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PERMEABILITY AND CONSOLIDATION BEHAVIOR OF COMPOSITE GROUND REINFORCED WITH SAND COLUMNS

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ABSTRACT: In this paper, the behavior of the composite ground reinforced with sand columns with and without smear effect installed in 200mm long and 100mm diameter cylindrical clay specimens was investigated using conventional triaxial consolidation tests under different confining pressures ranging from 50kPa to 575kPa. Change in volume of the specimen was measured using automatic volume change apparatus. This typically required a consolidation time of about 100minutes compared to more than 6-7days required to consolidate the specimen without the sand columns. 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. The test results showed that the dissipation of excess pore water pressure occur faster in the radial direction due to the greater coefficient of soil permeability in the horizontal direction and the reduced drainage path.

Keywords: Composite ground, Sand column, Soil improvement, Smear, Permeability, Consolidation

1. INTRODUCTION

Soft clay deposits usually have a low bearing capacity and undergo excessive settlement over a long period of time. One of the important problems geotechnical engineers are often to deal with is the accurate and reliable measurement of permeability and compressibility characteristics of soft soils. The coefficient of consolidation is an essential soil parameter required for seepage, settlement, stability calculations and for predicting the rate of settlement of soft soils. The importance of compressibility characteristics are further increased in case of environmental problems, such as waste disposal and detrimental effects on the surrounding ground due to contamination.

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. But one of the major problems associated with soft soils is the presence of thick deposits of soft clayey ground. Thus, soft clay foundations present considerable construction problems. Therefore, where poor ground conditions make traditional forms of construction expensive, it may be economically viable to attempt to improve the engineering properties of the ground before building on it. This can be done by reducing the pore water pressure, by reducing the volume of voids in the soil, or by adding stronger materials. Although there are a variety of ground improvement techniques under different categories, granular piles such as sand columns or sand compaction piles (SCPs) are considered as cost-effective method as well as alternative solution to the problem of stability and settlement posed by construction on soft ground. In particular, the insertion of stone or sand columns 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 [1]. In addition, sand columns generally act as vertical drains in the clay thus accelerating the dissipation of excess pore water pressures that are generated during preloading. As such, sand columns currently stand as one of the most viable and practical techniques for improving the mechanical properties of soft clays. The consolidation time can be reduced to achieve a required degree of consolidation by selecting suitable drain spacing and an appropriate installation pattern [2]. 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. [3]-[4]. In India, the sand columns have been used to improve ground for container freight station at Navi Mumbai and the construction of dry dock at Pipavav shipyard Gujarat [5]. But, installation of the sand columns is known to cause disturbance due to smear in a limited zone of the soil surrounding the sand column [6]-[8]. Thickness of the disturbed zone depends upon the roughness of the casing used during the installation 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 [9]-[11]. Recently, Weber TM et al. [12] compared the smear zone around model SCPs installed on the centrifuge to that observed around driven piles. The smear zone around the SCP was observed to extend up to 1.2 to 1.4 times the SCP diameter. It was perhaps not a coincidence that the thickness of the smear zone was comparable to the thickness of the disturbance, which is usually observed around piles driven in soft clays [9]. Similarly, Bond and Jardine [13] observed that the thickness of the smear zone was narrow when the piles were driven in overconsolidated clays. If the extent of the disturbance around SCPs is taken analogous to that observed around driven piles, then any change in the clay fabric during the SCP installation will also affect the permeability and pore pressure dissipation, and consequently the load-carrying capacity of the composite ground [14]-[15].

Laboratory tests on model sand drains have shown 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 [16]-[18]. 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 [19].

In this paper, the behavior of the composite ground reinforced with sand columns is analyzed. The consolidation of model sand columns installed in 100mm diameter and 200mm long clay specimens was investigated using conventional triaxial consolidation 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 casing was painted using sand glued with araldite prior to the insertion to create smear zone. Diameter of the sand particles glued to the casing was taken as a measure of the smear zone. The composite specimens were first saturated and then consolidated isotropically under different confining pressures ranging from 50kPa 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 100minutes compared to more than 6-7days required to consolidate the specimen without sand columns. 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 column application is to accelerate soil consolidation by shortening the drainage path and activating radial drainage, thereby reducing post-construction settlement [20].

2. EXPERIMENTAL WORK

2.1. Materials and methods of sample preparation

Isotropic consolidated triaxial tests were performed on 100mm diameter and 200mm long specimens [21] prepared from commercially available kaolin clay. The experimental program consisted of 18 triaxial consolidation tests on composite specimen. The triaxial samples were prepared in 250mm diameter and 450mm long stainless steel cylindrical mould. Up to 3 specimens could together be prepared using this mould. De-aired clay slurry was consolidated on the laboratory floor, first under its own self-weight and later under surcharge of 211- to 404kN/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 specimens using soil lathe (Fig. 1).

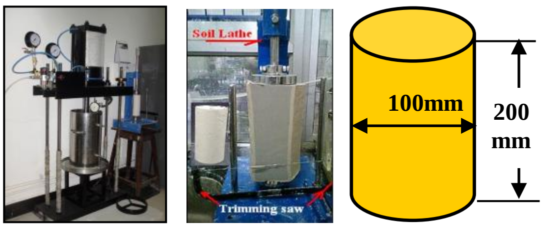


Fig.1 Consolidation set-up on the laboratory floor and specimen trimming

Three additional steps were undertaken to prepare the composite samples. In the first step, a cylindrical hole was cored through the centre of the sample using a thin, smooth casing. The diameter of the hole varied between 25 and 45 mm in different tests. In the second step, air-dry sand (d_{50} = 0.3 mm) was poured into the hole in layers and each layer compacted at 90% relative density using a pneumatic compactor. The final diameter of the sand column was equal to the diameter of the hole. In some tests, the outer surface of the casing was made gritty by painting a paste of coarse sand mixed with araldite. This helped to create a smear zone around the compacted sand column. In the third step, two circular rubber sheets with a hole at the centre were placed at the ends of the sample (Fig. 2).

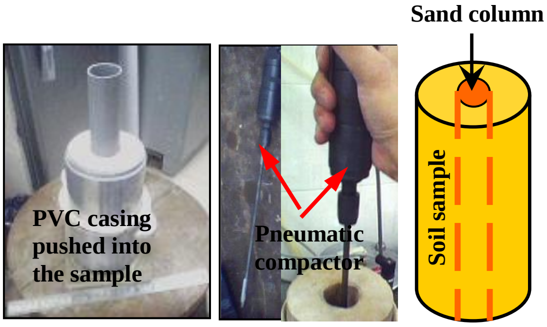


Fig. 2 Preparation of composite specimen

The diameter of the hole was slightly less than that of the sand column so as to only permit radial drainage during consolidation. Table 1 shows the properties of the clay and Table 2 shows experimental program used in this study.

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 composite samples

Test No	σ'_v* (kPa)	d_s# (mm)	Smear zone	p'_c $ (kPa)	p'** (kPa)	OCR = p'_c/p'
S1	404	25	✕(no)	285	100	3
S2	404	25	✕	285	150	2
S3	404	25	✕	285	300	1
S4	264	29	✓(yes)	187	100	2
S5	264	29	✓	187	150	1.2
S6	264	29	✓	187	300	1
S7	211	32	✕	149	450	1
S8	211	32	✕	149	200	1
S9	211	32	✕	149	50	3
S10	211	36	✓	149	450	1
S11	211	36	✓	149	200	1
S12	211	36	✓	149	50	3
S13	211	40	✕	149	375	1
S14	211	40	✕	149	575	1
S15	211	40	✕	149	75	2
S16	211	45	✓	149	575	1
S17	211	45	✓	149	375	1
S18	211	45	✓	149	75	2

*: σ'_v = Vertical stress at end of 1D loading,
#: d_s = Equivalent diameter of sand column,
$: p'_c = Preconsolidation pressure= $\sigma'_v/3\ (1+2k_o)$
**: P′ = mean effective stress at end of consolidation

In this table, σ_v is the 1-D vertical stress used for consolidating slurry in cylindrical mould on the laboratory floor. Mean effective stress (p′) towards the end of 1-D loading was estimated using K_o (0.56) obtained from undrained shear test results

3. RESULTS AND DISCUSSIONS

3.1. Variation of degree of consolidation

Triaxial consolidation tests were performed on 200mm long and 100mm diameter cylindrical specimens prepared from remolded and reconsolidated commercially available kaolin clay. Two circular rubber sheets with a hole at the centre were placed at the two ends of the sample so as to only permit radial drainage during consolidation. Change in volume of the sample during consolidation was automatically measured using the volume change apparatus. This typically required a consolidation time of about 40minutes compared to more than 6-7days required to consolidate the specimen without sand columns for achieving 90%consolidation (Fig.3).

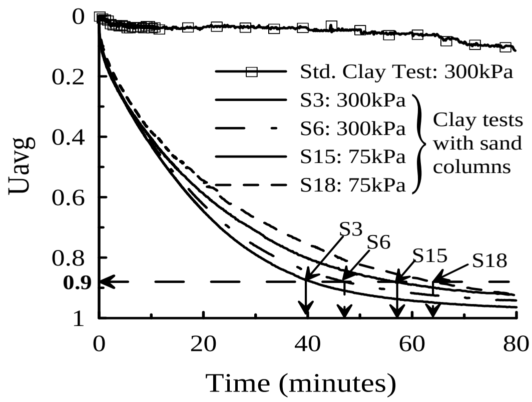
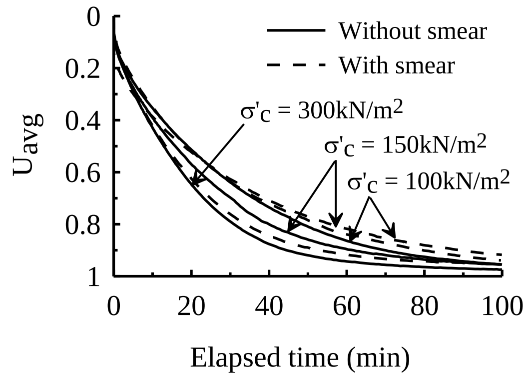
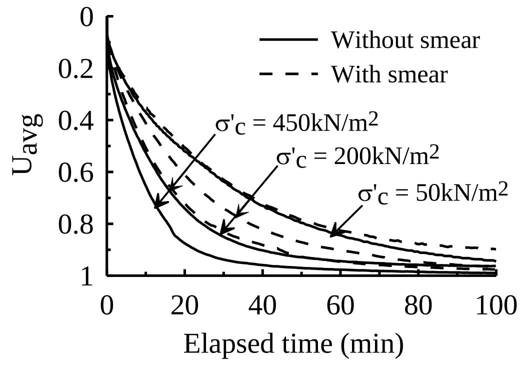


Fig. 3 Variation of time for consolidation of clay specimen with and without sand column

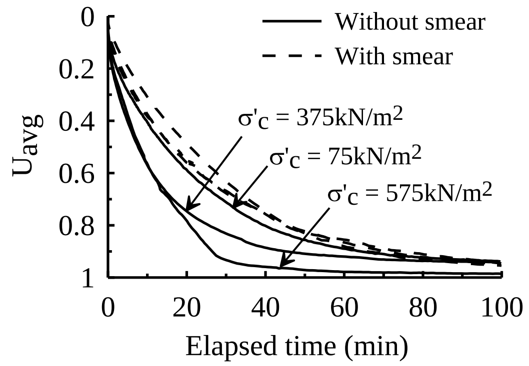
The effect of smear zone was also investigated by observing the change in pore pressure during consolidation of the composite specimen. Fig. 4a-c shows the average degree of consolidation, U_{avg} plotted against time during isotropic consolidation. As can be seen, the figures show that the time to 90% consolidation reduced to less than 40 min with the use of sand column under effective confining pressure of 300kPa (Fig. 4a). 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 figure also shows that not all specimens with smear effect were consolidated up to U_{avg} of 1. Similar results have been reported under radial drainage by many researchers [22]-[24].



(a)



(b)

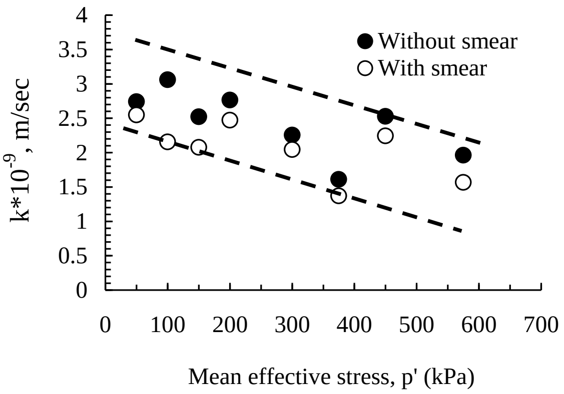


(c)

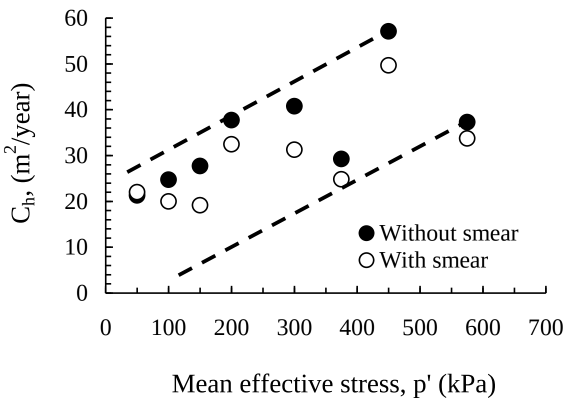
Fig.4a-c Variation of average degree of consolidation with time using sand columns of: (a) 25mm diameter; (b) 32mm diameter; and (c) 40mm diameter

3.2 Variation of coefficient of permeability and coefficient of consolidation

Figure 5a shows the variation of coefficient of permeability, *k* for selected soil specimens deduced from consolidation data against *p'* using the procedure suggested by [25]. 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 without the smear zone. The variation of coefficient of horizontal consolidation with mean effective stress is shown in Fig. 5b.



(a)



(b)

Fig. 5a-b Variation of: (a) coefficient of permeability; (b) coefficient of consolidation with mean effective stress for composite samples.

3.3 Variation of water content

After post compression tests, composite specimens were cut into slices for determination of variation of water content throughout the length of the samples. Figure 6 shows water content variation at different locations measured after the completion of few selected tests with and without smear effect. From Fig. 6, it is seen 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. The results seem to suggest that radial drainage can give rise to significant non-uniformities during consolidation of soil specimens. Similar results have also been reported by [22].

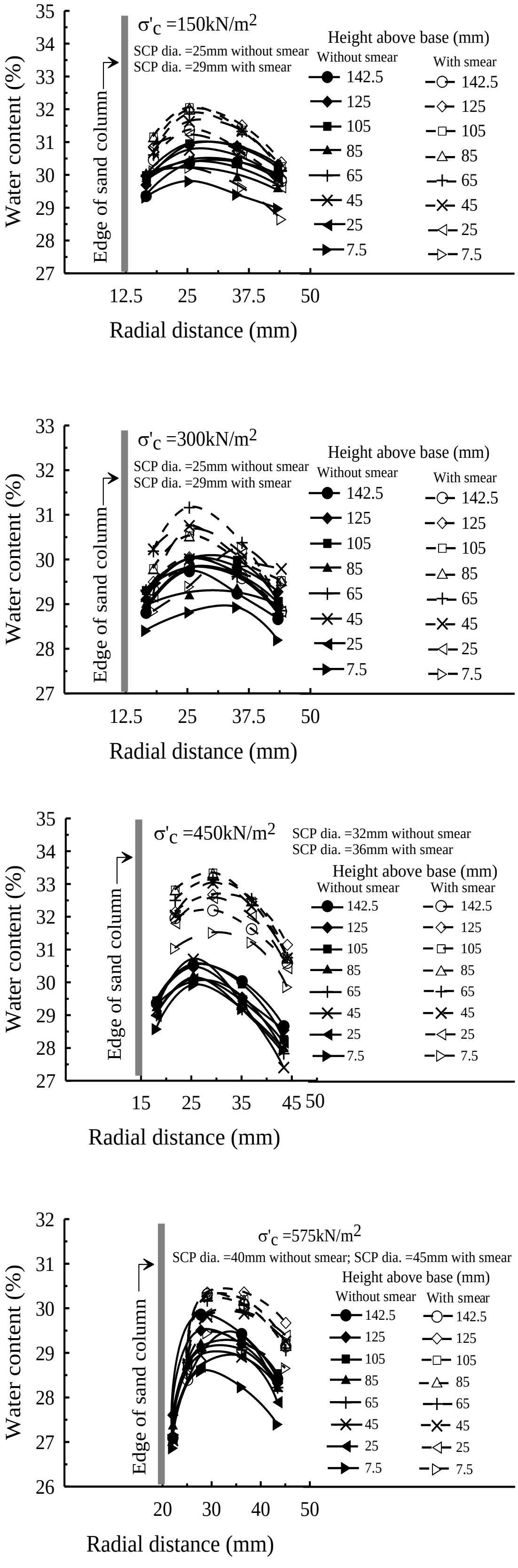


Fig. 6 Variation of water content at different locations measured after the completion of the tests for composite samples under different confining pressures with and without smear effect.

3.4 Effect of smear on the variation of volume change

The variation of volume change against consolidation cell pressure is shown in Fig. 7. As shown in Fig. 7, the effect of smear on the variation of volume change against low cell pressure (σ_c<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 in the composite specimen is considerably disturbed. In zone-III (σ_c> 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 40 mm to 45mm diameter sand columns. The relationship for volume change against given cell pressure for composite specimen with and without smear effect can be expressed as:

$$\Delta V = 4.34(\sigma_c)^{0.55} \quad \text{(without smear effect)} \qquad (1)$$

$$\Delta V = 2.68(\sigma_c)^{0.61} \quad \text{(with smear effect)} \qquad (2)$$

Where, ΔV is volume change and σ_c is the cell pressure during triaxial consolidation tests. It can be seen that the presence of smear zone affects the volume change against the cell pressure. It is interesting to note that the smear effect decreases with increasing consolidation pressure despite increasing the size of sand columns. Thus, these test results validates the variation of water content relationship for both smear and non-smear cases as illustrated in Fig. 6.

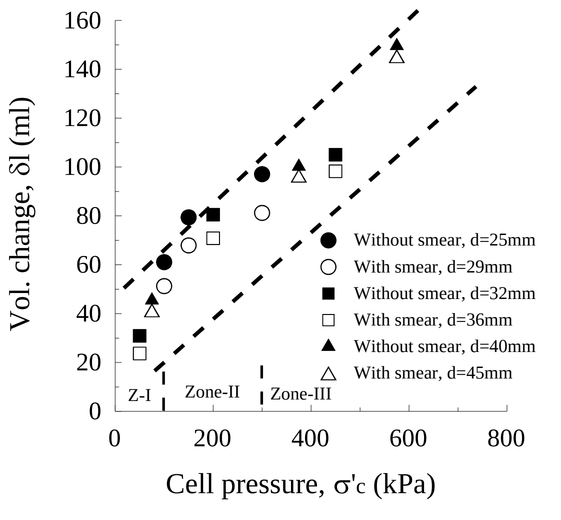
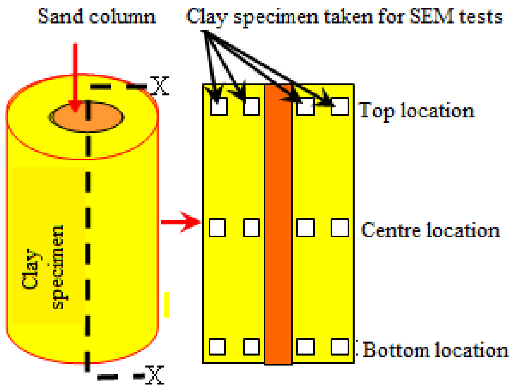


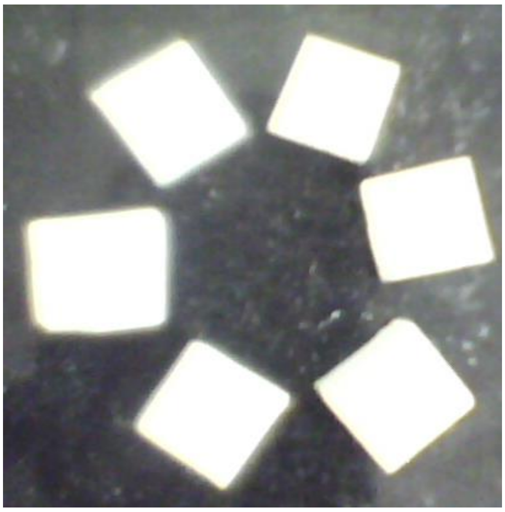
Fig. 7 Relationship of volume change with consolidation cell pressure

3.5 Effect of smear on the microstructure/micro fabric of composite specimens

Scanning Electron Microscope (SEM) tests were conducted on post consolidation tests. 7.5mm x 7.5mm x 7.5mm air dried samples were prepared at room temperature for SEM images as shown in Fig. 8.



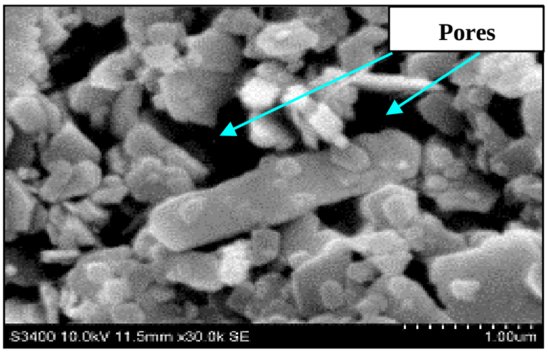
(a). SEM sample location



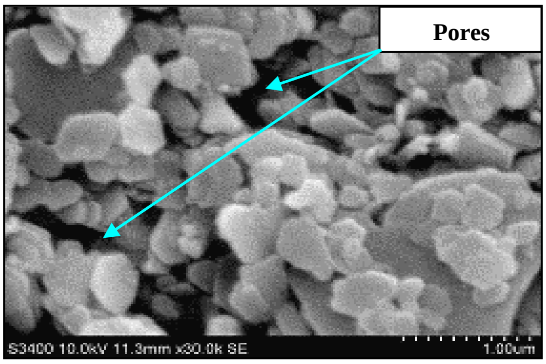
(b). SEM samples

Fig. 8 Samples for SEM tests taken after post compression tests

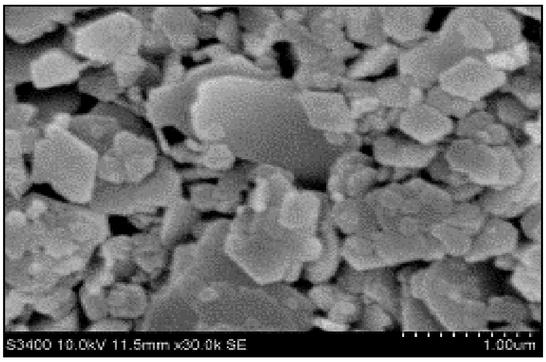
The images of samples with and without the smear zone show differences in the microstructure. The variation of volume change/water content is also evident from Scanning Electron Microscope (SEM) images (Fig. 9a-d) taken on post compression tests of composite specimens with and without smear. The clay minerals in the smear zone appear to be closely packed with reduced pore space. As such, permeability of the composite samples with the smear zone is reduced with reduced pore space in this zone. The properties within the smear zone are also shown to vary with the overburden pressure [26]-[27].



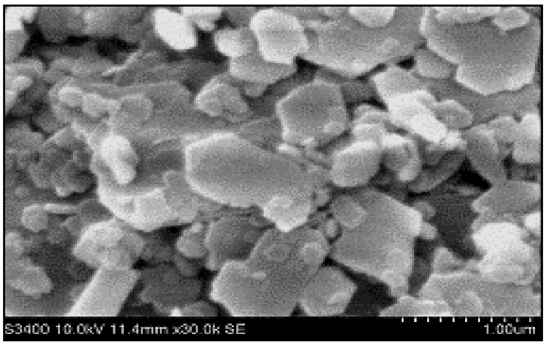
(a). Mean eff. stress at end of consolidation (50kPa)



(b). Mean eff. stress at end of consolidation (450kPa)



(c). Mean eff. stress at end of consolidation (50kPa)



(d). Mean eff. stress at end of consolidation (450kPa)

Fig. 9 SEM images: (a-b) Composite samples without smear zone, (c-d) Composite samples with smear zone.

Notwithstanding the above, the focus of this study is to note the difference in the soil behavior when a well defined smear zone is formed surrounding the sand column. The SEM tests were conducted in both directions on horizontal and vertical surfaces of the sample as shown in Fig. 10.

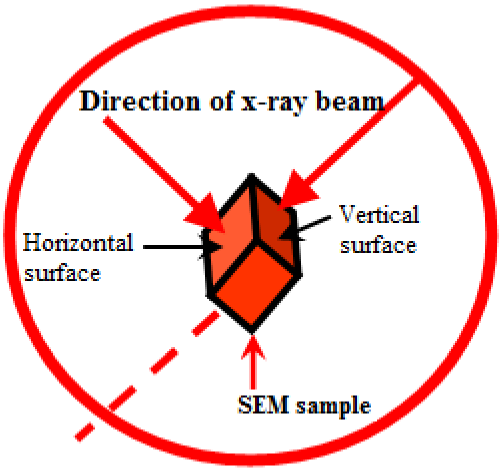


Fig. 10 Direction of x-ray beam during SEM test

4. CONCLUSIONS

The permeability and consolidation behavior of the composite ground reinforced with sand columns with and without smear effect was studied using 18 triaxial consolidation tests on composite specimens. Based on experimental test results, the following conclusions are drawn:

1. It is seen that specimens with sand column (inward radial consolidation) is more effective to improve permeability and consolidation characteristics than compared to conventional clay specimen, which require more than 6-7days to consolidate without the sand columns.
2. The test results showed that the dissipation of excess pore water pressure occur faster in the radial direction due to the greater coefficient of soil permeability in the horizontal direction and the reduced drainage path.
3. The installation of the sand columns by means of a rough casing cause remolding of the subsoil in a limited zone of the soil surrounding the sand columns.
4. The presence of smear zone was shown to affect the consolidation and permeability characteristics of the composite sample.
5. Effect of smear zone surrounding the sand column was evident from the additional time taken to consolidate the composite triaxial specimen and because of reduced soil permeability.
6. 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. Also, in present study, a hollow open ended casing was used to remove the soil and form a cavity for installing sand columns, which may not yields realistic pore pressures in the clay during installation. Hence, the effective stress manifested due to the all-round uniform cell pressure is not uniform throughout the specimen.
7. The non-uniformity of consolidated ground and its consequence on subsequent construction of structures needs further study.
8. In order to simulate the better field conditions, installation of driving-in of closed ended casing may be used. Further, amongst the various techniques for improving in-situ ground conditions, columnar inclusions such as sand columns/sand compaction piles, stone columns/granular piles etc., are considered as one of the most cost effective ground improvement techniques as well as good drainage systems.

6. ACKNOWLEDGEMENT

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7. FUTURE SCOPE

The non-uniformity of consolidated ground and its consequence on subsequent construction of structures needs further study

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