

Correlation between the liquid limit of clay derived by the Vasiliev and Casagrande test methods

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Abstract. The liquid limit is one of the most commonly used index properties of soils. The paper compares liquid limit values determined by the Vasiliev cone penetrometer method and by the Casagrande cup method, based on 45 natural clay samples collected from the Kozloduy Town area (North Bulgaria). An empirical correlation based on these liquid limit results has been derived.

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INTRODUCTION

The most important characteristic of cohesive soils, with respect to their engineering behaviour, is consistency. The consistency of cohesive soils is identified by critical water contents at certain limits, the Atterberg limits: liquid limit (w_L) and plastic limit (w_p), which are basic in the classification of cohesive soils.

The w_L parameter, also known as the upper plastic limit, was first defined by Swedish chemist and agricultural scientist Albert Atterberg (1911) and later refined and standardized by Arthur Casagrande (1958) for application in geotechnical research and practice. In addition, a number of geotechnical properties of soil have direct or indirect correlations with the w_L value, e.g., compressibility, shear strength, swelling potential, permeability, liquefaction and cation exchange capacity.

Two basic methods for the evaluation of w_L are in use, namely fall cone penetrometer test and Casagrande cup test. Both methods are adopted as a standard in many countries. The Casagrande test

has been taken in geotechnical standards in the USA (ASTM, AASHTO), the United Kingdom (BSI), European Union (EN), Japan (JIS) and many other countries. The Vasiliev cone penetrometer test was previously chosen as a standard for the evaluation of w_L in Bulgaria (BDS 648:1984), as well as in most Eastern European countries, including the former USSR (GOST 5184:85), Poland (PN-B-04481:1988) and others.

BDS 648:1984 was in force until 2010; afterwards, geotechnical investigations and testing in Bulgaria have been performed according to the European norms (EN), where the Casagrande test is one of methods for w_L determination (BDS EN ISO/TS 17892-12:2018). Both methods are based on measuring the shear strength (s_u) of the soil. At the w_L in the Casagrande test, s_u is 1–3 kN/m², while in the Vasiliev test it is 8.5 kN/m² (Škopek and Ter-Stepanian, 1975). As a result, the w_L values obtained by each test differ significantly.

Since the ground basis in Bulgaria consists predominantly of clayey soils, plenty of geotechnical

investigation tests performed before 2010 are available. There is a necessity for these archive results to be used in new projects and studies. Therefore, a correlation between the w_L values determined by the Vasiliev test (w_L^V) and the Casagrande test (w_L^C) would have a useful application.

The objective of the present study is to compare the results for liquid limit values of clayey soils determined by the Vasiliev cone and Casagrande cup apparatuses, and consequently, an empirical correlation between w_L^V and w_L^C for such soils to be derived. For that purpose, the w_L of 45 clayey soil samples was determined by the Vasiliev cone penetrometer method, in line with BDS 648:1984, as well as by the Casagrande method conforming to BDS EN ISO/ TS 17892–12:2018. Based on a regression analysis of the test results, an empirical correlation has been obtained.

MATERIALS AND METHODS

Forty-five samples of Quaternary and Pliocene clay soils from the Kozloduy Town area (North Bulgaria) were used in the present study. The soil samples were collected from borehole cores at different depths, mainly from 10 m to 50 m below ground level. Grain size distribution, particle density, plasticity limits, w_p and w_L were determined for each sample.

The liquid limit w_L was defined according to BDS 648:1984 and BDS EN ISO/ TS 17892–12:2018. The w_L tests were fulfilled at a room temperature of 20 °C by the same operator in order to reduce the possibility of human error. Measurements were run on duplicates to compare the results for each standard.

The w_L^V values were determined with a Vasiliev cone penetrometer with a mass of 76 ± 0.05 g, height of 25 mm, apex angle of $30^\circ \pm 0.1^\circ$ and fall time of 5 ± 1 s over a molded sample of soil as suggested by BDS 648:1984. In line with standard procedure, at least four data points at different water contents were taken. The water content corresponding to a cone penetration of 10 mm defines w_L^V , which was calculated on the linear graph obtained by plotting water contents against their corresponding penetration values.

As recommended in 5.4 of BDS EN ISO/ TS 17892-12:2018, the Casagrande apparatus with a hard base percussion cup and 25 blows was used to obtain the w_L^C values, and at least four data points at different water contents were taken. The water content corresponding to 25 blows was calculated on

the linear graph derived by plotting water contents against corresponding number of blows. In order to classify the soil samples, w_p was also determined according to BDS EN ISO/ TS 17892-12:2018.

The least square linear analysis was used to model the relationship between w_L^V and w_L^C . This method calculates the best-fitting line for the observed data by minimizing the variance, *i.e.*, the sum of squares of the errors. The analysis was performed and single-factor model of linear regression equation was obtained, expressed by the formula:

$$\check{y} = b_0 + b_1x,$$

where \check{y} denotes the predicted value of y for a given x and parameters of the model, b_0 is the intercept on the y -axis and b_1 is the slope of the straight line.

The w_L^V was used as an independent variable (x) to explain the dependent variable w_L^C (y). In order to estimate the quality of the regression fit, the determination coefficient (R^2), expressed by the following formula, was used:

$$R^2 = \frac{\sum_{i=1}^n (\check{y}_i - \bar{y})^2}{\sum_{i=1}^n (y_i - \bar{y})^2},$$

where n is the number of cases, y_i is the observations of dependent variable, \bar{y} is the mean of the observed data of dependent variable, and \check{y}_i is the predicted value of dependent variable (Draper and Smith, 1998).

R^2 gives an idea of the percentage of change that takes place in the dependent variable, which can be explained by the change in the independent variable and ranges from 0 to 1. Low values indicate that the outcome is relatively unrelated to the predictor, whereas values close to 1 indicate that the two variables are highly related.

RESULTS AND DISCUSSION

The test results carried out on the samples are presented in Table 1. Based on the particle size distribution, liquid limit and plasticity index, according to the ESCS, 15 samples were classified as medium plasticity clay (CIM) and 30 samples were classified as high plasticity clay (CIH) (Fig. 1).

Comparison of the liquid limits of the clayey soils, determined by the Vasiliev cone penetrometer w_L^V and Casagrande method w_L^C , is shown in Fig 2. It was observed that the w_L values determined by the Vasiliev cone penetrometer were mostly lower (in the range of 30–50%) than those obtained by the Casagrande apparatus (in the range of 39–70%).

Table 1
Index and classification of the tested clay samples

| Sample No. | ρ_s g/cm ³ | Grain size distribution [%] | | | Activity index | Liquid limit [%] | | w_p [%] | ESCS classification |
|------------|-------------------------------|-----------------------------|------|------|----------------|------------------|---------|-----------|---------------------|
| | | Sand | Silt | Clay | | w_L^V | w_L^C | | |
| 1 | 2.74 | 11 | 87 | 2 | 11.3 | 30.4 | 39 | 16.5 | CIM |
| 2 | 2.76 | 9 | 91 | 0 | – | 30.6 | 41.3 | 15.7 | CIM |
| 3 | 2.75 | 7 | 81 | 12 | 2.1 | 28.0 | 41.6 | 16.0 | CIM |
| 4 | 2.73 | 8 | 83 | 9 | 2.9 | 28.8 | 42.1 | 16.2 | CIM |
| 5 | 2.73 | 13 | 85 | 2 | 12.8 | 32.3 | 42.3 | 16.8 | CIM |
| 6 | 2.74 | 7 | 93 | 0 | - | 29.2 | 43.1 | 16.5 | CIM |
| 7 | 2.72 | 14 | 55 | 31 | 1.0 | 34.1 | 46.0 | 15.8 | CIM |
| 8 | 2.72 | 14 | 56 | 30 | 1.0 | 36.0 | 46.2 | 15.3 | CIM |
| 9 | 2.77 | 10 | 78 | 12 | 2.7 | 33.1 | 46.6 | 14.8 | CIM |
| 10 | 2.78 | 11 | 59 | 30 | 1.0 | 35.4 | 46.7 | 17.3 | CIM |
| 11 | 2.77 | 14 | 53 | 33 | 1.0 | 33.5 | 48.0 | 16.1 | CIM |
| 12 | 2.77 | 14 | 52 | 34 | 0.9 | 36.8 | 48.5 | 17.1 | CIM |
| 13 | 2.74 | 19 | 81 | 0 | – | 34.3 | 48.9 | 14.8 | CIM |
| 14 | 2.73 | 15 | 85 | 0 | – | 36.3 | 49.2 | 18.7 | CIM |
| 15 | 2.73 | 14 | 86 | 0 | – | 34.4 | 49.6 | 14.2 | CIM |
| 16 | 2.72 | 14 | 81 | 5 | 6.8 | 35.0 | 51.5 | 17.4 | CIH |
| 17 | 2.77 | 5 | 92 | 3 | 10.8 | 36.6 | 51.7 | 19.2 | CIH |
| 18 | 2.73 | 12 | 70 | 12 | 2.7 | 38.4 | 52.0 | 20.0 | CIH |
| 19 | 2.78 | 6 | 69 | 25 | 1.3 | 40.0 | 52.1 | 20.2 | CIH |
| 20 | 2.77 | 9 | 78 | 13 | 2.7 | 36.5 | 52.9 | 17.3 | CIH |
| 21 | 2.75 | 10 | 71 | 19 | 1.9 | 39.6 | 53.0 | 17.5 | CIH |
| 22 | 2.74 | 14 | 65 | 21 | 1.7 | 37.7 | 53.1 | 16.8 | CIH |
| 23 | 2.74 | 6 | 91 | 3 | 11.0 | 39.2 | 53.6 | 20.7 | CIH |
| 24 | 2.76 | 6 | 90 | 4 | 8.4 | 40.0 | 54.1 | 20.7 | CIH |
| 25 | 2.78 | 9 | 76 | 15 | 2.5 | 36.0 | 54.6 | 17.8 | CIH |
| 26 | 2.75 | 10 | 60 | 30 | 1.2 | 40.5 | 55.9 | 20.1 | CIH |
| 27 | 2.71 | 15 | 64 | 17 | 2.2 | 39.1 | 57.0 | 20.0 | CIH |
| 28 | 2.75 | 5 | 56 | 39 | 1.0 | 41.3 | 57.5 | 19.6 | CIH |
| 29 | 2.78 | 13 | 66 | 20 | 2.1 | 41.2 | 59.6 | 16.7 | CIH |
| 30 | 2.76 | 7 | 73 | 20 | 1.9 | 43.4 | 60.1 | 21.9 | CIH |
| 31 | 2.77 | 19 | 73 | 5 | 8.7 | 41.2 | 61.4 | 17.7 | CIH |
| 32 | 2.77 | 5 | 60 | 35 | 1.2 | 41.9 | 61.7 | 20.8 | CIH |
| 33 | 2.76 | 4 | 79 | 17 | 2.4 | 44.3 | 62.5 | 21.6 | CIH |
| 34 | 2.76 | 16 | 66 | 18 | 2.3 | 43.0 | 62.9 | 20.7 | CIH |
| 35 | 2.75 | 3 | 83 | 14 | 3.0 | 41.8 | 63.0 | 20.7 | CIH |
| 36 | 2.74 | 1 | 86 | 13 | 3.1 | 45.3 | 63.0 | 22.7 | CIH |
| 37 | 2.75 | 10 | 87 | 3 | 14.0 | 45.3 | 63.9 | 21.8 | CIH |
| 38 | 2.74 | 8 | 66 | 26 | 1.7 | 45.6 | 65.0 | 21.2 | CIH |
| 39 | 2.75 | 8 | 50 | 42 | 1.1 | 44.8 | 66.0 | 21.1 | CIH |
| 40 | 2.74 | 6 | 55 | 39 | 1.2 | 43.4 | 67.1 | 21.9 | CIH |
| 41 | 2.76 | 6 | 59 | 35 | 1.4 | 43.2 | 67.4 | 17.8 | CIH |
| 42 | 2.75 | 8 | 57 | 35 | 1.4 | 47.8 | 67.4 | 19.4 | CIH |
| 43 | 2.77 | 10 | 65 | 25 | 2.0 | 47.9 | 68.4 | 18.8 | CIH |
| 44 | 2.72 | 15 | 69 | 16 | 3.0 | 48.4 | 69.3 | 21.4 | CIH |
| 45 | 2.78 | 5 | 55 | 40 | 1.2 | 49.3 | 69.7 | 21.7 | CIH |

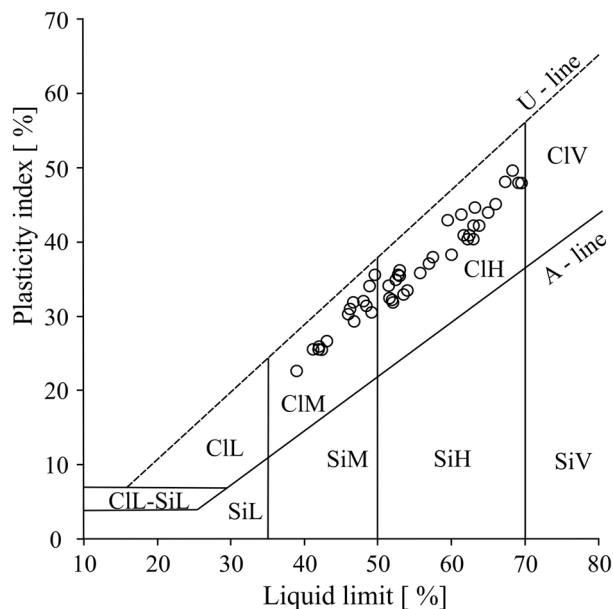


Fig. 1. Tested samples shown on Casagrande’s plasticity chart (ESCS).

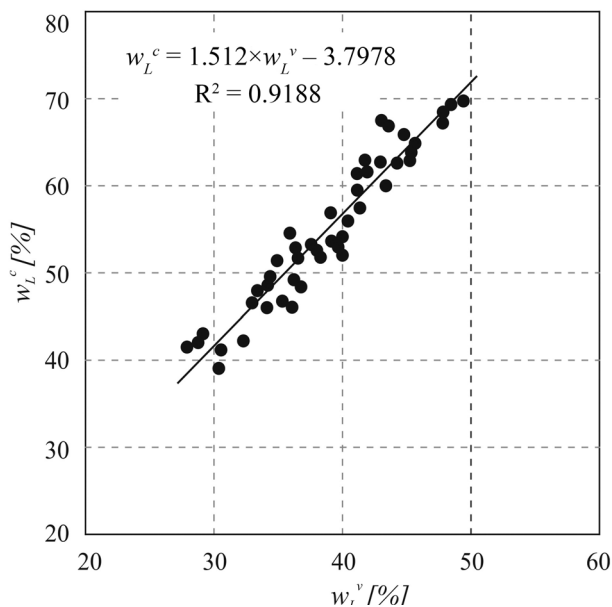


Fig. 2. Comparison of the liquid limit values determined by the standard Vasiliev cone penetrometer (w_L^V) and the Casagrande apparatus (w_L^C).

This is consistent with the results of other studies (e.g., Stefanoff, 1957; Škopek and Ter-Stepanian, 1975). The coefficient of determination is $R^2 = 0.92$ (Fig. 2), which means that there is a high correlation between liquid limits obtained by both methods. The following empirical correlation was derived from least square linear regression analysis:

$$w_L^C = 1.51 \times w_L^V - 3.80,$$

where w_L^C is the Casagrande apparatus liquid limit, and w_L^V is the Vasiliev cone penetrometer liquid limit. The high value of the coefficient of determination demonstrates the validity of the proposed relationship. The derived empirical equation is applicable for medium to high plasticity clayey soils with values of w_L^V in the range of 30–50%.

CONCLUSION

In order to compare liquid limit values of clay soil determined by the Vasiliev cone penetrometer (BDS 648:1984) and the Casagrande cup (BDS EN ISO/TS 17892–12:2018), 45 clay samples were tested. The results indicated that:

- according to ESCS, 15 samples were classified as medium plasticity clay (CIM) and 30

samples were classified into high plasticity clay (CIH);

- the liquid limits determined by the Vasiliev cone penetrometer were rather lower than those obtained by the Casagrande cup apparatus;
- there is a strong correlation between liquid limits obtained by both methods ($R^2 = 0.92$);
- an empirical correlation allowing conversion of the liquid limit obtained by the Vasiliev cone penetrometer to the liquid limit by the Casagrande cup apparatus has been derived. The model is not static, and new values could be incorporated, defining an updated equation.

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ABBREVIATIONS AND SYMBOLS

| | |
|----------|--|
| BDS EN | Bulgarian State Standard European Norm |
| BDS | Bulgarian State Standard |
| ESCS | European Soil Classification System |
| s_u | Shear strength, kN/m ² |
| w_L | Liquid limit, % |
| w_p | Plastic limit, % |
| I_p | Plasticity index, % |
| ρ_s | Particle density, g/cm ³ |

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