Correlation between strength and index properties of mixed kaolinite soils by cone penetration and fall cone tests

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ABSTRACT

In this study, the undrained shear strength of sand-mixed kaolinite soils were evaluated in laboratory by using a portable Static Cone Penetration Test (SCPT) and the new Fall Cone Test (FCT) method. Laboratory samples have been made by mixed proportion (Kaolinite : Sand) of sand mixture (10%, 20%, and 30%), water content (60%, 65%, and 70%), and preconsolidated at different stress levels (0, 13, 17.5, 22 kPa). Variation of void ratio, density and cohesion of the mixed soil was observed. Correlations were established with the physical properties and the undrained shear strengths derived from the results of SCPT and FCT tests on the same sample. Comparison of the results showed a significant relationship between the two methods.

1. INTRODUCTION

To determine the undrained shear strength of the variety of soil deposits in ground have been one of the primary objectives in field investigations. The natural ground is spatially composed of different physical and engineering properties. However, most of the engineering design methods, parameters and correlations have been generally developed for ideal soils only such as pure sands or pure clays (Tembe et al. 2010) regardless of the mixed constituents (e.g. sand or clay content). As it is practically impossible to find a soil which is homogeneous in nature, it is necessary to study the mixed soil properties. Laboratory studies and field observations indicate that cohesive soils may contain granular geomaterials with different shape and size properties. The

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presence of cohesion-less geomaterials should be expected to affect the properties of cohesive soils (Cabalar et al. 2015).

One important characteristic of cohesive soil its undrained shear strength. These soils have a very low consolidation stresses, so they cannot be tested with traditional geotechnical techniques. A device that can measure the undrained strength of extremely weak soils without disturbance and at small depth intervals is desirable for many engineering applications. (Diana A. et al. 1995, Garam Kim et al. 2015). Analysis of both the Fall Cone Test (FCT) (Hansbo 1957, Wroth and Wood 1978) and the Static Cone Penetration Test (SCPT) (Houlsby et al. 1982) has shown that the undrained shear strength (S_{uf}) is related to the penetration depth (d) by the simple expression (Benjamin S. et al. 2012).

$$S_{uf} = k\frac{Wg}{d^2} \tag{1}$$

Where, g is the gravitational acceleration, W is weight, d is the depth of penetration and k is a constant, which changes based on the angle of the cone.

The FCT is a simple testing method in which a cone is penetrated into a soil specimen by its self-weight and the penetration depth is measured. This test is extensively used for measuring atterberg limits, i.e., liquid limit (LL) and plastic limit (PL), undrained shear strength (S_{uf}) for intact as well as remolded clay sample (Tanaka et al. 2012).

On the other hand, SCPT has long been used to estimate the undrained shear strength of clay. However, the undrained shear strength itself is not a unique measure of soil strength; different laboratory or in-situ tests may give different undrained shear strengths for the same soils. (L. Wei et al. 2014). Most SCPT can measure tip resistance (q_c), sleeve friction (f_s) and pore water pressure (u_1, at the cone tip or u_2, behind the cone base) simultaneously (Tumay et al. 1981, Zuidberg et al. 1982).

In this study pure kaolinite clay soil was mixed with sand to make test samples in laboratory. The effect of sand on the void ratio and density was observed. Both SCPT and FCT tests were done on the same sample. By the FCT, the speed of penetration of the cone and undrained shear strength was measured. Kinetic energy calculated from the speed of penetration was compared with the strengths measured by both SCPT and FCT method. The relation between water content and undrained shear strength was derived. Finally, cone resistance measured by the SCPT was compared with the strengths measured by FCT and empirical cone factor for CPT were determined for the kaolinite clay mixed with a different percentage of sand.

2. RESEARCH METHODOLOGY

2.1 Fall Cone Test (FCT)

The test consists of a digital set of device and a data log which will measure the speed of rod penetration into the soil. The soil was molded in some still hollow cylinders with a diameter of 17 cm and a height of 99 cm. Bottom of the cylinder was enclosed by a porous steel plate which would drain the water out of the soil during consolidation.

After finishing of consolidation the final settlement of the sample was measured. The triaxial wheel type fall cone device was mounted on the top of the mold and the cone was penetrated through it. The weight used for penetration was changed to get a uniform speed of penetration of the rod into the soil sample. The device was connected to data log to record the length and time of penetration.

The data log was also connected to a laptop by which the test was controlled and operated. First, the height of each sample was measured and according to that height, a mark was given in the penetration rod to ensure that at the time of penetration there is no gap between the rod and the top of the soil. Otherwise, some inaccuracies could be obtained due to the free fall of the weight. A total of 8 tests were performed on one sample and the average value of 8 tests was calculated as undrained shear strength (S_{uf}) by FCT from Eq. (1). The penetration depth "d" selected for this experiment was at the time, t = 5s.

2.2 Static Cone Penetration Test (SCPT)

The use and application of the SCPT are being more frequently considered for the in-situ investigation of soils for engineering purposes (Karim et al. 2006). In this experiment after finishing the FCT test on the sample, the SCPT test was then performed on the same sample. The test was done by a portable cone penetrometer (Model HJ-4500). The cone had a 30°tip angle with a cross-sectional base area of 6.45 cm^2. The portable penetrometer was pushed inside the soil manually with the handle with a speed of 10 mm/sec. Reading was taken carefully from the dial gauge after every 10 seconds of penetration and average cone resistance was calculated. It is widely accepted that the undrained shear strength may be estimated using the following bearing capacity equation (Terzaghi 1943).

$$S_{uc} = \frac{q_c - \sigma_v}{N_c} \tag{2}$$

Where, S_{uc} is the undrained shear strength and q_c is the measured tip resistance and σ_v is the total overburden pressure. N_c is the cone factor, which is a value of about 9 has been proposed based on measurements and analysis (Meyerhof 1951, Skempton 1951).

2.3 Selection of Cone Factor (k) for FCT

The cone factor (*k*) is an empirical constant that varies with the cone angle. Most commercially available cones have tip angles of 30° and 60°, the weight typically varies between 0.1 N and 1 N in order to achieve penetration depths of 5 mm to 20 mm (Diana et al. 1995). The flat circle can be regarded as a cone with a top angle of 90° As a cone factor (*k*) value for 90° cone angle is not available so it was extrapolated from Eq. (3) based on the empirical k values and calculated as 0.116.

$$k = 2.2549\, e^{-0.033\alpha} \tag{3}$$

3. LABORATORY SETUP AND PROCEDURE

3.1 Laboratory Apparatus

The undrained shear strength tests were carried out using two methods: the SCPT and FCT. The SCPT was done with a portable cone penetrometer with a rod diameter of 16mm and cone angle of 30°. A new fall cone device was used for the FCT. The diameter of the rod was 5 mm. The apex of the cone was flat with an angle of 90°. Fig. 1 represents the both test methods. Section (Fig. 1, A-A) is the top view of the fall cone apparatus. The penetrometer for the fall cone was a triaxial wheel type penetrometer. It was rotated clockwise and a total of 8 FCT were performed on one sample.

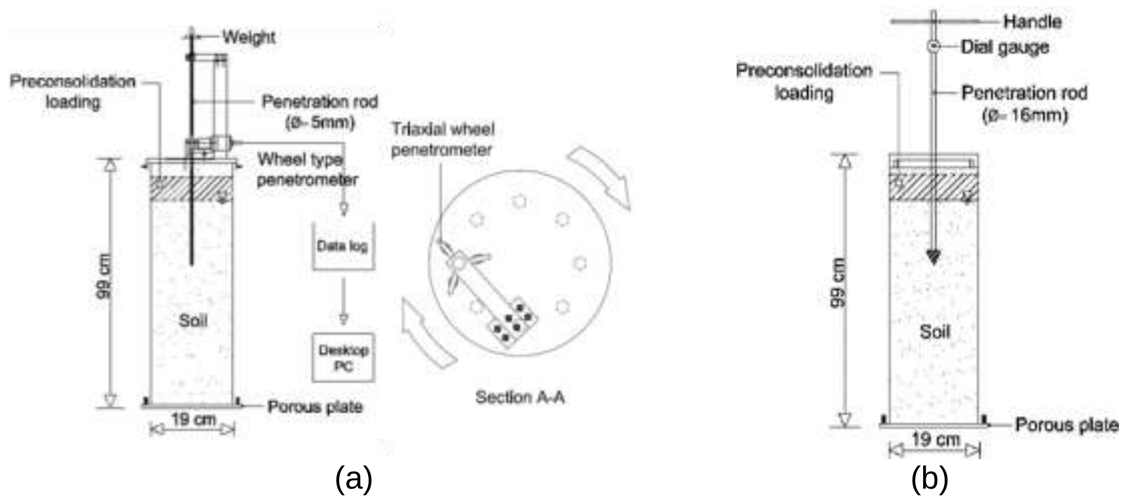


Fig. 1 Experimental setup (a) fall cone test; (b) static cone penetration test

3.2 Material Properties

Table 1. The Properties of the Soil

Item	Kaolinite	Sand
Specific Gravity, (Gs)	2.598	2.645
Density, (kN/m^3)	14.83	15.15
Liquid limit, (LL)	64.74	-
Plastic limit, (PL)	29.83	-
Plasticity index, (PI)	33.75	N.P*
Percentage passing #200 sieve, (%)	98.19	0.5
Unified soil classification system, (USCS)	CH	SP

N.P* = Non-plastic

The clay soil used in this study was kaolinite. The properties of the soil are given in Table 2. From the grain size distribution it was found that the sand used in this experiment was a medium well-graded sand.

3.3 Sample Preparation

The sample preparation technique was same for all specimens. The weight of kaolinite and sand was measured by a weight balance. In the case of a pure kaolinite sample, no sand was added to it. The soil was put in the mixer and the desired amount of water was added to it (60%, 65% or 70%). The mixer was run until the sample was visually homogeneous. The mixture was then put into the steel mold by using a hand. Bottom of the mold was enclosed by a porous plate. The filter paper was put over the porous plate to get a uniform drainage of water while consolidation. At the time of putting soil into the mold, about a uniform density is sustained and without inserting any possible air voids. A constant height was maintained for all the samples. 16 samples were made for each water content in Table 3. After pouring the sample inside the mold, top of the mold was covered very tightly and was kept for 12 hours to allow for some self-consolidation. After 12 hours upper covers of the samples were removed and the preloading stress (13 kPa, 17.5 kPa, and 22 kPa) were applied to the samples during 7 days for drainage of water from the sample. After 7 days the preloading stress was removed from the sample and fall cone test and static cone penetration tests were performed on the sample.

Table 2. Parameters for Each of Soil Samples Prepared for Tests

Case	1	2	3	4	5	6	7	8	9	10	11	12
Water content (%)	60%				65%				70%			
Percent of kaolinite (%)	100	90	80	70	100	90	80	70	100	90	80	70
Percent of sand (%)	0	10	20	30	0	10	20	30	0	10	20	30
Preconsolidation stress (kPa)	(0, 13, 17.5, 22)				(0, 13, 17.5, 22)				(0, 13, 17.5, 22)			

4. RESULT AND DISCUSSION

4.1 Effect of Index Properties on Shear Strength

As the percentage of sand in a clay matrix increases, liquid limit, and undrained shear strength values decrease (Cabalar et al. 2015). In Fig. 2 the undrained shear strength values obtained from the fall cone test and water content were plotted in a semi-log scale graph for a different amount of sand contents. The results showed a decrease in undrained shear strength with increasing amount of sand. This relationship could be used to correlate the S_{uf} results with various water content values for pure kaolinite and kaolinite mixed with a different percentage of sand.

In spite of the same water content, undrained shear strength is reduced as the adhesion is decrease due to sand. Due to increasing sand percentage with respect to decreasing kaolinite clay proportion, it becomes denser.

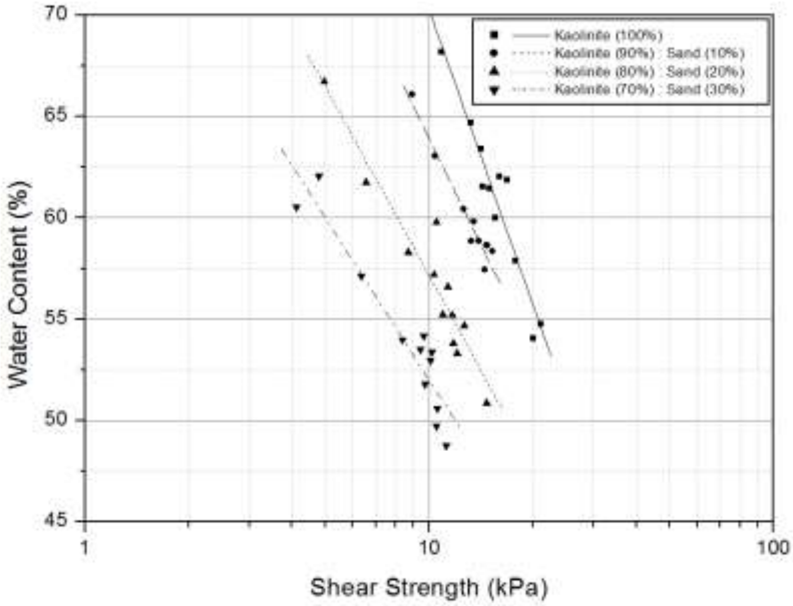


Fig. 2 Relation between undrained shear strength and water content

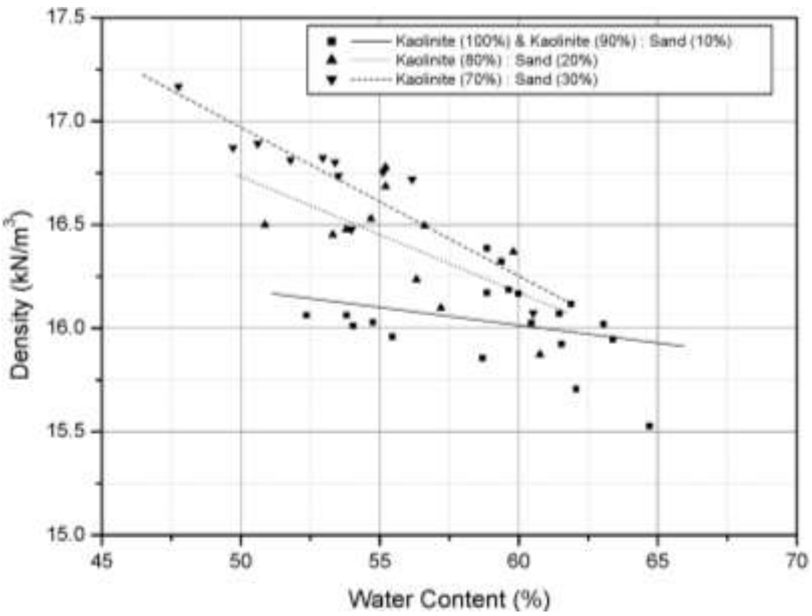
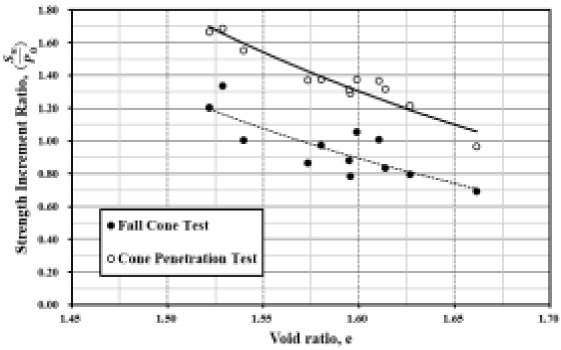


Fig. 3 Relation between density and water content

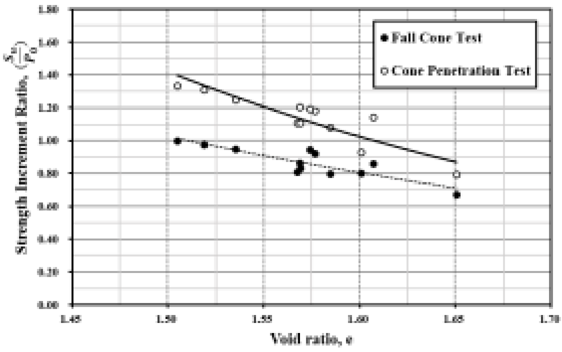
The difference between sands and clays is that for sand the density of deposition controls the behavior in the engineering stress range, while for clay initial differences in depositional density are erased more quickly because specific volumes at deposition are much higher so that the normal compression line is encountered at low stresses (Nocilla, A. et al. 2006). It is also considered that fine textured surface soils such as silt loams, clays, and clay loams generally have lower bulk densities than sandy soils. This is because the fine textured soils tend to organize in porous grains especially with adequate organic matter content. This results in high pore space and low bulk density. From Fig. 3 it was observed that when sand is added with kaolinite the density of the soil increased and water content decreased. This phenomenon can be described as the increase in permeability of soil with increasing sand content. The addition of sand in the kaolinite clay increased the permeability of the soil and caused the water from the soil to drain out more fluently and thus making the sample denser.

If the proportion is more than 20% of the mixing sand then it is shown that the change in density is a distinctively noticeable. However, for lower than 10% amount of sand mixed, there is little change in density to water content.

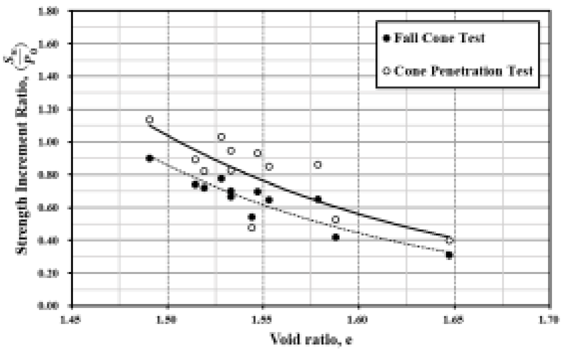
As the soil is consolidated under the effectively applied pressure, a reduction in water content and a corresponding increase in shear strength occurs. Anderson (1981) stated that soil deposit can be considered to be normally consolidated under the maximum effective applied pressure, and there is a definite relation between preconsolidation pressure and undrained shear strength. Actually, a slight reduction in undrained shear strength will probably occur, since the void ratio will increase slightly as the effective pressure decreases.



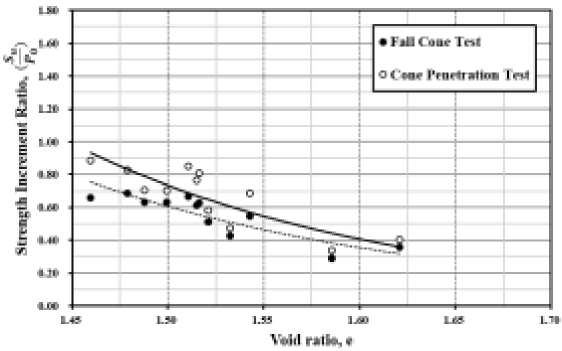
(a) Kaolinite (100%)



(b) Kaolinite (90%) : Sand (10%)



(c) Kaolinite (80%) : Sand (20%)



(d) Kaolinite (70%) : Sand (30%)

Fig. 4 Relation between Strength increment ratio and void ratio

Fig. 4 represents the graph of strength increment vs void ratio. From the figure, it can be observed that a decrease in stress increases the void ratio slightly and as a result of the undrained shear strength also decreases.

The undrained shear strength relationship from FCT and CPT are observed to be related with consolidation load, which is shown by strength increase ratio (S_u / P_o) and void ratio (e_0). The smaller the sand content as shown in the figure, the undrained strength value between FCT and CPT in same void is more increased. As preconsolidation load increases, void ratio is reduced, the adhesive force affecting the substantial strength is increased, and kinetic energy by FCT is decreased as density is increased. At higher sand content (e.g. > 20%), there is almost no difference in the strength increase ratio (S_u / P_o) between FCT and CPT.

5. CONCLUSION

This research was conducted in laboratory scale model to investigate the index and strength properties of kaolinite mixed with various proportions of sand, range of water content, and applied preconsolidation stress. The strength properties were calculated with a conventional Static Cone Penetration (SCPT) method and a new Fall Cone Test (FCT) method.

The following conclusions were obtained from the results of the study:

- The results showed a decrease in undrained shear strength with increasing amount of sand. This relationship could be used to correlate the S_{uf} results with various water content values for pure kaolinite and kaolinite mixed with a different percentage of sand.
- From the results of FCT and SCPT, there is a decreasing trend of undrained shear strength, strength increase ratio (S_u/P_o) and void ratio (e_0) as the sand content increases. As preconsolidation load increases, void ratio is reduced, the adhesive force affecting the substantial strength is increased, and kinetic energy by FCT is decreased as density is increased.

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