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Reappraisal of the fall cone test

Réexamen de l'essai de la cône tombant

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ABSTRACT
The fall cone test has been recommended in many test standards for determining the liquid limit of fine-grained soils. A number of the existing fall cones and test methods are reviewed. A new approach of using the fall cone test to determine the plastic limit has recently been recommended. Key factors in using the fall cone test to determine both the liquid limit and the plastic limit are examined. It is concluded that the fall cone test with a fall cone of one weight is suitable for determining both the liquid limit and the plastic limit.

RÉSUMÉ
L'essai de la cône tombant a été recommandé dans plusieurs normes d'essais pour la détermination du limit de liquide dans terres fines. Un nombre d'outils de la cône tombant et des moyens d'essais actuels sont réexaminés. Une nouvelle façon de déterminer le limit de plastique en utilisant l'essai de la cône tombant vient d'être recommandée. Des facteurs majeurs pour la determination des deux limits : ceux de plastique et de liquide en utilisant l'essai de la cône tombant son examinés. L'essai de la cône tombant donne la conclusion suivante : un cône tombant de seulement un poid est adéquat pour determiner les limits de liquide et, également, de plastique.

1 INTRODUCTION

The fall cone test for determining the liquid limit of fine-grained soils has widely been recommended in favor of the conventional cup percussion test in many test standards, e.g. British Standard (BS 1377:pt2:1990), Japanese Standard, Swedish Standard (SS 027120:1990), and Canadian Standard (CAN/BNQ 2501-092-M-86). The main reason is that the fall cone test is less operator dependent than the percussion test, so that the test result is more reproducible and therefore more reliable. According to Feng (2000), the fall cone test can also be used for determining the plastic limit of fine-grained soils. It is highly desirable to use the same test to determine the liquid limit and the plastic limit. This paper reviews the existing fall cone apparatus and test methods and presents some significant findings in verifying the fall cone test for determining both the liquid limit and the plastic limit.

The fall cone test was originally used to measure the undrained strength of fine-grained soils. Hansbo (1957) proposed Eq. (1) for calculation of the undrained strength s_u from the depth of fall cone penetration d.

$$s_u = k \frac{W}{d^2} \tag{1}$$

where the cone factor k and the weight of the fall cone W are both constants for any fall cone apparatus. Equation (1) shows that s_u is inversely proportional to d^2. The adoption of Eq. (1) for determining the liquid limit is based on previous experiences that the undrained strength of most fine-grained soils falls within a narrow range. Thus, with an assumed value of undrained strength at the liquid limit, the corresponding depth of fall cone penetration can be determined from Eq. (1). For example, the depth of fall cone penetration is calculated to be 20 mm for the BS (British Standards) fall cone of 30° apex angle and 0.79 N weight. Therefore, the water content of a soil specimen that allows 20 mm of BS fall cone penetration is taken as the liquid limit of the soil specimen. In practice, at least four fall cone tests are required for each soil to obtain a relationship between the water content w and the depth of penetration d. The liquid limit is then obtained by interpolation. The relationship has conventionally been expressed by using a linear regression line in a *w-log d* plot for the depth of penetration falling between 15 and 25 mm. However, Feng (2000) reported that a curved regression line in the semi-log plot is more representative of the relationship for the depth of penetration falling between 3 and 25 mm. On the other hand, based on a large number of experimental data, Feng (2001) proposed a model of linear *log w-log d* relationship as described by Eq. (2) and shown in Fig. 1.

$$\log w = m \log d + \log c \tag{2}$$

where m and c are the slope and the intercept on the ordinate axis, respectively. In Fig. 1, w_{Lc} and w_{Pc} denote the liquid limit and the plastic limit determined by the fall cone method, respectively. If it is assumed that the ratio between the strength at the plastic limit and the strength at the liquid limit is 100 (Feng 2000), then it is clear from Eq. (1) that the ratio between the depth of penetration at the plastic limit and the depth of penetration at the liquid limit is 1/10. This gives a 2 mm depth of penetration at the plastic limit for using the BS fall cone of 30° apex angle and 0.79 N weight (BSI 1990), since its depth of penetration at the liquid limit is 20 mm.

When a linear *log w-log d* relationship is determined from the regression analysis on fall cone test data, both m and c values in Eq. (2) are also determined. Then the plastic limit is the water content determined by using Eq. (2) with the depth of penetration equal to 2 mm. The plastic limit determined by using this method compares closely to the plastic limit determined by the thread-rolling test (Feng 2001, 2004) that was carried out by operators with strong laboratory experience. It should be noted that further research is required to clarify the variation of the cone factor k with the depth of penetration

(Brown and Huxley 1996) and its effect on using Eq. (2) to estimate the plastic limit.

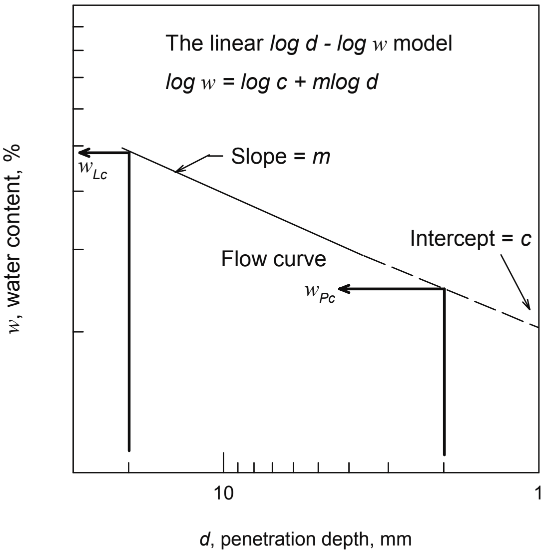

Fig. 1. Relationship between water content and penetration depth of the kaolinite sample tested

2 APPARATUS AND TEST METHOD

Table 1 lists the common fall cones and shows that the fall cones and therefore the depth of penetration at the liquid limit vary in different countries. The duration of time allowed for the penetration of the fall cone varies from 5 seconds to 10 seconds. It is a natural development that different fall cone apparatus and test methods have been created in different countries, since it represents a different way of thinking for scientists and engineers in different countries. On the other hand, in order to be able to exchange experiences internationally, it is important to compare the test results obtained from different fall cone apparatus and test methods. For example, a standardized fine grained soil should be tested with all of the fall cone apparatus listed in Table 1.

Table 1. The fall cones in a number of countries

Country	Cone apex angle (degrees)	Cone weight (N)	d at w_{Lc} (mm)
USSR	30	0.75	10
India	31	1.45	25.4
USA	30	0.74	10
Japan	60	0.59	11.5
France	30	0.79	17
UK	30	0.79	20
Canada	60	0.59	10
Sweden	60	0.59	10

The fall cone apparatus is typically composed of a fall cone with a stand, a dial gage, a specimen cup, and sometimes an electirc timer unit. When the water content of the specimen is near the liquid limit, it is rather easy to fill the specimen cup with soil paste using a spatula. Care during filling should be taken so that air is not trapped within the specimen. Laboratory experiences show that the ease of filling soil paste into the specimen cup is reduced wtih decreasing the water content of the soil paste. Therefore, a specimen ring is used to replace the specimen cup so that the process of soil filling is facilitated and the quality of the specimen is increased (Feng 2000). A small specimen ring of 2 cm in diameter and 2 cm in height has been verified for determining the plastic limit by using the fall cone test (Feng 2004). The advantage of using such a small specimen ring is that only a small amount of soil sample is required. Graphs in a log-log plot format can be used to interpret the test result to estimate the plastic limit by one-point method (Feng 2004).

It is a common practice to measure the undrained strength of fine-grained soils by the laboratory vane shear test. The Wykeham Farrance laboratory vane shear apparatus was used in this study. The vane blade of the standard dimension (12.5 mm in diameter and 12.5 mm in height) and four springs of different capacities in measuring torque were used to determine the undrained strength of the kaolinite sample. The vane shear test was conducted right after the fall cone test so that soil sample of the same batch was used in both tests. The soil sample was carefully filled into a specimen tube of 42 mm in diameter and 50 mm in height. The vane blade was inserted into the specimen to a depth twice of the height of the vane blade and was electronically driven at a standard speed of rotation of 10° per minute. In each vane shear test the rotation of vane blade was continued until the maximum torque was clearly observed. The undrained strength of the soil specimen was then calculated from the maxumum torque measured and the constant of the spring used. No repeated vane shear test was conducted since it was not necessary in the standard testing procedure .

3 VARIATION OF THE CONE FACTOR *K* WITH THE DEPTH OF PENETRATION

It has been recognized that the cone factor *k* is a function of depth of penetration (Houlsby 1982 ; Brown and Huxley 1996). However, relevant experimental data have not been reported. It is of great interest to establish the variation of cone factor *k* with the depth of penetration between 3 and 25 mm. For it can be used to calibrate the fall cone test for determining the undrained strength between the plastic limit and the liquid limit. In Eq. (1), the undrained strength must be separately determined so that the variation of the cone factor *k* with depth of penetration can be evaluated. Figure 2 shows the test results of BS fall cone test on a kaolinite sample. A linear regression line with $r^2 = 0.922$ can be seen in Fig. 2. The fall cone liquid limit and the fall cone plastic limit determined from this linear regression are 64% and 35%, respectively. It may be noted that these values correspond to the depth of penetration of 20 mm and 2 mm, respectively, which are based on the assumption of a constant cone factor *k*. These values agree very well with the conventional percussion liquid limit of 63% and the thread-rolling plastic limit of 33%. Four trials were conducted with the conventional percussion method and two trials were conducted with the thread-rolling method.

Figure 3 shows the results of laboratory vane shear test on the kaolinite sample. These tests were carried out immediately after the fall cone test so as to assure that the water content of the specimens was the same. It can be seen from Fig. 3 that there exists a linear log-log relationship between the undrained strength and the water content. Furthermore, the strength at the thread-rolling plastic limit is equal to 60 kPa and the strength at the percussion cup liquid limit is equal to 1.6 kPa, which give a strength ratio of 38.

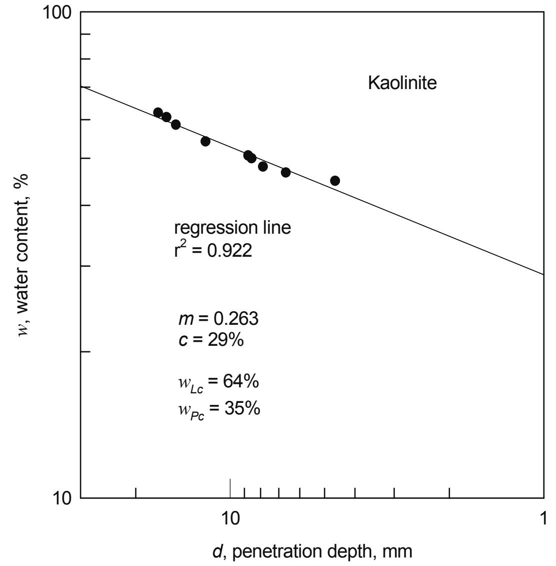

Fig. 2. Relationship between water content and penetration depth of the kaolinite sample tested

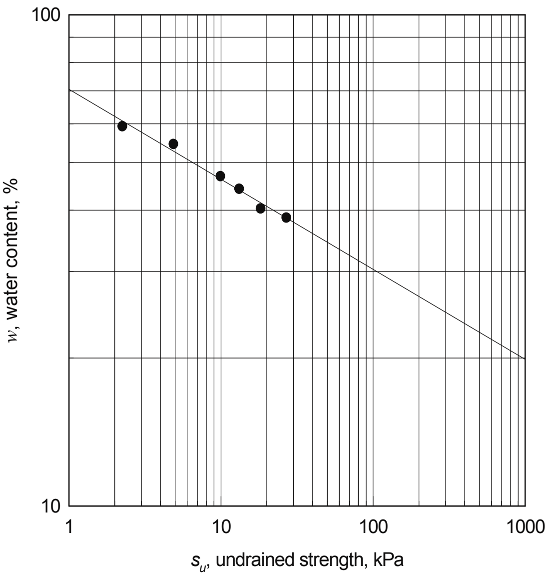

Fig. 3. Relationship between water content and undrained strength of the kaolinite sample tested

Data presented in Fig. 2 and Fig. 3 were used to calculate the cone factor by using Eq. (1), and the results are shown in Fig. 4. It is clear from Fig. 4 that the cone factor *k* decreases with decreasing depth of penetration. It may be noted from Fig. 4 that the cone factor is equal to 0.96 at the liquid limit and is equal to 0.24 at the plastic limit. Thus, by using Eq. (1), the depth of penetration at the liquid limit can be calculated as 21 mm and the plastic limit can be calculated as 1.8 mm, which are very close to those determined from the assumptions of a constant cone factor value. Therefore, it was observed from the fall cone test results on the kaolinite sample that the plastic limit corresponded closely to a depth of penetration of 2 mm. The results of fall cone tests and laboratory vane shear tests on a kaolinite sample presented in this paper are used to illustrate an extensive effort on verifying the fall cone method for determining both the liquid limit and the plastic limit. Further verification by conducting the fall cone test and the laboratory vane test on other fine grained soils are underway. In the laboratory vane shear tests, the reconstituted soil specimens with different water contents were prepared by the same procedure. Different vane shear strength measured at different water content of remolded soil specimen simply reflects the effect of water content on the strength. It may be noted that Skempton and Northey (1953) used the laboratory vane shear test to study the relation between shear strength and liquidity index of four remolded clays.

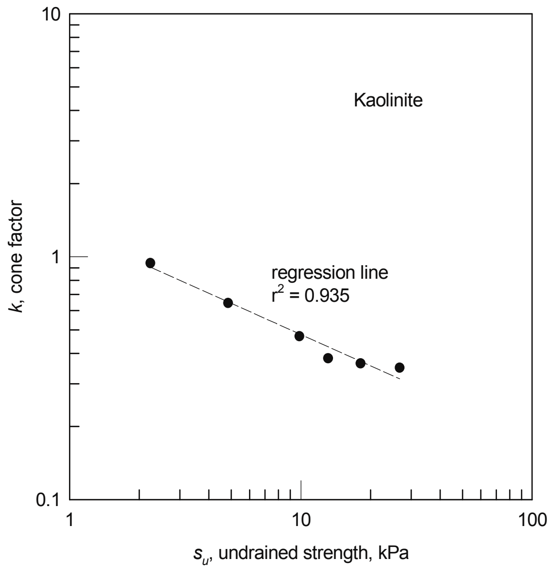

Fig. 4. Relationship between cone factor and undrained strength of the kaolinite sample tested

4 CONCLUSIONS

The fall cone test has been used to determine a linear log-log relationship between water content and depth of penetration for a kaolinite soil. This relationship can be used to determine both the liquid limit and the plastic limit, since the depth of penetration reflects the undrained strength and soils at the liquid limit and the plastic limit posses characteristic undrained strength values. It has been demonstrated that both the liquid limit and the plastic limit can be determined from a fall cone with only one weight. A specimen ring is helpful in preparing soil specimens for the fall cone test.

Previous experiences have shown that, with the assumption of a constant cone factor *k* and of a strength ratio of 100, the estimated fall cone plastic limit compared well to the thread-rolling plastic limit. On the other hand, it is confirmed in this study that the cone factor *k* decreases greatly with increasing undrained strength and thus with decreasing depth of penetration. Also, it was observed that the strength ratio is likely lower than 100. For the kaolinite sample tested, it was found that the reduction in cone factor and in strength ratio did not alter the criterion in the depth of penetration in estimating the liquid limit and the plastic limit.

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