Purpose of Plastic Limit of Soil Using Adapted Procedures

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Abstract: Plastic limit is an important property of fine-grained soils. The standard thread-rolling method for determining the plastic limit has long been criticized for requiring considerable judgments from the operator. This study was conducted to seek for a new method on the determination of the plastic limit in a way to overcome the inconsistence result produce by using the standard thread-rolling method. Four different methods were tested. The first method was the modified fall cone method, a method commonly used to obtain a liquid limit. The second method was the rolling device method which is previously proposed by Bobrowski and Griekspoor (1992). The third method was proposed by Wood and Wroth (1978) using a heavier cone. The fourth method was the one proposed by Tao-Wei Feng (2004) which made use of a small soil container. Eight soil samples representing plasticity index (PI) ranging from 15 to 42% were tested. The results indicated that the correlation factor between the standard methods and the suggested methods were in the range 0.72 and 0.99. Regarding to the regression analysis result, the first method is more comparable to the standard thread method.

Keywords: Cone Penetration, Rolling Device, Liquid Limit, Plastic Limit.

1. INTRODUCTION

Plastic limit defined as the moisture content in percentage, at which the soil crumbles, when rolled into threads of 3 mm in diameter. The test for the determination of the plastic limit is simple and can be performed by repeated rolling of ellipsoidal-size soil mass by hand on a ground glass plate. However, there are several criticisms on this test since the operator is required to judge the state of crumbling and the 3-mm diameter of the thread (Tao-Wei Feng 2004). Despite, the method is tedious and operator bias.

Several studies has been conducted by previous researchers to introduce an alternative method for the determination of plastic limit of soil and to overcome the inconsistence of results obtained from standard method stated in BS 1377 (Thread Rolling Method). Wood and Wroth (1978) suggested a cone with 240 g weight, 3 times heavier than standard liquid limit cone and with same geometry and penetration depth. Bobrowski and Griekspoor (1992) suggested a rolling device method made from plexiglas with 101.6 mm width and 215.9 mm long. Tao-Wei Feng (2004) suggested the same liquid limit cone but with a small specimen container with an inside diameter of 20 mm and a depth of 20 mm.

In the present study, a cone of 101 g weight with 20^o apex angle, (method a) had been tested to compare with the pervious study done by Bobrowski and Griekspoor(1992) (method b), Wood and Wroth (1978) (method c), Tao-Wei Feng (2004) (method d) and standard thread-rolling method. A slight modification on cone specification of method (a) was made to make it sharper than the normal cone in a way to study the effect of sharp angle. As mentioned, the objective of this study is to seek for an alternative method for the determination of the plastic limit value of soil with the hope it would overcome the inconsistence result using standard method established in BS 1377 (Thread Rolling Method).

2. METHODS AND MATERIALS

2.1 Design of Method (a)

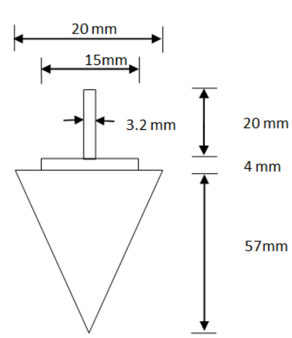

Figure 1. Schematic of method (a)

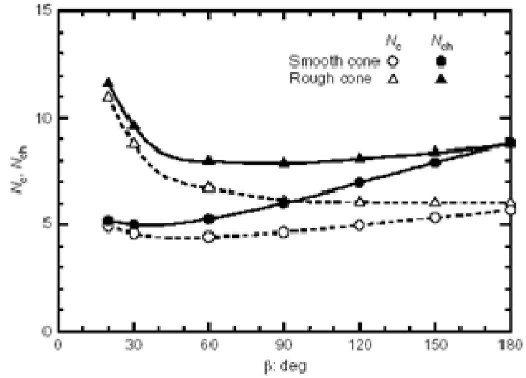

Figure 2 Calculated Bearing Capacity Factors for Smooth and Rough Cones (Koumoto and Houlsby, 2001)

Method (a) as shown in Figure 1 was fabricated with a size of 57 mm height, 20 mm width and 20º cone angle. The total weight is 101.47 g. Hansbo (1957) proposed the general equation to determine the depth of penetration of cone, *d*:

$$C_u = k\frac{W}{d^2}$$

(1)Where c_u is the undrained shear strength, k is a cone constant and *W* is the weight of the cone. According to Koumoto and Houlsby (2001), the undrained shear strength can be expressed as a function of the fall cone penetration, *d*, as

$$c_u = \frac{3W\xi}{Fd^2} = \frac{3W\xi}{\pi N_{ch}\tan^2(\beta|2)d^2} = \frac{kW}{d^2}$$

(2)Where *k* is the fall cone factor as earlier defined by Hansbo. Therefore by using equation
(1) And (2), term *k* can be rewritten as,

$$K = \frac{3\xi}{\pi N_{ch}\tan^2(\beta|2)}$$

(3)

To obtain *k*, N_{ch} and ξ must be known first. The value of N_{ch} can be determinedby referring to Figure 2, for smooth cone.

To estimate ξ , data on the rate of shear strain during the fall cone test is needed.The value of ξ depends on the average of shear strain rate during penetration, γ, which is in percentage per hour, and can be estimated by the following equation:

$$\gamma(\%/hr) \approx \frac{0.671\times10^6}{1-\delta(deg)/45}\frac{\delta(deg)}{\sqrt{h(mm)}}$$

(4)Where δ is the angle of the heaved surface of the clay (in degrees) shown in Figure 3. Inthis case, the cone is assumed smooth.

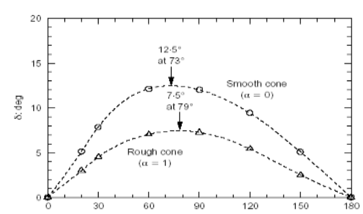

Figure 3: Relationship between Angle of Heaved Surface, and Cone Angle (Koumoto(Koumotoand Houlsby, 2001)

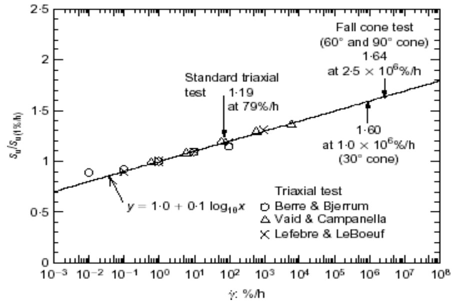

Figure 4: Graph (s_u / $s_{u(1\%/h)}$) versus (γ : % / hr) and Houlsby, 2001)

The value of ξ for 20º cone is determined by dividing the strain rate for a typical standard triaxial test with the average shear strain rate during penetration (Figure 4). As shown, the strain rate for a typical standard triaxial test, s_u / $s_{u(1\%/h)}$ is 1.19 at γ = 79 % / hr, and for 20º cone, the expression then gives s_u / $s_{u(1\%/h)}$ of 1.60 at $\gamma = 1.27 \times 10^6$ %/hr. If standard triaxial tests are adopted as the benchmark for the comparison of the undrained strength values, ξ can be estimated as follows:

$$\xi \approx \frac{1.19}{1.60} \approx 0.74 \text{ for the } 20^{o} \text{ cone} \qquad (5)$$

From the above analysis, it can be concluded that, with the value of undrained shear strength for plastic limit of 170 kN/m^2 (Youssef,1965), weight of cone of 101.47 g andthe *k* value of 1.893, the computed cone penetration at the plastic limit according to Hansbo equation (Eq. 1) is equal to 3 mm.

2.2 Design for Method (b)

A testing device was developed using 0.635 cm Plexiglas. A three-sided box was constructed with dimensions shown in Figure 5. At the interior intersection between the two sides and the base, a Plexiglas rail 3.2 ± 0.5 mm high was placed. This rail can accurately dictate the exact diameter of the soil threads. A plexiglas plate with a handle is used to roll the soil into threads. This is accomplished by placing the ellipsoidal soil mass(es) (1 to 5) on the bottom plate. The top plate is then brought down into contact with these masses and rolling motion employed. Downward force is then applied simultaneously with the rolling motion until the top plate comes into contact with the 3.2 mm side rails. The soil threads are then remolded and the above procedure repeated until the soil threads begin to crumble. From this point forward, the procedure is identical to current standard procedures. A paper attached at the bottom fixed plate and the moving top plate to eliminate sliding of the soil as well as to expedite the drying process.

2.3 Design for Method (c)

Wood and Wroth (1978) proposed the use of 2.35 N (240 g) cone to determine the value of soil plasticity index (PI) as illustrated in Figure 6 and equation (6). Changes inpenetration with variation in moisture content are plotted for both the standard liquid limitfall cone (80g) and the modified cone (240g) represented by parallel lines W_2 and W_1 respectively. W_2 line represents the plot for determining the liquid limit whereas the W_1 Line is the plot for the modified cone. The value of Δ is the difference between the two Parallel lines. The plasticity index (PI) can be determined using the following equation:

$$PI = \frac{2\Delta}{\log_{10}(W_1/W_2)} \qquad (6)$$

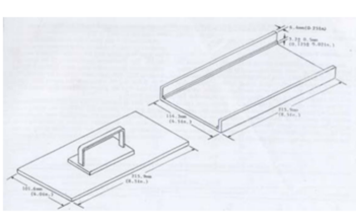

Figure 5 Schematic of method (b)

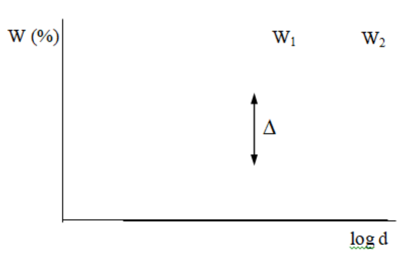

Figure 6 Diagram of fall cone results with different cone weight (Wood and Wroth, 1978)

2.4 Design for Method (d)

Feng (2004) suggested using the standard liquid limit cone but with smaller soil container as shown in Figure 7 to determine the plastic limit. The penetration depth of 2 mm is used as criteria to determine the plastic limit. The justification for the use of smaller container is due to the facts that the influence zone for a stiff soil is much less compare to the soft soil. Thus, a small specimen container with an inside diameter of 20 mm and a depth of 20 mm was designed to contain 6.3 cm^3 of soil sample for cone penetration less than 10 mm.

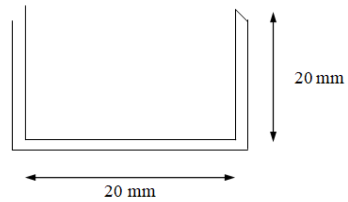

Figure 7 Schematic of method (d)

2.5 Soil sample tested

Soil samples were collected from the vicinity Southern Johor. Sample A- black clay from Kota Tinggi area, Sample B - white clay from Kulai, Sample C - red clay also from Kota Tinggi, Sample D – kaolin clay, Sample E - marine clay from Pontian, Sample F - yellowish clay from UTM Campus, Sample G - silty clay from Skudai and Sampel H - lateritic soil from Pekan Nenas, were tested. Classification and Atterberg limit tests were conducted on all the soil samples for analytical and comparison purposes.

(3) RESULTS AND DISCUSSION

3.1 Soil classification and comparison

Table 1 provides the liquid limit value and the classification of all soil sample tested using Uniform Soil Classification System (USCS). The Plasticity Index (PI) value of the samples ranged between 15.5 to 41.8. It means that, the study had been conducted using various soil type of distinguished plasticity values.

Table 1: Liquid Limit, Plasticity Index and Soil Classification of the Sample

Soil	LL*	PI**	Soil Classification
Sample A	73.1	26	SC
Sample B	56.9	27.1	SW-SC
Sample C	64.5	33.6	SC
Sample D	45.5	15.5	CL
Sample E	44.6	21.4	ML
Sample F	74.4	23.3	CL
Sample G	88.1	41.8	SP
Sample H	71.6	36.6	SW

* LL = Liquid Limit (%)   ** PI = Plasticity Index (%)

Table 2 compared the plastic limits obtained from Standard Method and all other suggested method. The difference between standard method and method (a) range from 0.3 to 4.0 %, while for method (b) is from 2.0 to 15 %, method (c) is from 2.0 to 10.8 % and method (d) is from 3.9 to 11.3 %. It is clear that method (a) produced the smallest difference compared to all other methods.

Table 2.Comparison between the Plastic Limits Obtained from BS Standard Method and AllSuggested Methods

Soil	PL (%) Standard	PL (%) Method (a)	Difference (%)	PL (%) Method (b)	Difference (%)
Sample A	47.1	45.3	3.8	43.4	7.9
Sample B	29.8	29.3	1.7	29.0	2.7
Sample C	30.9	30.8	0.3	31.8	2.9
Sample D	30.0	28.8	4.0	27.0	10
Sample E	23.2	24.0	3.6	21.0	9.5
Sample F	51.1	49.8	2.5	45.0	11.9
Sample G	45.2	43.4	3.9	38.0	15.9
Sample H	34.9	35.6	2.0	45.0	14.6
Soil	PL (%) Standard	PL (%) Method (c)	Difference (%)	PL (%) Method (d)	Difference (%)
Sample A	47.1	43.4	7.9	44.2	6.2
Sample B	29.8	29.0	2.7	27.6	7.3
Sample C	30.9	31.8	2.9	29.7	3.9
Sample D	30.0	30.6	2.0	26.6	11.3
Sample E	23.2	25.7	10.8	21.3	8.2
Sample F	51.1	47.4	7.2	55.4	8.4
Sample G	45.2	42.5	5.9	41.4	8.3
Sample H	34.9	33.3	4.7	32.2	7.7

3.2 Performance of the new cones

The relative performance of the cones in measuring plasticity limit (PL) of soil is the ultimate criterion for its selection and capability. The measured PL using new methods isthen compared with the result generated from the standard one. A simple statistical parameter, Root Mean Square Error (RMSE) was used to quantify agreement between data obtained from new methods and the standard ones. The parameter is defined as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(PL_{new} - PL_{std})^2}{N}} \qquad (7)$$

Where PL $_{new}$ = Plastic limit obtained from new methods, PL $_{std}$ = Plastic limit obtainedfrom standard method, N = number of measurement (sample). In the present study, N = 8.

The *RMSE* calculated is 1.1726 for method (a), 5.2445 for method (b), 2.3793 for method (c) and 2.9597 for method (d). This mean that method (a) was in a better agreement with the standard one compared to other methods. Figure 8, 9, 10 and 11 showed the comparison of the PL measured using new method and standard cone using 1:1 line to examine the agreement level between the values. The new methods is over measured when a point falls above the equal value (1:1 line) and under measured when a point fall below the equal value line.

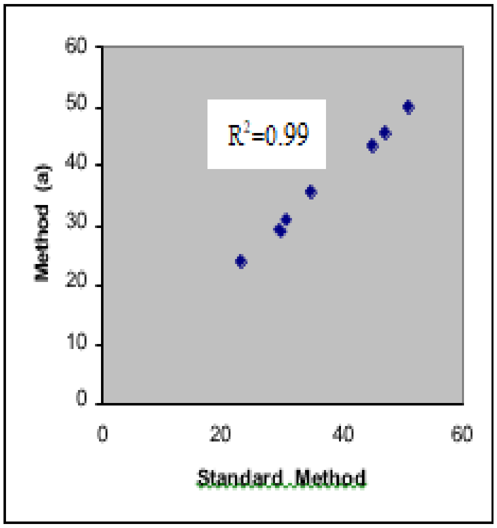

Figure 8 Comparison between plastic limits determined by method (a) and Standard Method

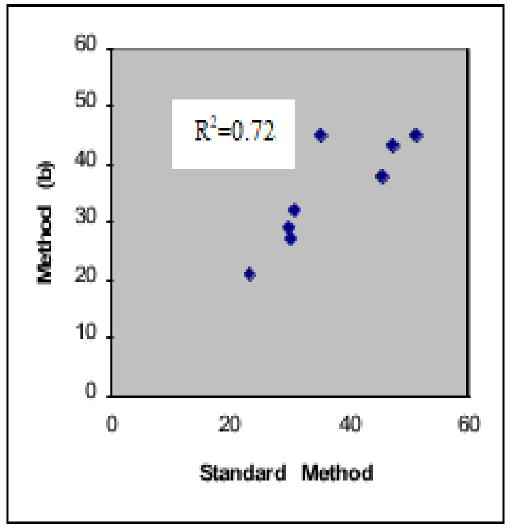

Figure 9 Comparison between plastic limits determined by method (b) and Standard Method

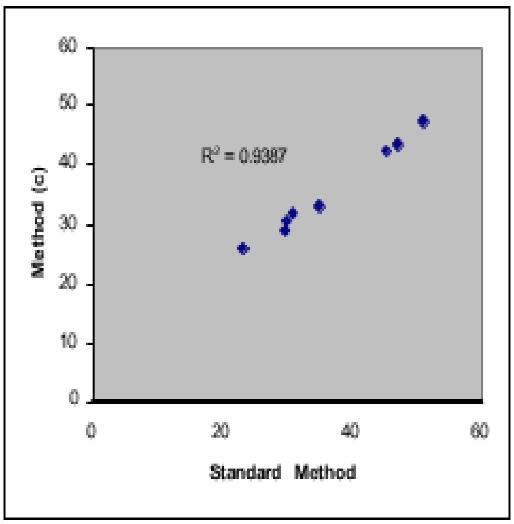

Figure 10. Comparison between plastic determined by method (c) and Standard Method

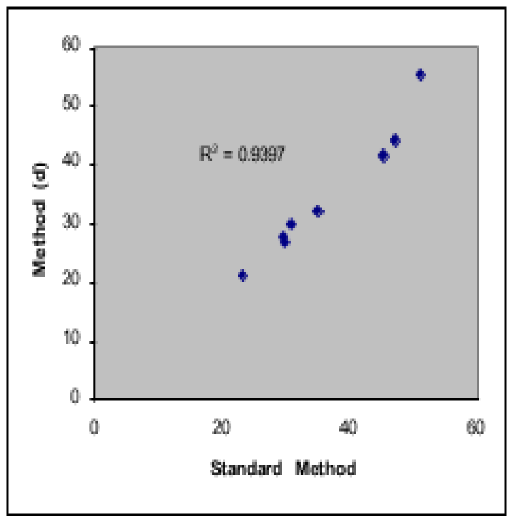

Figure 9. Comparison between plastic limits determined by method (d) and Standard Method

Ordinary linear regression analyses were conducted to determine the relationship between predicted and observed runoff. The coefficient of determination (R^2) measures goodness of fit. It is calculated using a standard method as follows,

$$R^2 = 1 - \frac{RSS}{CSS} \quad (8)$$

$$RSS = \sum_{i=1}^{N} Y_i^2 - \left[\frac{\left(\sum_{i=1}^{N} X_i Y_i \right)^2}{\sum_{i=1}^{N} X_i^2} \right] \quad (9)$$

$$CSS = \sum_{i=1}^{N} (Y_i - \bar{Y})^2 \quad (10)$$

where, *RSS* is residual sum of squares, *CSS* is corrected sum of square, X_i is PL values using new method, Y_i is PL values using standard method and N is number of data.

From the regression line and their R^2 values, the following discussion could be made. As shown in Figure 8, method (a) gives almost exact values to standard cone under the PL 20-40 but having little under predicted when PL above 40. For method (b) on the other hand, produced 28% (R^2=0.72) over-predicted value for the whole range of PL, while for method (c) and (d), produced 6 % over-predicted value for the whole range of PL. This is indicated by the scatter points located above the 1:1 line.

Hypothesis test for Pearson's population correlation coefficient, *R*, square root of coefficient of determination, was carried out to determine whether to accept or to reject the null hypothesis, which implies that there is no correlation of plastic limit between standard method and method (a). The correlation coefficient, *R,* measures the strength and the direction of a linear relationship between two variables. The *t* distribution also known as Student's *t* distribution was used to perform the hypothesis test. The test statistic, *Calc t*, is estimated from the sample and then compared with the standard tabulated teststatistic, *Tab t*. If $|Calc\ t| > Tabt\ t$, the null hypothesis is rejected and vice versa. The *Calc t* value can be estimated using the following expression;

$$Calc\ t = R\sqrt{\frac{N-2}{1-R^2}} \qquad (11)$$

The test was run at 5% significance level with one-sided alternative hypothesis (positive correlation between method (a) and standard method) and degree of freedom, *v*=(N-2). The *Calc t* yields value of 17.19. By referring to standard table of the *t* distribution, the *Tab t* value was found to be 1.943. Since $|Calc\ t| > Tabt\ t$, the null hypothesis is rejected implying strong and significant positive correlation of plastic limit values between standard method and method (a). Both plastic limit values predicted usingstandard method and method (a) are assumed separately normally distributed.

4. CONCLUSION

The accuracy of measuring Plastic Limit of fine grained soil has been debatable. The study proposed four new techniques based on modified cone geometry (method a), modified rolling device (method b), modified weight (method c) and modified container (method d). The results produced from these methods were compared to the standard method stated in British Standard thread rolling method. Based on the statistical analysis, the study concluded that the method (a) has provided a more relevant result compared to that produced by the other modified methods. It is apparent that method of less operator dependent product least variability and is expected to be more feasible means of measuring Plastic Limit of soil.

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