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Research Article

Estimation of consistency limits of fine-grained soils via regression analysis: A special case for high and very high plastic clayey soils in Istanbul

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ABSTRACT

Consistency limits are essential and simple design parameters that are utilized as standard entries of all kinds of soil investigation programs conducted for geotechnical projects which are constructed in/on fine grained soils. These limits also represent mineralogical and physical properties of clayey soils directly and used to estimate their strength and rigidity properties indirectly. However, the consistency tests are assumed as the simple and basic tests of geotechnical engineering investigations, but the effects of operator, calibration of the device and environmental aspects at the tests damage the reliability and correctness of results. In this paper, it is aimed to overcome these challenges by evaluating the consistency characteristics of clayey soils considering only the values of liquid limit of specific clays with the use of simple regression analysis. A database is prepared by using 500 soil investigation reports that are involving the site characterization information, laboratory and field tests of Istanbul Province European side clayey soils, including Avcılar, Esenyurt, Küçükçekmece, Büyükçekmece, Çatalca, Zeytinburnu, Bahçelievler, Bakırköy districts. 1523 liquid limit tests are obtained from the mentioned database for high and very high plastic clays. The regression analyses have been applied to query the parameter effect ratio on the consistent characteristics and relationships have been tried to be developed to evaluate the values of plastic limit and plasticity index directly from only liquid limit test applications. The effects of fine material content, depth and natural water content is also investigated. Verifications of the suggested equations have been done for different cases and comparisons are made with the well-known sources of literature. Consequently, strong equations are acquired to determine the plasticity index value in terms of liquid limit, liquid limit-depth, liquid limit-fine content, natural water content-fine content respectively based on the actual experimental tests conducted in Istanbul.

1. Introduction

The existence of clay minerals in fine grained soil medium leads soil to be remolded in the presence of some moisture without crumbling. This nature of behavior is represented by cohesion phenomenon that is caused by the adsorbed water which surrounds the clay particles [1]. The mentioned natural behavior trend is initially revealed by Atterberg [2] with the use of a conservative method to describe the consistency of fine grained soils with various water contents. The relationship between the water contents are specialized as consistency limits and mainly divided into four basic phases such as solid, semisolid, plastic and liquid to classify the physical state of soils [3]. The properties that are obtained with the use of water content values characterize the most prominent physical properties of clays and specific classification systems use the plasticity degree values of clays to identify the dominant characteristics of evaluated soils. In order to determine the typical engineering properties, besides the natural water content value of any type of soil

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medium, various boundary water content values should be obtained to identify the physical state that is qualifying consistence. The water content of the soil at the point of transition from solid to semisolid state is described as the shrinkage limit, and from semisolid to plastic state is identified as the plastic limit. In addition to these, the water content of the soil at the point of transition from plastic to liquid state is defined the liquid limit [1]. These three boundary water content values are named as Atterberg limits. The knowledge about the natural water content values that are obtained from the field or laboratory experiments carried out during the design phase of the application projects, is used to find the location of the determined water content value between the Atterberg limits. This application provides only a premise information in terms of the engineering behavior to be exhibited. To acquire the real behavior characteristics of envisaged soil profile, advanced studies were conducted and the concepts of consistency limits were expressed more precisely by Casagrande [4] after 1920 in accordance with the engineering purposes and then the use of the plasticity index in the classification systems was standardized. Plasticity index (*PI*) value is defined as the difference between the liquid limit (*LL* or w_L) and the plastic limit (*PL* or w_P) of the inspected soil. The water content degrees between liquid and plastic limits are reflecting the measure of the range of plasticity behavior of especially fine grained soils. Hence the acquirement process of liquid and plastic limit values gains importance to calculate the plasticity index value. In this connection, Casagrande [4], [5] developed the liquid limit test instrument (Casagrande cup) in order to standardize its acquisitions and enabled the experiment to become the least dependent on the practitioner and become repeatable. The proposed technique is based on the preparation step of the different soil samples with various water contents by remolding. The second step of the method includes the application of the test with the Casagrande cup [4], [5]. Although these foreseen experiments seem easy and fast to implement; serious experience, attention and time are required to obtain valid and consistent results. Insufficient remolding effect applied during sample preparation in water contents other than the soils used in the experiments is one of the physical problems that may occur during the limit tests and this may trigger the interpretation errors and cause the wrong limit values to be obtained. Besides, the plastic limit test is shaped entirely based on the experience of the operator who is performing the experiment, and the main reason for the errors related to the experiment is the preparation and testing of the sample depending on the operator. In addition, the ambient temperature and remolding sensitivity of the operator while preparing the sample may cause the sample prepared in a certain water content to lose water and in fact the predicted content value cannot be obtained. This situation makes it difficult to interpret the average water content value and causes the data to be obtained in a wide range. For this reason, the experiment should be reproducible and interpretation should be made considering the conditions that pose risks in the experiments. In addition, apart from the usage of plasticity index value to classify the fine-grained soils, many engineering features can be calculated in relation to this value. Thus, the prediction of engineering characteristics of soils in terms of index properties has a great applicability in the discipline of geotechnical engineering. Various studies were performed from different points, including experimental, theoretical and empirical relationships to obtain some engineering properties of fine grained soils. In this context, there are many empirical formulas proposed by Skempton [6] based on obtaining the strength and compaction parameters of the soil using the limit water content values. However, the fact that natural soils are not stacked homogeneously as a single formation complicates the issue of which of these empirical expressions can be selected and evaluated for the soil types of the project and also creates a subject that requires expertise. Fall [7] developed a correlation to obtain the plastic limit and plasticity index value by using liquid limit experiments applied on clays. The relevant study is a widely used reference in the literature, and the success of the equations in estimating the plasticity index of low and high plasticity clays is still one of the topics to being evaluated within the studies. Chenari et al. [8] attempted to relate soil compaction characteristics, hydraulic conductivity, and strength and consistency parameters in the study titled obtaining soil geotechnical properties with index parameters. Tanzen et al. [9] used a two-step test procedure for estimating the plastic limit value that was conducted by using a fall cone test. In the first of these studies, the classical fall cone test was applied for eight fields and at the second stage, a test revision with a load value to obtain the plastic limit was proposed. Kuriakose et al. [10] suggested equations using the liquidity index and the water content ratio in estimating the shear strength of clays Naveena et al. [11] were applied the classical consistency limits tests for specific soils that are provided the relationship between simple linear regression analysis and plasticity index and liquid limit value were examined. The correlation obtained as a result of regression analysis has been shown to give results consistent with the results of the Casagrande plastic limit test. Jasim et al. [12] conducted a study based on estimation of the bearing capacity, shear strength angle, cohesion value and plasticity value using artificial intelligence technology. Cantillo and Pajaro [13] have presented a technical note including some correlation equations that are suggested to predict the swelling pressure based on the consistency limits with statistical methods. Spagnoli and Feinendegen [14] have used 40 different clay samples with different mineralogies and have performed some laboratory tests to evaluate the strength and consistency characteristics. Some solutions are conducted with the use of liquidity index depending on the estimated plastic limit values to verify the suggested relationships. Shimobe and Spagnoli [15] have considered 500 data from both literature and laboratory tests and have compared the undrained shear strength, liquidity index and water content ratio. In addition, it is aimed to acquire the relationship between the strength and liquidity index of remolded specimens. Barnes [16] has suggested a semi-logarithmic relation between the undrained shear strength and liquidity index and has defended to be accurate shear strength values at the liquid and plastic limits can be achieved. Golavska et al. [17] have used the outcomes of the laboratory tests of plastic and liquid limit tests of Eemian gyttja that are characterized by different organic contents. The statistical analyses have been performed to query the effect of the organic content on the single and two-factor relationships obtained between the plastic and liquid limit. Hussain and Atalar [18] have investigated the relationship between the liquid limit and the compaction characteristics with the use of 8 samples of North Nicosia Kythrea group soils in North Cyprus were subjected to Atterberg limits and compaction laboratory tests. Besides, multiple linear regression analyses have been made to obtain the mathematical expression of relationships and the R^2 values of the suggestions have been determined over 75%.Singh and Gupta [19] have enhance a correlation between the strength and the water content ratio and also a correlation between the strength and the liquidity index. Comparisons have been conducted between the obtained relationships with the use of experimental results.

The excessiveness and the actuality of the conducted studies about the evaluation and the derivation process of consistency limits show the importance and actuality of the subject. In addition, the developing information and computer technologies leads researchers to obtain the easy way to calculate all the soil engineering properties by the usage of advanced methods with prediction. So it will be possible to say that the verity of the used prediction method is preliminary depends on the acquirement of the consistency limits. Concordantly, in this study, it is aimed to use the liquid limit test values to predict the representative plasticity index values of high and very high plastic clayey soils that are selected from the European side of Istanbul. For that purpose, a database is generated by the use of different 500 soil investigation reports, including the site characterization information, laboratory and field tests of Istanbul Province European side clayey soils, including Avcılar, Esenyurt, Küçükçekmece, Büyükçekmece, Çatalca, Zeytinburnu, Bahçelievler, Bakırköy districts. Totally, 1523 liquid limit tests are obtained from the mentioned huge database for high and very high plastic clayey soils. Special locations are selected from Istanbul and four zones are arranged depending on the closeness and the wideness of districts to conduct regression analysis with Matlab R2016a. Regression analysis is conducted to query the parameter effect ratio on the consistency characteristics and then regression relationships are tried to be developed to evaluate the values of plastic limit and plasticity index directly from only liquid limit test applications. On the other hand, the effects of natural water content, depth of the specimen in the field and fine content ratio are also taken into account to acquire more detailed and accurate results to predict the plasticity index value. Verification of the developed equations is conducted for different cases and comparison is done by the well-known sources of literature. Consequently, this study is differentiated from other studies by determining the plasticity index value via liquid limit with the use of characteristic soil types of Istanbul soils because there are not enough literature studies about these kind of soils to correlate their original characteristics. In addition to this, the selected influencer variants of plasticity index are not similar to other conducted studies that exist in the literature. Besides, the present study provides an opportunity for authors to form a huge database to attain novel approaches to define the geotechnical properties of Istanbul.

2. Materials and Methods

2.1 Application details of consistency limit tests

Liquid limit test device, named Casagrande cup, includes a brass cup and a hard rubber base that can be dropped onto the base by a manually operated by a crank [4]. The soil specimens that are prepared with different moisture contents, placed in the cup to parallel to the horizontal surface. A standard knife is used to cut the specimen and a groove is formed at the vertical axis. Subsequently, the cup is lifted and dropped from 10 mm height. The moisture content of the performed test is specified the required blows to close the distance of approximately 13 mm through the bottom of the groove after N blows. At least three cup tests have to be experienced to obtain the water content that corresponds to the 25 blows of the cup is identified as liquid limit. The water content of the soil specimens, in percent, and the corresponding number of blows N is plotted on semi-logarithmic axes. The relationship between the moisture content and log N is approximated as a straight line. This straight line is named as the flow curve. The numerical value of the moisture content corresponding to N=25 blows, determined from the drawn flow curve, constitutes the liquid limit of the soil. The procedure for the plastic limit test is defined in ASTM in Test Designation D-4318. The plastic limit is identified as the water content at which the soil crumbles, when rounded into threads of 4.2 mm in diameter. The test is simple and it is conducted by repeated rolling of an ellipsoidal-sized soil mass by manually with the hand on a glass plate. The soil specimens that are prepared to conduct plastic limit test have to be divided into pieces at the length of 3-10 mm. In such a case, if the soil pieces are rolling into smaller sized pieces, it is possible to understand that the specimens are still too wet and the water content is over the plastic limit. But if the soil pieces are crumbed before the diameter size 3 mm, it can be said that the soil specimen is too dry and the water content is under the plastic limit. Because of this sensitive and operator depended application of the test, it is so hard to obtain accurate results at the first experience. The liquid limit is defined as the upper water content limit and plastic limit is defined as the lower water content limit of the plastic state of the soil. The plastic behavior is occurred between these upper and lower boundaries and taken into consideration in determining a specific parameter *PI* as before mentioned. Special descriptions are given to evaluate the consistency states of clayey soils in the literature. Burminster [20] classifies the *PI* value in a qualitative manner and defines the states of consistency given in Table 1.

Besides, the plasticity index is significant in the classification of the soils and it is fundamental to the Casagrande plasticity chart, which constitutes the basis for the Unified Soil Classification System (*USCS*).

The plasticity chart is given in Figure 1. The A-line drawn in the figure separates the inorganic silts from inorganic clays. The clays are located above and the silts are located under the A-line. The organic silts are also located under the A-line and the liquid limit is existed between 30% and 50%. Organic clays are located in the same region as inorganic silts, under the A-line and the liquid limit value is bigger than 50%. The line that is located above the A-line is U-line. The U-line represents the approximate upper limit of the relationship of the *PI* and *LL* for any envisaged soil.

In this study, all the used soil types are classified according to the USCS and liquid limit tests are conducted with Casagrande cup method.

Table 1. Description of soil consistency depended on the *PI* value [1, 20]

Plasticity Index	Description
0	Non-plastic
1-5	Slightly plastic
5-10	Low plasticity
10-20	Medium plasticity
20-40	High plasticity
>40	Very high plasticity

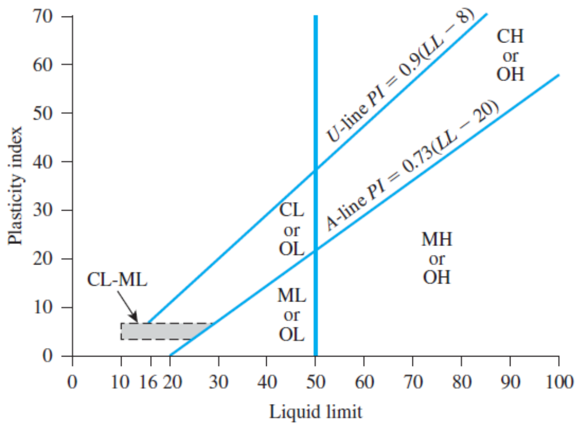

Figure 1. Plasticity chart [1]

2.2 Materials and database preparation

In the context of this study, fine-grained soils are taken into consideration to determine their plasticity characteristics via regression analysis. A special database is prepared with the use of 500 soil investigation reports that are supplied with special permission from The Departments of Investment Monitoring and Coordination (DIMCs), Turkey. The soil investigation reports are identifying all the geotechnical soil characteristics of the European side of Istanbul Province. But, the mentioned database is prepared only with the use of the results of natural water content tests, sieve analysis, hydrometer tests, Casagrande cup tests, and plastic limit tests.

Special locations are selected from the European side of Istanbul and four zones are arranged depending on the closeness and the wideness of districts to conduct regression analysis. These districts that are evaluated in the analysis were selected especially from the areas where high and very high plasticity clayey soils that are described in Table 1, are found in the formation. The first zone of the study includes Avcılar, Esenyurt and Küçükçekmece (Zone 1); the second zone includes Büyükçekmece (Zone 2), the third zone includes Çatalca (Zone 3) and the fourth zone includes Zeytinburnu, Bahçelievler, Bakırköy (Zone 4) districts. The locations of the mentioned districts are given in Figure 2. Zone 2 and Zone 3 is formed with the use of only one district due to the existence of huge field volume and attainment of enough soil investigation reports.

Totally 3200 consistency limit tests are used to define the selected districts but only 1523 test results are obtained for high and/or very highly plastic clayey soils (*CH*). The results of 3200 consistency limit tests are illustrated in Figure 3 with the use of Plasticity Chart.

In Figure 3, the high and very highly plastic clays are shown with red dots and named as *CH* according to *USCS*. The distribution of the numbers of consistency limit tests that are used to create the database are given in Table 2 according to the envisaged districts and zones via the regression process variants.

It can be seen from Table 2 that the total number of consistency limit tests conducted for high and very high plastic clays are 249 for Zone 1, 453 for Zone 2, 201 for Zone 3 and 562 for Zone 4 respectively.

Figure 2. The districts of Istanbul and envisaged zones in the study [21]

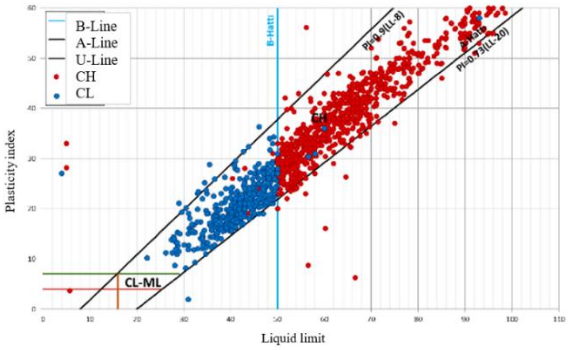

Figure 3. The configurations of liquid limit test results on plasticity chart

Table 2. The number of total consistency limit tests performed for high and very high plastic clays according to the zones

	Objective via variant	*PI via LL*	*PI via LL, h*	*PI via LL, FC*	*PI via w_n, FC*
Zone 1	*Avcılar*	23	23	10	10
	Esenyurt	101	101	24	23
	Küçükçekmece	125	125	82	60
Zone 2	*Büyükçekmece*	453	453	138	368
Zone 3	*Çatalca*	201	201	229	0
Zone 4	*Zeytinburnu*	26	26	11	35
	Bahçelieveler	110	110	23	376
	Bakırköy	426	426	396	0

The regression analysis is conducted initially to obtain the relationship of the plasticity index in terms of liquid limit. Second step analysis is performed to obtain the relationship of plasticity index in terms of both the specimen depth from the field (*h*) and liquid limit. Third step analysis is conducted to acquire the relationship of plasticity index in terms of liquid limit and fine content of the soil (*FC*). Then the last step is performed to find out the relationship of plasticity index in terms of natural water content (w_n) and fine content of soil. The numbers of the tests are reduced due to the increase of the variants of the regression analysis and the number of the tests are also given in Table 2.

3. Results and Discussion

Regression analyses are conducted with Matlab R2016a by the use of both 2 and 3 dimensional graph systems to find the most proper expression of plasticity index. Eight different types of functions such as interpolant, linear fitting, polynomial, power, rational, smoothing spline, sum of sine and weibull, are used for 2D analyses and also four different types of functions such as custom equation, interpolant, lowess and polynomial, are used for 3D analyses to search for the best fitting relationship between the variants in Matlab. Several analyses are performed for each existing method and finally it is found that the proper type of the method is power for 2 dimensional analysis and polynomial for 3 dimensional analyses. In the explorement process of the expression of plasticity index, a two stepped application is conducted. At the first stage, all the envisaged zones are analyzed individually and after, the total evaluations are also conducted for all the existing datasets to find the representative relationship of high and very high plastic clayey soils. At the second stage the equations that are acquired from both 2 and 3 dimensional regression analyses are transferred to Microsoft Excel to search for verification of the result equations. The results obtained by the application of the suggested equations are checked against the actual values of plasticity indexes which are calculated by the application of both experimental liquid and plastic limit tests. Based on the comparison of the results of suggested method and experimental equations, the maximum error, the average error and the percentage of the average errors are achieved. These calculations can provide insight about the probable encountered errors while the use of suggested equation. Therefore, the information about the mentioned details are also added in the content of the results of the analyses.

3.1 Analysis of Zone 1

Regression analyses are conducted for Zone 1 (Avcılar, Esenyurt, Küçükçekmece) with the application of three different conditions arouse due to the used variants.

1. Determination of PI via the use of LL: This investigation is performed with two dimensional “power” regression analysis. In that case, 249 liquid limit tests are used and the relationship between PI and *LL* is found by Equation (1).

$$PI = 0.18LL^{1.28} - 1.2 \quad (1)$$

The result curve that is acquired with the calculation of Equation (1) according to the actual values of liquid limit tests are given in Figure 4.

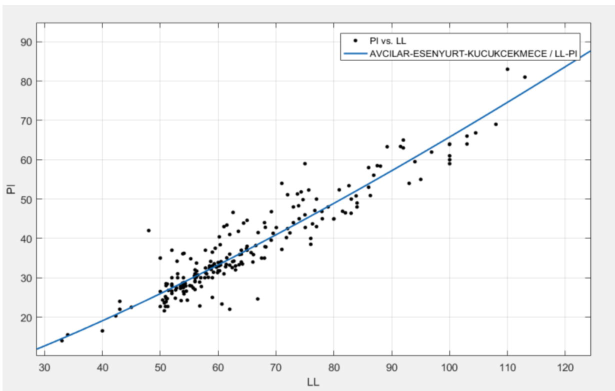

Figure 4. Determination of *PI* via *LL* for Zone 1

The outcomes of the analyses are summarized in Table 3. The R^2 value of the most fitting equation is obtained as 0.8918 and the average percent of the errors of the suggested equation is found 7.6%. It can be seen from both Figure 4 and Table 3 that according to the performance values reached in the experimental studies, the regression model shows an effective performance.

2. Determination of PI via the use of both LL and h: This investigation is performed with three dimensional "polynomial" regression analysis. In that case, 249 liquid limit tests are used and the relationship between *PI* and *LL* and h is found by Equation (2).

$$PI = -13 - 0.01 \times h + 0.77LL \quad (2)$$

The resultant graph that is acquired with the calculation of Equation (2) according to the actual values of liquid limit tests are given in Figure 5.

The outcomes of the analyses are summarized in Table 4. The R^2 value of the most fitting equation is obtained as 0.9304 and the average percent of the errors of the suggested equation is found 7.74%. It can be seen that the addition of the depth factor to the variants of the relationship is strengthening the determination function of *PI*. Besides, the average percent of the errors of the suggested equation approximately remain constant.

Table 3. Results of regression analyses for Zone 1 (Condition 1)

Number of the data	249
Value of R^2	0.8918
Adjusted R^2	0.8909
Average error of the equation	2.8
Average percent of the errors of the equation (%)	7.6

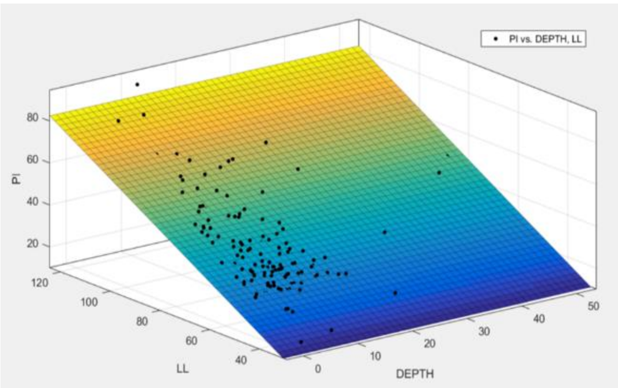

Figure 5. Determination of *PI* via *LL* and *h* for Zone 1

Table 4. Results of regression analyses for Zone 1 (Condition 2)

Number of the data	249
Value of R^2	0.9304
Adjusted R^2	0.9299
Average error of the equation	2.84
Average percent of the errors of the equation (%)	7.74

3. Determination of PI via the use of both LL and FC: This investigation is performed with three dimensional "polynomial" regression analysis. In that case, 116 liquid limit tests are used and the relationship between *PI* and *LL* and *FC* is found by Equation 3.

$$PI = -10 + 0.03 \times FC + 0.75 \times LL \quad (3)$$

The resultant graph that is acquired with the calculation of Equation (3) according to the actual values of liquid limit tests are given in Figure 6.

The outcomes of the analyses are summarized in Table 5. The R^2 value of the most fitting equation is obtained as 0.9464 and the average percent of the errors of the suggested equation is found 5.75%. It can be seen that the addition of the fine content factor to the variants of the relationship is more strengthening the determination function of *PI*. In addition to this situation, the average percent of the errors of the suggested equation reduce. Comparison of the analysis performed for *PI* via the consideration of *h* and *FC* individually, demonstrates that the rate of influence of the fine content quantity is relatively bigger than the effect of depth.

3.2 Analysis of Zone 2

Regression analyses are conducted for Zone 2 (Büyükçekmece) with the application of three different conditions arouse due to the used variants.

1. Determination of PI via the use of LL: In that case, 453 liquid limit tests are used and the relationship between *PI* and *LL* is found by Equation (4). The amount of the laboratory tests is more than Zone 1 for Zone 2.

$$PI = 8.3LL^{0.56} - 46 \quad (4)$$

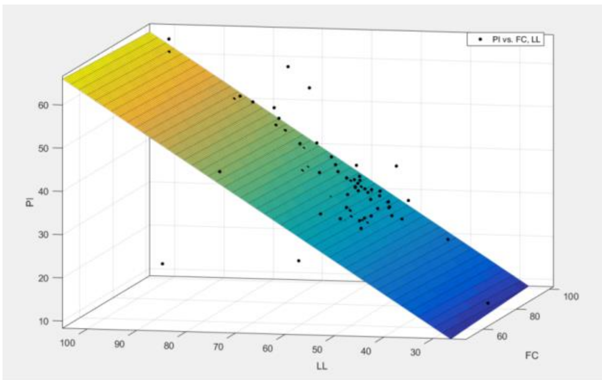

Figure 6. Determination of *PI* via *LL* and *FC* for Zone 1

Table 5. Results of regression analyses for Zone 1 (Condition 3)

Number of the data	116
Value of R^2	0.9464
Adjusted R^2	0.9454
Average error of the equation	1.86
Average percent of the errors of the equation (%)	5.75

The resultant curve that is acquired with the calculation of Equation (4) according to the actual values of liquid limit tests are given in Figure 7.

The outcomes of the analyses are summarized in Table 6. The R^2 value of the most fitting equation is obtained as 0.9062 and the average percent of the errors of the suggested equation is found 6.40%.

2. Determination of PI via the use of both LL and h: In that case, 453 liquid limit tests are used and the relationship between *PI* and *LL* and *h* is found by Equation (5).

$$PI = -6.8 - 0.005 \times h + 0.71 \times LL \quad (5)$$

The resultant graph that is acquired with the calculation of Equation (5) according to the actual values of liquid limit tests are given in Figure 8.

The outcomes of the analyses are summarized in Table 7. The R^2 value of the most fitting equation is obtained as 0.9123 and the average percent of the errors of the suggested equation is found 6.35%. It can be seen that the addition of the depth factor to the variants of the relationship strengthens the determination function of *PI*. Besides, the average percent of the errors of the suggested equation approximately remain constant similar with the response of Zone 1.

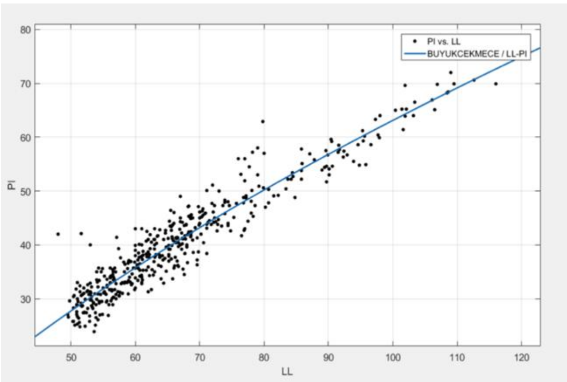

Figure 7. Determination of *PI* via *LL* for Zone 2

Table 6. Results of regression analyses for Zone 2 (Condition 1)

Number of the data	453
Value of R^2	0.9062
Adjusted R^2	0.9058
Average error of the equation	2.4
Average percent of the errors of the equation (%)	6.40

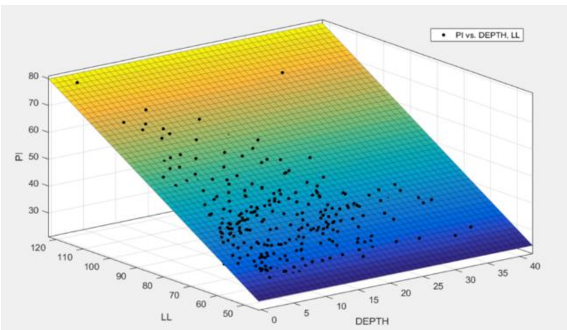

Figure 8. Determination of *PI* via *LL* and *h* for Zone 2

Table 7. Results of regression analyses for Zone 2 (Condition 2)

Number of the data	453
Value of R^2	0.9123
Adjusted R^2	0.9119
Average error of the equation	2.43
Average percent of the errors of the equation (%)	6.35

3. Determination of PI via the use of both LL and FC: In that case, 138 liquid limit tests are used and the relationship between *PI* and *LL* and *FC* is found by Equation (6).

$$PI = -9.4 + 0.06 \times FC + 0.8 \times LL \quad (6)$$

The resultant graph that is acquired with the calculation of Equation (6) according to the actual values of liquid limit tests are given in Figure 9.

The outcomes of the analyses are summarized in Table 8. The R^2 value of the most fitting equation is obtained as 0.7936 and the average percent of the errors of the suggested equation is found 6.7%. In contradistinction to the results of Zone 1 Condition 3, the addition of fine content variant to the solution research, decreases the approximation validity. The effect of depth becomes the significant effective factor for the analyses to establish the actual solution. This situation may be arose due to the evaluated dataset for performing analysis of Condition 3.

3.3 Analysis of Zone 3

Regression analyses are conducted for Zone 3 (Çatalca) with the application of three different conditions arouse due to the used variants.

1. Determination of PI via the use of LL: In that case, 201 liquid limit tests are used and the relationship between *PI* and *LL* is found by Equation (7).

$$PI = 0.35LL^{1.14} - 4 \quad (7)$$

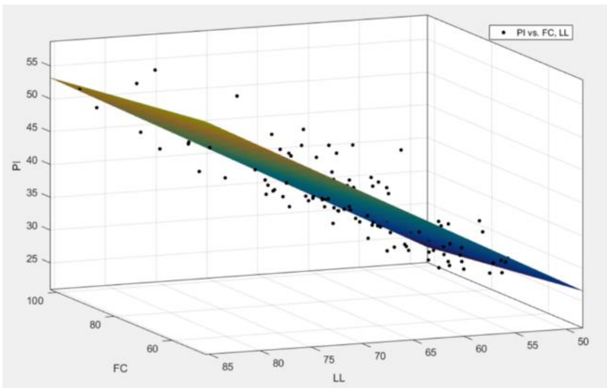

Figure 9. Determination of *PI* via *LL* and *FC* for Zone 2

Table 8. Results of regression analyses for Zone 2 (Condition 3)

Number of the data	138
Value of R^2	0.7936
Adjusted R^2	0.7902
Average error of the equation	2.42
Average percent of the errors of the equation (%)	6.7

The resultant curve that is acquired with the calculation of Equation (7) according to the actual values of liquid limit tests are given in Figure 10.

The outcomes of the analyses are summarized in Table 9. The R^2 value of the most fitting equation is obtained as 0.8788 and the average percent of the errors of the suggested equation is found 7.13%.

2. Determination of PI via the use of both LL and h: In that case, 201 liquid limit tests are used and the relationship between *PI* and *LL* and *h* is found by Equation (8).

$$PI = -11 - 0.09 \times h + 0.72 \times LL \quad (8)$$

The resultant graph that is acquired with the calculation of Equation (8) according to the actual values of liquid limit tests are given in Figure 11.

The outcomes of the analyses are summarized in Table 10. The R^2 value of the most fitting equation is obtained as 0.8815 and the average percent of the errors of the suggested equation is found 6.82%.

It can be seen that the addition of the depth factor to the variants of the relationship strengthens the determination function of *PI*. Besides, the average percent of the errors of the suggested equation approximately remain approximately constant similar with the response of Zone 1 and Zone 2.

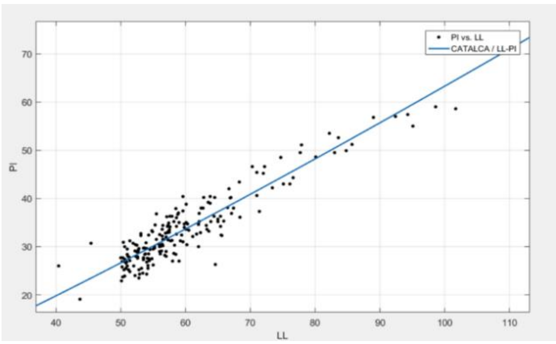

Figure 10. Determination of *PI* via *LL* for Zone 3

Table 9. Results of regression analyses for Zone 3 (Condition 1)

Number of the data	201
Value of R^2	0.8788
Adjusted R^2	0.8776
Average error of the equation	2.37
Average percent of the errors of the equation (%)	7.13

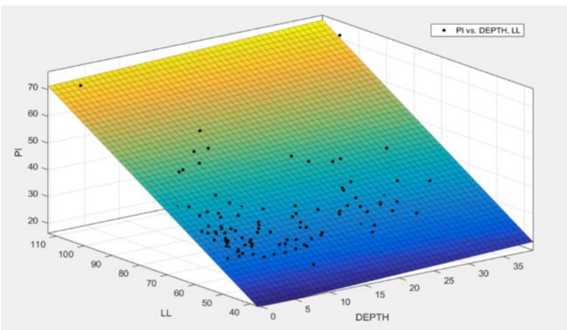

Figure 11. Determination of *PI* via *LL* and *H* for Zone 3

Table 10. Results of regression analyses for Zone 3 (Condition 2)

Number of the data	201
Value of R^2	0.8815
Adjusted R^2	0.8803
Average error of the equation	2.26
Average percent of the errors of the equation (%)	6.82

3. Determination of PI via the use of both LL and FC: In that case, 229 liquid limit tests are used and the relationship between *PI* and *LL* and *FC* is found by Equation (9).

$$PI = -6.7 + 0.04 \times FC + 0.72 \times LL \quad (9)$$

The resultant graph that is acquired with the calculation of Equation (9) according to the actual values of liquid limit tests are given in Figure 12.

The outcomes of the analyses are summarized in Table 11. The R^2 value of the most fitting equation is obtained as 0.8848 and the average percent of the errors of the suggested equation is found 8.2%. The interchange of *h* and *FC* in the solution function, approximately affects the ultimate result of the suggested method similar but the average percent of the errors of the equation are a little bigger for the effect of *FC* rather than the effect of *h*.

3.4 Analysis of Zone 4

Regression analyses are conducted for Zone 4 (Zeytinburnu, Bahçelievler, Bakırköy) with the application of three different conditions arouse due to the used variants.

1. Determination of PI via the use of LL: In that case, 562 liquid limit tests are used and the relationship between *PI* and *LL* is found by Equation (10).

$$PI = 1{,}55 LL^{0{,}86} - 17 \quad (10)$$

The resultant curve that is acquired with the calculation of Equation (10) according to the actual values of liquid limit tests are given in Figure 13.

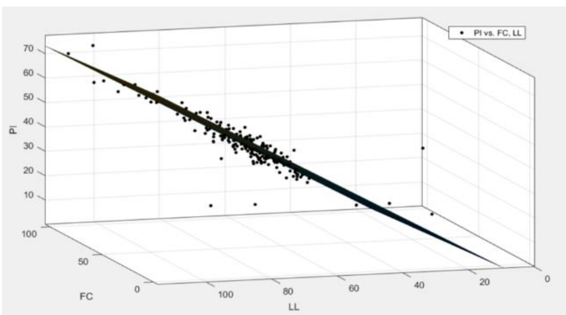

Figure 12. Determination of *PI* via *LL* and *FC* for Zone 3

Table 11. Results of regression analyses for Zone 3 (Condition 3)

Number of the data	229
Value of R^2	0.8848
Adjusted R^2	0.8836
Average error of the equation	2.37
Average percent of the errors of the equation (%)	8.2

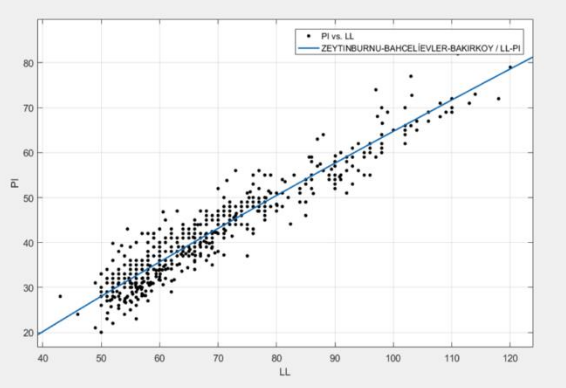

Figure 13. Determination of *PI* via *LL* for Zone 4

The outcomes of the analyses are summarized in Table 12. The R^2 value of the most fitting equation is obtained as 0.9032 and the average percent of the errors of the suggested equation is found 7.10%.

2. Determination of PI via the use of both LL and h: In that case, 562 liquid limit tests are used and the relationship between *PI* and *LL* and h is found by Equation (11).

$$PI = -7.8 - 0.03 \times h + 0.73 \times LL \qquad (11)$$

The resultant graph that is acquired with the calculation of Equation (11) according to the actual values of liquid limit tests are given in Figure 14.

The outcomes of the analyses are summarized in Table 13. The R^2 value of the most fitting equation is obtained as 0.9057 and the average percent of the errors of the suggested equation is found 7.23%. It can be seen that the addition of the depth factor to the variants of the relationship is not effected the determination function of *PI*.

Table 12. Results of regression analyses for Zone 4 (Condition 1)

Number of the data	562
Value of R²	0.9036
Adjusted R²	0.9032
Average error of the equation	2.8
Average percent of the errors of the equation (%)	7.10

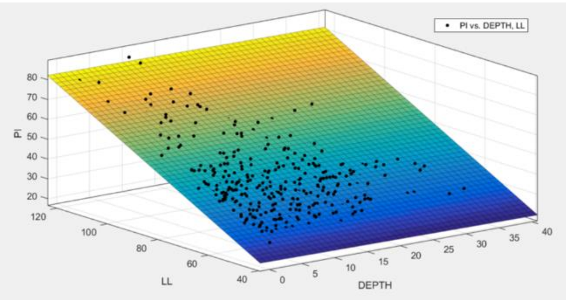

Figure 14. Determination of *PI* via *LL* and *h* for Zone 4

Table 13. Results of regression analyses for Zone (Condition 2)

Number of the data	562
Value of R²	0.9057
Adjusted R²	0.9054
Average error of the equation	2.81
Average percent of the errors of the equation (%)	7.23

3. Determination of PI via the use of both LL and FC: In that case, 430 liquid limit tests are used and the relationship between *PI* and *LL* and *FC* is found by Equation (12).

$$PI = -9.5 + 0.03 \times FC + 0.7 \times LL \qquad (12)$$

The resultant graph that is acquired with the calculation of Equation (12) according to the actual values of liquid limit tests are given in Figure 15.

The outcomes of the analyses are summarized in Table 14. The R^2 value of the most fitting equation is obtained as 0.9207 and the average percent of the errors of the suggested equation is found 6.54%. The change of *h* with *FC* affects the accuracy of the suggested equation. The approximation is strengthening and also the average percent of the errors are decreased.

Besides all the investigated cases, the integrated effects of the use of the natural water content and fine content of the soil within the search of proper function to calculate *PI* is studied. But none of the functions defined in Matlab are fitted to obtain the relationship of w_n and *FC*.

The distribution of the w_n and *FC* values are shown in Figure 16. Although the illustration shows a convergent relationship between the mentioned values, the calculated values of R^2 are staying between 0.1-0.2. This situation is not a meaning of the ineffectiveness of the parameters on the calculation process of *PI*. Indirect relationships can be obtained if multivariate regression analysis is conducted.

In addition to all these, in order to compare the effect of the data number, common field analyses are conducted with the use of total number of all experimental studies done through all the considered district. The total number of the evaluated dataset is 1532. The similar three conditions, that are mentioned before, about the variants of the solutions for the zones are also taken into account in the analyses. The relationship between plasticity index and liquid limit is obtained by performing two-dimensional analysis and solution result is given in Equation (13) and shown by Figure 17.

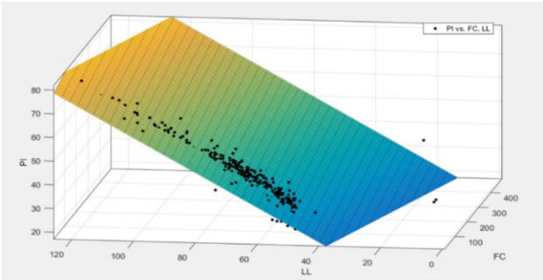

Figure 15. Determination of *PI* via *LL* and *FC* for Zone 4

Table 14. Results of regression analyses for Zone 4 (Condition 3)

Number of the data	430
Value of R²	0.9207
Adjusted R²	0.9203
Average error of the equation	2.5
Average percent of the errors of the equation (%)	6.54

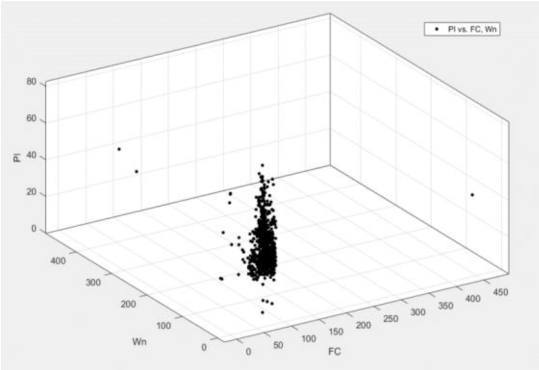

Figure 16. Determination of *PI* via w_n and *FC*

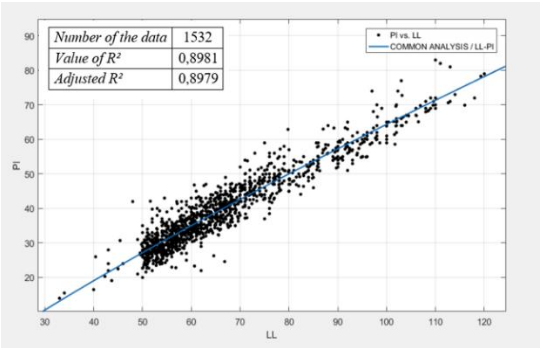

Figure 17. Determination of *PI* via *LL*

$$\mathrm{PI} = -1.96\mathrm{LL}^{0.82} - 21.6 \qquad (13)$$

The R^2 value of the most fitting equation is obtained as 0.8981 for common field analysis.

It is found that the change in plasticity index in terms of *LL* and *h* can be obtained by Equation (14) and shown by Figure 18.

$$\mathrm{PI} = -9.7 + 0.015\mathrm{h} + 0.74\mathrm{LL} \qquad (14)$$

The R^2 value of the most fitting equation is obtained as 0.9062 for common analysis.

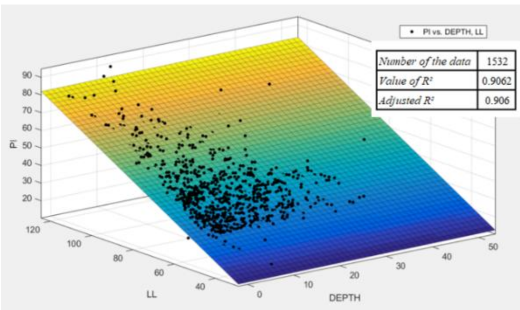

Figure 18. Determination of *PI* via *LL* and *h*

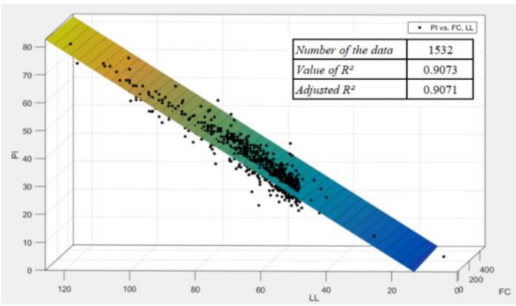

Figure 19. Determination of *PI* via *LL* and *FC*

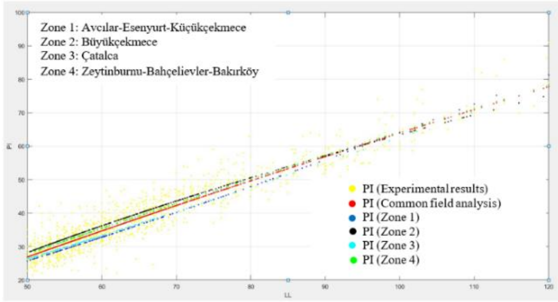

Figure 20. Comparison of the regression analysis of determination of *PI* via *LL*

The regression analysis conducted in the three dimensional "sphere" gives *PI* value as a function of *LL* and *FC* in Equation (15) and shown by Figure 19. The R^2 value of the most fitting equation is obtained as 0.9073 for common analysis.

$$\mathrm{PI} = -10 + 0.002\mathrm{FC} + 0.73\mathrm{LL} \qquad (15)$$

According to the R^2 values, it is possible to say that the results of the regression analysis of common evaluation of districts give satisfactory approaches. The compatibility of all the envisaged equations is calculated approximately 90%. When the analysis made for the regions are checked separately, it is seen that the accuracy convergence is lower in the zones with low data compared to common analysis. Consequently, this situation is a direct proof of the data set number effects on the prediction of soil properties.

In Figure 20, an integrated illustration of the experimental test results and the results of the suggested equations are given together. The graph system is arranged to represent the acquirement process of *PI* in terms of *LL* value. The individual equations of envisaged zones and the equation of common field analysis have been used for the locations that the data are valid. It will be consistent to say that the solution of the common field analysis approximately scans all the experimental test results and the suggested equation of common field analysis may be used as the representative solution function of *CH* type soils present at Istanbul. Besides, it is a significant issue that the results of Zone 1-Zone 4 and Zone 2-Zone 3 are close to each other and the curves of solution functions of these mentioned zones constitute the upper and lower *PI* boundaries of common filed analysis curve respectively. These close results are arising due to the locations of the districts. The closeness of the districts increases the similarity between the obtained results.

In addition to all these, the comparisons between the suggested equations to determine *PI* value, are not be enough to confirm the exact solution function. Therefore, in the context of the study, different comparisons are made to check the accuracy of all the attained relationships. The confirmation process of the equations is continued with two focused ways. Comparisons with actual experimental dataset forms the first way of the confirmation process. In addition, the discussion with the literature sources creates the second way. The first step of the confirmation process has been studied and explained before, together with the studies of the acquirement of the equation. Therefore, the study is continued with the description of the comparisons between the literature studies. Three different studies are selected from the literature to compare the results of regression analysis. This selection has been done according to the accessibility opportunities of the literature sources. In the selected studies, the determinations are presented for the calculation of *PI* in terms of *LL*. The first study is suggested by Seed et al. [22]. This study is based on the investigation of the plasticity characteristics of artificial kaolinite-quartz mixtures and Equation (16) is suggested to predict the *PI* value of constituted soil specimens.

$$PI = 0.98xLL - 27.5 \tag{16}$$

The second study is proposed by Nagaraj and Jayadeva [23]. Their study is based on the tests of natural clays coming from different depths with heterogeneous mineralogy. Equation (17) is suggested by Nagaraj and Jayadeva [23] to determine *PI*.

$$PI = 0.74xLL - 8 \tag{17}$$

The third study is conducted by Spagnoli et al. [24]. Their study is based on the investigation of the plasticity characteristics of smectite and kaolinite types of clay minerals. Equation (18) is suggested for smectite and Equation (19) is suggested for kaolinite type of minerals to calculate the *PI* value.

$$PI = 0.97xLL - 37.6 \tag{18}$$

$$PI = 5.94e^{0.023LL} \tag{19}$$

Equation 16-18 is selected to calculate all of the *PI* values with the use of the mutual data with common field analysis. In Figure 21, the results of the experimental tests, the common field analysis and the Equation 16-18 is given. The results of the common field analysis are closer with both the experimental test results and the solutions of the equations suggested by Nagaraj and Jayadeva [23]. Besides, the tendency of the behavior of common filed analysis and solutions of Nagaraj and Jayadeva [23] is similar. But especially the solution of Spagnoli et al. [24] differentiates from all appreciated studies and the solutions of Seed et al. [22] presents a different tendency than other relationships. The close similarity between the suggested equation solutions and Nagaraj and Jayadeva [23] arose directly due to the similarity of used kind of soil specimens. Nagaraj and Jayadeva [23] prefers to use natural clays coming from different depths with heterogeneous mineralogy. This preference is in common with the logic of the presented study. Seed et al. [22] and Spagnoli et al. [24] searches for a relationship to determine the plasticity characteristics of special types of minerals.

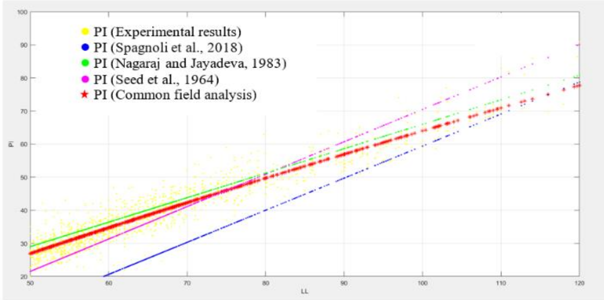

Figure 21. Comparison of the suggested equation with literature sources

This condition zooms out the results of suggested equations and investigated literature sources.

4. Conclusion

This study is conducted to investigate the relationships and effect degrees of parameters on the determination process of the plasticity index in terms of different geotechnical properties. High and very high plastic clay types that are acquired from the special districts of Istanbul province are entreated within the context of the study. Regression analysis is performed for envisaged zones of the investigated field with both the use of two and three dimensional analyses. Individual identifier equations are obtained for each of the defined zones to calculate *PI* value and the effect degrees of the parameters are discussed. Common field analysis is also performed to compare the representability of a mutual equation for defining the plasticity parameters of the foreseen zones. Additionally, comparisons are made with the literature sources to verify the suggested equations. Consequently, in this study, these outcomes are obtained:

- Relatively strong equations have been acquired to determine the *PI* value in terms of *LL*, *LL-h*, *LL-FC*, w_n-*FC* respectively based on the actual experimental tests conducted for Istanbul.
- The comparison process of the suggested relationships with the literature sources also supports the applicability of the envisaged relationships.
- A significant result of the study is to attract attention on the relationships of which are selected to represent the simple geotechnical properties of the investigation site which constitutes the first step of the design.
- In cases where it is not possible to conduct an experimental study, the necessity of checking the validity of the expressions used in the geotechnical parameter estimation for the project sites in question constitutes the final point of view of this study. The parameter prediction methods have to be checked carefully according to the dominant soil type of the research or project.
- Having all those in mind, the current study presents an applicable acquirement process of *PI* value for *CH* types of clays existed in Istanbul. This situation also paves the way for different parameter estimations that can be made depending on the plasticity index value.

Declaration

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The author(s) also declared that this article is original, was prepared in accordance with international publication and research ethics, and ethical committee permission or any special permission is not required.

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Nomenclature

CH	: High plastic clayey soil
h	: Depth
FC	: Fine content
LL, w_L	: Liquid limit
N	: Blow number
PI	: Plasticity index
PL, w_p	: Plastic limit
USCS	: Unified soil classification system
w_n	: Natural water content

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