Effect of Smear on Strength Behavior of SCP-Reinforced Soft Ground

Effet de comportement de l'étalement de force du SCP- Sol mou renforcé

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ABSTRACT: Sand columns traditionally known as sand compaction piles-(SCPs) have been used to increase the load carrying capacity of soft clays and accentuate consolidation during preloading. Installation of SCPs is known to cause disturbance due to smear in a limited zone of the soil surrounding the SCP. In this study, conventional triaxial tests have been performed on 200mm long and 100mm-diameter clay samples installed with SCP to simulate the strength behaviour of composite ground under different confining pressures ranging from 50kpa to 575kpa. The SCPs were prepared using area replacement ratio of 6.25 to 64% and compacted using pneumatic compactor. The smear zone was created by using a rough casing to drill the hole. The results seem to suggest that the stress-strain behaviour of the clay was influenced by the presence of smear zone. The effect of smear zone on SCP was investigated by observing the change in pore pressure during undrained shear strength of the composite ground. The natural fabric of the soil was destroyed adjacent to the SCPs and the shear-induced pore pressures were less in composite specimens with smear-effect. In addition, as the area replacement ratio was increased, both the stiffness and the strength of the specimen increased.

RÉSUMÉ : Des colonnes de sable traditionnellement connues comme piles de compactage (SCPs) de sable ont été utilisées pour augmenter la capacité portante des argiles molles et accentuer la consolidation au cours du préchargement. L'installation de MCS est connue pour causer des perturbations dues au frottis dans une zone limitée du sol entourant le SCP. Dans cette étude, les essais triaxiaux conventionnels ont été réalisés sur les échantillons d'argile, de 100 mm de long et de 200 mm de diamètre, installés avec SCP pour simuler le comportement de la résistance du terrain composite sous différentes pressions de confinement allant de 50 kPa à 575 kPa. Les MCS ont été préparés à l'aide du coefficient de remplacement de 6,25 à 64 %, et compactées au pneumatique. La zone de souillure a été créée en utilisant une enveloppe rugueuse pour percer le trou. Les résultats donnent à penser que le comportement de contrainte-déformation de l'argile a été influencée par la présence de la zone de souillure. L'effet de zone de souillure sur SCP a été examiné en observant le changement de pression interstitielle au cours de la consolidation et de la résistance au cisaillement du sol composite. Le tissu naturel du sol a été détruit adjacent à la SCP et les pressions interstitielles induites par cisaillement étaient inférieures dans les échantillons composites avec un effet de maculage. En outre, lorsqu'on augmente le ratio de remplacement du frottis, la rigidité et la résistance de l'échantillon augmentent.

KEYWORDS: Sand compaction pile, installation effects, smear, soft ground
MOTS-CLÉS : Sable tas de compactage, les effets de l'installation, les frottis, sol mou

1 INTRODUCTION

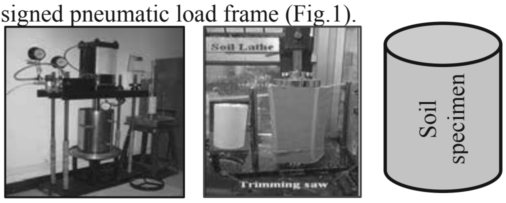
Soft ground is widely distributed especially along the coastal area, having large potential for settlement with low inherent shear strength. In the recent years, improvement of soft soils has been extensively implemented for the various development projects all over the world due to extremely limited stable construction sites. Granular piles such as sand compaction piles (SCPs) are considered as cost-effective and alternative solution to the problem of stability and settlement posed by construction on soft ground. The insertion of SCPs into soft clay has been shown to have a positive effect on the load carrying capacity of the clay, resulting in a composite soil mass that has greater shear strength and improved stiffness compared to the unreinforced clay. Sand compaction pile (SCP) is a method of constructing large diameter sand column 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 (e.g. Aboshi and Suematsu 1985, Bergado and Balasubramniam 1994). In India, the granular columns have been used to improve ground for container freight station at Navi Mumbai and the construction of dry dock at Pipavav shipyard (Raj and Dikshith 2009). Many researchers (e.g. Bergado et al. 1991, Juneja and Mir 2011) have investigated the effect of SCP installation on disturbance to the surrounding soil. The extent of the disturbed or smear zone can affect the engineering behaviour of the composite ground. The disturbance in this zone depends upon the column diameter and the tools used in the installation (e.g. Singh and Hattab 1979, Madhav et al. 1993). Shear induced pore pressures were found to be less in specimens which had the smear zone surrounding the sand column. However, pore pressures began to increase close to failure due to rearrangement of soil particles (Mir 2010). Laboratory and field tests previously conducted to determine the extent of the disturbance caused by pile driving into soft clay deposits have demonstrated that the natural structure of the clay around the pile is excessively disturbed (Randolph et al. 1979, Xu et al. 2006). It was observed that the diameter of the severely disturbed or remoulded ground around a driven closed-ended casing was about 1.4 times the diameter of the casing. Recently, Weber et al. (2010) compared the smear zone around model SCPs to that observed around driven piles. It was observed that the smear zone around SCPs installed on the centrifuge extended up to 1.2 to 1.4 times the SCP diameter. Dissipation of the excess pore pressures often results in increase in the shear strength. Aboshi et al. (1979) observed up to 50% increase in the undrained strength in about one month after the SCP installation at test sites in Japan. Matsuda et al. (1997) also reported an increase in strength of the composite SCP ground within three months of the SCPs installation.

In this study, the effect of smear zone on strength of model SCP installed in 100mm diameter and 200mm long clay specimens is investigated using conventional triaxial compression tests under different confining pressures ranging from 50kPa to 575kPa. The composite specimen were prepared by driving a small diameter PVC casing into the sample and then backfilling the cavity with sand column after removing the casing. The casing was roughened using sand glued to its outer walls prior to insertion to replicate the smearing effect. The SCPs were prepared using area replacement ratio of 6.25 to 64% and compacted using pneumatic compactor. SCPs of different diameters (25-80mm) were used to investigate the improvement in the load-carrying capacity of the specimens. The effect of smear zone on SCP was investigated by observing the change in pore pressure during consolidation and undrained shear strength of the composite ground. The test results suggest that, tress-strain behavior of the clay was influenced by the presence of smear zone. The natural fabric of the soil was destroyed adjacent to the SCPs with smear zone which in turn affected pore pressure response of the composite soil sample. Shear induced pore pressures were less in soil specimens with smear-effect, but this difference was not apparent when 80mm diameter SCP with smear zone was used. In addition, as the reinforcement area ratio increased, both the stiffness and the shear strength of the specimen increased. Thus, sand compaction piles currently stand as one of the most viable and practical techniques for improving the mechanical properties of soft clays.

2. EXPERIMENTAL WORK

2.1. *Materials and methods of sample preparation*

The test specimens were prepared in 450mm long and 250mm diameter stainless steel cylindrical mould. Deaired clay slurry was consolidated on the laboratory floor, first under its own self-weight and later under surcharge of 211- to 404 kN/m^2 applied in stages on top of the clay surface using a custom designed pneumatic load frame (Fig.1).



Slurry consolidation Specimen trimming Final specimen size

Figure 1. Consolidation set-up on the laboratory floor

Upon completion of the 1-D consolidation, the block of clay was extruded and trimmed into three 100mm diameter cylindrical specimens using soil lathe. Up to 3 specimens could together be prepared using this mould. The experimental program consisted of 20 tests on composite clay with sand column. The specimens were held in split cylindrical moulds and a smooth PVC casing slowly pushed along its length to form a cylindrical hole at the centre. The hole was backfilled with fine sand (d_{50}=0.3mm) compacted in layers at 90% relative density using a pneumatic compactor (Fig. 2).

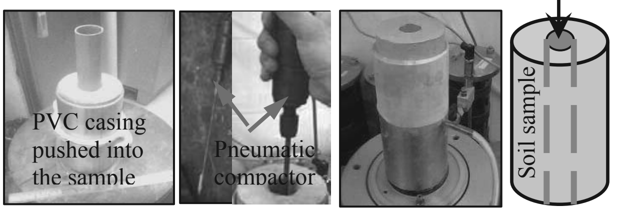


Figure 2. Preparation of composite specimen

Diameter of the sand column varied between 25- and 80mm in the specimens. This corresponds to an area replacement ratio, a_s (Aboshi et al. 1979) that ranges between 6.25- and 64%. The smear zone was created by using a rough casing painted with a paste of coarse sand (d_{50} = 1.3mm) to drill the hole. Thickness of the smear zone was taken equal to the thickness of the paste. The effect of smear beyond this zone was ignored. After preparing the sand column, the ends of the specimen were covered with a thin circular rubber sheets having a central hole. Diameter of the hole was slightly less than that of the sand column so as to only permit radial drainage. Two deaired porous stones were then placed at the two ends of the specimen and the entire assembly mounted on the triaxial chamber.Table 1 shows properties of the clay used in this study. The ratio of the diameter of sand column with smear zone to the diameter of sand column without smear zone (d_s/d) was about 1.1 to 1.2 in all tests, which compares well with the values reported by the previous researchers (e.g. Indraratna and Redana, 1998; amongst others). The specimen was enclosed in a rubber membrane and the chamber filled with water. The soil samples were then isotropically consolidated under mean effective stress, $\boldsymbol{p'}$ which varied between 50 and 575 kN/m^2.

Table 1 Properties of kaolin clay

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

3. RESULTS AND DISCUSSIONS

Consolidated undrained triaxial tests were performed on 200mm long and 100mm diameter cylindrical samples prepared from remoulded and reconsolidated commercially available kaolin clay installed with SCP. Table 2 shows the details of the soil specimens prepared for testing. In the table, OCR is defined as the ratio of the isotropic preconsolidation pressure, $\boldsymbol{p_0'}$ to $\boldsymbol{p'}$. $\boldsymbol{p_0'}$ was taken equal to the higher of either $\boldsymbol{p'}$ or the mean effective stress after 1D consolidation, $\boldsymbol{p'}$ estimated using the equation (Wroth 1984):

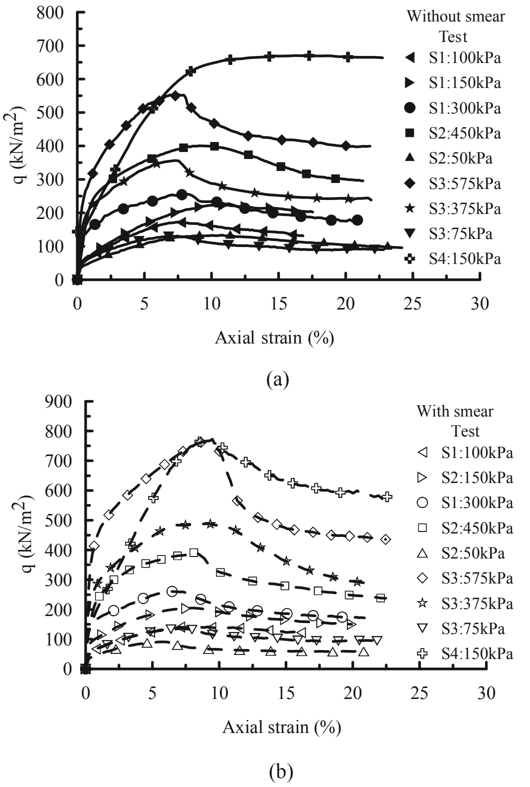
$$p' = \sigma'_v\left[1 - 0.67\sin\phi'\right] \qquad (1)$$

where ϕ' is the effective angle of friction (e.g. Schofield and Wroth 1968). The load-deformation data was analyzed using the unit cell arrangement proposed by Balaam et al. (1977). In this method, the column and surrounding clay are assumed to act as a single element with equivalent distributions of stresses and strains in composite specimens. Figures 3a-b show results of deviator stress, q plotted against axial strain, ε_a. As can be seen, all samples reached peak deviator stress (q_{max}) at 6 to 10% axial strain. Figures 3a-b also show that the ultimate strength exhibit transient peaks in some tests. This was expected since these soil samples were overconsolidated prior to the shearing. In few tests on normally consolidated clays, q decreased after passing q_{max} because of instability of the failed samples at high confining pressure.

Table 2 Experimental program

Test No	$\sigma'_v{}^{*}$ (kPa)	$d_s{}^{\#}$ (mm)	Smear zone	$p'_o{}^{\$}$ (kPa)	p'^{**} (kPa)	OCR
S1	404	24.6	✗	285	95	3
S1	404	24.6	✗	285	146	2
S1	404	24.6	✗	300	299	1
S1	264	29	✓	187	95	2
S1	264	29	✓	187	145	1.3
S1	264	29	✓	300	289	1
S2	211	31.7	✗	450	450	1
S2	211	31.7	✗	200	197	1
S2	211	31.7	✗	149	50	3
S2	211	35.7	✓	450	434	1
S2	211	35.7	✓	200	195	1
S2	11	35.7	✓	149	49	3
S3	211	40	✗	375	374	1
S3	211	40	✗	575	575	1
S3	211	40	✗	149	71	2.1
S3	211	45.2	✓	575	572	1
S3	211	45.2	✓	375	372	1
S3	211	45.2	✓	149	68	2.2
S4	211	80	✗	149	144	1
S4	211	80	✓	149	142	1

*: σ'_v=Vertical stress at end of 1D loading,
#: d_s = Equivalent diameter of sand column,
$: p'_o=Preconsolidation pressure,
**: p' = Mean effective stress at end of consolidation,



(a)

(b)

Figure 3a-b Deviator stress versus axial strain relationship for: (a) Samples without smear zone; and (b) Samples with smear zone.

The undrained shear strength (s_u) of composite specimen was taken equal to $\frac{q_{max}}{2}$, and the effect of stress history induced over consolidation on undrained strength ratio $\frac{s_u}{p'}$ was expressed as:

$$\left(s_u/p'\right)_{OC} = a\left(OCR\right)^m \tag{2}$$

where a is the normalized undrained shear strength of NC soil equal to $\left(s_u/p'\right)_{NC}$ for OCR=1, and m is an empirical exponent equal to $\left(1-\frac{\kappa}{\lambda}\right)$, κ, λ are soil model parameters obtained from triaxial testing. Using test data, undrained shear strength (s_u) of composite ground was expressed in the following form:

$$\left(s_u/p'\right) = 0.44\left(OCR\right)^{0.99} \text{ - without smear} \tag{3}$$

$$\left(s_u/p'\right) = 0.33\left(OCR\right)^{0.90} \text{ - with smear effect} \tag{4}$$

The evidence of the smear zone was not significant on the ultimate undrained shear strength when 25mm and 30mm diameter sand columns were used. What was surprising is that the effect of smear was apparent on the ultimate shear strength when 80mm diameter sand columns were used. It seems clear that the presence of smear zone has reduced the ultimate undrained shear strength by 25%. In addition, as the area replacement ratio was increased, both the stiffness and the shear strength of the composite samples also increased. Figure 4 show results of Skempton's (1954) pore pressure parameter, *a*, plotted against axial strain, ε_a. As seen, the A-factor in specimens with smear effect was less from early stage of shearing even when the specimens had the same OCR. This was expected because the smear zone did not permit the pore pressures to dissipate within the SCP. However, there was a marginal increase in a-factor after passing q_{max}. a_f of these samples was between 0.7 and 1.1 which is typical for normally consolidated clays.

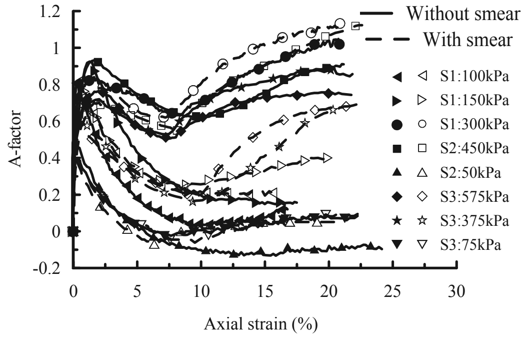


Figure 4. Variation of Skempton`s parameter A with axial strain for samples with and without smear zone.

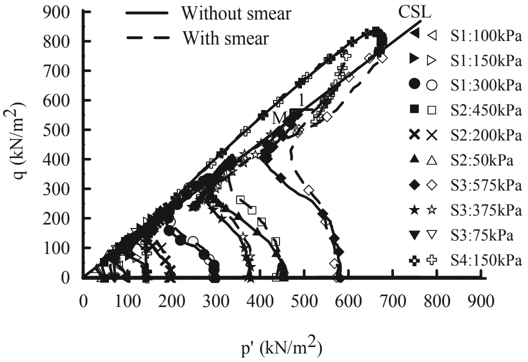
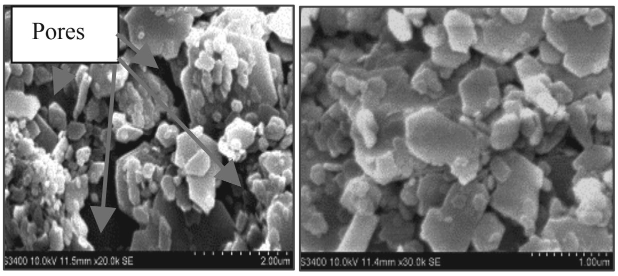


Figure 5. Effective stress paths for samples without smear and with smear zone

Figure 5 show the effective stress path in *p'*-*q* stress space.

The figures show that the shear induced pore pressures were found to be less in specimens which had the smear zone surrounding the sand column. Due to the smear zone, these pore pressures within the SCP were reduced because the water was not permitted to flow towards the column during shearing.

This was also evident from Scanning Electron Microscope (SEM) images (Fig. 6a-b) taken on post shear tests of specimens with and without smear. The images of samples with and without the smear zone show differences in the microstructure. The clay minerals in the smear zone appear to be closely packed with reduced pore space. 7.5 mm x 7.5 mm x 7.5 mm air dried samples were prepared at room temperature for the SEM images.



(a) (b)

Figure 6. SEM images: (a) Composite samples without smear zone; and (b) Composite samples with smear zone.

4. CONCLUSIONS

The strength behavior of composite ground reinforced with sand compaction piles has been studied using 20 consolidated undrained triaxial tests. Vertical stress of the sand column was examined when the composited specimens were tested to failure in conventional triaxial tests. The test results suggest that the stress-strain behavior of the clay was influenced by the presence of smear zone. It seems clear that the presence of smear zone has reduced the ultimate undrained shear strength by 25%**.** SEM images indicated that the natural fabric of the soil was destroyed adjacent to the SCPs with smear zone which in turn affected pore pressure response of the composite soil sample. Specimens sheared with smear effect appear closely packed and more homogeneous with partly discernible particle systems, while specimen without smear condition indicate a distinct division between smaller intra-aggregate pore spaces and the larger inter-aggregate voids. Shear induced pore pressures were less in soil specimens with smear-effect because the water was not permitted to flow towards the column during shearing. It was postulated that the difference in the behavior of smear and non-smear specimens was because that the pore pressure measurements were taken within the sand column. This difference was not apparent when 80mm diameter SCP with smear zone was used. These changes affect the effective horizontal stress in the clay and hence the load carried by the individual sand columns.

5. ACKNOWLEDGEMENT

The first author would like to acknowledge the financial support from the Indian Institute of Technology Bombay (IITB) in the form of research scholarships.

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