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Soil Liquid Limit Determination Using a Single-Trial Methodology

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ABSTRACT

A new model equation has been constructed to estimate the liquid limit value, using the rapid one point method. Data processing was carried out in Microsoft Excel and SPSS, visualizing and using 6,210 theoretical trial points, which resulted from 135 samples along the actual flow index line, with the number of blows varying from 5 to 50 with an interval of unity. The model has two correction factors (CF), both of which are functions of the number of blows at the trial point in the test. The first CF is applied to the trial moisture content, while the second CF is applied to the previously estimated liquid limit. This technique was checked against real data points. For estimating the liquid limit for a large range of blows (N) from 10 to 45 the model achieved a high R^2 value of over 0.99. It also has a low RMSE of 3.8 for the set of 6,210 theoretical points and 2.2 for 220 actual points. In this research, the flexibility of the model is crucial as it provides a wider range of blows from 10 to 45, unlike the ASTM procedure for which there are set requirements that state the amount of blows to be between 20 and 30.

Keywords: Liquid limit, Rapid method, One-Point method, Flow index.

1. INTRODUCTION

ASTM or the American Society for Testing and Materials has two different but established methods for measuring the liquid limit. These have been named the multipoint method and the one-point method. The multipoint method uses a series of tests with the aim of minimizing human error, this method is intended to produce very precise and consistent outcomes. Apart from this, let us continue with the discussion of the **(ASTM D4318, 2010)** one-point method, which method known as method B. There are two point conditions: Firstly, the N value, which determines how many blows are necessary to close the groove is set to be between 20 and 30. If the N value falls below 20 or goes above 30 the water content of the soil has to be altered and the procedure begins from the start once again. Secondly, in the second soil groove closing if a second water content value is sought, the N value has to be equal or at least within two units of the N value of the first attempt. If the criteria are not

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met, a specimen has to be prepared and remixed and then reattempted. Furthermore, if two consecutive single-point measurements exceed a single percentage point, then a new test has to be performed. These tests of the N value and moisture are all on the one-point method and are within the reasonable limits mentioned. So, for N value between 20 and 30 the one-point method is reliable as it focuses on a small moisture content range and the output is accurate **(Das, 2019)**.

In the 1960s, significant attention was directed toward a more rapid one-point procedure for determining the LL **(Fang, 1960)**. Various methods have been explored for this one-point determination, including a tabular approach suggested by Fang, which is constrained by a flow index (FI) range of 5 to 32.5 and a limited N between 17 and 36. This range is considered the extent to which one can reliably use the interpolation function to determine the water content at 25 blows.

One study proposed a rapid method for determining the LL, based on a chart method developed by the Washington State Highway Department, along with a modification that incorporates a slide rule **(Olmstead and Johnston, 1955),** According to Olmstead and Johnston this approach can reduce testing time by as much as 30 to 70 percent. In this nomographic chart method, the N required to close the groove varies between 15 and 40.

In 1949, the U.S. Army Corps of Engineers (USACE) conducted a study on LL results at the Waterways Experiment Station in Mississippi, proposing an experimental Eq.(1) for this purpose **(Waterways, 1949).** In this equation, (N) represents the N required to close the groove during a given trial, (M) denotes the water content for that trial expressed as a percentage, and tan(B) indicates the slope of the flow line on a logarithmic plot of water content versus N. Although tan(B) is typically 0.121, it is important to note that this value may not hold true for all soil types **(Waterways, 1949).** This procedure is commonly referred to as the one-point method and has also been adopted by ASTM standards **(Das, 2019)**.

$$LLp = M\left(\frac{N}{25}\right)^{tan(B)} \quad (1)$$

Experimental equations are utilized in geotechnical engineering to determine liquid limits, including experimental Eq. (2) approved by **(ASTM D4318, 2010),** following the guidelines established in **(Waterways, 1949**), British Standard Eq. (3) **(BS1377, 1990),** and Australian Standard Eq. (4) **(AS1289, 2009**). The Indian Standard **(IS2720, 1985)** employs a slightly different formula, represented as Eq. (5) **(Nagaraj and Jayadeva, 1981)**, which is equivalent to a value of tan(B) equal to 0.101 **(Haigh and Vardanega, 2014).** Olmstead and Johnston suggested that if the errors from the one-point method fall within a $\mp 2\%$ range for LL, then this method should be considered acceptable **(Olmstead and Johnston, 1955).**

$$LLp = M\left(\frac{N}{25}\right)^{0.121} \quad (2)$$

$$LLp = M\left(\frac{N}{25}\right)^{0.092} \quad (3)$$

$$LLp = M\left(\frac{N}{25}\right)^{0.091} \quad (4)$$

$$LLp = \frac{M}{1.3215 - 0.23logN} \quad (5)$$

The LL of clay can be determined using the fall cone **(BS1377, 1990)** with the parameters derived for British Standard equipment, a forecast of tan (B) with a standard deviation of 0.021 is obtained. This aligns closely with the findings of **(Mohan and Goel, 1958; Norman, 1959; Jain and Patwardhan, 1960; BS1377, 1990)** using a value of 0.092 **(Norman, 1959).** Further analysis, comparison, and re-examination study of estimating LL by a single-point method using cone penetrometer **(Clayton and Jukes, 1978; Nagaraj and Jayadeva, 1981; Moon and White, 1985; Son et al., 2003). (Üyetürk and Huvaj, 2018; Haigh and Vardanega, 2014)** investigated the power coefficient in the one-point LL equation and identified the following values for tan(B):

- 0.121 **(Waterways, 1949**) for 767 soil tested, adopted by **(ASTM D4318, 2010).**
- 0.135 **(Olmstead and Johnston, 1955)** for 759 soil tested.
- 0.108 **(Eden, 1955; Eden, 1960)** for 484 soil tested.
- 0.118 **(Kim, 1973)** for 1017 soil tested.
- 0.112 **(Önalp and Kılıç, 1994)** for 332 soil tested.
- 0.132 **(Roje-Bonacci, 2004)** for 88 soil tested.
- 0.120 **(Uysal, 2004)** for 79 soil tested.
- 0.120 **(Önalp and Arel, 2013)** for 20 soil tested.
- 0.120 **(Üyetürk and Huvaj, 2018)** for 35 soil tested.
- 0.068 **(Mohan and Goel, 1958)** for 250 soil tested.
- 0.092 **(Norman, 1959)** for 455 soil tested**,** adopted by **(BS1377, 1990**).
- 0.085 **(Jain and Patwardhan, 1960)** for 32 soil tested.

The aim of this study is to theoretically determine the LL using a single-point test with a broad range of blows while achieving a low Root Mean Square Error (RMSE), contrasting this approach with the limited range specified by ASTM standards and findings from existing literature. This assists engineers in determining the LL and making informed decisions about soil suitability for construction.

Furthermore, the liquid limit (LL) is instrumental in estimating key soil properties, including the plasticity index, shrinkage limit, and soil classification. By employing advanced techniques, engineers can optimize the soil testing process, facilitating faster decision-making for construction projects.

2. STATISTIC METRICS AND MODEL

Estimating values in various contexts inherently involves a risk of error, making it essential to use mathematical approaches that minimize bias. One of the most commonly employed techniques for determining regression lines is the method of least squares, which remains a popular choice **(Smith, 1986)**. Multiple regression analysis is employed to develop theoretical equations for calculating the liquid limit (LL) based on single-point tests. These predictive models are designed to reduce the sum of squared errors while optimizing the Pearson product-moment correlation coefficient (R^2) within a specific dataset, enabling accurate estimation of the liquid limit (LLp).

Two widely utilized metrics, RMSE and R^2, are applied to thoroughly assess the performance of a model. Employing a combination of metrics, such as RMSE, is often crucial for a more comprehensive evaluation **(Chai et al., 2014).**

In this study, the performance and reliability of the model in predicting the liquid limit (LL) of soil are evaluated by testing the model equation against an independent dataset. The effectiveness of the equation is assessed using both the coefficient of determination (R^2) and RMSE metrics. Notably, while an RMSE value of zero guarantees an R^2 value of 1.0, a coefficient of determination of R^2 = 1 **(Mallikarjunappa et al., 2024)** does not necessarily correspond to an RMSE of zero.

RMSE is a metric that measures the average deviation between predicted and observed values within a dataset. By giving greater emphasis to larger errors, RMSE is especially useful for identifying variations in model performance under unfavorable conditions **(Chai et al., 2014)**. A smaller RMSE value reflects a closer fit of the model to the dataset. It is calculated as follows:

$$RMSE = \sqrt{MSE} = \sqrt{\frac{1}{n}\Sigma(error)^2} = \sqrt{\frac{1}{n}\Sigma(Pi - Oi)^2} \tag{6}$$

where:

- MSE is a mean squared error.
- Σ is a symbol that means "sum".
- Pi is the predicted value for the ith observation.
- Oi is the observed value for the ith observation.
- n is the sample size.

R^2 is a statistical metric that indicates the proportion of variance in the response variable that is accounted for by the predictor variables in a regression model. An R^2 value ranges from 0 to 1, with higher values reflecting a better fit of the model to the dataset. It is calculated as:

$$R^2 = 1 - \frac{RSS}{TSS} \tag{7}$$

Where RSS denotes the residual sum of squares, and TSS refers to the total sum of squares **(Hayter, 2012).**

Mean Absolute Error (MAE) quantifies the average magnitude of errors in a set of predictions, disregarding the direction of the errors. It is calculated as the mean of the absolute differences between predicted and actual values and is commonly used to evaluate the performance of a regression model. The mean absolute error MAE is calculated as **(Chai and Draxler, 2014):**

$$MAE = \frac{1}{n}\Sigma|error| = \frac{1}{n}\Sigma|Pi - Oi| \tag{8}$$

RMSE measures the average prediction error of a model, while R-squared indicates the proportion of variance in the response variable that is explained by the predictor variables. Furthermore, metrics such as Mean Absolute Error (MAE) and Mean Squared Error (MSE) can be utilized to provide a more comprehensive evaluation of the model's performance.

3. MATERIALS AND METHODS

The liquid limit (LL) is determined using the Casagrande percussion cup method, following ASTM D4318's Multipoint Method, which involves 25 blows. Water content is plotted on an arithmetic scale against the number of blows (N) on a logarithmic (log10) scale. The resulting line, assumed to be linear, represents the flow curve, with its slope referred to as the flow index (FI).

Experimental data from 135 soil samples were compiled from various studies. Of these, 33 samples were sourced from Karakan **(Karakan, 2022),** involving binary mixtures of highly plastic Na-montmorillonite (NaM) combined with Ca-montmorillonite (CaM), kaolinite (K), or sepiolite (S). Additionally, 55 samples from Sridharan et al. **(Sridharan et al., 1999)** consisted of natural soils, including commercially available bentonite, kaolinite, and bentonite-kaolinite blends. Another 32 samples were obtained from Gutierrezestrada et al **(Gutierrezestrada et al., 1983)** in the Gulf of California, Mexico, and 15 samples were acquired from Adebisi **(Adebisi, 2012)** in Ibadan, Nigeria. In this study, the 135 soil samples were used to generate 6,210 simulated data points by varying the number of blows (N) incrementally from 5 to 50 strokes, creating 46 data points for each sample. Following this, the parameter M was determined. Finally, the simulated dataset points were employed to derive the model equation for the LLp.

3.1 Model Phenomenon

The model is constructed based on the flow chart of the LL test to derive theoretical test points, designated as (A). **Fig. 1** illustrates the model's behavior and the phenomena discussed below.

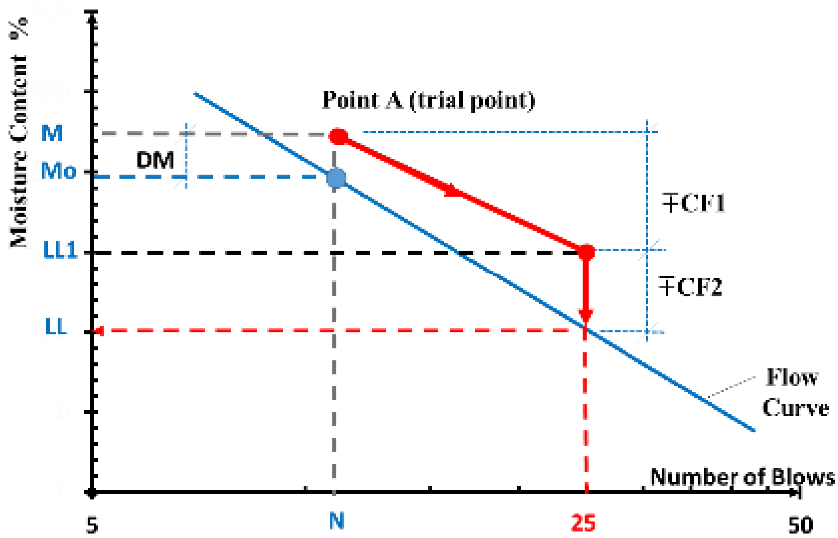

Figure 1. Typical Model Phenomenon

1- Point A (trial point) has a water content (M) and a number of blows (N).
2- The model relies on two correction factors: CF1 and CF2.
3- CF1, known as the first moisture correction factor, is influenced by the moisture content and the number of blows at the trial point.
4- CF2, referred to as the second correction factor, depends solely on the number of blows at the trial point.
5- Both correction factors are equal to 0 (CF = 0) when N = 25.
6- Both correction factors are greater than 0 (positive) when N < 25.
7- Both correction factors are less than 0 (negative) when N > 25.
8- Let DM represent the difference between the theoretical moisture content (M) and the imaginary moisture content (Mo).
9- Calculate the imaginary moisture content (Mo) based on N and FI.
10- Calculate the actual moisture content (M).

$$M = Mo + DM \quad (9)$$

where DM is assumed to be within the range of ∓5% to ∓15% see **Fig. 1**.

11- The model is based on FI, as shown in Eq. (10) **(Das, 2019)**.

$$FI = \frac{M1 - M2}{log\left(\frac{N2}{N1}\right)} \quad (10)$$

Consider point A, which has coordinates (M, N), and point (LL1, 25) represented as (M2, N2), where LL1 is the first liquid limit for the specified trial point A, expressed as a percentage.

12- The datasets are based on the number of blows, ranging from 5 to 50 in increments of 1. Then

$$FI = \frac{M - LL1}{log\left(\frac{N}{25}\right)} \quad (11)$$

Note that the exchange results in a positive value, despite the slope of the flow line being negative. Then

$$LL1 = M - FI * log\left(\frac{N}{25}\right) \quad (12)$$

13- Assume the first predicted liquid limit (LL1) is given by the equation LL1 = M + cK, where the moisture correction factor (CF1) is equal to cK, where:

$$c = -0.434\, ln(N) + 1.398 \quad (13)$$

$$K = \frac{343.558(M + M^{1.265})}{10000} \quad (14)$$

14- To predict LLp, the second correction factor (CF2) is required. Where:

$$LLp = LL1 - CF2 \quad (15)$$

$$CF2 = a * LL1 + b \quad (16)$$

$$a = -0.176ln(N) + 0.567 \quad (17)$$

$$b = 3.043ln(N) + 0.205 \mp DM \quad (18)$$

$$LLp = (1 - a)(M + cK) - b \quad (19)$$

$$LLp = (0.176ln(N) + 0.433)(M + cK) - (3.043ln(N) - 9.795), \quad R^2 = 0.998 \quad (20)$$

15- The model equation can be simplified to:

$$LLp = A[1 + M + A(M + M^{-3.40})] \qquad R^2 = 0.992 \quad (21)$$

$$A = \frac{4.44ln(N) + 47.44}{100} \quad (22)$$

4. RESULTS AND DISCUSSION

The statistical soil properties of the Reduplication sample (FI and LL) for 6,210 theoretical points are presented in **Table 1.** The relationship between them is expressed as:

$$FI = 0.238LL + 0.274 \quad (23)$$

This equation indicates that the flow index increases consistently with the liquid limit.

Table 1. Statically soil properties.

135 Samples	LL %	FI	PI %	PL %
Minimum limit	28.0	3.2	5.0	9.0
Maximum limit	492.0	133.1	404.0	106.1
Median	91.1	17.9	53.8	35.6
Average	111.7	26.9	71.7	40.1
St. dev.	81.4	23.2	65.3	20.1

The data were analyzed using Microsoft Excel and SPSS software. The model was developed through multiple regression analysis, with LLp as the dependent variable and 6,210 points as the independent variables in the model formula. Multiple linear regression analyses were performed using the method of least squares to derive a model equation and calculate statistical parameters, including R^2 values and RMSE. The model equation Eq. (20) demonstrates a strong coefficient of determination, R^2 = 0.998 (see **Fig. 2**), with an RMSE of 3.85. Additionally, the equivalent power coefficient, tan(B), was determined to be 0.131 for the 6,210 fictitious trial points. When N = 25, the model equation Eq. (20) yields:

$$LLp = M + cK \qquad Note: N = 25 \quad (24)$$

Eq. (24) provides excellent predictions with an R^2 value of 1.0 (see **Figs. 3 and 4**). Despite a notable difference in moisture content (DM), Eq. (21) effectively corrects the trial point to accurately align LLp, achieving an RMSE of less than 1.0 (see **Fig. 5**).
It was essential and logical to examine the R^2 value of the model in Eq. (21) as a function of N, as illustrated in **Fig. 4.** The model indicates an increase in the R^2 value approaching N = 25 from both directions. This behavior is attributed to the design of both correction factors, CF1 and CF2, which aim to minimize error and maximize R^2 at N = 25.
The RMSE is utilized to assess the model equation in Eq. (21). RMSE values were calculated across N, which is categorized into 9 statistical classes. As shown in **Fig. 5**, the RMSE is below 1.0 for N values ranging from 20 to 30, below 2.0 for the range of 15 to 35, below 4.0 for the range of 10 to 45, and below 5.0 for the range of 45 to 50. The RMSE reaches its minimum when R^2 equals 1.0 at N = 25. Consequently, we can conclude that **Fig. 4** is closely related to **Fig. 5** through a simple proportional relationship between RMSE and R^2.
Model Eq. (21) was validated using 220 data points from LL tests conducted by **(Snyder, 2015)** across 44 soil samples. Each soil sample included five actual points (A, B, C, D, and E), which were treated as trial points in the model equation Eq. (21) to predict the LLp. **Fig. 6** presents a typical LL chart for one of the soil samples. The properties of the 44 soil samples, including liquid limit (LL), plastic limit (PL), flow index (FI), and their corresponding values of N and M, are detailed in **Tables 2 and 3**, respectively.

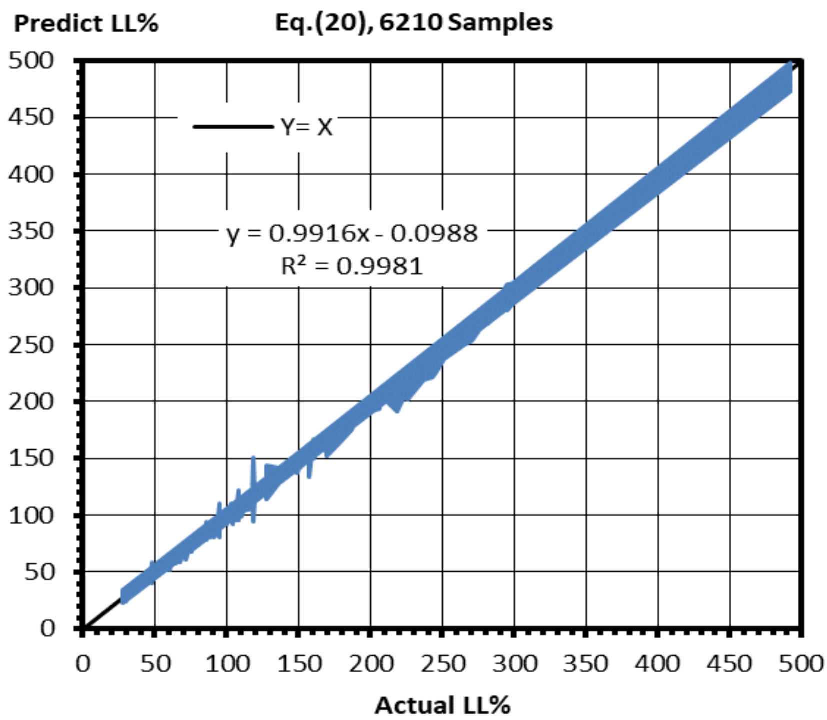

Figure 2. The Relationship between predict and actual LL using 6210 trail point.

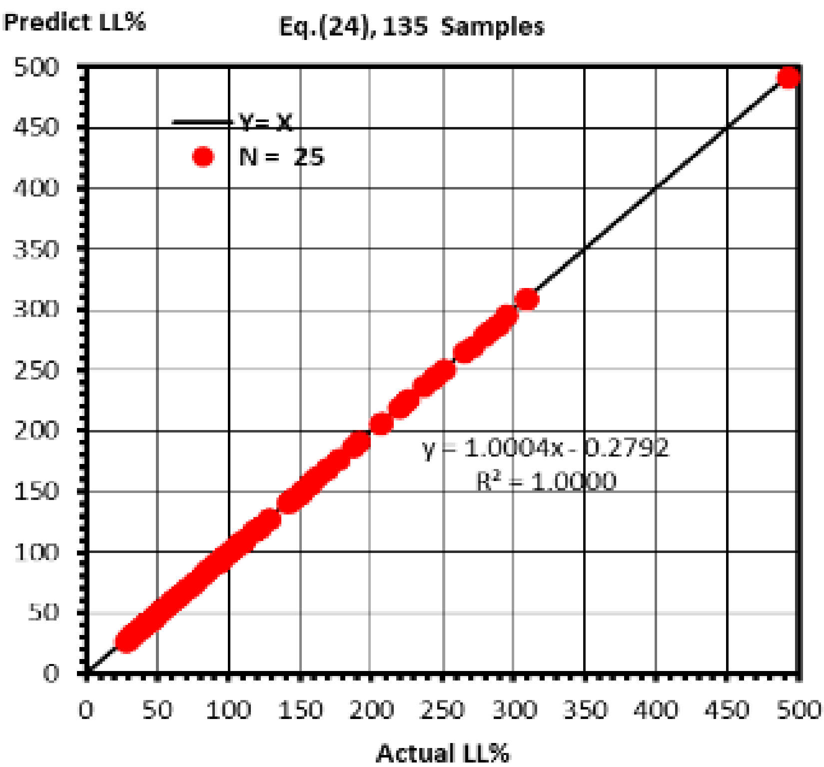

Figure 3. The Relationship between predict and actual LL of 135 trial points at N=25.

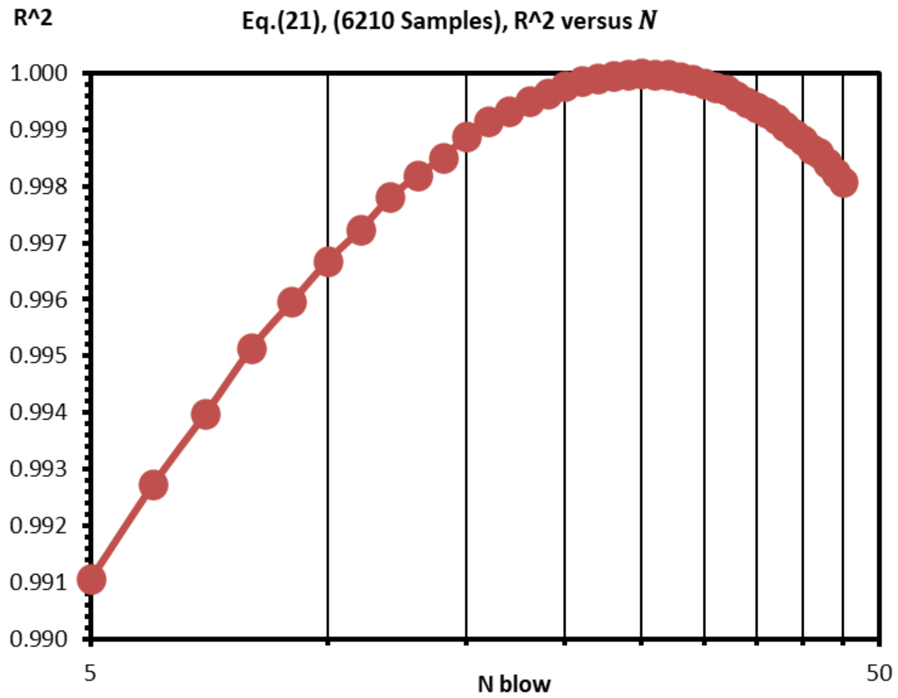

Figure 4. Coefficient of determination R-squared vs. N.

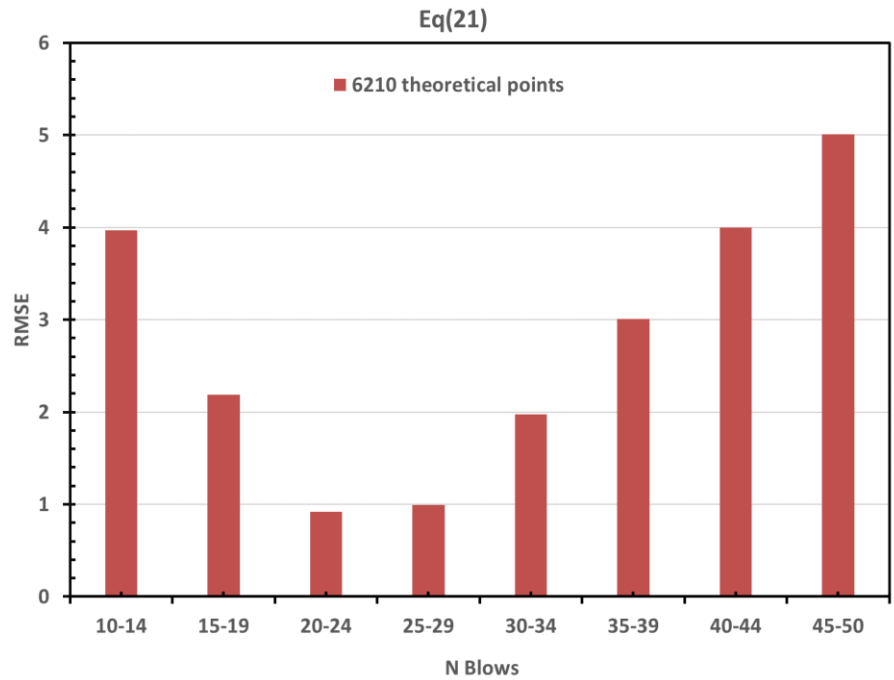

Figure 5. The Root Mean Square Error (RMSE) vs. N classes.

The calibration of the model equation in Eq. (21) using a total of 220 data points (44 samples × 5 points each) yielded an R^2 value of 0.992 and an RMSE of 2.2. This RMSE is lower than that obtained when the model equation was developed using 6,210 points. The reduced RMSE can be attributed to the fact that the 220 points represent actual measurements from LL tests, with an actual (DM) variation of ∓3%. In contrast, the 6,210 points consisted of hypothetical data with a higher critical DM variation of ∓10%.

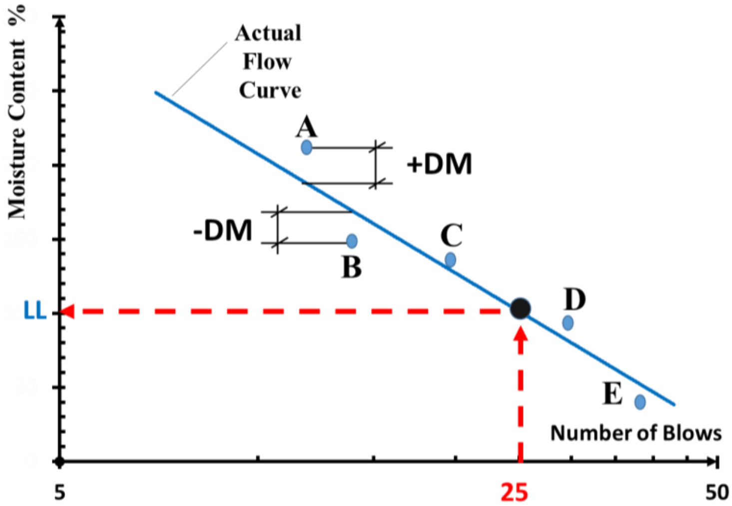

Figure 6. Typical liquid limit chart (44 samples 220 actual points).

Table 2. Statically soil properties.

44 Samples	LL%	PL%	FI
Minimum limit	40.9	12.2	1.6
Maximum limit	96.6	27.6	18.0
Average	69	22	8
Median	72.5	22.2	7.0
St. dev.	15.8	3.2	2.8

Table 3. Statistically of output data from liquid limit test.

Trial points	N (number of blows)					M (moisture content)				
44 Samples	A	B	C	D	E	A	B	C	D	E
Minimum limit %	10	15	18	22	27	44	41	40	39	37
Maximum limit %	20	25	36	45	50	104	98	94	93	91
Average %	14	20	26	35	44	73	70	68	66	64
Median %	13	19	25	35	45	76	73	71	69	68
St. dev.	2.9	2.7	4.4	5.3	5.9	16.5	16.0	15.7	15.2	15.3

The equivalent power coefficient, tan(B), identified in this study was 0.121 for the 220 trial points, which aligns with the tan(B) value specified in ASTM and Waterways **(Waterways, 1949)**. Both R^2 and RMSE values were calculated for class N (see **Table 4**).

Table 4. Statistically of output data from the liquid limit test.

Moisture Content %	Ma	Mb	Mc	Md	Me
220 Points	44 Points	44 Points	44 Points	44 Points	44 Points
Point N-range	Point A 10-20	Point B 15-25	Point C 18-36	Point D 22-45	Point E 27-50
RMSE	3.6	2.4	1.4	1.2	1.7
R^2	0.9852	0.9881	0.9953	0.9958	0.9907

The lower RMSE and high R^2 value indicate a strong relationship between the N and the LL, suggesting that the model is highly effective in predicting the LL across a wide range of N values, specifically from 10 to 45 (see **Fig. 5**). This is in contrast to the narrower ranges reported by ASTM method (20 to 30) and **(Fang, 1960)** (17 to 36), as well as the range of 15 to 40 suggested by **(Olmstead and Johnston, 1955).**
Additionally, the low RMSE values (see **Fig. 7**) for both theoretical and actual point samples indicate that the model's predictions consistently align closely with the observed values. This level of accuracy and precision further reinforces the model's reliability in estimating the LL based on a single data point.

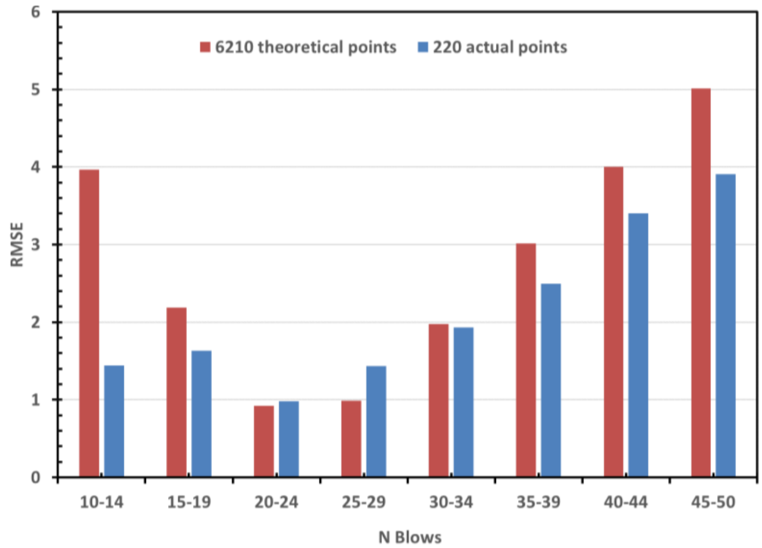

Figure 7. Bar chart of RMSE vs. N range

Fig. 7 presents a comparison of RMSE values between the theoretical 6,210 points and the actual 220 points, demonstrating that the actual 220 points exhibit lower overall RMSEs. Specifically, the overview indicates RMSEs of less than 3.6 for N values ranging from 10 to 45 and less than 2.4 for N values between 15 and 34.
Additionally, the error identified in LL prediction, denoted as DLL (the difference between the predicted liquid limit (LLp) and the actual liquid limit (LLa)), is also highlighted.

$$DLL = LLp - LLa \tag{25}$$

The simplified Eq. (21) indicates that over 19% of samples exhibit zero error (DLL = 0), and 79% of samples fall within an acceptable error margin of ∓2.0%. **(Olmstead and Johnston, 1955)** proposed that if the errors from the one-point method remain within the ∓2.0% range in LL, then the one-point test should be considered a valid procedure.

5. CONCLUSIONS

The Casagrande method is a widely adopted and efficient test for determining the liquid limit and plasticity index of soils, making it an essential tool in geotechnical engineering and soil mechanics. In this study, we evaluated the liquid limit of fine-grained soils using a one-point method with a new model equation that encompasses a broad range of blow counts, demonstrating a strong correlation and low error:

1. Functional relationships derived from this single-point liquid limit test can rapidly predict the liquid limit with a theoretical deviation of ∓5% in water content.
2. By employing dual correction factors to predict the liquid limit based on a single trial point, the model achieves high reliability, evidenced by an RMSE of 3.85 and an R^2 value of 0.992. This theoretical model provides precise and consistent predictions across a wide range of blows, specifically from 10 to 45.
3. Furthermore, the difference in water content (∓3%) for the actual trial point in the liquid limit test does not significantly impact liquid limit predictions within the N range of 10 to 45.
4. A significant outcome of this new liquid limit model is the absence of restrictions on the number of blows, allowing for a range from 10 to 45. This contrasts with the ASTM's initial guideline, which specifies that the number of blows required to close the groove should be between 20 and 30.

NOMENCLATURE

Symbol	Description	Symbol	Description
CF	Correction factors, %.	M	Water content, %.
CF1	First correction factor, %.	MAE	Mean absolute error.
CF2	Second correction factor, %.	Mo	Imaginary moisture content.
DLL	Difference between the predicted and actual liquid limit, %.	MSE	Mean squared error.
DM	Difference between the theoretical and imaginary moisture content, %.	N	Number of blows.
FI	Flow index.	PL	Plastic limit, %.
LL	Liquid limit, %.	R^2	Pearson product correlation coefficient.
LL1	First predicted liquid limit, %.	RMSE	Root mean square error.
Lla	Actual liquid limit,%.	RSS	Sum of squares of residuals.
LLp	Predict liquid limit,%.	TSS	Total sum of squares.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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تحديد حد السيولة للتربة بطريقة نقطة اختبار الواحدة

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الخلاصة

تم تطوير معادلة نموذجية جديدة للتنبؤ بقيمة حد السيولة باستخدام طريقة النقطة الواحدة السريعة. تم إجراء تحليل البيانات باستخدام مايكروسوفت اكسل وبرنامج SPSS، باستخدام 6210 نقطة تجريبية نظرية مستمدة من 135 عينة على طول خط مؤشر التدفق الفعلي، حيث تتراوح عدد الضربات من 5 إلى 50 بزيادة قدرها 1. يشتمل النموذج على عاملين تصحيحيين (CF)، يعتمد كلاهما على عدد الضربات في كل نقطة تجريبية. يتم تطبيق CF الأول على محتوى الرطوبة التجريبي(M) ، بينما يتم تطبيق CF الثاني على حد السيولة المقدر الاولي LL1 . ثم التحقق من صحة هذه المنهجية باستخدام نقاط البيانات الفعلية. يظهر النموذج الجديد قيمة معامل ارتباط بيرسون (R^2) عالية تتجاوز 0.99 للتنبؤ بحد السيولة عبر مجموعة واسعة من عدد الضربات (N) من 10 إلى 45. علاوة على ذلك، فإنه يوضح خطأ متوسط الجذر التربيعي (RMSE) منخفض حوالي (3.8) لـ 6210 نقطة نظرية و2.2 لـ 220 نقطة فعلية .وفي هذا البحث، تعد مرونة النموذج ميزة كبيرة، حيث يسمح بمدى من الضربات من 10 إلى 45، على النقيض من طريقة ASTM التي لها قيود محددة ، حيث يجب أن يكون عدد الضربات بين 20 إلى 30.

الكلمات المفتاحية: حد السيوالة، الطريقة السريعة، طريقة النقطة الواحدة، مؤشر التدفق.

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