

Correlation between effective cohesion and plasticity index of clay

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Abstract. Correlations of engineering properties are a useful tool in geotechnical engineering practice. This paper aims to provide a correlation between the effective cohesion and plasticity index for natural, undisturbed clay soils from the Kozloduy area (NW Bulgaria), based on the results from laboratory tests. It has been demonstrated that there is a strong correlation between the plasticity index and the effective cohesion. The derived regression equation can be used to estimate the effective cohesion as first approximation in preliminary design of engineering projects of Pliocene and Quaternary clays encountered in northwest Bulgaria.

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INTRODUCTION

The effective cohesion (c') of soils is one of the most important soil parameters that is evaluated in slope stability and suitability for building foundations. Effective cohesion is considered as a part of the shear strength that can be mobilized due to forces arising at particle level and is independent from the effective stress (Lambe, 1960). As per Yong and Warkentin (1966), c' of soils is extremely dependent on the interaction characteristics of the clay–water system. Thus, c' is affected by the Atterberg limits of soils.

Essentially, the Atterberg limits are controlled by soil mineralogy, pore structure, and particle size distribution and reflect the ability of fine-grained soil to resist external shear loading (Seed *et al.*, 1966). Atterberg (1911) derives seven limits that describe changes in the behavior of cohesive soils at varying water content. Nowadays, in practice, only three are in use: liquid limit (w_L), plastic limit (w_p) and shrinkage limit (w_s). The liquid and plastic

limits represent the plasticity characteristics of soils and are essential in the classification of fine-grained soil. They are also used to calculate the plasticity index (I_p), which could be correlated with many soil properties.

Correlations between the index properties parameters and the strength and deformation properties of cohesive soils are widely employed in geotechnical engineering practices as first approximation of the soil characteristics in the preliminary design of geotechnical structures, and later as a mean to validate the results of laboratory tests (Sørensen and Okkels, 2013).

Beneficial empirical equations associated with various soil properties correlated with Atterberg limits have been provided by many researchers, such as Fener *et al.* (2005), Dolinar and Trauner (2007), Mehta and Sachan (2017), Spagnoli and Shimobe (2020), and others.

Obtaining of the Atterberg limits in a laboratory setting is relatively simple to perform, quick, and inexpensive compared to tests for the determination

of soil strength parameters such as c' . Also, obtaining c' requires undisturbed test samples, the derivation of which is time-consuming and costly. In that connection, this study was carried out to predict the drain c' of fine-grained soils from their I_p , which will be useful for the preliminary analysis of an engineering project. The Atterberg limits and cohesion of 33 soil samples were determined. Based on statistical methods, an empirical equation, for the prediction of c' based on I_p , has been obtained for practical use.

MATERIALS AND METHODS

The soil tests were performed on 33 undisturbed soil samples of Pliocene and Quaternary clays from the Kozloduy area (NW Bulgaria). The soil samples were collected from borehole cores at different depths, mainly from 10 m to 25 m below the surface. Grain size distribution, particle density, plasticity limits, and cohesion were determined according to BDS EN ISO/ TS 17892. Classification of soil samples was performed according to the European Soil Classification System (ESCS).

The Atterberg limits were defined according to BDS EN ISO/ TS 17892–12:2018. The tests were performed at a room temperature of 20 °C by the same operator in order to reduce the possibility of human error. The liquid limit was obtained as recommended in the clause 5.4 of BDS EN ISO/ TS 17892-12:2018 with Casagrande apparatus with a hard base percussion cup.

The effective cohesion was derived at saturated consolidated-drained conditions from direct shear test. The shear resistance envelope was obtained by three shear tests, each using a different effective normal stress (100 kPa, 200 kPa, and 300 kPa), performed on specimens from the same soil sample. The least squares method was used to obtain the corresponding c' values.

A variety of statistics was applied to explore the relationship between c' (response variable) and I_p (predictor variable). The curve fitting procedure was used for estimation of the regression model. In regression analysis, curve fitting is the process of specifying the model that provides the best fit to the specific curve set of data.

Regression analyses were performed and single-factor models were obtained, using the equations as described in Table 1, where x is a predictor variable, denotes the predicted value of the response variable \hat{y} for a given x ; b_0 , b_1 , and b_2 – coefficients of the independent variable; and e is Euler's constant.

Table 1
Regression models

Regression Model	Equation
Simple linear	$\hat{y} = b_0 + b_1x$
Logarithmic	$\hat{y} = b_0 + [b_1 * \ln(x)]$
Quadratic	$\hat{y} = b_0 + b_1x + b_2x^2$
Exponential	$\hat{y} = b_0 * e^{(b_1 * x)}$

RESULTS AND DISCUSSION

The tested soils cover a wide range of classifications. Based on ESCS, samples are classified as follows: low plasticity clay (CIL) – 13 specimens; medium plasticity clay (CIM) – seven specimens; high plasticity clay (CIH) – six specimens; and very high plasticity clay (CIV) – seven specimens (Fig. 1). Summary of the obtained results for I_p and c' is presented in Table 2.

Correlation and regression analysis were conducted with I_p as an independent variable, and c' as a dependent variable. The regression models of c' and I_p are presented in a graphic form in Fig. 2. The first procedure was estimation of the strength of the relationships between variables by Pearson's correlation test and the F-test related to it. The F-test was targeted to the significance of entire regression models and to detect if the independent variable could be used to predict the models.

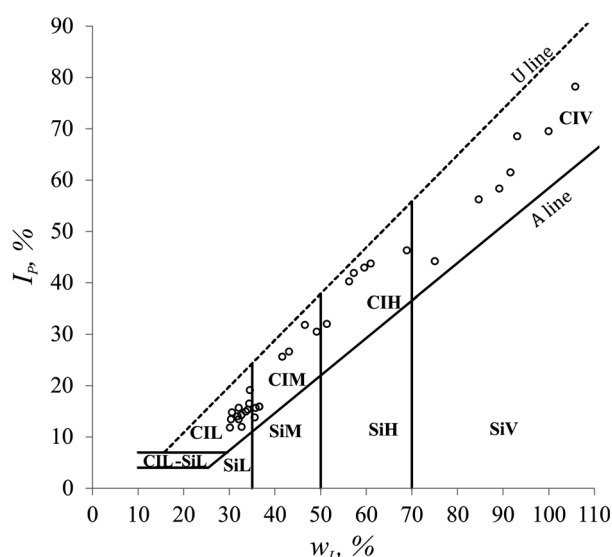


Fig. 1. Tested samples shown on plasticity diagram for the ESCS classification.

Table 2
Summary of obtained results for I_p and c'

Soil type	Number of specimens	Range of I_p , %	Range of c' , kPa
CIL	13	11.8–14.6	14.8–23.5
CIM	7	13.8–30.5	19.3–33.4
CIH	6	32.0–46.3	36.4–53.0
CIV	7	44.2–78.2	47.7–76.0

Table 3
Pearson correlation and F-test results

Regression model	R	R^2	F-test	
			F	p -value
Exponential	0.953	0.908	304.745	0.000
Linear	0.982	0.964	830.572	0.000
Logarithmic	0.962	0.925	381.482	0.000
Quadratic	0.983	0.966	420.450	0.000
Power	0.968	0.938	466.874	0.000

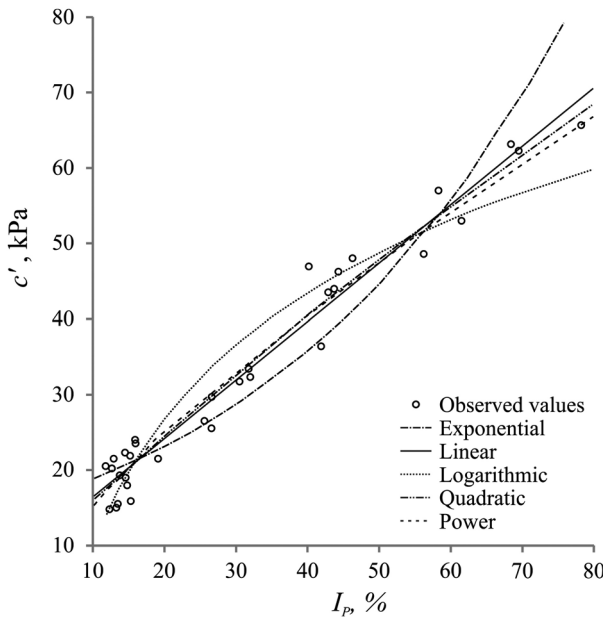


Fig. 2. Regression models of c' and I_p .

Table 3 provides the results from these tests. Pearson's correlation coefficient (R) gives information about the magnitude of the correlation, as well as the direction of the relationship. The obtained R values range from 0.953 to 0.983. This indicates that there is a very strong and positive correlation between c' and I_p .

The coefficient of determination (R^2) was also obtained, as it provides information of how good a model fits the data. The derived values for R^2 are closer to 1 (Table 3), signifying that the regression models cover most of the variance of values for the dependent variable (from 90.8% to 96.6%); the total variation of c' was explained by I_p and just about 9.2% of it are unclear.

The exponential model has the lowest R^2 value (0.908), but it still had a strong relationship. The quadratic model has the highest R^2 value, but it is di-

rectly related to adding predictor variable and could not be accepted as the best-fitted model.

The results of the F-test show that the regression modes are statistically significant (p value < 0.05 ; Table 3). This is sufficient evidence to conclude that I_p will provide a better fit than a model with zero independent variable, and could be used to predict the models.

The next step of regression analysis is performing the T-test. The T-statistic measures the statistical significance of the coefficients of the independent variable in explaining the dependent variable y . Generally, any t value greater than +2 or less than -2 is acceptable. The higher the t value, the greater the confidence we have in the coefficient as a predictor. Low t values are indications of low reliability of the predictive power of that coefficient (Draper and Smith, 1998).

The outcomes of the T test analyses are summarized in Table 4. All models passed the test with the exception of the Quadratic one. The coefficient b_2 of the model is insignificant and it has been rejected.

The derived regression models, which passed all statistical tests and their mean absolute errors (MAE), are presented in Table 5. In judging the efficiency of the regression models, the lower MAE is the better model. A MAE of zero means a perfect model. An advantage of MAE is the fact that its score is in the same units as the variable of interest.

The exponential and the logarithmic regression equations show the highest MAE with values of 3.75 kPa and 3.59 kPa, respectively. The MAE of the regression for the linear model (2.50 kPa) is almost as low as the MAE for the power model (2.57 kPa). The difference between them is so small that we could use either one for the best-fitted model if we did not take into account the R^2 value.

Regression model selection criteria used in the current paper are the highest R^2 value, least MAE and statistical significance of the model and its

Table 4
T-test results of regression models

Regression model	T-test								
	b_0	t	p -value	b_1	t	p -value	b_2	t	p -value
Exponential	14.613	21.011	0.000	0.022	17.457	0.000			
Linear	8.476	8.487	0.000	0.776	28.820	0.000			
Logarithmic	-46.186	-11.205	0.000	24.254	19.532	0.000			
Quadratic	6.520	3.322	0.002	0.915	7.439	0.000	-0.002	-1.156	0.257
Power	2.767	21.607	0.000	0.727	21.607	0.000			

Table 5
Regression model equations

Regression model	Equation	Adjusted R^2	MAE, %
Exponential	$c' = 14.613 * e^{0.022I_p}$	0.905	3.746
Linear	$c' = 8.476 + 0.776I_p$	0.962	2.502
Logarithmic	$c' = 24.254 * \ln(I_p) - 46.186$	0.922	3.590
Power	$c' = 2.767 * I_p^{0.727}$	0.936	2.570

Table 6
Statistical data of the best fitted model

Equation	R	R^2	MAE	F-test		T-test			
				F	p value	b_0	p value	b_1	p value
$c' = 8.476 + 0.776 * I_p$	0.982	0.964	2.502	830.572	0.000	8.476	0.000	0.776	0.000

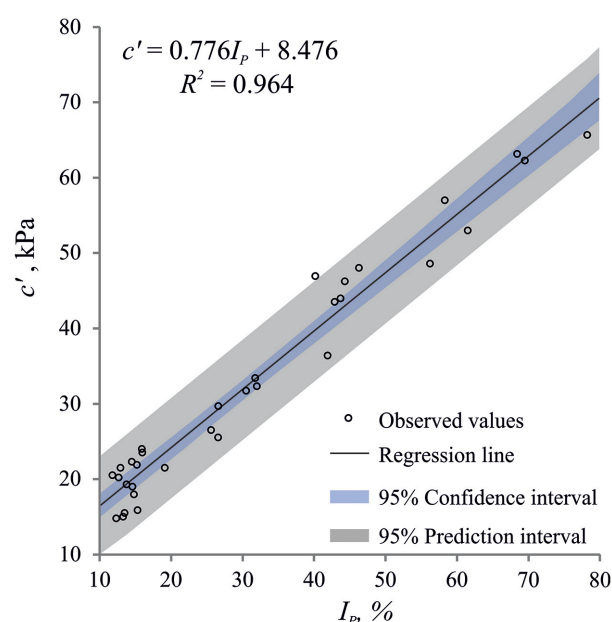


Fig. 3. Uncertainty of the derived linear model.

coefficients. The best-fitted regression model for predicting c' of clay soils from their I_p according to these criteria is the linear regression model (Table 6).

The uncertainty of the derived linear model is calculated by a 95% confidence interval (blue band) and 95% prediction interval (gray band; Fig. 3). The limitation of the suggested equation is that it is applicable for the values of I_p in the range of 11% to 78% and can be used just for preliminary estimation of c' .

CONCLUSION

In order to provide a correlation between the effective cohesion and plasticity index for natural undisturbed soils from NW Bulgaria, 33 clay soil specimens were laboratory tested to determine their index properties and effective cohesion. Correlation and regression analysis were performed with

plasticity index as an independent variable, and effective cohesion as a dependent variable. The test results confirm that the effective cohesion can be related to the plasticity index. It was observed that the linear regression model gives the best equation with a coefficient of determination of 0.964 and mean absolute error of 2.50 kPa. The derived equation likewise appears to be appropriate to a wide range of clays with an I_p value in the range of 11% to 78%. The authors believe the suggested correlation would be a useful assessment tool for the preliminary design stages.

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