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Model Studies on SCP Reinforced Reconstituted Kaolin Clay

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Abstract—**The physical properties of clay are of extreme importance in soil engineering and are largely controlled by reactions in which clay plays a leading part. Kaolin clay has been widely used both in fundamental studies of soil behavior and in physical model tests. In this paper, compression and shear behavior of reconstituted consolidated kaolin clay specimen reinforced with sand compaction pile (SCP) is examined by using consolidated undrained triaxial tests. The aim of this study is to study the behavior of soft cohesive soil reinforced with different diameter SCPs by observing the change in pore pressure during consolidation and undrained shear strength of the composite ground with/without smear. The experimental results show that the mechanical properties of soft kaolin clay can be tremendously improved with this ground improvement technique.**

Keywords—**Reconstituted, SCP, *pore pressure*, smear**

I. Introduction

Construction projects often encounter weak deposits which pose problems of stability. In such a situation, modification of the existing ground is usually beneficial [1]. A large number of ground improvement techniques such as compaction including vibro-replacement, vibro-flotation and dynamic consolidation, pre-loading with and without vertical drains, grouting, soil stabilization, soil reinforcement, and installation of sand or granular columns have been developed to improve poor ground conditions. Consideration of factors governing the choice of a method include volume and the degree of treatment, availability of the equipment and materials, ground conditions, experience, time and cost. Amongst the various techniques for improving in situ ground conditions, granular columnar inclusions are considered versatile and cost effective. Granular columns behave as piles in soft ground and carry load greater than the surrounding soft ground. Among the columnar inclusions, the Sand Compaction Pile (SCP) method is one of the most preferred worldwide column type soil improvement techniques.

Sand compaction pile (SCP) is a method of constructing large diameter sand columns in the ground. This method of ground improvement has been widely used for rapid improvement of soft ground, and also in near-shore regions for land reclamation works [2]. SCPs are also referred to as vibro-composer piles, because of the similarity of the two in the method of installation. The installation procedure is illustrated in Fig. 1. But the process of SCP installation affects the in-situ clay first, by remoulding the clay fabric immediately surrounding the SCP leading to the development of large shear strains in this zone; secondly, the clay is laterally compressed to accommodate the sand column. The disturbed or the smear zone depends upon the column diameter and the tools used in the installation [3]. The compression zone extends up to 2 to 3 times the pile diameter and depends upon the diameter of the casing as well as the final sand column and the depth from the surface [4].

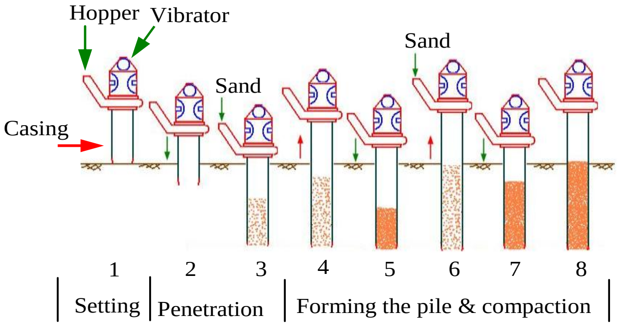

Fig.1. Sand pile installation by Vibro-composer
(after Aboshi and Suematsu 1985)

Laboratory tests are commonly used to determine design parameters of natural clays. Many aspects of the engineering behavior of cohesive soils have been explained by various authors [5]. Sample disturbance is one of the major factors influencing the accuracy of measured mechanical properties of natural soft clays [6-7] Kaolin clay has been widely used both in fundamental studies of soil behavior and in physical model tests. Tests on reconstituted kaolin clay have played a key role in establishing conceptual frameworks for explaining soil behavior [8-9]. In this paper, compression and shear behavior of reconstituted kaolin clay specimen wrapped with filter paper cage as side drains and reinforced with SCP diameter varied between 25 to 80mm in 100mm diameter and 200mm long cylindrical specimens is examined in a series of conventional triaxial consolidated undrained stress path tests. A custom-designed arrangement was developed for installation of SCPs in kaolin specimen consolidated on the

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laboratory floor before the triaxial testing. In this study, a composite specimen is prepared by driving a thin smooth casing into the soft clay deposits and then removing it to form a hollow cavity which is then backfilled with well-compacted sand using a vibration or impact load. The casing had a gritty texture in some specimens to create a smear zone surrounding the casing. Using this procedure, the effect of smear on the mechanical response of the composite soil could be investigated using well-defined testing procedures. These results are compared to the standard tests conducted on homogenous clay.

II. Experimental Program

Isotropic consolidated undrained triaxial shear (CIU) tests were conducted using kaolin clay. Table 1 summarises the index properties of the clay. The experimental program consisted of 10 tests on homogeneous clay and 20 tests on composite clay with SCP. The samples were prepared from slurry in 250mm diameter and 450mm long stainless steel cylindrical mould. The de-aired clay slurry was consolidated on the laboratory floor, first under its own self-weight and later under a surcharge which varied between 194 and 352 kN/m^2 applied in steps using a custom designed pneumatic load frame. Experimental program for homogeneous and composite specimens is given in Tables 2 & 3. Figure 2 shows the consolidation setup and specimen trimming process.

TABLE 1 PROPERTIES OF KAOLIN CLAY

Clay (%)	Silt (%)	Liquid limit (%)	Plastic limit (%)	Shrinkage limit (%)	G_s
75	25	49	23	16	2.64

TABLE 2. EXPERIMENTAL PROGRAM FOR HOGOGENEOUS CLAY SPECIMENS

Test No	1-D loading σ_v (kN/m^2)	Mean eff. Pr. (kN/m^2)			Pre consol pr . p_c' (kN/m^2)	OCR (P_c' /p_o')
		At the end of 1-D loading	At the end of consoln.	At th e end of shearing (p_o')		
P-1	194	141	500	500	500	1
P-2	211	153	300	300	300	1
P-3	277	160	50	50	160	3
P-4	277	159	30	30	30	5
P-5	277	165	100	100	165	1.65
P-6	352	267	500	50	500	10
P-7	352	253	500	100	500	5
P-8	211	153	300	100	300	3
P-9	211	153	300	300	200	1
P-10	211	149	400	50	400	8

TABLE 3. EXPERIMENTAL PROGRAM FOR COMPOSITE CLAY SPECIMENS

Test No.	Dia. of casing/ SCP (mm)	Mean effective stress p' (kN/m^2		Preconsol. pressure p_c' (kN/m^2)	OCR
		At the end of 1-D loading	At the end of consolidation/ shearing, (p_o')		(p_c' /p_o')
S-1	25	285	100 (no smear)	285	2.85
S-2		285	150 (no smear)	285	1.87
S-3		285	300 (no smear)	300	1
S-4		187	100 (with smear)	187	1.87
S-5		187	150 (with smear)	187	1.25
S-6		187	300 (with smear)	300	1
S-7	30	149	450 (no smear)	450	1
S-8		149	200 (no smear)	200	1
S-9		149	50 (no smear)	149	2.98
S-10		149	450 (with smear)	450	1
S-11		149	200 (with smear)	200	1
S-12		149	50 (with smear)	149	2.98
S-13	40	149	575 (no smear)	575	1
S-14		149	375 (no smear)	375	1
S-15		149	75 (no smear)	149	1.99
S-16		149	575 (with smear)	575	1
S-17		149	375 (with smear)	375	1
S-18		149	75 (with smear)	149	1.99
S-19	80	149	150 (no smear)	150	1
S-20		149	150 (with smear)	150	1

Fig. 2. Consolidation setup on the laboratory floor

Conventional consolidated undrained triaxial tests were performed on homogeneous specimens prepared from remoulded and reconsolidated commercially available kaolin clay under different cell isotropic confining pressures (30-500kN/m^2). Side drains of filter king paper was used to accelerate the rate of drainage of specimens. Kawakami [10] compared different filter paper cage positions in his tests. A similar procedure was adopted in the present study in which the upper end of the specimen was tucked over the top porous disc by $L_{P/}2.5$ (=5mm) of thickness of the porous stone, while the lower portion of the specimen was kept bare of the filter paper to avoid short-circuit between the back pressure and pore pressure systems [11].

For preparation of SCP specimens, the clay specimens were held in split cylindrical moulds while a thin steel casing was slowly pushed along its length to form a cylindrical hole at the centre. The hole was backfilled with fine sand and well-compacted in layers with the help of pneumatic compactor. Diameter of the sand column was varied between 25- and 80mm in different specimens. This corresponds to an area replacement ratio, a_s [12] that ranges between 6.25%, and 64%. Specimens were also prepared by inserting the casing painted with a paste of coarse sand and araldite adhesive to create smear effect. This thickness of the smear zone relative to the diameter of the sand column compares well with the values reported by the previous researchers [13]. The ratio of the diameter of SCP with smear zone to the diameter of SCP without smear zone (D_s/d_s) was about 1.1 to 1.2 in all tests. Preconsolidation pressure (p_c') in 1-D consolidation test was calculated using the equation:

$$p_c' = \sigma_V' (1 - 0.67 \sin \phi') \qquad (1)$$

where ϕ' is the effective angle of friction obtained from post consolidated undrained shear tests. Likewise, p_c' on the unloading-reloading line (URL) was calculated using the equation:

$$p_c' = \sigma_v' \left[\begin{array}{l} 0.33 + 0.67(1 - \sin \phi') \\ \exp\{(0.93 - 0.85(1 - \sin \phi'))\ln(OCR)\} \end{array} \right] \qquad (2)$$

Where OCR is the over consolidation ratio (p_c'/p') and p' is the mean effective stress. The soil specimen was then isotropically consolidated under mean effective stress, p' given as:

$$p' = \frac{\sigma_1' + 2\sigma_3'}{3} \qquad (3)$$

where σ_1' is the effective axial stress and σ_3' is the effective radial stress. p' was varied between 30- and 575kN/m^2 in different tests. Tables 2 and 3 also show the over consolidation ratio (OCR) of the specimens after isotropic consolidation. As the tables 2 & 3 shows, OCR was not 1 in all the specimens. It has often been argued that undrained shear strength of soil deposited due to pure volumetric compression often does not exactly follow the behaviour that is prescribed by K_o-consolidated soil [14]. Furthermore, results indicate that the behaviour of the failure zone which has reached critical state is essentially the same irrespective how the specimen has been prepared, as expected. The main difference between the predictions of the two methods of preparation lay in the response of the yielded zone that is which has not reached the critical state. Notwithstanding the above, the soil was remoulded and reconsolidated and there is unlikely to be any significant development of the fabric.

III. Results and discussion

Isotropic triaxial consolidation of reconstituted clay specimens

Triaxial consolidation tests were performed on 200mm long and 100mm diameter cylindrical specimens prepared from reconstituted commercially available kaolin clay without and with SCP. The effect of smear zone was investigated by observing the change in pore pressure during consolidation of the composite specimen. Figures 3 and 4 shows the average degree of consolidation, U_{avg} plotted against time during isotropic consolidation for selected clay specimen, clay specimen wrapped with side drain and reinforced with SCPs.

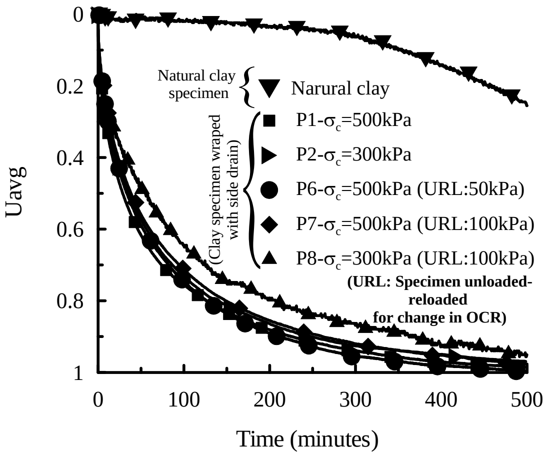

Fig. 3. Relationship between average degree of consolidation and time for homogeneous specimens

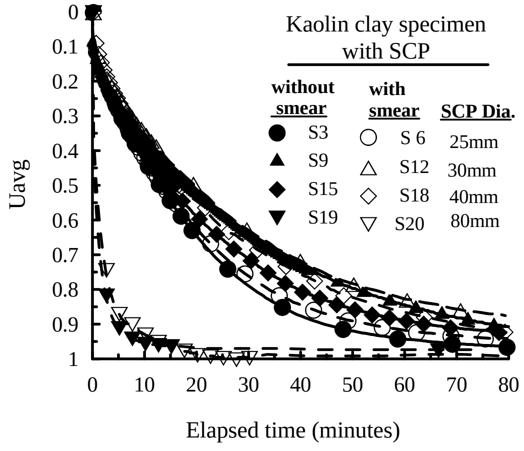

Fig. 4. Relationship between average degree of consolidation and time for composite specimens

It is seen that side drains take about 300minutes for 90% consolidation against SCP`s 80 minutes compared to 6-7 days of natural clay specimens. The effect of smear zone was also investigated by observing the change in permeability behavior with increasing mean effective stress. Figure 5 shows the variation of permeability with mean eff. stress for kaolin clay specimens with out and with reinforced with SCP. It is seen that clay specimens reinforced with SCP exhibit higher permeability than homogeneous clay specimens.

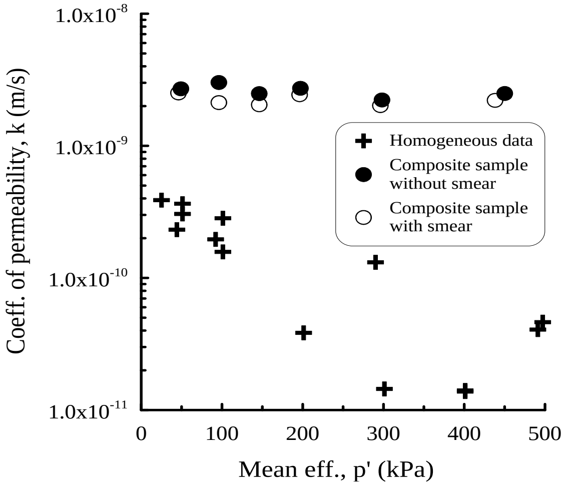

Fig. 5. Variation of permeability with mean eff. stress for kaolin clay specimens with out and with reinforced with SCP

Undrained compression behaviour of reconstituted clay specimens with and without SCP

Figure 6 shows the results of deviator stress, q plotted against axial strain, ε_a for selected unreinforced and reinforced clayey specimens under effective stress ranging from 100kPa to 575kPa.

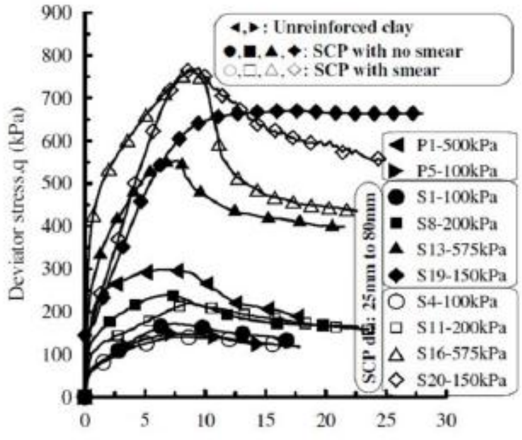

Fig. 6. q versus ε_a for unreinforced and reinforced clay specimens

As can be seen, unreinforced samples reached peak deviator stress (q_{max}) at 5 to 8% axial strain and reinforced samples at about 7 to 12% respectively. In few tests on normally consolidated clays, q decreased after passing q_{max} because of instability of the failed samples at high confining pressure. From Fig. 6, it is seen that for low stress level tests (P5 & S4), the ultimate strength for both types of samples is same. However, with increase in stress level SCP diameter and smear effect, the strength behavior is quite different.. It is also seen that in case of increasing SCP diameter (S20=80mm) and confining stress (S16-575kPa), the stress-strain curves exhibit a hardening behavior. This is understandable that in case of higher replacement ratio for 80mm dia SCP (though low stress level of 150kPa), the stiffness is controlled by SCP rather than clay alone. On the other hand, for S16 of 40mm SCP, the stiffness under high stress level (575kPa) is equally contributed by SCP and clay. For normally consolidated samples, the stress-strain curves do not show any significant change in q after passing peak stress. This will help in framing the design charts for field engineers and designers to select a proper SCP size and stress level for improvement of soft ground.

The undrained shear strength (s_u) of homogeneous and composite specimens was taken equal to $q_{max}/2$. Figure 7 shows the variation of undrained shear strength of homogeneous samples, s_u with OCR. In the figure, s_u was normalized by p_0' and was taken equal to $q_{max}/2$.. $\boldsymbol{s_u}$ obtained from the Cam Clay family of soil models are also superimposed in the figure. It was beyond expectations to observe that none of the two advanced soil models are able to correctly predict the variation of s_u/p_o' with OCR. Notwithstanding the above, the results permit a semi-empirical relationship to be fitted to the data of the form:

$$\frac{s_u}{p_0'} = 0.24[OCR]^{-0.13} \tag{4}$$

Figure 8 shows the variation of [s_u/p_o'*D/d] and OCR in composite samples after normalizing s_u/p_o' to the ratio of the diameters of SCP (D/) to reduce substantial scatter amongst the data points. Notwithstanding the above, the results permit

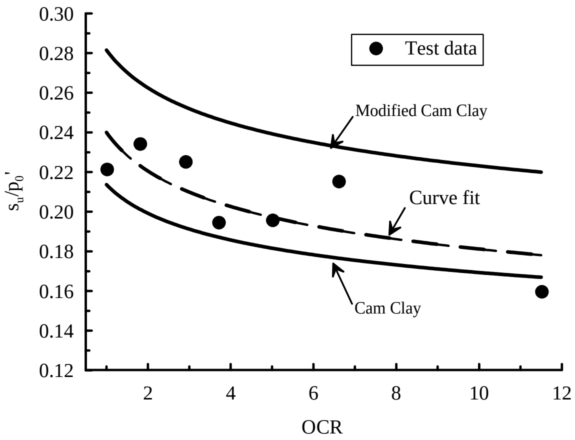

Fig. 7. Variation of shear strength of homogeneous samples with OCR.

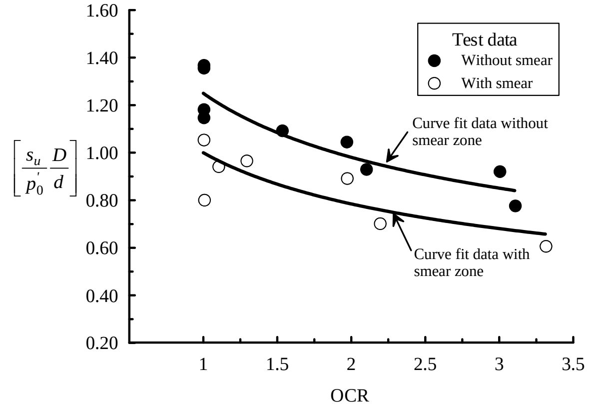

Fig. 8. Relationship between $\left[\frac{s_u}{p_0'}\frac{D}{d}\right]$ and OCR.

a semi-empirical relationship to be fitted to the data of the form:

$$\frac{s_u}{p_0'} = 1.25\frac{d}{D}[OCR]^{-0.36} \tag{5}$$

and curve fit to the data with the smear zone is of the form:

$$\frac{s_u}{p_0'} = \frac{d}{D}[OCR]^{-0.36} \tag{6}$$

It is seen that the decrease in s_u/p_o' with the increase in OCR is apparent. It seems clear that the presence of smear zone has reduced the ultimate undrained shear strength by 25%. Figures 9 which show water content at different locations measured after the completion of the tests. The figure shows that water content was not uniform throughout the sample.

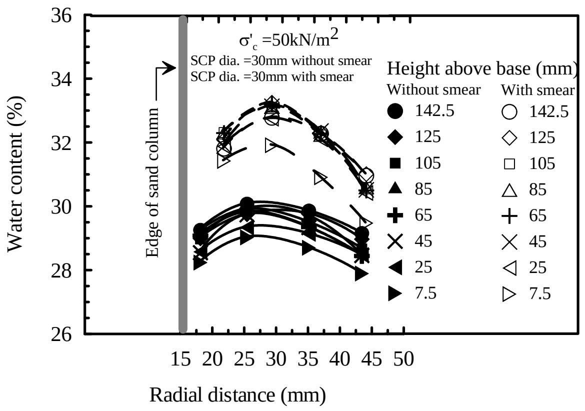

Fig. 9. Water content at different locations measured after the completion of the tests for composite samples

It is interesting to note that the water content was higher in the samples with the smear zone which supports the above supposition that the smear zone does not permit the complete dissipation of the pore pressure.

Conclusions

In this investigation, model studies on reconstituted clay has been studied using 10 consolidated undrained triaxial tests on homogeneous and 20 tests on composite samples It is concluded that SCP method is a viable method of improvement of soft ground. However, the presence of smear zone around SCP reduces pore water pressure dissipation and hence reduced permeability by about 20%. The stress-strain behavior of the clay was also influenced by the presence of smear zone and undrained shear strength is reduced by about 25%. However, with increase in area replacement ratio and SCP size, the effect of smear is not much prominent.

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