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DETERMINATION OF PLASTIC LIMITS OF SOILS USING CONE PENETROMETER: RE-APPRAISAL

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ABSTRAK

Metode penetrasi kerucut telah banyak dikaji oleh peneliti terdahulu sebagai cara yang lebih akurat untuk menentukan batas plastis tanah. Beberapa peneliti menyimpulkan bahwa batas plastis dapat ditentukan pada kedalaman penetrasi berkisar 2 – 4 mm. Naskah ini menyajikan hasil analisis untuk menentukan batas plastis menggunakan kerucut penetrasi. Benda uji tanah disiapkan menurut prosedur dalam BS 1377 – Test 2(a). Hasil uji dan analisis data menunjukkan hubungan non linier antara indek cair dan skala logaritmik kedalaman penetrasi kerucut pada kadar air antara batas cair hingga batas palstis. Analisis korelasi ini menunjukkan bahwa batas plastis ditetapkan untuk nilai kedalaman penetrasi kerucut sebesar 2.2 mm. Nilai ini ditentukan dari ekstrapolasi kurva dengan minimal empat data uji. Analisis data memberikan bahwa nilai batas cair berdasarkan uji penetrasi kerucut adalah 0.94 kali dari pengujian digiling yang mana ditunjukan dengan koefisien korelasi yang sangat baik, $R^2 = 0.852$.
Keywords: batas plastis, indeks cair, kerucut penetrasi, lempung.

ABSTRACT

Cone penetrometer method has been proposed by many researchers as more reliable method to determine plastic limit. In general, plastic limit can be determined at depth of cone penetration in range of 2 – 4 mm. This paper presents the re-appraisal determination of plastic limit by using fall-cone penetrometer. Soil samples were prepared according to the procedure stated in BS 1377 - test 2(a). The test results and data analyses show that the correlation between liquidity index and logarithmic depth of cone penetration is clearly appeared as non-linear relationship in the range of water content from near liquid limit to plastic limit. The correlation defined the plastic limit at the depth of penetration 2.2 mm. For a soil, the value can be determined at least four fall cone tests by extrapolating the flow curve to d = 2.2 mm. The data analysis proves that the result give very satisfy correlation with the rolling thread test which is shown by the coefficient of determination, $R^2 = 0.852$. The computed plastic limits of the soils tested are 0.94 times of the tested plastic limit (rolling thread test).
Keywords: plastic limit, liquidity index, cone penetrometer, clay.

1 INTRODUCTION

Most method for determination of plastic limit is by rolling a thread of soil (on glass plate) until it crumbles at a diameter of 3 mm (Figure 1). The traditional plastic limit test (the rolling thread test) has several disadvantages perhaps the main of which is operator sensitivity. According to Whyte (1982), if full saturation and incompressibility are assumed, plasticity theory indicates that the soil yield stress will be a function of a number of parameter:

(a) the pressure applied to the soil thread,
(b) the geometry, i.e. the contact area between hand and thread,
(c) the friction between the soil, hand and base plate,
(d) the rate of rolling.

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None of these variables is controlled easily, and consequently the traditional plastic limit test does not provide a direct measurement of soil strength.

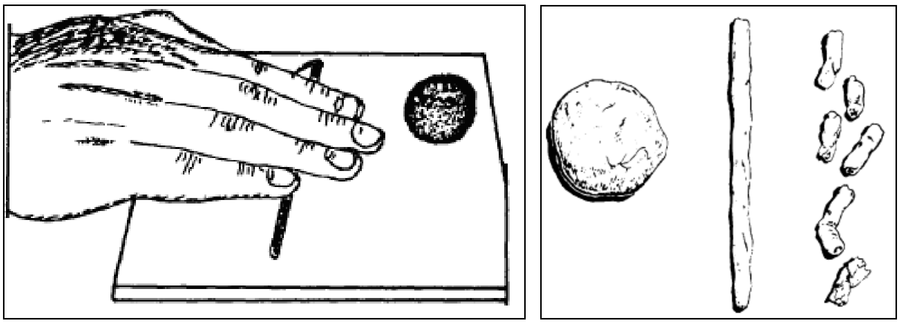

Figure 1 The crumbling thread of traditional plastic limit test

By using a cone penetrometer device to establish the plastic limit of a soil, both of these problems can be overcome. However, It was generally recognized that fall-cone tests were difficult to perform at water contents near the plastic limit, since soil samples were stiff and difficult to mix (Stone & Phan, 1995; Feng, 2000). Since the difficulties encountered, the relationship between logarithmic depth of fall-cone penetration and water content has been used to estimate the value of the plastic limit. Wood and Wroth (1978) interprets the penetration and water content data as a linear relationship between liquid limit and plastic limit. The slope of this relationship is equal to one half of the plasticity index. Then, the plastic limit can be computed by subtracting the plasticity index from liquid limit. However, the relationship has been found to be highly non-linear for a number of soils studied by Wood (1985), Wasti and Bezirci (1986), Harisson (1988), and Feng (2000).

Some previous researcher has been concluded that the plastic limit determination using fall-cone penetrometer, principally, provide more accurate technique rather than the conventional rolling thread test. Each researcher define the plastic limit at varies cone penetration depth (d), between 2 to 5 mm, even though they develop the determination correspond to the same theory. For example, Worth and Wood (1978) define the plastic limit as water content at d = 5 mm. Harrison (1988) determine at d = 2 mm, and Feng (2000) define at d = 2 - 3 mm. Further study experienced by Sharma and Bora (2003) define the plastic limit as the water content correspond to the cone penetration depth at d = 4.4 mm. From the point of view of the previous results, this paper is aimed to re-appraise the result arranged by the previous researcher of which deals with the determination of plastic limit of fine-grained soil by using fall-cone penetrometer.

2 INTERPRETATION OF CONE PENETRATION TEST

The penetration depth corresponding to the liquid limit is 20 mm for the 30^{o} BS cone. Hansbo (1957) proposes the following equation:

$$s_u = k\,\frac{W}{d^2} \qquad (1)$$

where s_u is undrained shear strength, k is a constant, W is the weight of cone, and d is depth of penetration. Wood and Wroth (1978) proposed that the present best estimate of undrained shear strength, s_u, of a soil when at their respective liquid limits is 1.7 kPa and the plastic limit should be redefined as the water content at which the strength is hundredfold that at the liquid limit, based on the experimental evidence from Skempton and Northey (1953) on four soils as shown in Figure 2. Whyte (1982), however, claims that liquid limit is the water content associated with a strength of 1.6 kPa and the plastic limit is the water content correspond to a strength of 110 kPa, and, thus, the strength ratio is about 70.

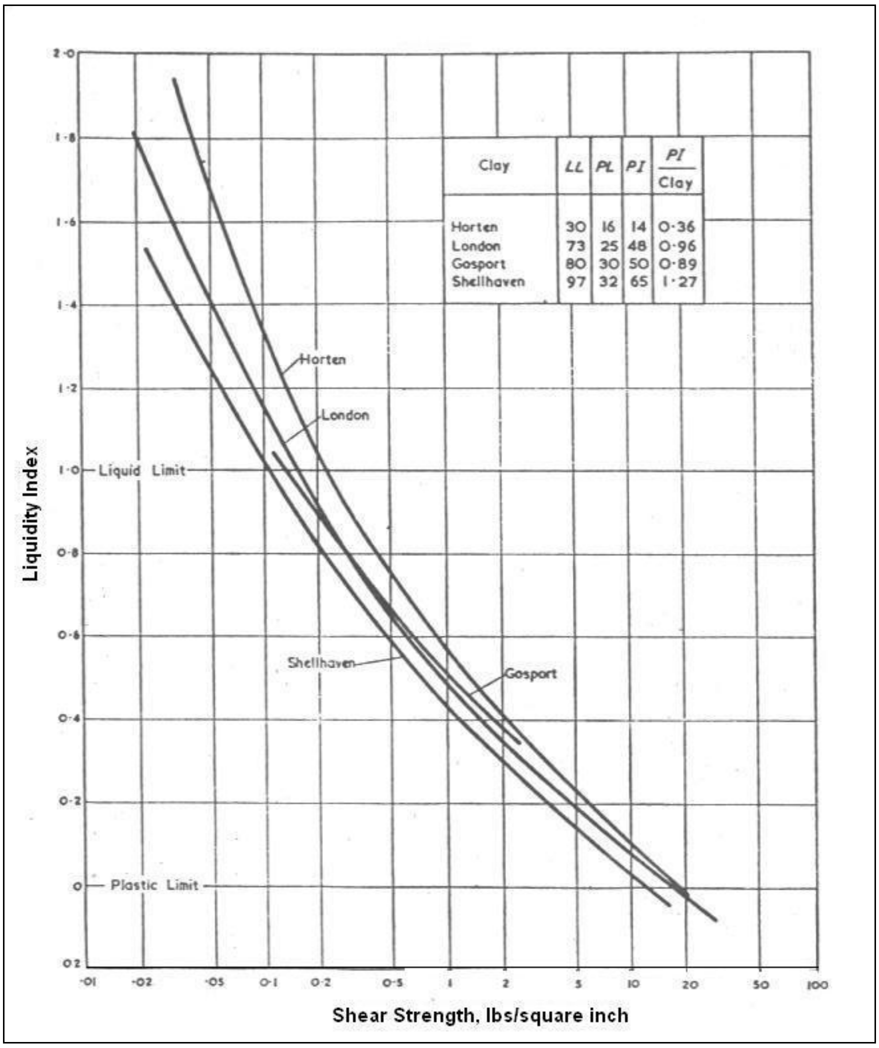

Figure 2 Relationship of shear strength and liquidity index (Skempton & Northey, 1953).

Wood and Wroth (1978) have suggested a procedure for determination the plastic limit using fall cone test that involves series of tests with different weight W_1 and W_2. Introducing idea of critical state soil mechanics, Wasti and Bezirci (1986) derives the following expression for the plasticity index, PI, from which the plastic limit is to be calculated:

$$PI = \Delta \frac{\log 100}{\log \frac{W_1}{W_2}} = \Delta \frac{\ln 100}{\ln \frac{W_1}{W_2}} \qquad (2)$$

Where Δ is the vertical separation in term of water content, w, on the linear plot of w versus the logarithmic of the cone penetration, d, for the two cones (see Figure 3).

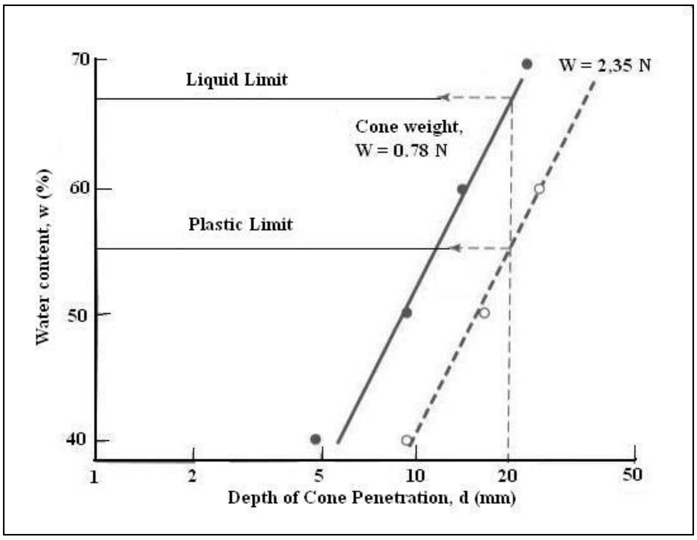

Figure 3 Determination of plastic limit using double fall-cone (Wood & Wroth, 1978)

Harison (1988) stated a method for determination of plastic limit as shown in Figure 4. Based on the figure, the upper line is used for determination of the liquid limit with a range of penetration value from about 14 – 15 mm. The lower line indicates the plastic limit determination. Theoretically, according to assumption that the point of intersection of the two line is at d_{2SL} = 14 mm, the lower line can be simply constructed by performing an additional penetration test until at say 5 mm. From the lower line, the water content at d_{PL} can be determined in which refer to the depth at 2 mm.

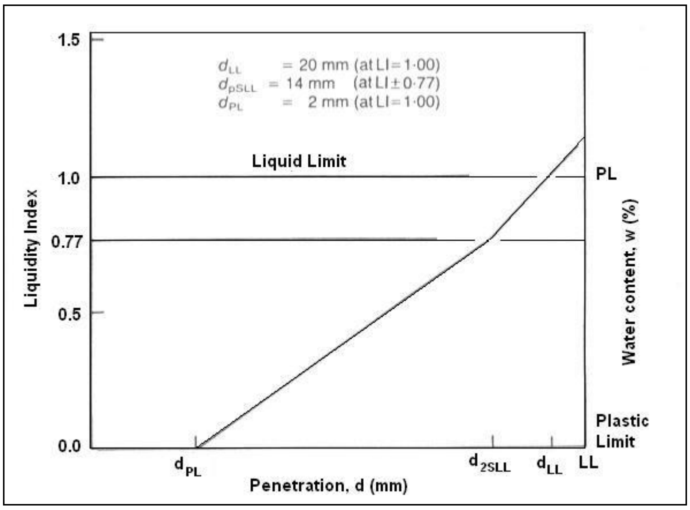

Figure 4 Liquidity index and depth of cone penetration (Harisson, 1988)

A semi-logarithmic bilinear model for the penetration depth (d) and water content (w) relationship has been suggested by Harisson (1988) to obtain the plastic limit of soil. However, Feng (2000) shows that the semi-logarithmic depth of cone penetration versus water content relationship model is highly non-linear. Further, a linear log d – log w model is proposed for the relationship as shown in Figure 5. Defining the log d – log w relationship is recommended by using as few as four data pints with depth of penetration approximately evenly distributed between 25 and 3 mm.

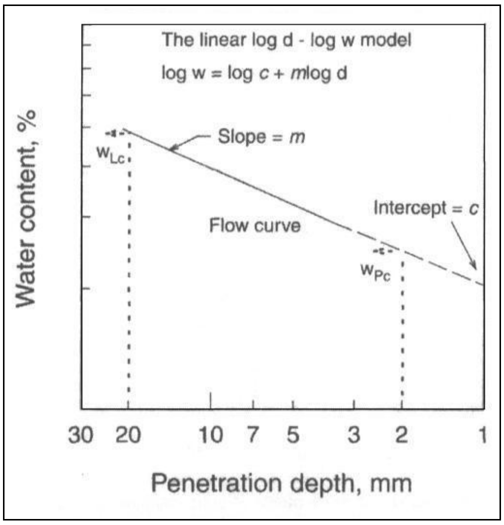

Figure 5 A linear logarithmic penetration depth versus logarithmic water content model (Feng, 2001)

The linear log d – log w model is expressed as follows:

$$log\ w = log\ c + m\ log\ d \tag{3}$$

where w is water content, c is water content at d = 1 mm, m is slope of the flow curve, and d is depth of cone penetration. For computing the plastic limit is written as:

$$PL = c(2)^m \tag{4}$$

where the value of 2 corresponds to the depth of cone penetration d = 2 mm as suggested by Harisson (1988).

3 TEST PROGRAM

3.1 Fall-cone penetration test

The British fall cone apparatus (BS 1377, British Standard Institution, 1990); manufactured by Wykeham Farrance, Inc; with a 30^o cone and weighing 0.785 N was used during the experimental investigation. The fall cone apparatus includes a specimen cup of 55 mm in diameter and 40 mm in height. In the BS 1377 test procedure for the penetration shall be in range of depth 15 to 25 mm for determination of liquid limit. However, in the present study, the tests were performed in the range of depth of penetration about 4 to 25 mm.

Figure 6 BS Fall-cone penetration apparatus

3.2 Sample preparation for fall-cone penetration test

Soil mixtures were used at the present investigation by means mixing a proportion of bentonite with kaolin. The method will result in the various soil-plasticity. In the BS 1377, test 2(a), the test procedure for determination of the liquid limit includes the following: "The re-mixed soil shall be pushed into the cup with a palette knife, taking care not to trap air". However, the soil paste was difficult to transfer in the cup at water contents near the plastic limit, since soil samples were stiff and difficult to mix as considered by Stone & Phan (1995) and Feng (2000). A different method was suggested in the present study to ignore the difficulty encountered. The specimen preparation procedure was started with mixing the soil sample thoroughly at glass plate at water content near plastic limit (Figure 7a). The mixed soil was then made as soil mound as shown in Figure 7b, with dimensions greater than the dimension of cup. The cup was pushed into soil mound with hand pressure as shown in Figure 7c until reach the glass-plate surface. The excess soil on the cup surface was strike-off by bevelled edge of the straight edge to give a smooth surface. Lastly, the soil specimen was assembled on the device with the cone just touch the soil surface. The penetration was started with reading the penetration of about 4 mm to 25 mm. After the fall cone test, the water content of the specimen was measured. The test was repeated for different soil mix at the higher water content than previous test.

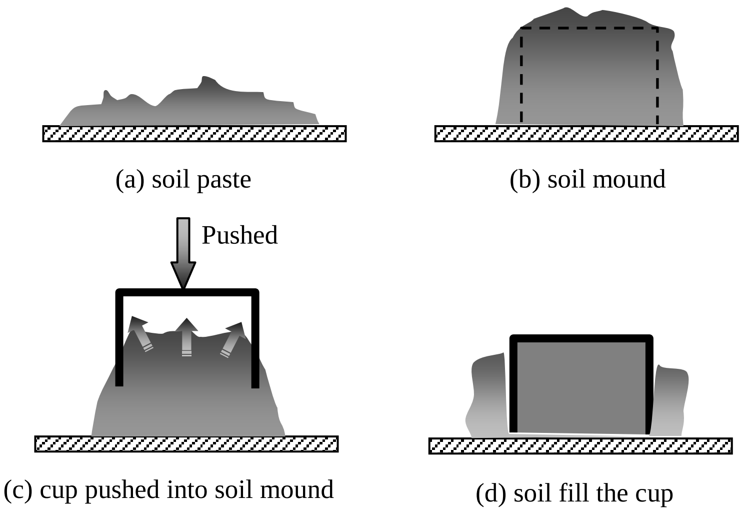

Figure 7 Specimen preparation for fall-cone penetration test

3.3 Plastic limit test

About 25 g mass of soil sample was taken from soil paste as prepared for fall cone test. The plastic limit procedure was according to BS 1377: 1990. The sample was allowed to dry on the glass plate until it became plastic enough to be shaped in to a ball. The soil-ball was moulded between the finger and rolled between the palm of the hands until the sample appear to crack on its surface. The sample was divided into small pieces and rolled to form a thread to about 3 mm under an enough pressure. The pressure was maintained by five to ten complete movement of the hand (forward and backward) to result the uniform thread. The first crack appear on the thread surface was determine as plastic limit. The water content at this state was measured.

4 DATA ANALYSIS

4.1 Relationship between Depth of Penetration and Water Content

Relationship between logarithmic depth of cone penetration and water content for the soils tested in the present investigation is established as shown in Figure 8. Similar plots are made for the data plotted by Harisson (1988), Wood (1978), and Feng (2000) as shown in Figure 9 and 10. The plots show that the relationship is really non-linear in nature. The non-linear relationship was also publicized by Feng (2000).

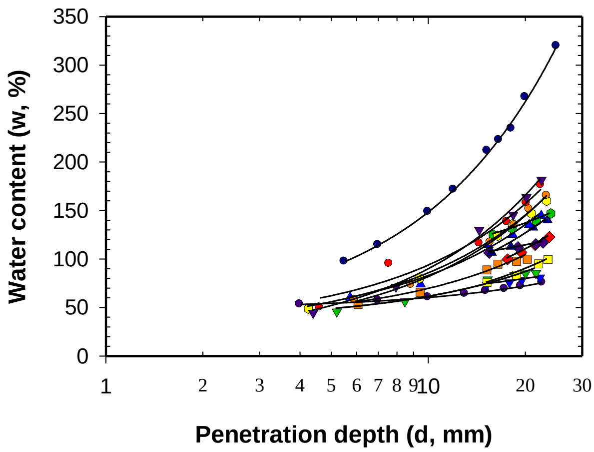

Figure 8 Cone penetration data from 15 soil mixtures

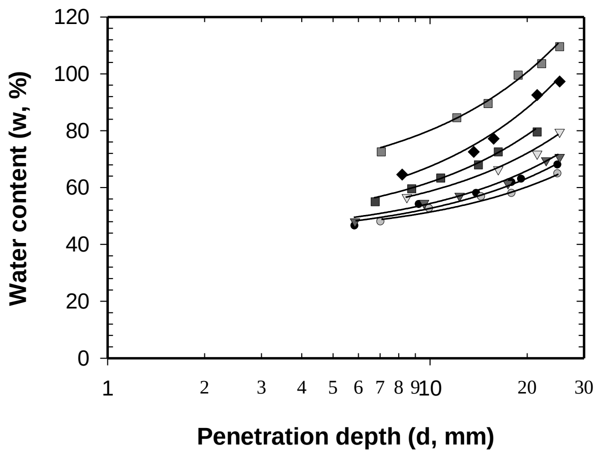

Figure 9 Cone penetration data of Bandung Clay (Harisson, 1988)

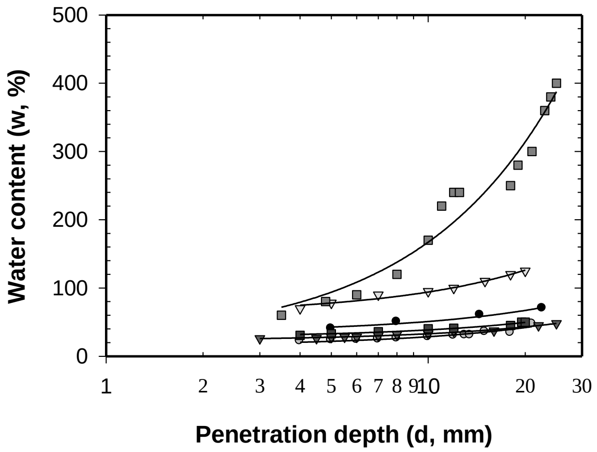

Figure 10 Cone penetration data of Gault clay, Sinjun clay, Taipei clay, Panama clay, Kaolin and Bentonite (Wood, 1978; Feng, 2000)

4.2 Relationship between Depth Of Penetration And Liquidity Index

Harisson (1988) determine the plastic limit at depth of cone penetration about 2 mm. The method was approached by the relationship between depth of penetration and the liquidity index as bilinear correlation. Principally, liquidity index (*LI*) indicates the state of potential state of consistency of a soil which can be expressed through Equation (5).

$$LI = \frac{w_n - PL}{LL - PL} \tag{5}$$

Where, w_n is water content of soil sample at given state, LL and PL is liquid limit and plastic limit respectively.

Equation (5) shows that the *LI* will equal to zero ($LI = 0$) if the water content reached the plastic limit state. And, the *LI* is equal to one ($LI = 1$) when the water content is at its liquid limit state. Figure 11 plot the relationship between the depth of cone penetration and liquidity index. It was clearly revealed that the data plotting tends to give a non-linear relationship. The best fit of the curve for non-linear correlation results the depth of cone penetration about 2.2 mm ($d_{PL} = 2.2$ *mm*) for the $LI = 0$. The statistics description of the relationship shows that the correlation is very strong which indicate by the $R = 0.98$ or *Adjusted* R^2= 0.95, and *Standard Error = 0.0745*. It means that the plastic limit of the soil can be determined at the depth of cone penetration 2.2 mm. The result is slightly higher than the value proposed by Harisson (1988), $d_{PL} = 2$ *mm*. He approached the non-linearity by bi-linear correlation on the plot of LI and log-d as shown in Figure 4.

Residuals analysis is also a common method for checking the model adequacy (Montgomery & Runger, 2002). In this analysis, residual is defined as the difference between tested LI and predicted LI and then it is plotted in Figure 12 due to depth of penetration. The residuals are expected distributed lie on zero absica axes to indicate a very strong correlation. It was observed that the largest difference is –0.25 and 0.21 where is found at depth of penetration in range of 5 mm – 8 mm. It occurs possibly by the difficulties encountered when the soil specimens were being prepared at the water content near the plastic limit. However, in general, the residuals plot implies that the model has a significant correlation.

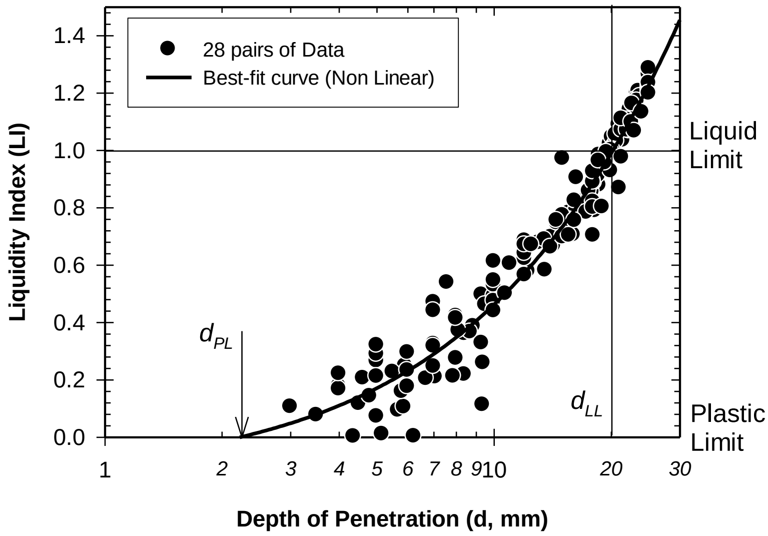

Figure 11 Correlation of cone penetration and liquidity index.

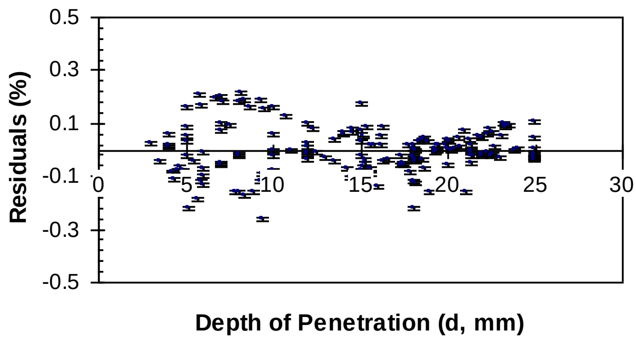

Figure 12 Residuals analysis of liquidity index due to depth of penetration

5 DETERMINATION OF PLASTIC LIMIT

The analysis was successfully yielded that the plastic limit can be determined at depth of cone penetration d = 2.2 mm. The PL_{cone} was determined by using the flow curve of data plot in the *log d – w* relationship. The value is determined from at least four fall-cone tests and extrapolating the flow curve will give the water content at d = 2.2 mm as shown in Figure 13. Table 1 present the plastic limit of the soil samples for cone method (PL_{cone}) and thread method (PL_{test}). Using the flow index, plastic limit at d = 2 mm, according to Harrison (1988), is also presented in Table 1.

Figure 14 presents the correlation between the PL_{test} and $PL_{cone\ (d\ =\ 2.2\ mm)}$. It is observed that the data points should be laid near the 45° line to indicate a strong linearity correlation. Statistical analysis proves very strong line correlation between the data tested which indicated by the value of coefficient of determination, R = 0.92 or Adjusted R^2 = 0.82. The residuals, are defined as the difference between PL_{Test} and PL_{Cone}, are plotted in Figure 15. The plots express that the model is underestimate. Two extreme differences are found that are –31.362 and +12.06 respectively for sample No. F5 (Bentonite) and F1 (Sinjun Clay). It implies that the two samples should not be used for analysis or rejected.

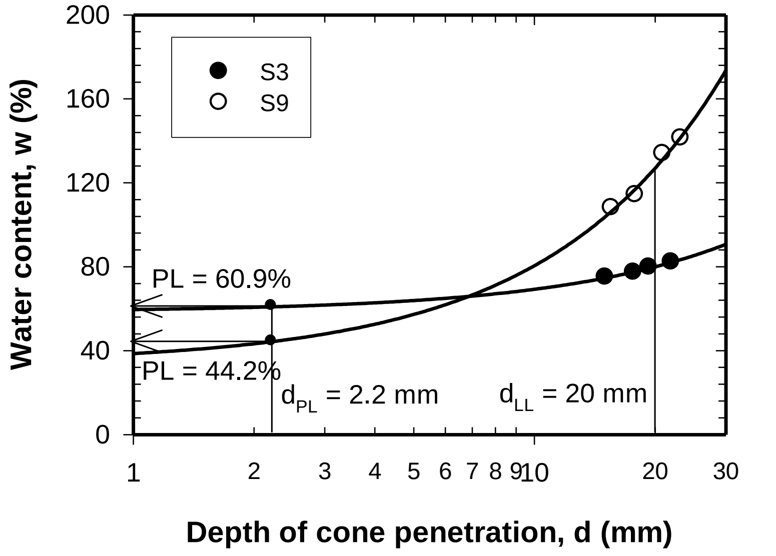

Figure 13 Extrapolating curve for plastic limit determination.

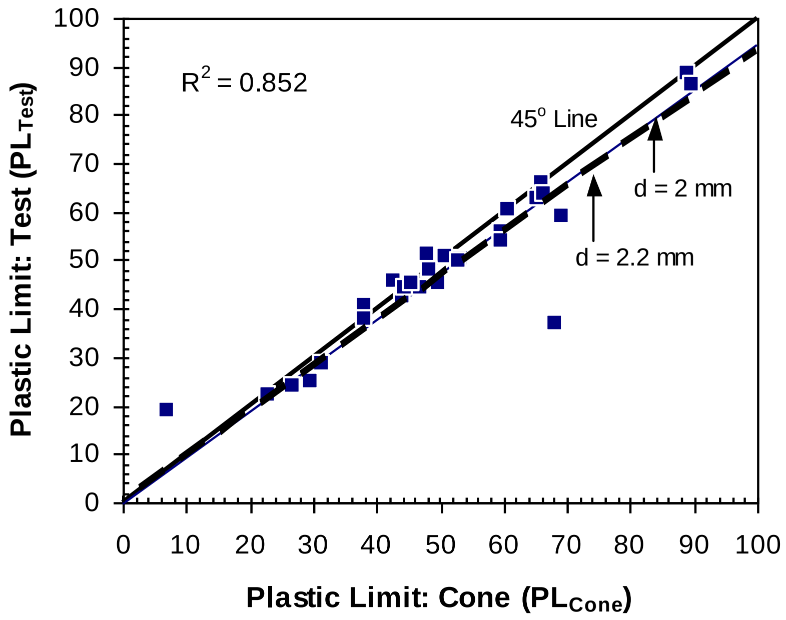

Figure 14 Correlations between PL_{Test} and PL_{Cone}

Table 1 Plastic limit determination for the soils examined.

Sample No.	PL_{Test}	$PL_{Cone\ (d\ =\ 2.2\ mm)}$	$PL_{Cone\ (d\ =\ 2\ mm)}$	References
S-1	50.8	51.0	50.7	Present Investigation
S-2	55.7	59.6	57.3	Present Investigation
S-3	60.6	60.9	60.7	Present Investigation
S-4	66.0	65.9	65.7	Present Investigation
S-5	40.7	38.2	37.6	Present Investigation
S-6	62.8	65.5	65.1	Present Investigation
S-7	45.5	42.9	42.1	Present Investigation
S-8	88.5	89.0	88.7	Present Investigation
S-9	42.2	44.2	43.3	Present Investigation
S-10	54.1	59.8	58.9	Present Investigation
S-11	86.0	89.8	89.2	Present Investigation
S-12	50.2	53.5	52.5	Present Investigation
S-13	28.5	31.3	30.0	Present Investigation
S-14	22.3	22.9	21.4	Present Investigation
S-15	45.3	49.9	48.7	Present Investigation
H-1	44.2	47.1	46.9	Harisson (1988)
H-2	44.3	44.5	44.3	Harisson (1988)
H-3	45.1	45.7	45.5	Harisson (1988)
H-4	48.0	48.3	48.0	Harisson (1988)
H-5	49.6	53.0	52.7	Harisson (1988)
H-6	63.8	66.5	66.1	Harisson (1988)
H-7	51.0	47.9	47.5	Harisson (1988)
F-1	19.0	6.9	6.5	Feng (2000)
F-2	24.0	26.8	26.6	Feng (2000)
F-3	59.0	69.3	68.7	Feng (2000)
F-4	25.0	29.7	29.5	Feng (2000)
F-5	37.0	68.3	65.4	Feng (2000)
Gault Clay	37.9	38.2	37.9	Wood (1978)

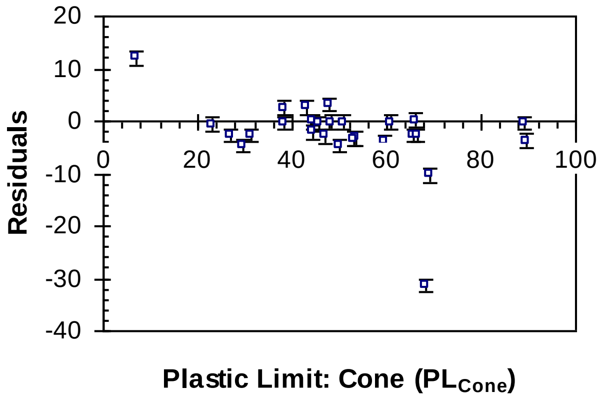

Figure 15 Residuals plot between PL_{Test} and PL_{Cone} at d = 2.2 mm

6 CONCLUSIONS

The following conclusions can be pointed out based on the test performed and data analyses presented. The test shows that the correlation between liquidity index and logarithmic depth of cone penetration (*LI – log d* plot) is clearly appeared as non-linear relationship in the range of water content from near liquid limit to plastic limit. The plastic limit can be determined by using BS-1377 cone penetrometer method at the depth of penetration 2.2 mm. For a soil, the value can be determined at least four fall cone tests by extrapolating the flow curve to d = 2.2 mm. The analysis of correlation proves that the result give very satisfy correlation with the traditional plastic limit determination (rolling thread test) which is shown by the coefficient of determination, $R^2 = 0.852$. The computed plastic limits of the soils tested are 0.94 times of the tested plastic limit (rolling thread test).

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