Effect of Smear on Consolidation of Sand Columns in Soft Clay Subsoils

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ABSTRACT

Granular columns such as sand columns are considered as cost-effective solution to the problem of stability and settlement posed by construction on soft ground. Installation of the sand columns is known to cause disturbance due to smear in a limited zone of the soil surrounding the sand columns. In this paper, the effect of smear on consolidation of model sand columns installed in 200mm long and 100mm diameter cylindrical clay specimens was investigated using conventional triaxial consolidation tests under different confining pressures ranging from 100kPa to 575kPa. Change in volume of the specimen was measured using automatic volume change apparatus. This typically required a consolidation time of about 100 minutes compared to more than 6-7 days required to consolidate the specimen without the side drains. However, specimens prepared with smear-effect took slightly more time to consolidate thereby lending further confidence to the method used to create the smear zone.

1. INTRODUCTION

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. Soft clay foundations present considerable construction problems. Therefore, the design and construction of surface structures requires thorough geotechnical knowledge of these soft foundations, in order to prevent excessive settlements and associated structural damage. Granular columns are considered as cost-effective method as well as alternative solution to the problem of stability and settlement posed by construction on soft ground. Sand columns behave as vertical drains in soft ground and accentuate consolidation during preloading. 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). It creates well-compacted sand piles in soft ground by using a vibration or impact load. Installation of the sand columns is known to cause disturbance due to smear in a limited zone of the soil surrounding the sand drain. Thickness of the disturbed zone depends upon the roughness of the casing used during the installation amongst other factors and, is associated with reduced permeability and high pore pressures. 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. Laboratory tests on model sand drains have shown that there was significant reduction in the horizontal permeability in the vicinity of the drain, and the extent of the smear zone caused by mandrel driven vertical drains, which otherwise was estimated based on the pore pressure generated (Sathananthan and Indraratna 2006). The extent of the smear zone was also confirmed from the change in permeability of the clay layer in the smear zone obtained from oedometer tests (Sharma and Xiao 2000).

In this paper, the consolidation of model sand columns installed in 100mm diameter and 200mm long clay specimens was investigated using conventional triaxial compression tests. The composite specimens
were prepared by driving a small diameter PVC casing into the specimen and then backfilling the cavity with sand column after removing the casing. The smear zone was created by using a rough casing to drill the hole. The composite specimens were first saturated and then consolidated isotropically under different confining pressures ranging from 100kPa to 575kPa. Change in volume of the specimen during consolidation was measured using automatic volume change apparatus. This typically required a consolidation time of about 100 minutes compared to more than 6-7 days required to consolidate the specimen without the side drains. However, specimens prepared with smear-effect took slightly more time to consolidate thereby lending further confidence to the method used to create the disturbed zone. The results show that the dissipation of excess pore water pressure occurs faster in the radial direction due to the greater coefficient of soil permeability in the horizontal direction and the reduced drainage path. Thus, the main function of sand drain application is to accelerate soil consolidation by shortening the drainage path and activating radial drainage, thereby reducing post-construction settlement.

2. EXPERIMENTAL PROGRAM

The test specimens were prepared in 450mm long and 250mm diameter stainless steel cylindrical mould. Up to 3 specimens could together be prepared using this 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. Upon completion of the 1-D consolidation, the block of clay was extruded and trimmed into three 100mm diameter cylindrical specimens. 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 using pneumatic compactor.

Diameter of the sand column varied between 25- and 40mm in the specimens. This corresponds to an area replacement ratio, a$_s$ (Aboshi et al. 1979) that ranges between 6.25- and 16%. 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. 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/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). Table 2 shows the details of the soil specimens prepared for testing.

### Table 1: Properties of Kaolin Clay

<table>
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<tr>
<th>Clay (%)</th>
<th>Silt (%)</th>
<th>Liquid limit (%)</th>
<th>Plastic limit (%)</th>
<th>Shrinkage limit (%)</th>
<th>G$_s$</th>
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### Table 2: Experimental Program

<table>
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<tr>
<th>Test No</th>
<th>$\sigma'_0$ (kPa)</th>
<th>d$_s$ (mm)</th>
<th>Smear Zone</th>
<th>$p'_o$ (kPa)</th>
<th>$p''$ (kPa)</th>
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* $\sigma'_0$ = Vertical stress at end of 1D loading,

$\sigma'_o$ = Preconsolidation pressure,

$\sigma''$ = Mean effective stress at end of consolidation.

3. RESULTS AND DISCUSSIONS

Triaxial consolidation tests were performed on 200mm long and 100mm diameter cylindrical specimens prepared from remoulded and reconsolidated commercially available kaolin clay. The effect of smear zone was investigated by observing the change in pore pressure during consolidation of the composite specimen. Fig. 1a-c shows the average degree of consolidation, U$_{avg}$ plotted against time during isotropic consolidation. As can be seen, specimens prepared with smear-effect took slightly more time to consolidate thereby lending further confidence to the method used to create the disturbed zone.

Theure also shows that not all specimens with smear-effect were consolidated up to U$_{avg}$ of 1. This is also evident from Fig. 2a, which shows the variation of coefficient of permeability, k for selected soil specimens deduced from consolidation data against $\sigma''$ using the procedure suggested by Barron (1948). The results seem to suggest that there was a marginal reduction of permeability by about 20% when specimens were prepared using the smear-effect compared to the k of the composite samples prepared
Fig. 1: a-c Variation of Average Degree of Consolidation with Time Using Sand Columns of: (a) 25 mm Diameter; (b) 30 mm Diameter; and (c) 40 mm Diameter, without the smear zone. The variation of coefficient of horizontal consolidation with mean effective stress is shown in Fig. 2b.

This is also obvious from Figs. 3a-c which show water content at different locations measured after the completion of the tests. The figures show that water content was not uniform throughout the sample length, and 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. Similar results have been reported under radial drainage by many researchers (e.g. Atkinson et al. 1985, Robinson and Shilpa 2008).

Fig. 2: a-b Variation of: (a) Coefficient of Permeability; (b) Coefficient of Consolidation with Mean Effective Stress for Composite Samples

Fig. 3: a-c Variations of Water Content at Different Locations Measured after the Completion of the Tests for Composite Samples

The variation of volume change ($\Delta V$) against consolidation cell pressure ($\sigma_c$) is shown in Fig. 4.

Fig. 4: Variations of Volume Change with Consolidation Cell Pressure

Summary of Table 1:

<table>
<thead>
<tr>
<th>Area Ratio, $a$ (%)</th>
<th>$\sigma_c$ (kPa)</th>
<th>Water Content (%)</th>
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</thead>
<tbody>
<tr>
<td>10.25%</td>
<td>200kN/m$^2$</td>
<td>2.5</td>
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As shown in Fig. 4, the effect of smear on the variation of volume change against low cell pressure (<100kPa) in zone-I is not much dominant. In zone-II, the smear effect increases under confining pressures ranging from 100kPa to 300kPa and the material is considerably disturbed. In zone-III ($\sigma > 300kPa$), it is interesting to note that the smear effect was not evident with increasing consolidation pressure despite increasing the area replacement ratio of improved ground. This may be attributed due to the high area replacement ratios used in 40mm diameter sand columns. The results seem to suggest that radial drainage can give rise to significant non-uniformities during consolidation of soil specimens. The properties within the smear zone are also shown to vary with the overburden pressure (Bergado et al. 1993). Notwithstanding the above, the focus of this study is to note the difference in the soil behaviour when a well defined smear zone is formed surrounding the sand column.

4. CONCLUSIONS

The effect of smear was studied using 18 triaxial consolidation tests on composite specimens. The installation of the sand columns by means of a rough casing causes remoulding of the subsoil in a limited zone of the soil surrounding the sand columns. The presence of smear zone was shown to affect the consolidation characteristics of the composite sample. The soil permeability was reduced by about 20% which was also manifested by the water content variation and pore pressure dissipation in the composite specimen. The smear zone did not permit the excess pore water in the clay to dissipate quickly towards the sand column as the result the pore pressure transducer located below the sand column recorded less pore pressure changes. Hence, the effective stress manifested due to the all-round uniform cell pressure is not uniform throughout the specimen. The non-uniformity of consolidated ground and its consequence on subsequent construction of structures needs further study.

ACKNOWLEDGEMENT

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REFERENCES


