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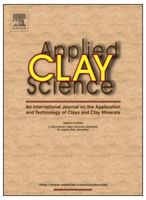

Note

Determination of liquid limit of a low swelling clay using different cone angles

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ABSTRACT

The fall cone test is one of the most popular methods used to determine the soil liquid limit. In this study, a series of laboratory tests were conducted on kaolin soil, which is considered representative of low-swelling clays, in order to determine the penetration depths for different cone parameters (angle and weight) under a liquid limit state. The required soil undrained shear strength of kaolin at liquid limit was determined using a hand-held vane shear device. Based on the analysis of the test results, the relationship between the angle of the fall cone and the ratio of undrained shear strength and fall cone penetration depth over cone weight was obtained and represented by a power function. The established relationship was then used to determine the penetration depth at liquid limit for different cone parameter values. A difference in liquid limit of less than 15% was recorded between tests using standard and alternative cone parameter values, respectively. Furthermore, a better and more reliable result was obtained when cone angles were below 90°, with a standard deviation of less than 2.5% from the standard method. Based on critical analysis of the test data, an equation with which to determine the penetration depth under a liquid limit state, as well as a one-point test method with which to determine the liquid limit for different cone parameter values are proposed for low-swelling clays.

1. Introduction

Soil consistency limits, which describe the behaviour of clays under different ranges of water content values, play an important part in the use of such clays for geotechnical and industrial applications (Andrade et al., 2011). The soil liquid limit (*LL*) is defined as the moisture content, expressed as a percentage, at which the soil changes from being in a liquid to a plastic condition. The two standard methods used to determine *LL* are the cup apparatus developed by Casagrande (1958) and the fall cone method, with the latter originally described by the Geotechnical Commission of the Swedish State Railway (GCSSR) in 1914 (Hansbo, 1957). Different cone properties have been employed to determine *LL* in different countries (Koumoto and Houlsby, 2001). Based on British Standard (BS) 1377 (British Standards Institution, 1990), *LL* is determined when the penetration depth is 20 mm using a cone with a mass of 80 g and angle of 30°. In order to standardise the penetration depth and cone properties of the fall cone test in determining the soil liquid limit value, Tanaka et al. (2012) proposed the adoption of different cone types to provide a unified method and thus avoid unnecessary confusion.

The fall cone test plays an important role in determining the value of both *LL* and the undrained shear strength, s_u (Hansbo, 1957; Wood, 1985; Koumoto and Houlsby, 2001; Tanaka et al., 2012). Initially developed to determine the shear strength of remoulded cohesive Scandinavian soils (Koumoto and Houlsby, 2001), the fall cone test has since been extensively adopted as the standard method with which to determine the *LL* of clays (Koumoto and Houlsby, 2001), with s_u calculated based on the fall cone test using Equation 1 proposed by Hansbo (1957).

$$s_u = \frac{K \times \beta \times g}{h^2} \tag{1}$$

where K is a constant value that depends on cone mass, β is the apex angle (°), g is acceleration due to gravity ($\mathrm{m\,s^{-2}}$) and h is the cone penetration depth (mm). Based on the results of tests conducted on both remoulded clay and undisturbed samples, Hansbo (1957) suggested values of K of0.25 for $\beta = 60°$ and 0.8 for $\beta = 30°$, although an alternative suggested range of K was later proposed by Wood (1982) of 0.8 for

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$\beta = 60°$ and 1.2 for $\beta = 30°$. From Eq. (1), the penetration depth h at any target s_u for different apex angles and weights can be determined once K is known.

Nagaraj et al. (2012) and Haigh and Vardanega (2012) reported values of s_u at LL ranging from 0.5 to 5.6 kPa, obtained from a series of laboratory tests conducted by previous researchers (Norman, 1958; Skempton and Northey, 1953; Youseff et al., 1965; Skopek and Ter-Stepanian, 1975; Wroth and Wood, 1978; Houlsby, 1982, 1983; Federico, 1983; Wasti and Bezirci, 1986; Leroueil and Le Bihan, 1996). Based on the fall cone test, Haigh (2012) reported that the undrained shear strength at LL is essentially the same for various soils. Logically, by assuming a value of s_u at LL and the acceptance range of K, the cone penetration depth can be determined for different cone weights and apex angles. To the present authors' knowledge, the relationship between K and cone parameters (weight and angle) for a wide range of cone parameter values is very limited; hence a standard method with which to determine LL under different cone parameter values is not available.

The aim of the present study was to develop a relationship between the penetration depth h at the LL state and cone parameters, as well as a one-point test method with which to determine LL under different cone parameter values (cone angles and weights), for low-swelling clay. The outcome of this research is novel and significant, and is fundamental for developing a code of practice and a standard with which to determine LL using the fall cone method under a range of cone parameter values. A relationship between the undrained vane shear strength of soil and the fall cone parameters was first established by using kaolin with an over-consolidation ratio equal to two. This established relationship was then employed to determine K values for various apex angles β. Hence, the value of h at the LL state under which s_u is approximately 2.52 kPa according to BS 1377 can be determined. The validity of the proposed method is finally discussed by comparing it with previous research.

2. Material and methods

The analysed kaolin soil sample was supplied by Kaolin Malaysia (Berhad) and possessed consistency limits (listed in Table 1) of 52.6% and 29.1% for LL and Plastic Limit (PL), respectively, values similar to those obtained by Liu et al. (2016). The fall cone and thread-rolling methods were respectively used to determine the LL and PL of the kaolin soil according to the standard BS 1377-2:1990 (British Standards Institution, 1990; Barnes, 2013). Considering a Plasticity Index (PI) value of 23.4% and based on the Unified Soil Classification System, the analysed kaolin soil is classified as a highly plastic clay (CH).

Table 1
Atterberg limit value.

Atterberg limits	Percentage (%)
Liquid limit	52.6
Plastic limit	29.1
Plasticity index	23.4

Table 2
The angle and weight of the cones, penetration depth, undrained shear strength and K factor value for kaolin soil sample.

β (°)	m (g)	h (mm)	s_u (kPa)	K
20°	102	16.3	7.19	1.897
30°	80	10.8	6.64	0.987
45°	75	6.7	7.19	0.432
60°	70	6.0	5.57	0.292
90°	62.8	3.7	6.64	0.147
120°	59.2	2.5	6.64	0.0717
180°	82.0	0.3	5.03	0.00056

2.1. Sample preparation

A consolidation method was used to prepare a soil model in a cylindrical testing rig. Kaolin was mixed at twice the liquid limit to obtain a uniform sample, with the slurry then consolidated in a loading frame equipped with a pneumatic cylinder (Rashid et al., 2015a; 2015b). The consolidation test was carried out by increasing the loading on the sample, starting from 3.13 kPa through 6.5 kPa, 12 kPa and 25 kPa up to 50 kPa; unloading down to 25 kPa was then carried out in order to obtain an over-consolidation ratio of two. Loading sequences were applied for 24 h to ensure that consolidation reached 90%. Eq. (2) (Springman, 2004) was used to estimate the s_u of the kaolin, which depends on the soil over-consolidation ratio, OCR, as follows:

$$\frac{s_u}{\sigma'_v} = a.OCR^b \tag{2}$$

where a and b are respectively 0.19 and 0.67 (Phillips and Valsangkar, 1987), 0.22 and 0.62 (Nunez, 1989), or 0.22 and 0.71 (Springman, 1989), and σ'_v is the vertical effective pressure. The predicted range of s_u was from 7.6 kPa to 9.0 kPa, very similar to the measured result obtained from the vane shear test as listed in Table 2.

The consolidation characteristics of the kaolin sample in the form of compression (C_c) and recompression (C_r) indices are shown in Fig. 1. Values of C_c and C_r range from 0.63 to 0.74 and 0.007 to 0.025, respectively, indicating that the studied soil is highly compressible. The obtained C_c and C_r values are also similar to those recorded by Effendi (2007) and Rashid (2011).

After the completion of the consolidation test, the top cylinder cap was removed in order to perform the fall cone tests. Firstly, the cone penetration test was carried out to determine the penetration depth of cones with different angles and weights, as shown in Table 2. This test was performed according to BS 1377-2:1990 (British Standards Institution, 1990). After the completion of each test, the vane shear test was conducted on the undisturbed part of the sample in order to determine the strength of the soil samples according to BS1377-7:1990 (British Standards Institution, 1990). The soil moisture content was determined after the vane test. The obtained s_u and cone parameters (W and β) were used to determine K and hence h at liquid limit (s_u = 2.52 kPa) under different cone parameter values.

3. Laboratory results

The obtained values of h and s_u for kaolin at OCR = 2.0 are listed in Table 2. Analysis of this table reveals that s_u varied between 5.03 kPa

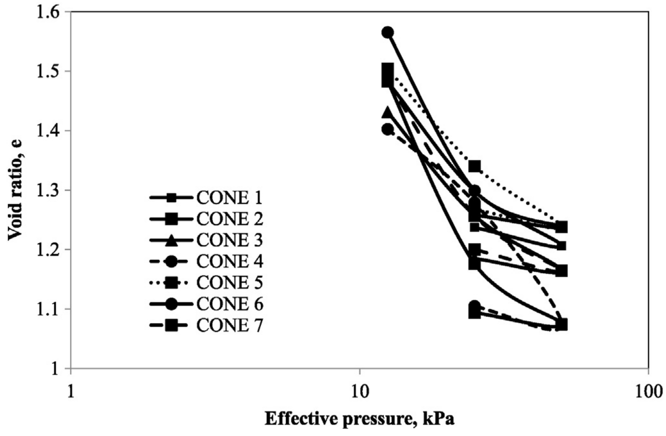

Fig. 1. Consolidation characteristics.

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