Determination of Shear Strength, Shear Viscosity and Liquidity Index using Fall Cone Penetrometer

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Abstract. In the usual case, the fall cone test has been used to estimate the undrained shear strength of insensitive remoulded clays. Its concept was based on the critical state soil mechanics and is well established. It is only recently that the use of this simple laboratory equipment has been extended to estimate the shear viscosity of soils which are well below their liquid limit. At these water contents, the viscous strength helps to understand the resistance of soils to flow in penetration tests, pile driving and landslides. This paper reports the results of fall cone tests under different loads. In this study, the effect of water content on shear viscosity was investigated by varying the weight of the cone. All the tests were conducted using speswhite kaolin clay. The samples were thoroughly mixed with water and then kept overnight in air-tight containers to ensure proper mixing of the clay with water. The fall cone apparatus was modified to accommodate an LVDT connected to a high-speed data logger which enabled the cone penetration to be logged at every 0.01s. The mass of the standard cone was increased by 390 to over 1000 g with the use of stainless steel discs. In some tests, the cone was not permitted to fall freely but was driven at a constant rate of 1.25 mm/min. The load versus penetration resistance measured at different water contents showed that the penetration increased with the increase in LI and at a given load, the results were consistent with the triaxial test results. Shear viscosity was calculated using the rate at which the cone penetrated into the soil and was shown to decrease with the increase in LI. Design curves were obtained for the different weight of the cone which can be implemented in the selection of soil characteristics e.g. in estimating the capacity of different driven piles.

Keywords: Fallcone, Viscosity, Liquidity Index, Undrained Shear Strength.

1 Introduction

Remoulded sensitive clays have the ability to move or be moved freely and easily and often noticed in many landslides [1–3]. Flow properties are the main parameters used to estimate the behaviour of remoulded clays. Eden and Kubota [4] were the first to introduce the relationship of remoulded undrained shear strength and viscosity of sensitive clays. The viscosity of water changes with temperature and pressure [5–7]. The viscosity of a fluid can be altered by adding different minerals such as iron, potassium, chloride and sulphate into it [8,9]. Yield stress measured from viscometer was later used to evaluate the liquid limit of soils [10]. However, Garneau and LeBihan [11] reported the possibility of using fall cone to measure the remoulded shear strength of the soil.

Shear viscosity measures the resistance of flow. Its knowledge plays a significant contribution to interpreting the viscous resistance in dynamic penetration tests. The soil penetration tests which make use the apprehension of shear viscosity are cone penetrometers, landslides and driven piles. This property can be calculated with the help of data obtained by fall cone penetration tests. The Swedish fall cone test for determination of shear strength and sensitivity which is now using as a standard tool of soil mechanics was first introduced in 1915 by a Swedish geotechnical engineer John Olsson (Secretary of the commission of Swedish State Railways) to measure the strength of soft clays in a remarkably simple manner. In regular geotechnical engineering practice, soft clay is considered as a soil having a shear strength less than 250 g/cm^2. Traditionally fall cone tests have been used to determine the undrained shear strength of remoulded soils [12–15]. Using this device, Hansbo [13] made an extensive study on cone penetration testing with the help of four different cones to correlate their penetration to the shear resistance. Wood and Wroth [14] were developed a relationship between the plasticity index (PI) and the compression index (C_C). The ratio between the strength of the soils at its plastic limit and the strength of the soil at its liquid limit was taken to be a unique value. Shear viscosity is needed to compute the viscous resistance of soil and also fall cone test has recognized to be a favourable method for calculating the shear viscosity of soft soils at low liquidity indices [16].

Mudflows are considered to be initiated by the changes in soil viscosity. Many researchers were reported that Atterberg limits, liquidity index and flow velocity are the three main factors which influence the mudflow [17–19]. Widjaja and Lee [20] observed that the main criteria for describing the commencement of mudflows due to changes in the soil conditions are its viscosity. Mudflows occur very quickly and unexpectedly or without warning and thus it can be considered a very hazardous event [21]. Deformation of soil mass happens when the phase of soil changes from liquid to plastic. Soil mass will flow like a liquid when its water content reaches to the liquid limit. This is the state at which soil behaves like a liquid and thus mudflow occurs [22]. Viscosity is an important factor in predicting mudflows as well. The commercially available viscometer only predicts the liquidity index of liquids which is more than one [23–25]. But due to the lack of such an apparatus to measure the viscosity of soil near to their liquid limit, calculation of undrained shear strength to validate the shear viscosity is unavoidable.

In this paper, an attempt was made to compare the undrained shear strength calculated by the fall cone test with undrained shear strength using triaxial apparatus [26]. Also, an attempt was made to compare and validate the shear viscosity calculation [16] with the addition of weights up to 10.8 N using fall-cone apparatus.

2 Methods of Measuring Undrained Shear Strength of Cohesive Soils

An experiment in the field provides the scientific procedure to examine involvement in the original world (or from the view of experimentalists, naturally occurring environments) precisely than in the laboratory. Irrespective of this, tricky instrumentation and also complex and expensive equipment often leads to laboratory testing rather than in-situ field testing even though independent lab testing provides defensible, repeatable results. Very recently lab vane test and fall cone test overtopped to find the strength of cohesive soils. This simple testing cannot be extruded from their cores and easy in case of weak samples. European countries are following the fall cone test to calculate the strength from the last few decades. The notable words provided by Ladd and Foot [27] is that “the in-situ undrained shear strength of clay is a unique function of its water content and that it can be readily measured by virtually any in-situ or laboratory vane shear test that does not allow changes in water content”. Any change in water content can easily be prevented using these tests. Thus the strength measured is the undrained shear strength where the soil is sheared at constant water content, and if saturated, also at constant volume. Since the work is focused on kaolin clay samples fall cone is found to be best suited.

3 Overview of the Problem

Shear viscosity is an important factor which plays an inevitable position in studying the viscous resistance in the dynamic penetration of clays. Role of the viscosity of soil is applicable in soil engineering fields such as submarine and subaerial slide dynamics and also in cone penetrometers, landslides and jacked piles. Viscometers are used to measure the viscosities of soil in which their water content is greater than or equal to the liquid limit. It is known that no such basic method is there to calculate shear viscosities of clays at lower water contents (i.e. less than the liquid limit).

The proposed explanation has made on the basis of limited evidence for this study are:

1. Creeping flow hydrodynamics can be used to examine the viscous drag which is a part of the total penetration resistance. This total resistance is presented in rigid bodies such as shaft during uninterrupted penetration.
2. Shear viscosity of clay can be evaluated with the help of the fall cone test, which is a prospective device.

The purpose of the present research program is to make use of the application of viscous flow (hydrodynamics) principles to soils at a critical state. This will help to figure out the results of viscous resistance on penetrating rigid bodies into the soil. Additionally, this will act as an important parameter to measure the inducing factors during mudflow.

4 Goal and Objectives of the Current Research

1) To develop a modified fall cone apparatus which will accept worldwide to relate liquidity index, shear strength and shear viscosity.
2) To find out the variation of the pattern obtained to shear viscosity versus liquidity index graph with the addition of weights in fall cone so that we can correlate the same with the prevailing site conditions.
3)To find out the variation of liquidity index with time using the help of modified fallcone apparatus as well as triaxial apparatus.
4) The comparison of shear strength from the cone penetration test as well as from the strain-controlled loading frame test using the same kaolin with the same properties.

5 Experimental Program

5.1 Materials Used

The clay used in this study was commercially produced speswhite kaolin obtained from Kutch in Gujarat All the basic properties of kaolin used for the experiment is shown in Table 1.

Table 1. Basic properties of kaolin used for the experiment

Sl no	Properties	Value
1	Natural moisture content (%)	1.5
2	Gradation analysis:	
	fine sand (%)	02
	silt (%)	38
	clay (%)	60
3	Specific gravity	2.65
4	Atterberg limits:	
	Liquid limit (%)	46.30
	plastic limit (%)	27.69
	liquidity index (%)	18.60
	shrinkage limit (%)	26
	Classification symbol	CI
5	Compaction characteristics:	
	Max dry density (g/cm3)	1.46
	Optimum moisture content (%)	26.5
6	pH	7.2
7	Elemental analysis by EDAX	
	SiK (%)	39.90
	OK (%)	35.81
	AlK (%)	11.08
	MgK (%)	7.07
	CaK (%)	6.14

5.2 Methodology

The fall cone apparatus was slightly modified by removing the dial gauge and rack. The dial gauge was replaced by a potentiometer using 2 mm thick fabricated aluminium plate casing and fixed to it (Figure 1a). All the procedures are followed as per BS 1377 [28]. Continuous penetration of fall cone was ensured with the help of a calibrated potentiometer. This was connected at the top of the shaft and readings are continuously measured and stored in a data logger. The angle at the tip of the cone was 30^0. The cone and the shaft together weighed 0.9 N in which all the test were conducted by changing the liquidity index from 0.29 to 2.

The apparatus was then connected to a data logger to receive the data at less than 0.01 s so as to obtain at least 50 data point at all water contents. The new fall cone device provides the same general principles as that of the traditional fall cone. The total weight of the cone was about 0.9 N.

Fig. 1. a) Modified fall cone apparatus b) Cone connected to the loading frame.

Extra weights were added to vary the cone weight from 0.9 N to 10.8 N. Weights were added to find out the difference in penetration rate and shear viscosity while changing the weights of the cone. Fall cone penetration apparatus (BS 1377, British Standard Institution, 1990) with a 30^0 cone was used during the experimental investigations. To ensure the homogeneity of the sample, the soil was kept inside the desiccator for an overnight.

Cone driving is also conducted with the help of a triaxial apparatus (Figure 1b) in which the same cone, which is used for fall cone testing is utilized. A load cell and a potentiometer were fixed so that load and the cone were driven at a rate of 1.25

mm/min to the soil sample which is kept at the cylinder (used for the fall cone test). Both the load cell and potentiometer were connected to the data logger so that it directly provides the data to the computer.

6 Theoretical Considerations

The theory is based on the traditional fall cone test described by Hansbo in 1957 [13] and Wroth & Wood [14] in 1978 and Wodd in 1982 [15]. To explain the theory; a brief background for this experiment is reported as follows. Hansbo [13] conducted a comprehensive experiment with the help of different cones to observe the undrained shear strength. He used the expression

$$\tau_{cs} = \frac{KW}{{h_f}^2} \tag{1}$$

relating undrained static shear strength τ_{cs} with penetration h of a cone of weight W, and deduced different values of cone factor K (which depends on the angle of cone & sampler used to collect soil from the ground). For these correlations with the shear strength of undisturbed samples, he found that $K_{30}{}^0=4\times K_{60}{}^0$. Hansbo [13] suggested $K\approx0.3$ for 60^0 cones for remoulded clays that correspond to a K value of 1.2 for 30^0 cones. Koumoto and Houlsby [29] developed a reduction factor (λ) to revise the fall cone factor (K) to estimate the value of static undrained shear strength and they also suggested that the undrained shear strength is a dynamic shear strength and is higher than the static undrained shear strength which has higher strain rates in the fall cone test. The equation of motion of a cone having mass m, acceleration due to gravity g, a is the acceleration of the cone at a depth h and τ is the dynamic shearing resistance and F is the non-dimensional cone resistance factor is

$$ma = mg - F\tau h^2 \tag{2}$$

and F is calculated as per the theory of Houlsby 1982 [30], Koumoto & Houlsby 2001 [29] having modified bearing capacity factor N_{ch} and semi-rough cone angle θ is

$$F = \pi N_{ch} \tan^2 \theta \tag{3}$$

(for a 30^0 cone N_{ch}=7.457)

When cone intrudes into the soil, acceleration of the cone reduces from its commencing range (g). The acceleration of cone reaches to zero when we reach a certain depth. The depth is considered a dynamic equilibrium position h_{eq}. At final depth, h_f the cone will be at a position of rest.

At dynamic equilibrium condition (a=0)

Considering viscous soil as a Casson fluid, the term $\mu_p\ddot{\Upsilon}$ can be calculated as

$$\mu_p \ddot{\gamma} = [\tau^{\frac{1}{2}} - \tau_{cs}^{\frac{1}{2}}]^2 = [(\frac{W}{Fh_{eq}^{2}})^{\frac{1}{2}} - (\frac{KW}{Fh_f^{2}})^{\frac{1}{2}}]^2 \tag{4}$$

$$K = 3\frac{\lambda}{F} \tag{5}$$

K =1.33 & λ =0.74 for a 30^0 cone.
μ_pŸ (the viscous component of shear resistance) can be written as

$$\mu_P \ddot{\gamma} = KW[\frac{0.67}{h_{eq}} - \frac{1}{h_f}]^2 \tag{6}$$

The average shear strain rate calculated by Koumoto & Houlsby, 2001 with

$$\ddot{\gamma} = \frac{2\delta}{2.44}\sqrt{\frac{g\sqrt{2}}{h_f}} = 0.34\sqrt{\frac{1}{h_f}} \tag{7}$$

The shear viscosity of the soil at dynamic equilibrium is

$$\mu_p = 2.94KW\sqrt{h_f}[\frac{0.67}{h_{eq}} - \frac{1}{h_f}]^2 \tag{8}$$

With the help of penetration Vs. time graph velocity can be calculated.

7 Results and Discussion

Figure 2a shows the penetration of the 10.8 N cone at two different liquidity indices (i.e. 0.30 and 0.18). The two curves in Figure 2a were differentiated to obtain the velocity of the cone as shown in Figure 2b.

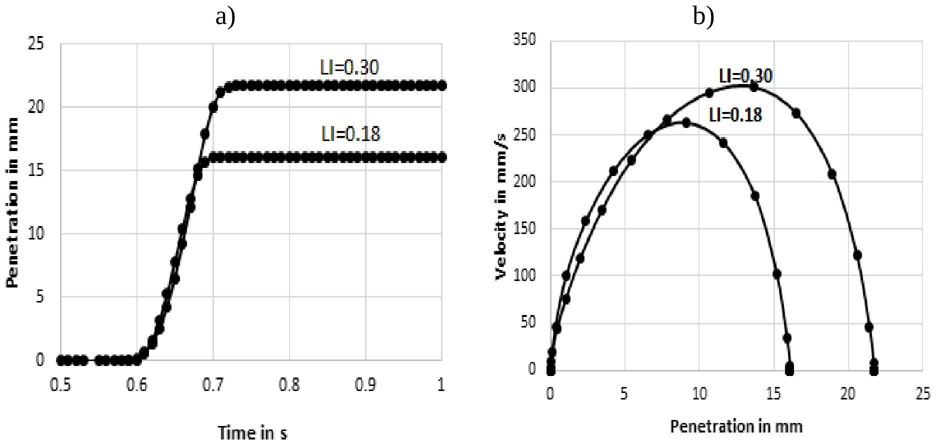
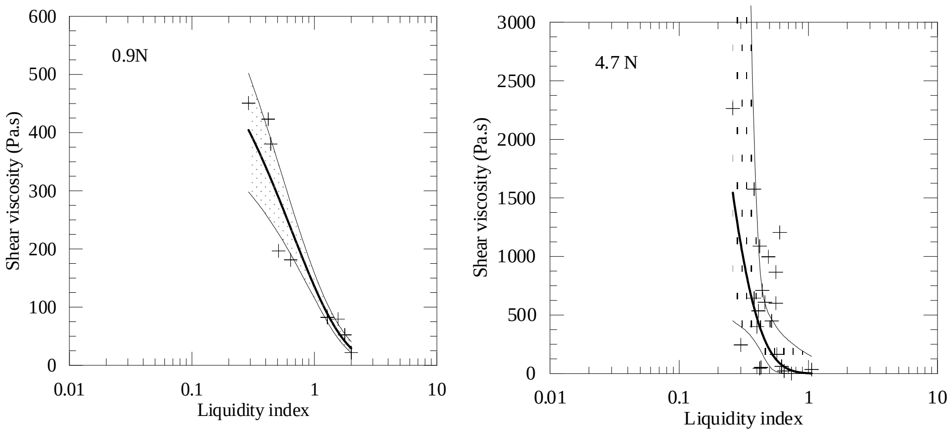


Fig. 2. a) Penetration versus time :b) Penetration versus velocity

After extracting the data which was obtained from the data logger, shear viscosity was calculated by the relations provided by Budhu [16]. Figure 3 shows the variation of liquidity index with shear viscosity by changing cone weights. Figure 4 shows the relation between shear strength, S_u and liquidity index (LI) of kaolin clay for different cone weights. The shear strength reduces with increasing liquidity index for all different weights of the cone.



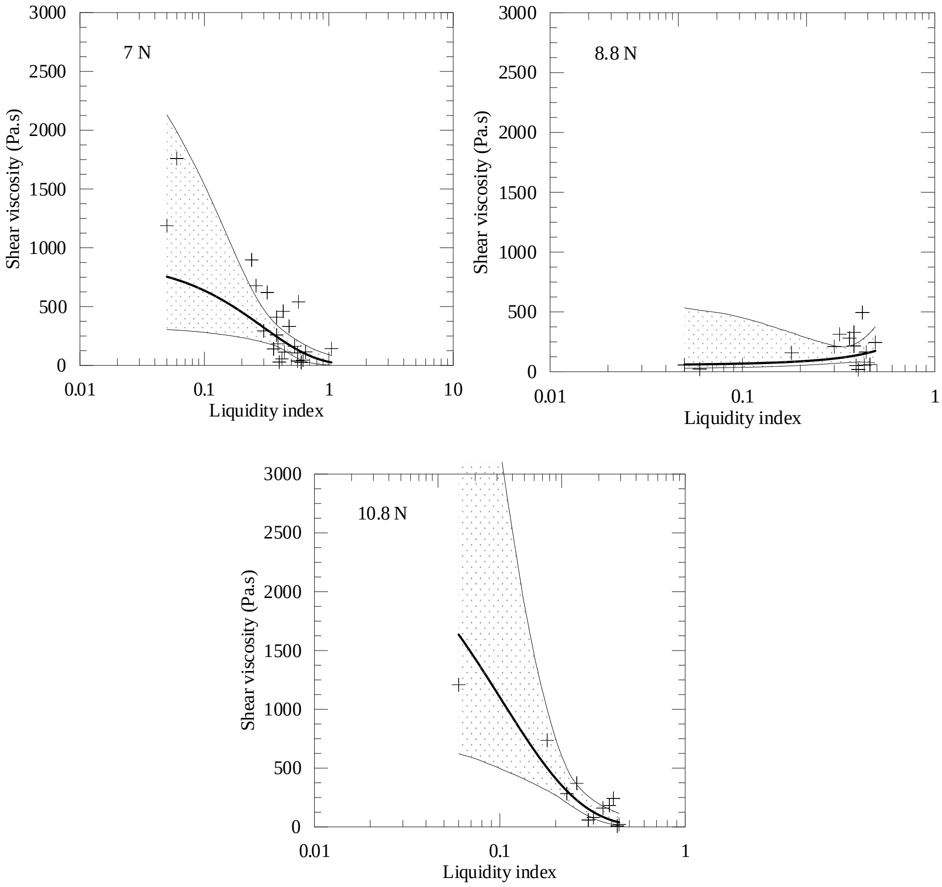


Fig. 3. Variation of shear viscosity with liquidity index (different weight of cone)

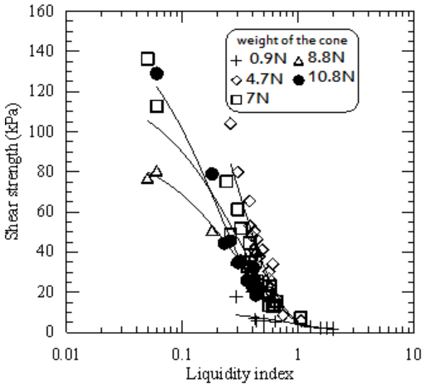


Fig. 4. Variation of undrained shear strength with Liquidity index for the different weight of cone.

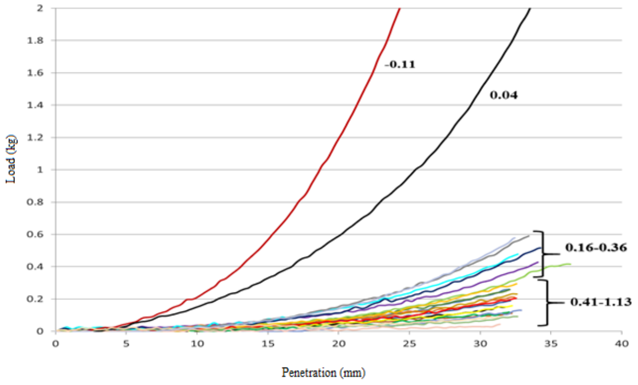


Fig. 5. Plots of load against penetration depth obtained from cone diving.

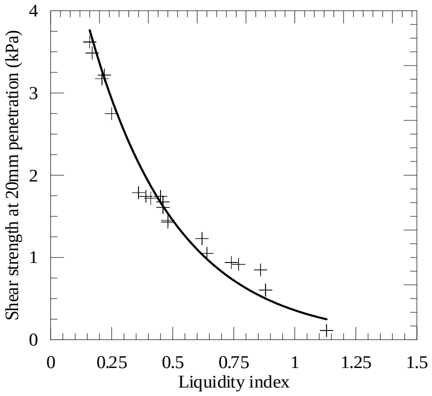


Fig. 6. LI Vs Shear strength at 20mm penetration depth.

From plots of load against penetration depth (Figure 5) obtained from cone driving, load at 20 mm penetration depth was considered and divide with the area to plot shear strength Vs. Liquidity index (Figure 6). Shear strength obtained from cone driving, load at 20 mm penetration depth showed that shear strength increases with reducing liquidity index.

The comparison of shear strength obtained from the cone penetration was done with the results obtained from the strain-controlled loading frame tests using the same kaolin with the same properties [26].

Strength equation

$$\frac{S_u}{p'} = 0.23 \times (OCR)^{0.8} \tag{9}$$

For normally consolidated clays, OCR is equal to 1. Furthermore $p_0^{'}$ can be obtained for the equation

$$\upsilon = \upsilon_\lambda - \lambda \ln p_0^{'} \tag{10}$$

Substituting equation (2) in (1) leads to

$$S_u = 0.23 \times e^{\frac{0.451-w}{0.0379}} \tag{11}$$

8 Conclusions

The observations obtained from the laboratory experiments conducted by varying the weight of the cone are

- Liquidity index varies exponentially with time.
- Weight of the cone is an important factor which makes exponential changes in liquidity indices.
- Shear strength versus LI obtained from both triaxial test results and fall cone connected to loading frame are in good agreement.
- . The shear strength reduces with increasing liquidity index for all different weights of the cone.
- The undrained shear strength obtained from cone driving, load at 20 mm penetration depth showed that shear strength increases with reducing liquidity index.
- The current research has also created a modified fall cone apparatus to effectively measure the viscosity levels as soil changes from the plastic state to the liquid state.
- The test results can be utilized to figure out the variations of viscous resistance on penetrating rigid bodies into the soil. Additionally, this will act as an important parameter to measure the inducing factors during mudflow.

9 Future Work

- Comparison of fall cone with Casagrande apparatus for liquid limit determination.
- Comparison of fall cone test results with laboratory vane shear test.
- To check the liquidity Index versus shear strength variation using different cone angles (30^0).
- To check the liquidity Index versus shear strength variation using blunt cones.

- To find out the penetration versus load graph of cone driving using different cones and thus to develop a relationship between load, penetration and different cone angles.

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