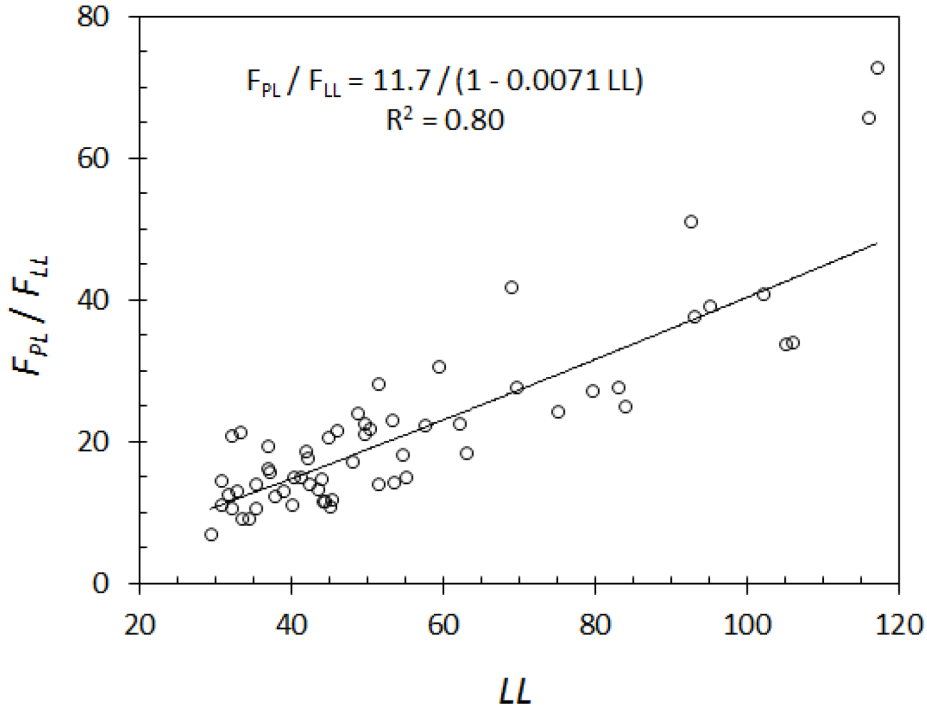

Figure 9. The ratio of the computed extrusion force at the plastic limit to the computed extrusion force at the liquid limit versus the liquid limit.

Şekil 9. Plastik limitte hesaplama yoluyla bulunan ekstrüzyon kuvvetinin likit limitte hesaplama yoluyla bulunan ekstrüzyon kuvvetine oranı ile likit limit arasındaki ilişki.

extrusion forces and the soil plasticity. Considering that the extrusion force at failure with the MPM technique is akin to the undrained shear strength, it could be asserted that the shear-strength ratio is unique for soil of a certain plasticity and that it increases with the increasing plasticity. It should be noted that the strength ratio ranges from about 10 for low-plastic soils to greater than 40 for high-plastic soils. Figure 9 also includes the empirical relationship between the extrusion-force ratio and the liquid limit as expressed by equation (1) (R^2 = 0.80):

$$F_{PL} / F_{LL} = 11.7 / (1 - 0.0071\ LL) \quad (1)$$

Now that the MPM technique has been shown to have a meaningful relationship between the extrusion force at failure, which could be considered akin to the undrained shear strength, and soil plasticity, this supplementary tool might be considered as a new method to predict the undrained shear strength of remolded soils. While it is not the major aim of the present investigation, the introduction of a new tool and method for determining the undrained shear strength of remolded fine-grained soils would be considered an important contribution for the geotechnical community. Before analyzing the capability of the new tool and method to predict the undrained shear strength of tested soils, searching for a relationship between the VST technique and the undrained shear strength would be an appropriate first step. This procedure is also a necessity for the VST method to be taken as a reference for proposing the MPM approach as a new tool for predicting soil strength.

As noted earlier, the miniature vane shear test was repeated at least five times per soil sample at different water contents. This resulted in a total of 300 experiments for 60 soils. Various methodologies were applied to relate the undrained shear strength to the water content along with the soil plasticity. It turned out that the best results could be obtained when the undrained shear strength is correlated with the liquidity index (LI), which combines the water content (w) and soil plasticity, as expressed by equation (2):

$$LI = (w - PL) / (LL - PL) \quad (2)$$

A simple regression analysis revealed that the undrained shear strength (in kPa) obtained from the VST method could be related to the liquidity index as given by equation (3) ($R^2 = 0.63$; Figure 10):

$$s_u = 84.8\,(0.02044^{LI}) \quad (3)$$

This last equation appears to have two important implications. The first one is that all soils have an undrained shear strength of about 1.7 kPa at the liquid limit because the liquidity index is to be 1.0 at the liquid limit for any soil, which concurs with the findings of Wroth and Wood (1978), who proposed a mean value of 1.7 kPa for the s_u at the LL. The second implication is that all soils have an undrained shear strength of about 85 kPa at the plastic limit because the liquidity index is to be 0.0 at the plastic limit for any soil.

Another simple regression analysis revealed that the extrusion force has a relationship with the liquidity index as expressed by equation (4) ($R^2 = 0.60$; Figure 11):

$$F_{MPM} = 78.3\,(0.026^{LI}) \quad (4)$$

Where F_{MPM} is the extrusion force at failure (in kgf). The similarity between Equations (3) and (4) should be noted. Considering that the regression constants are very similar for the VST and MPM methods, it can be stated that the MPM technique has potential as a new tool for determining the undrained shear strength of fine-grained soils. Further elaboration is necessary to refine the results of the MPM method, preferably with a greater number of soil samples.

This investigation includes a great body of data from two different techniques. One might argue that the extrusion forces (F) obtained from the MPM method might be directly correlated with the (s_u) from the VST method. However, it should be emphasized that the water contents of the MPM tests are not the same as those for the VST test because each of the test methods was performed by different operators at different times. Thus, the equations (3) and (4) relating the soil strength to liquidity index are provided separately.

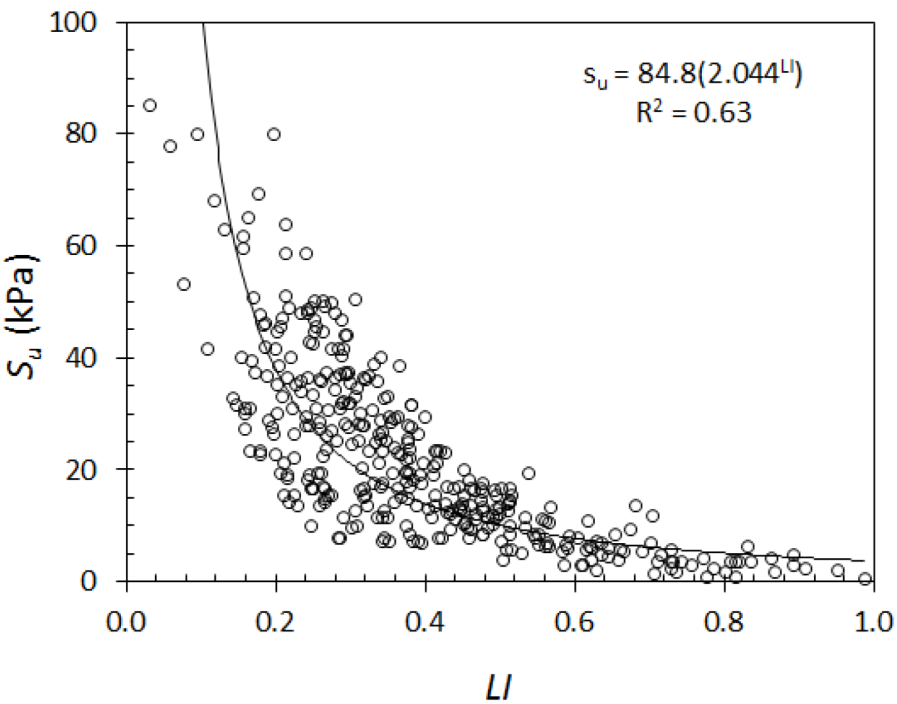

Figure 10. Undrained shear strengths from the VST method versus the liquidity index.
Şekil 10. VST'den bulunan drenajsız kesme dayanımı ile likitlik indeksi arasındaki ilişki.

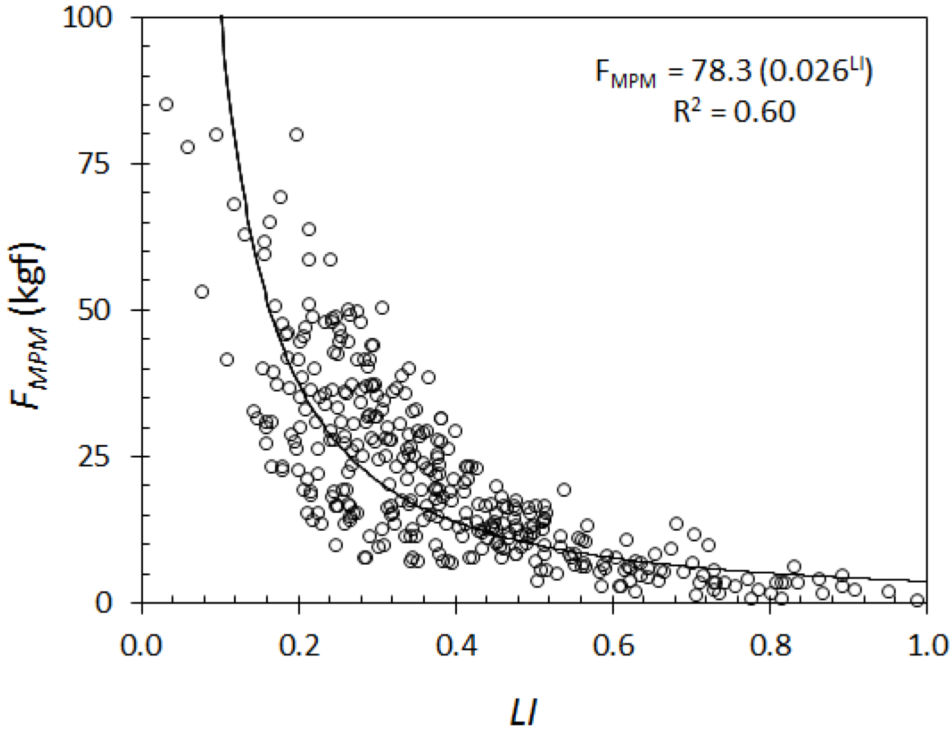

Figure 11. Extrusion forces from the MPM method versus the liquidity index.
Şekil 11. MPM'den bulunan ekstrüzyon kuvveti ile likitlik indeksi arasındaki ilişki.

CONCLUSIONS AND DISCUSSION

The following conclusions can be derived from this investigation:

1) The miniature vane shear test appears to relate the undrained shear strength at the consistency limits to soil plasticity; however, the observed relationships are not satisfactory.

2) The newly introduced tool, called the mud press machine, shows a remarkably good relationship between the extrusion force at failure, which is considered akin to the undrained shear strength, and soil plasticity. The computed extrusion forces at the liquid limits correlate well with the liquid limits themselves. The similar observation is also valid for the computed extrusion forces at the plastic limits; however, it is not as remarkable as those for the liquid limit.

3) A relationship between the strength ratio at the two consistency limits and the soil plasticity was sought, and it was shown that the strength at the plastic limit to the strength at the liquid limit are somewhat related to each other. The strength ratio between the two increases with the increasing soil plasticity. While there is about a tenfold difference between those strengths at the plastic limit and liquid limit for low-plastic soils, respectively, the ratio jumps up to the 50s for highly plastic soils. In this respect, the 100-fold of strength ratio discussed in the literature turns out to be invalid.

4) Although it is not the major aim of the study, the ability of the MPM technique to predict the shear strength of fine-grained soils was also examined. It was concluded that the MPM has a great promise to be used as a new and simple tool to determine the undrained shear strength of both remolded and natural soils.

5) A great similarity between the extrusion forces at failure versus the liquidity index and between the undrained shear strength versus the liquidity index was observed. It is strongly recommended that the MPM be applied to a greater number of soil samples for further refinement. It is very likely that the refinement of the proposed method could end up with a

promising new testing method in geotechnical engineering.

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