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Influence of coarse particles on the physical properties and quick undrained shear strength of fine-grained soils

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Abstract. Soils are generally classified as fine-grained or coarse-grained depending on the percentage content of the primary constituents. In reality, soils are actually made up of mixed and composite constituents. Soils primarily classified as fine-grained, still consists of a range of coarse particles as secondary constituents in between 0% to 50%. A laboratory scale model test was conducted to investigate the influence of coarse particles on the physical (e.g., density, water content, and void ratio) and mechanical (e.g., quick undrained shear strength) properties of primarily classified fine-grained cohesive soils. Pure kaolinite clay and sand-mixed kaolinite soil (e.g., sand content: 10%, 20%, and 30%) having various water contents (60%, 65%, and 70%) were preconsolidated at different stress levels (0, 13, 17.5, 22 kPa). The quick undrained shear strength properties were determined using the conventional Static Cone Penetration Test (SCPT) method and the new Fall Cone Test (FCT) method. The corresponding void ratios and densities with respect to the quick undrained shear strength were also observed. Correlations of the physical properties and quick undrained shear strengths derived from the SCPT and FCT were also established. Comparison of results showed a significant relationship between the two methods. From the results of FCT and SCPT, there is a decreasing trend of quick undrained shear strength, strength increase ratio (S_u/P_o), and void ratio (e) as the sand content is increased. The quick undrained shear strength generally decreases with increased water content. For the same water content, increasing the sand content resulted to a decrease in quick undrained shear strength due to reduced adhesion, and also, resulted to an increase in density. Similarly, it is observed that the change in density is distinctively noticeable at sand content greater than 20%. However, for sand content lower than 10%, there is minimal change in density with respect to water content. In general, the results showed a decrease in quick undrained shear strength for soils with higher amounts of sand content. Therefore, as the soil adhesion is reduced, the cone penetration resistances of the FCT and SCPT reflects internal friction and density of sand in the total shear strength.

Keywords: fall cone test; static cone penetration test; kinetic energy; physical properties; quick undrained shear strength; bearing capacity factor

1. Introduction

Soils are generally classified as fine-grained or coarse-grained depending on the percentage content of the primary constituents. For example, ASTM D2487 (2006) Unified Soil Classification System (USCS) classifies fine-grained soils as those with more than 50% passing the No. 200 sieve. In reality, soils are actually made up of mixed and composite constituents. Soils primarily classified as fine-grained, as per ASTM D2487 (2006), still consists of a range of secondary constituent coarse particles (around 0% to 50% retained in No. 200 sieve). Kaolinite soils are examples of fine-grained soils with fine contents (passing in No. 200 sieve) up to 98-100% (or 0-2% coarse particles retained in No. 200 sieve).

Determining the undrained shear strength of a variety of soil deposits in the ground have been one of the primary objectives in field investigations. The natural ground is spatially composed of different physical and engineering properties (Mission *et al.* 2013). However, most of the engineering design methods, parameters and correlations have been generally developed for ideal soils only, such as fine-grained (e.g., clay) or coarse-grained soils (e.g., sand) (Tembe *et al*. 2010) regardless of the mixed constituents (i.e., amount of coarse or fines content in sandy clay, clayey sand, silty clay, or clayey silt). As it is practically impossible to find a soil which is homogeneous in nature, it is necessary to study the mixed or composite soil properties. Laboratory studies and field observations indicate that cohesive soils may contain granular (sand or silt) geomaterials with different shapes and size properties. The presence of these granular geomaterials should be expected to affect the properties of cohesive or fined-grained soils

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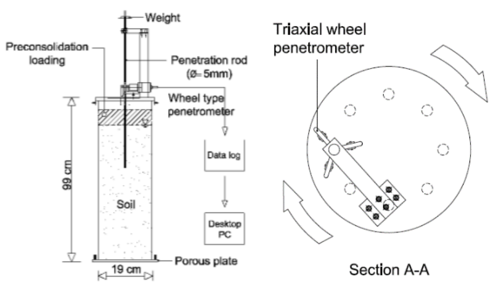
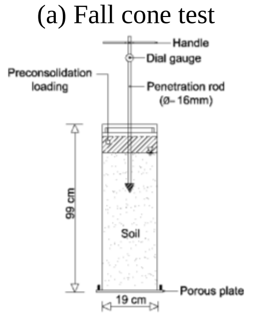
with various sand contents (Cabalar and Mustafa 2015).

One important characteristic of fine-grained cohesive soil is its undrained shear strength. These soils have very low consolidation stresses and 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 (Zriek *et al*. 1995, Kim *et al*. 2015, Kim *et al.* 2016). The Fall Cone Test (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, the portable Static Cone Penetrometer Test (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 (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 fine-grained cohesive soil (pure kaolinite clay) was mixed with sand to make test samples in the laboratory of various percentage content of coarse particles (less than 50%). Both SCPT and FCT tests were done on the same sample, and the effect of sand content on the physical properties (e.g., density, water content, and void ratio) and mechanical property (e.g., quick undrained shear strength) were observed. Kinetic energy calculated from the speed of penetration was also compared with the strengths measured by both SCPT and FCT method. The relationships between density, water content, void ratio, and quick undrained shear strength were derived for the fine-grained soil with various percentage of sand content, and results using the FCT and SCPT were compared.



(a) Fall cone test



(b) Portable static cone penetration test

Fig. 1 Experimental setup

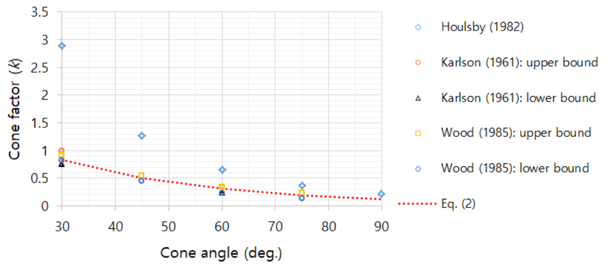


Fig. 2 Theoretical and empirical correlations of cone factor with cone angle

Table 1 Theoretical and experimental values of cone factors for cohesive soils from literature (Zriek *et al*. 1995)

Reference	α=30°	α=45°	α=60°	α=75°	α=90°
Houlsby (1982)	2.890	1.250	0.645	0.360	0.205
Karlson (1961)	0.79±0.05	-	0.29±0.05	-	-
Wood (1985)	0.85±0.05	0.49±0.05	0.29±0.05	0.19±0.05	
Eq. (2)	0.838	0.511	0.311	0.190	0.116

2. Measurement of quick undrained shear strength

2.1 Fall cone test (FCT)

The experimental setup for the FCT is shown in Fig. 1(a). The test consists of a digital set device and a data logger which measures the speed of rod penetration into the soil. The soil was molded in hollow cylinders with a diameter of 17 cm and a height of 99 cm. The bottom of the cylinder was enclosed by a porous steel plate which would drain the water out of the soil during consolidation.

After 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 logger to record the length and time of penetration. The data logger 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 (Tanvir 2016).

Analysis of both the Fall Cone Test (FCT) (Hansbo 1957, Wroth and Wood 1978, Zreik *et al.* 1995, Cabalar and Mustafa 2015) and the Static Cone Penetration Test (SCPT) (Houlsby 1982) has shown that the undrained shear strength (S_{uf}) is related to the penetration depth (d) by the simple expression (Stone and Kyambadde 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.

In Eq. (1), the FCT 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 (Zriek *et al*. 1995). Theoretical and experimental values of cone factors for cohesive soils are presented in Table 1 and are also plotted in Fig. 2. In this test, a flat cone was used. The flat circle can be regarded as a cone with a top angle of 90° in which the cone factor value (k=0.116) was extrapolated from Eq. (2) based on the fitted correlation with theoretical and experimental k values in literature and as shown in Fig. 2.

$$k = 2.2549\, e^{-0.033\alpha} \tag{2}$$

A total of 8 tests were performed on one sample and the average value of 8 tests was calculated as quick undrained shear strength (S_{uf}) by FCT from Eq. (1). The penetration depth (d) selected for this experiment was at the time, t = 5s.

By the FCT, the speed of penetration of the cone and undrained shear strength was measured. The kinetic energy produced by the speed of the penetration rod was also calculated using the following formula

$$E_k = \frac{1}{2} m v^2 \tag{3}$$

where E_k is the kinetic energy, m is the weight used for penetrating the rod into the soil and v is the speed of penetration.

2.2 Portable static cone penetration test (SCPT)

The use and application of the portable SCPT are being more frequently considered for the in-situ and laboratory investigation of soils for engineering purposes (Kim *et al*. 2015). In this experiment, after finishing the FCT test on the sample, the SCPT test was then performed on the same sample as shown in Fig. 1(b). The test was done using 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 at a speed of 10 mm/sec. Reading was taken carefully from the dial gauge after every 10 seconds of penetration and the 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).

$$S_{uc} = \frac{q_c - \sigma_v}{N_c} \tag{4}$$

where S_{uc} is the undrained shear strength, q_c is the measured tip resistance, and σ_v is the total overburden pressure. N_c is the cone factor, which has been proposed by Terzaghi (1943), Meyerhof (1951), and Skempton (1951) based on measurements and analysis to have a value of about 9.

On the other hand, some researches tend to simply use a fraction of the measured tip resistance as the undrained shear strength (Wei and Pant 2014) (Eq. (5)).

$$S_{uc} = \frac{q_c}{N_c} \tag{5}$$

where q_c is the measured tip resistance and N_c is the cone factor which tends to increase with increasing plasticity and decrease with increasing soil sensitivity. The derived theoretical expressions have pointed out that a reliable correlation can be found between the shear strength and SCPT tip resistance. In this experiment, Eq. (4) was used to calculate the quick undrained shear strength by SCPT. Finally, cone resistance measured by the SCPT was compared with the strengths measured by FCT, and the empirical cone factor for the SCPT were determined for the kaolinite clay mixed with various percentages of sand.

3. Laboratory setup and procedure

3.1 Laboratory apparatus

The quick undrained shear strength tests were carried out using two methods: the SCPT and FCT as described in Section 2. 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 both test methods. Section A-A is the top view of the fall cone apparatus. The penetrometer for the fall cone test was a triaxial wheel type penetrometer. It was rotated clockwise and a total of 8 FCT were performed on one sample.

3.2 Material properties

The clay soil used in this study was kaolinite. The properties of the soil are given in Table 2 and grain size distribution is shown in Fig. 3. From the grain size distribution, it was found that the sand used in this experiment was a medium well-graded sand.

Table 2 Properties of the soil

Item	Kaolinite	Sand
Specific Gravity, (G_s)	2.598	2.645
Density, (kN/m^3)	14.83	15.15
Liquid limit, (LL)	64.74	-
Plasticity index, (PI)	34.91	N.P*
D_{50}	0.029	1.39
Percentage passing #200 sieve, (%)	98.19	0.5
Unified soil classification system, (USCS)	CH	SP

*N.P = Non-plastic

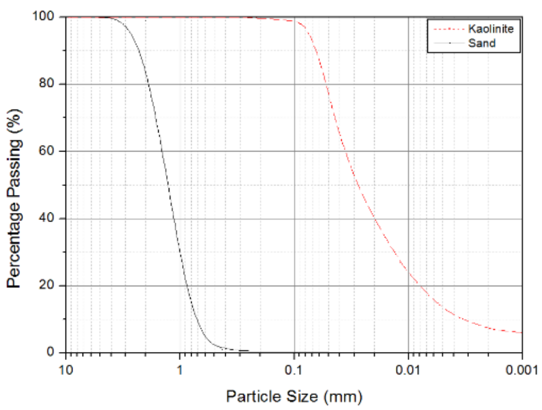


Fig. 3 Grain size distribution

Table 3 Parameters for each of soil samples prepared for the 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)			

3.3 Sample preparation

The sample preparation technique was the same for all specimens. The weight of kaolinite and sand was measured using 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 hand. The bottom of the mold was enclosed by a porous plate and filter paper was put over the porous plate to get a uniform drainage of water during the application of the preconsolidation stress. At the time of putting the soil into the mold, a uniform density was sustained, without inserting any possible air voids to obtain full saturation. 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, the top of the mold was covered very tightly for 12 hours, allowing self-weight consolidation to occur. After 12 hours, the upper covers of the samples were removed and the preloading stress (13 kPa, 17.5 kPa, and 22 kPa) were applied on the samples for 7 days, allowing water to drain out of the sample. After 7 days, the preloading stress was removed from the sample, and the fall cone test and static cone penetration tests were performed on the sample.

4. Result and discussion

4.1 Strength and kinetic energy relationship

The velocity of penetration is plotted against kinetic energy to quick undrained shear strength ratio in Fig. 4 to evaluate the relations (v–E_k/S_{uf}) of the fall cone shear strength. A good relationship is observed between speed and kinetic energy to fall cone shear strength ratio for different water contents.

The high regression coefficient shows that there is a close correlation between the speed of penetration and kinetic energy to shear strength ratio. Thus, it could be very useful to correlate these two parameters. Kaolinite with water content more than 65% have a greater drop of energy relative to quick undrained shear strength. The reason is because, relatively, the FCT penetration rate does not accurately reflect the adhesive strength of the sample in which the kinetic energy is greater than the degree of dirt taken by the fall.

In FCT, the cone penetration rate increases as the kinetic energy is increased for soft soils of high water content. On

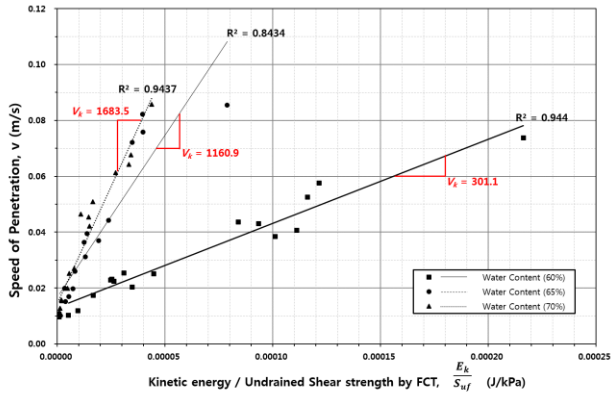


Fig. 4 Relation between speed and kinetic energy to quick undrained shear strength ratio

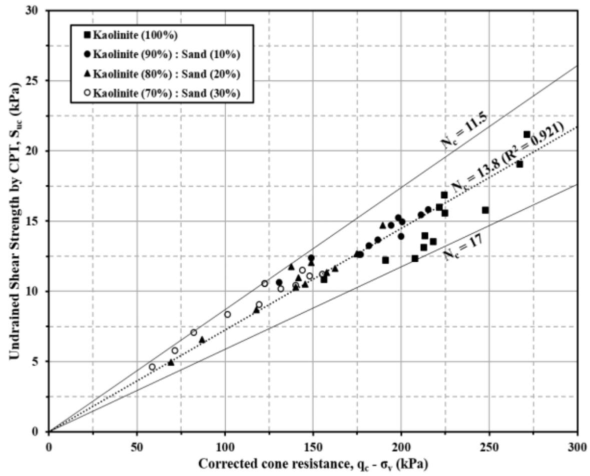


Fig. 5 Relation between quick undrained shear strength and SCPT tip resistance

the other hand, the cone penetration rate is reduced for samples with smaller initial water content because the quick undrained shear strength is also relatively increased. In Fig. 4, the observed minimum penetration velocity measurements are in the range of 0.013-0.017 m/s regardless of the initial water content, with an average of 0.0150 m/s. From these results, the suggested linear relationship between the quick undrained shear strength (S_{uf}) and kinetic energy is given by Eq. (6).

$$S_{uf} = \frac{V_k E_k}{(V - 0.015) m/sec} \tag{6}$$

4.2 SCPT cone factor (N_c)

There are many theoretical correlations between the undrained shear strength and SCPT tip resistance. Sanglerat (1972) observed that N_c may range from 10 to 20 and often very close to a value of 15 for soft clays. From Terzaghi's bearing capacity factors, it is proven that with increasing amount of sand, the value of N_c increases. In Fig. 5 the quick undrained shear strength observed from SCPT was plotted against the tip resistance. The total vertical stress (σ_v) at the bottom of the soil was subtracted from the SCPT tip resistance to obtain the effective soil resistance. The line of best fit was determined by the least squares method which minimizes the total deviation between predicted values. The best fit N_c value was 13.8, and appropriately, reflect the internal friction of the soil.

4.3 Effect of index properties on shear strength

As the percentage of sand in a clay matrix increases, liquid limit, plasticity, and undrained shear strength values decrease (Cabalar and Mustafa 2015). In Fig. 6, the quick undrained shear strength values obtained from the fall cone test and water content were plotted in semi-log scale for different amounts of sand content. Portions of the soil samples at different depths were extracted after each test to obtain the water content by oven drying. Assuming a degree of saturation of 100%, the void ratios were obtained by $e = wGs$. The G_s value used was from the kaolinite.The results showed a decrease in quick undrained shear strength with increasing amounts of sand content. This is because as sand content increases, the cohesion also decreases. This relationship could be used to correlate the S_{uf} results with various water content values for pure kaolinite and sand-mixed kaolinite soil.

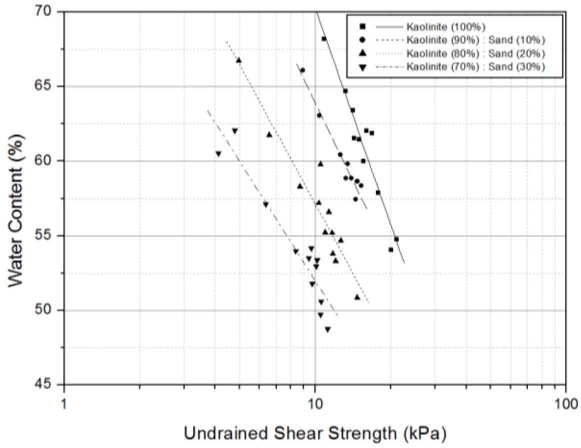


Fig. 6 Relation between quick undrained shear strength and water content

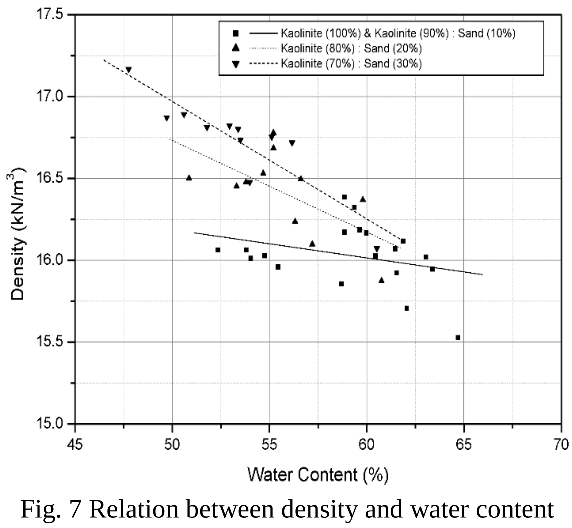
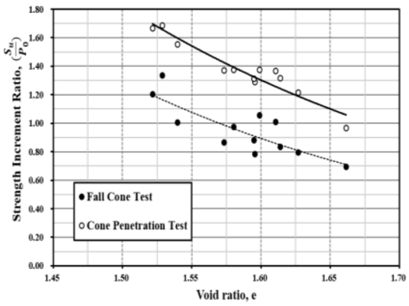
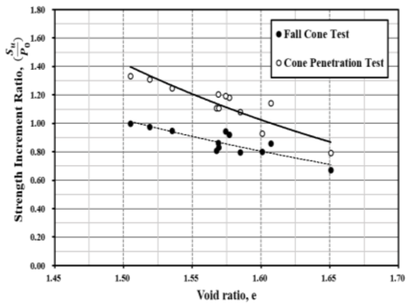


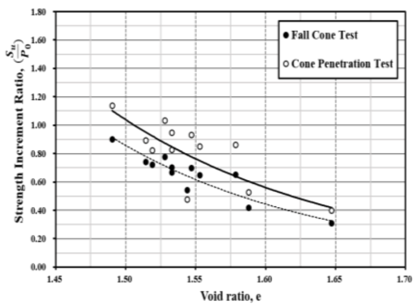
Fig. 7 Relation between density and water content



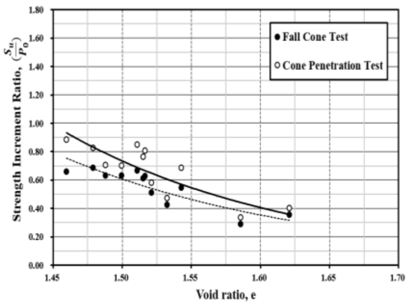
(a) Kaolinite (100%)



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



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



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

Fig. 8 Relation between strength increment ratio and void ratio

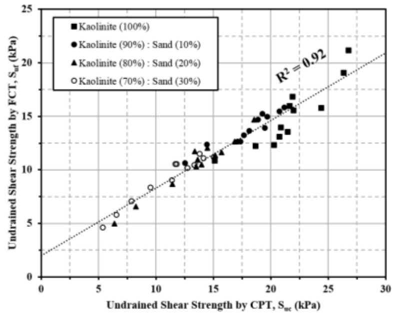


Fig. 9 Correlation between quick undrained shear strength of SCPT and FCT

Due to increasing sand percentage, with respect to decreasing kaolinite clay proportion, the sample becomes denser as shown in Fig. 7. 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 *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. 7, it was observed that when sand is added with kaolinite, the density of the soil increased and water content decreased. 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. In cases where sand content is more than 20%, it is shown that the change in density is distinctively noticeable. However, for sand content lower than 10%, there is minimal change in density with 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 and Lukas (1981) stated, that soil deposits 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 quick undrained shear strength will probably occur for lower effective pressures since the void ratios are higher at lower effective pressures. Fig. 8 represents the graph of strength increment vs. void ratio. From the figure, it can be observed that at lower preconsolidation stresses, the void ratios are slightly higher, and as a result, the quick undrained shear strength is lower. As shown in the figures, considering the same void ratio, the sample with lower sand content has a higher quick undrained shear strength value due to stronger cohesion.
The quick undrained shear strength relationship from the FCT and SCPT are observed to be related with consolidation load, which is shown by strength increase ratio (S_u/P_o) and void ratio (e). As preconsolidation load increases, void ratio is reduced, the adhesive force affecting the substantial strength is increased, and the 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 SCPT.

Fig. 9 is a comparison of the overall test results, showing the relationship of the quick undrained shear strength obtained by FCT and SCPT as the sand amount is increased. The quick undrained shear strength obtained by FCT and SCPT appear significantly correlated. The quick undrained shear strength of 100% kaolinite in SCPT appear larger than FCT, and as the sand content is increased, the internal friction is also increased. Therefore, as the soil adhesion is reduced, the cone penetration resistance reflects internal friction and density of sand in the total shear strength.

From the results shown in Fig. 9, the quick undrained shear strength from FCT (Fall Cone Test, S_{uf}) and SCPT (Static Cone Penetration Test, S_{uc}) is given by the following suggested relationship (Eq. (7)).

$$S_{uf}\ (kPa) = 0.631\, S_{uc} + 1.989 \tag{7}$$

5. Conclusions

Soils are generally classified as fine-grained or coarse-grained soils depending on the percentage content of the primary constituents. In reality, soils are actually made up of mixed and composite constituents. Soils primarily classified as fine-grained, still consists of a range of coarse particles as secondary constituents in between 0% to 50%. A laboratory scale model test was conducted to investigate the influence of coarse particles on the physical (e.g., density, water content, and void ratio) and mechanical (e.g., quick undrained shear strength) properties of primarily fine-grained cohesive soils. Pure kaolinite clay and sand-mixed kaolinite soil (e.g., sand content: 10%, 20%, and 30%) having various water contents (60%, 65%, and 70%) were preconsolidated at different stress levels (0, 13, 17.5, 22 kPa). Variation of void ratio and density were observed and the quick undrained shear strength properties were determined using the conventional Static Cone Penetration Test (SCPT) method and the Fall Cone Test (FCT) method.

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

• In FCT, the cone penetration rate increases as the kinetic energy is increased for soft soils with high water content. On the other hand, the cone penetration rate is reduced with the smaller initial water content because the quick undrained shear strength is also relatively increased. The relationships between quick undrained shear strength (S_{uf}) and kinetic energy is observed to be linear.

• A linear relationship exists between the fall cone shear strength and kinetic energy of the penetration rod when the shear strength of soil is lower. Initially, with increasing shear strength the kinetic energy decreased. When the speed of penetration is plotted against the ratio of kinetic energy to shear strength, a close relation was also found with a high correlation value. Although the samples were made with different sand and water contents, preconsolidated at different stress levels, the energy and shear strength relations were very similar. The high regression coefficient shows that it could be very useful to correlate these two parameters.

• From the correlation of SCPT tip resistance, it was obtained that the empirical cone factor N_c was decreased with the increased percentage of sand. The best fitted N_c value was observed to be 13.8, but in the case of 100% kaolinite, N_c = 17.55 is the given best-fit linear correlation coefficient. 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 quick undrained shear strength, strength increase ratio (S_u/P_o) and void ratio (e) 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 increased.

• The quick undrained shear strength generally increases as water content decreases. For the same water content at increased sand content, the quick undrained shear strength is reduced as the adhesion is decreased, and also, the density is increased.

•At higher sand content greater than 20%, there is no observed difference in the strength increase ratio (S_u/P_o) between FCT and SCPT. Similarly, it is observed that the change in density is distinctively noticeable at higher sand content greater than 20%. However, for lower than 10% amount of sand content, there is minimal change in density with water content. The results showed a decrease in quick undrained shear strength with increasing amount of sand and water content.

In general, the results showed a decrease in quick undrained shear strength with increasing amount of sand content. Therefore, as the soil adhesion is reduced the cone penetration resistances of the FCT and SCPT reflects internal friction and density of sand in the total shear strength.

Acknowledgments

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