Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-286

Determination of undrained shear strength of remolded and undisturbed samples from different laboratory tests

Tina Đurić, Dragoslav Rakić, Jovana Janković Pantić, Irena Basarić Ikodinović, Marija Milosavljević
Faculty of Mining and Geology, University of Belgrade, Serbia, tina.djuric@rgf.bg.ac.rs

Stevan Ćorluka
Institute for Materials Testing - IMS, Belgrade, Serbia

ABSTRACT: Undrained shear strength is crucial parameter in geotechnical engineering, especially for characterizing the properties of soft, highly sensitive, and normally consolidated clays and silty clays. This paper investigates the relationships between various laboratory tests for estimating the undrained shear strength of fine-grained remolded and undisturbed soils in the Belgrade area. The undrained shear strength (c_u) was determined using the laboratory fall cone test, pocket vane test, pocket penetrometer test and unconfined compression test. The procedures of these tests are different, leading to differences in the obtained values of undrained shear strength. Additionally, the undrained shear strength was compared to some empirical correlations from the literature based on natural water content (w), plastic limit (w_P), liquid limit (w_L) and plasticity index (Ip). The proposed relationships demonstrate high correlation coefficients and align well with established data in the literature.

KEYWORDS: Undrained shear strength, fine-grained soil, laboratory tests, remolded samples, undisturbed samples.

1 INTRODUCTION

The physical and mechanical behavior of the soil is closely related to the water content. The different content of water in the silty clay soil affects the change in the consistent state and significantly changes their behavior, especially the undrained shear strength. To evaluate the consistency and engineering behavior of fine-grained soils, two primary consistency limits are used: the liquid limit (w_L) and the plastic limit (w_P). The difference between these two limits defines the plasticity index (Ip). This index quantifies the range of moisture content over which the soil exhibits plastic behavior and serves as an important parameter for soil classification and for predicting properties such as compressibility, shear strength and workability.

The undrained shear strength of remolded clays exhibits a strong correlation with both the liquid limit and the plastic limit, if the shear strengths corresponding to these limits are themselves interrelated. This relationship is grounded in the concept that soil assumes a distinct and reproducible state at the liquid limit, characterized by a specific shear strength. This characteristic strength at the liquid limit is known to maintain a consistent relationship with the undrained shear strength at the plastic limit as mentioned in Sharma and Bora (2003).

In this study, the relationship between undrained shear strength (c_u) and water content is examined, and the relationship between undrained shear strength (c_u) and the plastic limit, liquid limit and plasticity index is analyzed through the models M1, M2, M3, M4, M5, M6 and M7. Four laboratory methods were used for the analysis: the unconfined compression test, the fall cone test, the laboratory pocket shear vane test, and the pocket penetrometer test. The undrained shear strength was determined using these four tests on undisturbed soil samples, while the fall cone test was also used to determine it on remolded samples.

2 MATERIALS AND METHODS

The soil samples used in this paper were located in Serbia, on the territory of Belgrade, on the left bank of the Danube, where Quaternary sediments – both alluvial and aeolian are present. Geomechanically laboratory tests were conducted on five soil samples. According to the USCS classification, they belong to silty clays of medium plasticity (CI), with natural moisture content ranging from 20–34%, plastic limit values between 19–23% and liquid limit values between 41–50%. A summary of the basic identification parameters for the soil samples is shown in Table 1.

Table 1. Identification parameters for the soil samples

Simple ID	Water content w (%)	Consistency and Plasticity Parameters			
		w_L	w_P	Ip	I_C
PB-27 (1.1-1.5)	20	41	19	22	0.956
MB-25 (1.3-1.6)	23.1	49	23	26	0.996
MB-13 (1.5-1.8)	37	42	24	18	0.450
ABo-23 (2.5-2.8)	24.7	44	24	20	0.961
PB-27 (4.3-4.6)	22.2	42	21	21	0.945
ABo-41 (7.6-7.9)	24.3	47	22	25	0.907
ABo-41 (12.7-13)	24.6	50	23	27	0.941

Four laboratory tests were conducted to achieve the aim of the study. The primary test utilized was the fall cone test. This test was performed on remolded and undisturbed soil samples. One of the most common direct methods for determining undrained shear strength, the unconfined compression test, was also performed on undisturbed soil samples. In addition, two indirect methods: the hand vane test and the pocket penetrometer test were carried out.

2.1 *Fall cone test*

The fall cone method, originally developed by the Geotechnical Commission of the Swedish State Railways between 1914 and 1922, was designed as a simple, rapid, and reliable technique for determining the undrained shear strength, sensitivity of soils, and their liquid and plastic limits. This method is based on measuring the penetration depth of a cone with a specific angle and weight into a prepared soil sample (Hansbo, 1957). The cone, positioned above a remolded sample (contained in a standard metal cylinder) or an undisturbed sample. The depth of penetration is then measured, and the undrained shear strength is expressed through an equation based on the EN ISO 17892-6:2017 standard:

$$c_u = \frac{c \cdot Q}{h^2} \tag{1}$$

where c_u is the undrained shear strength of the soil sample (in kPa), c is a constant that depends on the type of cone, Q is the weight of the cone (in N), and h is the penetration depth (in mm).

2.2 *Unconfined compression test*

The unconfined compression test determines the unconfined compressive strength (q_u), and the undrained shear strength (c_u) is taken as half of this value. Since this method assumes conditions where the angle of internal friction (φ) is zero, the obtained values of c_u represent the undrained shear strength under short-term loading conditions. The tests were performed on cylindrical undisturbed soil specimens with a diameter of 38 mm and a height of 76 mm, in accordance with the standard SRPS EN ISO 17892-7:2018.

In some countries, such as Japan, the unconfined compression test is considered a reliable and fundamental method for determining undrained shear strength. It is a test that considers several factors, including anisotropy, sample disturbance, and strain rate. On the other hand, EU countries and those that have adopted Eurocode 7 regard the unconfined compression test, as well as the fall cone test, as less reliable methods for determining undrained shear strength.

2.3 *Hand shear vane and pocket penetrometer test*

The pocket shear vane and pocket penetrometer are a portable device that can be used both in the field and in the laboratory to determine the undrained shear strength of soil c_u of a cohesive or semi-cohesive soil.

The hand shear vane test is performed using a handheld torsional device, which measures the torque required to rotate a set of blades inserted into the soil. The undrained shear strength value is read directly (in kg/cm^2) from the graduated scale of the instrument. For the pocket penetrometer test the measurement is performed by placing the penetrometer vertically relative to the surface of the sample. The penetrometer's dial ring is set to zero, then penetration is carried out, and the force required for the given penetration is measured, which in this model is directly read from the dial ring.

Both tests are widely used for preliminary, rapid assessment of cohesive soils directly in the field. These methods enable efficient on-site evaluation of soil strength parameters, facilitating early decision-making during geotechnical investigations. However, their accuracy is inherently limited by factors such as sample disturbance, variations in soil moisture content, heterogeneity of the soil matrix, and operator-dependent variability. Consequently, results obtained from these field tests should be considered approximate and are recommended to be verified through comprehensive laboratory testing to ensure reliability and precision.

3 RESULTS AND DISCUSSION

The samples selected for this analysis were prepared in an undisturbed state, extracted from the soil using appropriate molds, and shaped into cylindrical form. Subsequently, remolded samples were prepared. The liquid limit was determined using the remolded samples, which were then dried and left to rest overnight each time to allow moisture to distribute evenly throughout the entire sample. This ensured the measurement of undrained shear strength at different moisture contents. Undisturbed samples were used for all four testing methods, while remolded samples were used specifically for the fall cone test.

3.1 *Relationship of undrained shear strength and water contents*

Seven samples with different water contents were used for the analysis. Each sample was analyzed separately by varying the water content. The samples were prepared starting from a moisture content approximately equal to the plastic limit, with a gradual increase in water content up to values exceeding the liquid limit, or in reverse, where overly moist samples were allowed to dry naturally. The fall cone test was performed on each sample, and the result represents the average value of all individual measurements.

Figure 1 shows the logarithmic relationship between the soil moisture content and the undrained shear strength, based on a total of 86 tests conducted using a cone with an angle of 30° and a mass of 80 g.

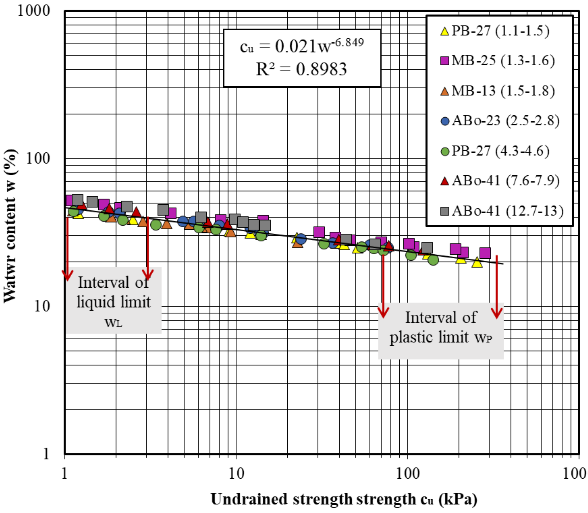

Figure 1. Relationship between undrained shear strength c_u and water content w for the 30°/80 g cone.

Based on regression analysis, the equation is given in the figure itself. As shown, the coefficient of determination R^2=0.8983 indicates a good fit, suggesting a strong correlation between these two parameters.

A similar analysis was performed using a different type of cone. Figure 2 presents the empirical logarithmic relationship between soil moisture content and undrained shear strength for a cone with an angle of 60° and a mass of 60 g.

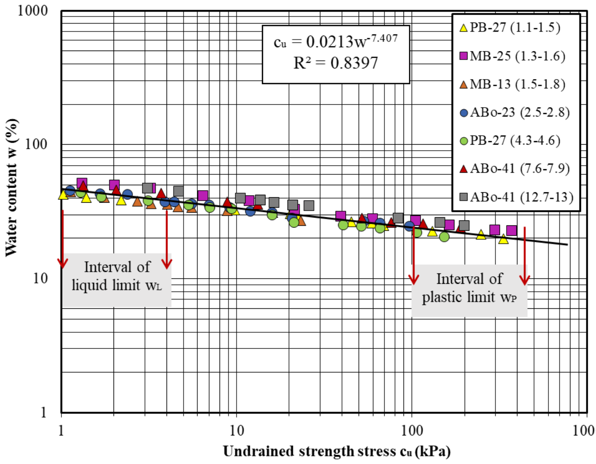

Figure 2. Relationship between undrained shear strength c_u and water content w for the 60°/60 g cone.

For each sample, the undrained shear strength was determined at a given moisture content, resulting in a total of 80 tests. The coefficient of determination for this case was R^2 =0.8397 which likewise demonstrates a strong agreement between the measured parameters.

Although both cone types show a strong logarithmic relationship between water content and undrained shear strength, the 30°/80 g cone produced a slightly stronger correlation compared to the 60°/60 g cone. This suggests that cone geometry and mass may influence measurement sensitivity at different moisture ranges.

To further evaluate the accuracy of the regression model, the Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) were computed for both cone configurations. For the 30°/80 g cone, the results are MAE = 4.00 kPa and RMSE = 34.73 kPa, while for the 60°/60 g cone, the values are MAE = 5.24 kPa and RMSE = 57.98 kPa. These results indicate that the regression models closely match the experimental data, particularly for the 30° cone, and confirm that the proposed relationships are reliable for estimating undrained shear strength based on water content.

These findings can be used to estimate undrained shear strength in practice based on simple water content measurements for the 30°/80 g cone, but the correlations are specific to the tested soil type and cone configuration.

3.2 *Comparison of undrained shear strength from four tests*

The undrained shear strength (c_u) was determined on undisturbed soil samples using all four different methods: fall cone test, unconfined compression test, hand vane test and the pocket penetrometer.

All results were analyzed and compared, with special emphasis on the fall cone test as a reference method. The following figures present the values obtained from each method for visual comparison, while numerical analysis of the differences was conducted to evaluate the consistency between the methods.

Research has shown a close relation between undrained shear strength taken from fall cone test and pocket penetrometer test (Figure 3).

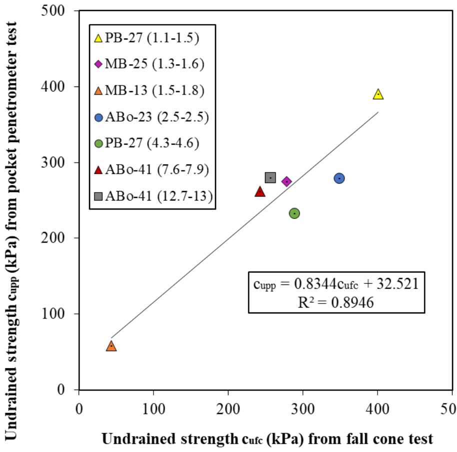

Figure 3. Comparison of undrained shear strengths from fall cone test and pocket penetrometer test.

The results show that the fall cone method yielded, on average, values 1.42% higher than those obtained by pocket penetrometer testing. The values obtained using the fall cone test ranged from approximately 43 kPa to 400 kPa, while the results obtained with the penetrometer ranged from 58 kPa to 390 kPa. Observing the distribution of results across the samples, both methods follow a similar trend in strength variation, indicating a good correlation between the tests. The greatest deviation occurred in the third sample, where the difference reached 35.39%. This indicates a relatively good agreement between the methods, except for outlier behavior in isolated cases. Despite the differences of values, the correlation between methods is sufficiently strong, where coefficient of correlation (R^2) is 0.89.

The comparison of undrained shear strength results taken from hand vane test and unconfined compression test with fall cone test results shown some differences. The values of undrained shear strength obtained from these tests are lower than those from the fall cone test. The difference between hand vane test and fall cone test is about 19.54 % (Figure 4) where coefficient of correlation (R^2) is 0.76.

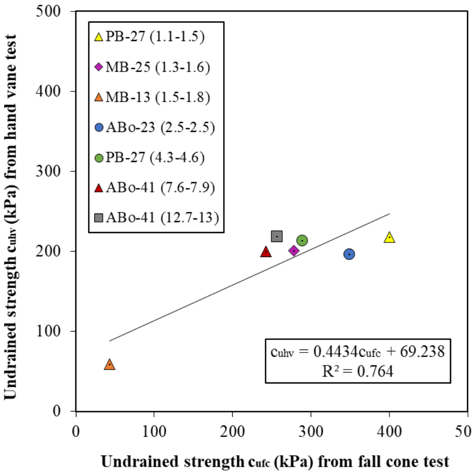

Figure 4. Comparison of undrained shear strengths from fall cone test and hand vane test.

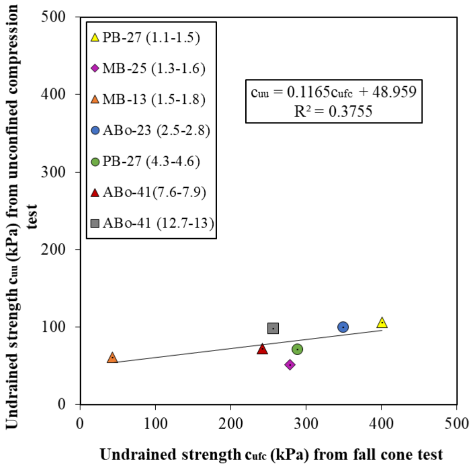

Figure 5. Comparison of undrained shear strengths from fall cone test and unconfined compression test.

A comparison of the obtained values indicates that the fall cone method generally produces significantly higher values of undrained shear strength compared to those obtained from the unconfined compression test. The coefficient of determination (R^2) for the comparison between the two methods is 0.37 which indicates a relatively weak correlation. The results showed that the best model for comparison is pocket penetrometer test and fall cone test, and the other two can be used for complementing other research methods and can be helpful to soil classification.

3.3 *Empirical correlations*

Casagrande (1932) reported that a material at the liquid limit exhibits an undrained shear strength of approximately 2.5 kPa. Skempton and Northey (1953) demonstrated, based on four samples with varying plasticity indices, that the undrained shear strength at the liquid limit ranges between 0.7 and 1.75 kPa. Wroth and Wood (1978) proposed indicative minimum and maximum values for undrained shear strength, suggesting that undrained shear strength is 1.7 kPa at the liquid limit and 170 kPa at the plastic limit. In a more extensive study, Sharma and Sridharan (2018) found that the undrained shear strength at the plastic limit ranges between 100 and 300 kPa. In contrast, some researchers questioned the existence of a fixed ratio between the undrained shear strengths at the liquid and plastic limits, attributing the observed variability to differences in the activity of clay minerals, particularly in soils rich in kaolinite and montmorillonite (O'Kelly, 2013).

Table 2 presents several mathematical expressions used to estimate undrained shear strength based on water content and plastic limit, as well as formulations that relate undrained shear strength to the plasticity index.

Table 2. Empirical correlations from several researchers

Model	Empirical correlations	Researcher
M1	$\mathrm{c_u} = (0.11 + 0.037\mathrm{Ip})\sigma'_v$	Skempton (1953)
M2	$\mathrm{c_u} = 0.45 \cdot \mathrm{w_L}\sigma'_v$	Hansbo (1957)
M3	$\mathrm{c_u} = 0.005 \cdot \mathrm{w_L}\sigma'_v$	Karlsson and Viberg (1967)
M4	$c_u = 182.93e^{-2.37\frac{w}{w_L}}$	Lee (2004)
M5	$\mathrm{c_u} = (0.08 + 0.0055\mathrm{Ip})\sigma'_v$	Larsoon et al. 2007
M6	$c_u = 1.7 \cdot \frac{w}{w_L}^{-4.9}$	Sharma and Sridharan (2018)
M7	$c_u = 0.021 \cdot \mathrm{w}^{-6.849}$	Đurić et al. (2025)

Figure 6 shows the relationship between the calculated undrained shear strength (obtained using existing equations as well as the equation developed in this study, presented in Figure 1) and the undrained shear strength determined by the fall cone test.

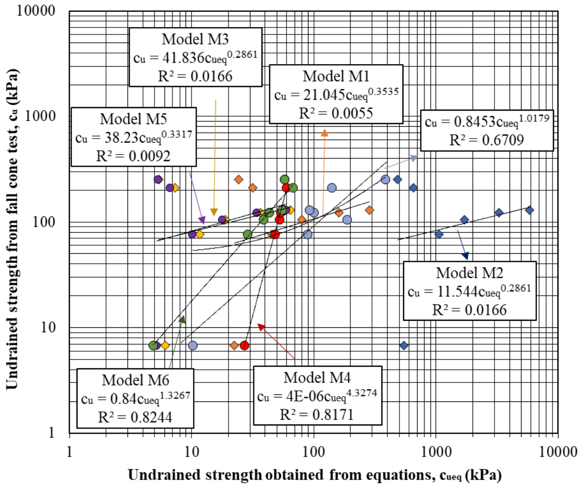

Figure 6. Relationship of undrained shear strengths from fall cone test and undrained shear strength from empirical correlations.

The comparison of empirical correlations with experimentally determined undrained shear strength (Figure 6) revealed notable variability among the models. Specifically, models based on correlations with the plasticity index (M1, M2, M3, M5) showed significant deviations from the fall cone test results, confirming that plasticity index alone may not be a sufficiently reliable predictor of shear strength across diverse soil types. In contrast, models M4, M6 and M7 demonstrated a much closer alignment with the measured data. This suggests that models incorporating water content and consistency limits directly, rather than relying solely on plasticity index, can provide more accurate estimations of undrained shear strength, especially for silty clays of medium plasticity like those from this study.

It is also evident that empirical models derived from broader datasets or specific soil types may not always generalize well, reinforcing the need to develop or calibrate correlations tailored to local soil conditions. The performance of model M7 underscores the value of incorporating local experimental data into model development to enhance prediction reliability.

4 CONCLUSIONS

This study comprehensively examined the undrained shear strength of fine-grained soils from the Belgrade area using four laboratory methods: fall cone test, unconfined compression test, hand vane test, and pocket penetrometer test. The results highlighted that the fall cone test provides reliable estimations of undrained shear strength, showing the closest agreement with the unconfined compression test, with a high correlation coefficient ($R^2 = 0.99$). Although the pocket penetrometer and hand vane tests yielded lower values compared to the fall cone test, they still demonstrated acceptable correlations and can be useful for preliminary assessments.

The research also confirmed a strong logarithmic relationship between undrained shear strength and water content, with better predictive accuracy when using the 30°/80 g cone compared to the 60°/60 g cone. Additionally, empirical models from the literature were evaluated, and their predictions compared with the experimental results. Models M4, M6, and M7 developed in this study showed the best agreement with the laboratory data.

The findings support the practical applicability of using water content and consistency limits to estimate undrained shear strength, though with caution due to the variability introduced by different clay mineral activities. The proposed M8 model offers an improved approach tailored to the specific soil types of this region of Belgrade, contributing to more accurate and practical geotechnical assessments.

5 REFERENCES

Sharma, B., and Bora, P. K. 2003. Plastic Limit, Liquid Limit and Undrained Shear Strength of Soil—Reappraisal, *Journal of Geotechnical and Geoenvironmental Engineering* 129/8,774–777

Hansbo, S. 1957. A new approach to the determination of the shear strength of clay by the fall cone test, *Royal Swedish Geotechnical Institute*. Proc. No.14.

EN ISO 17892-6:2017, Geotechnical investigation and testing – Laboratory testing of soil – part 6. Fall cone test.

SRPS EN ISO 17892-7:2018, Geotechnical investigation and testing - Laboratory testing of soil - Part 7: Unconfined compression test (ISO 17892-7:2017).

Casagrande, A. 1932. Research on the Atterberg Limits of Soil, *Public Roads*, 13, 121-136.

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

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.

Sharma, B. and Sridharan, A. 2018. Liquid and plastic limits of clays by cone method, *International Journal of Geo-Engineering* 9:22.

O'Kelly, B.C. 2013. Atterberg limits and remolded shear strength – water content relationships, *Geotech Test J.*, 36/6, 939–947.

Karlsson, R. and Viberg. L. 1967. Ratio c/p' in relation to liquid limit and plasticity index with special reference to Swedish clays. Proc. Geotechnical Conf., Oslo, Norway, 1 (1967): 43–47.

Lee, L.T. (2004). "Predicting Geotechnical Parameters for Dredged Materials Using the Slump Test Method and Index Property Correlations," DOER Technical Notes collection (ERDC TN-DOER-D-1), U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi.

Larsson, R. Eriksson L. and Broms, B. 2007. *Shear strength of Swedish clays*, Swedish Geotechnical Institute, SGI Report No. 65, Linköping, Sweden.