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Experimental analysis on the effect of overburden stress on the smear zone characteristics of clayey soil

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Technical Note

Keywords
Clay
Consolidation
Vertical drain
Smear effect
Overburden stress

Abstract

Preloading with vertical drains is a well-proven ground improvement technique suitable for soft clay deposits. This technique involves installing vertical drains that cause soil remolding in the immediate vicinity of its surface, creating a disturbed zone known as the smear zone. This study aims to investigate the impact of overburden stress on the characteristics of the smear zone. Very often, the vertical drains penetrate to depths up to 20 m. In such situations, the soil experiences varying stresses, leading to different responses to the drain-induced soil disturbances. Very few studies have investigated how overburden stress affects the smear zone. Through a series of experiments encompassing vertical and radial consolidation tests, along with vane shear tests, this paper evaluates the variation in shear strength and consolidation properties within the smear zone, simulating different depths. Employing three overburden pressure intensities (25 kPa, 50 kPa, 100 kPa, equivalent to depths of about 4 m, 8 m and 16 m), the study establishes that the remolding effect intensifies with depth. Furthermore, it demonstrates the influential role of the smear zone on the undrained shear strength properties of the improved ground, highlighting its variability based on overburden stress.

1. Introduction

Numerous regions across the world, particularly along the coastal area, feature very soft clay characterized by unfavourable geotechnical engineering properties. To improve the properties within the construction time available, it is essential to expedite the consolidation of such compressible soils. The use of preloading with prefabricated vertical drains (PVDs) is a viable option (Chakraborty et al., 2023; Baral et al., 2018; Sengul et al., 2017; Chu et al., 2004). In the course of PVD installation, an anchor plate is securely attached to the end of the drain and subsequently embedded into the ground using a hollow mandrel, ensuring penetration to the designated depth. PVD design entails specifying the spacing and length of PVDs based on the results of soil consolidation analysis (Wang & Shi, 2023). Vertical drains are commonly installed to significant depths, leading to varying overburden stresses along the soil depth. Consequently, the extent of remoulding the soil due to drain installation can differ across these depths.

Only a handful of studies (Indraratna et al., 2015; Juneja et al., 2013; Sathananthan et al., 2008; Hird & Moseley, 2000; Bergado et al., 1993; Akagi, 1981; Casagrande & Poulos, 1969) have attempted to capture the influence of overburden stress on the induced smear zone. Their studies have mentioned that the smear thickness and the properties of soil within the zone of disturbance vary with changes in the overburden stress. Akagi (1981) and Bergado et al. (1993) suggested from the field study that the disturbance increases with depth. Akagi (1981) conducted a field study at the Asian Institute of Technology campus in Bangkok, Thailand, to examine the impact of sand drains on the behavior of soft clay. The average ratio of the remolded to undisturbed coefficient of consolidation ranged from 0.58 to 0.24 for vertical drainage and from 0.63 to 0.12 for radial drainage as the depth increased from 2.5 m to 7 m. However, a contrasting conclusion was drawn by Indraratna et al. (2015) and Sathananthan & Indraratna (2006), asserting that the diameter of the disturbed zone decreases at greater depths. Indraratna et al. (2015) collected soil samples from a vertical drain installed site, at Ballina, to investigate the effect of smearing on the consolidation characteristics of soil. They observed that smear extent decreases with an increase in depth. This discrepancy was attributed to the stiffening of clay at deeper layers, resulting in reduced disturbance. However, the limitation of the study is that they have considered only up to a depth of 2 m. From the numerical study by Sathananthan et al. (2008), it was noted that the

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radius of the smear zone varies from 6.6 r_w to 4.9 r_w when the depth increases from 0 to 11 m, where r_w is the drain radius.

The zone of smear exerts a noticeable influence on the undrained shear strength characteristics of the improved ground, and this influence varies with overburden stress. A previous investigation (Juneja et al., 2013) aimed at studying the undrained shear strength (s_u) of Kaolinite clay reinforced with SCP (sand compaction piles) and induced smear zones revealed that the presence of the smear zone impacts the ratio of s_u value to mean effective stress in the composite sample. Further insight into the smear zone characteristics under varying overburden stresses is imperative, pertaining to the lack of studies in this area. A comprehensive investigation into the variation of the shear strength and consolidation properties of the clay in the smear zone with increasing overburden stress is necessary. The current study developed a methodology to experimentally investigate the influence of overburden pressure on the characteristics of the smear zone in soil.

2. Methodology

In the present study, one dimensional and radial consolidation tests were performed on the soil to examine the influence of overburden stress on the smearing effect. The sample used was IIT Lake clay, collected from the lake in the IIT Madras Campus, Chennai, India. The properties of the sample used in the present study are given in Table 1. Preconsolidated (PC) through reconstitutions and Remolded (RM) samples were tested under different overburden stress intensities.

One-dimensional consolidation tests were performed using a standard consolidation cell measuring 40 mm in height and 100 mm in diameter, meeting the specifications outlined in IS 2720-Part 15 (IS, 1986) and ASTM D2435 (ASTM, 2011). The schematic diagram and photograph of the consolidation cell used in the study are shown in Figure 1. A radial consolidation test was carried out on the same cell by the insertion of rubber sheets with holes at their centres, positioned on both the bottom and top surfaces of the specimen, thereby preventing vertical drainage. Sridhar & Robinson (2011) and Aparna et al. (2023) used a similar apparatus setup.

Table 1. Basic characteristics of the clay utilized in the study.

Properties	Value
Plastic Limit (%)	25
Liquid Limit (%)	45
Plasticity Index (%)	20
Specific gravity	2.60
Sand (%)	57
Clay size (%)	33
Silt size (%)	10

Soil slurry was prepared with an initial water content of 1.5 times the liquid limit water content. For simulating the stress state close to the in-situ field conditions, the soil was given a stress history through preconsolidation. The reconstituted soil samples were prepared by consolidating the soil slurry under an effective normal stress of 12.5 kPa. A clamping ring, which also acts as the collar, was placed above the consolidation cell and the sample was filled up to the top of collar (Figure 2a). The frame used for preconsolidation and the specimen in the consolidation cell with frame is shown in Figure 2b and Figure 2c.

Preconsolidation continued till the primary consolidation was complete. After preconsolidating the sample, it was unloaded and trimmed to the required sample height of 40 mm. Shear strength of the specimen was determined using the vane shear apparatus and the water content was measured. This study's preconsolidated (PC) sample simulates the undisturbed in-situ soil. The same PC sample was remolded (RM) to simulate the smear zone. Three overburden pressure intensities of 25 kPa, 50 kPa and 100 kPa, were employed. This corresponds to depths of about 4 m, 8 m and 16 m, respectively, in the field. The effective pressure intensities used in the tests range from 12.5 kPa to 200 kPa. Both radial inflow consolidation tests with central sand drain and 1-D consolidation tests with double drainage were conducted. Figure 3 illustrates the methodology adopted for PC and RM samples under vertical and radial drainage conditions with an overburden pressure of 25 kPa. A similar methodology was adopted for 50 kPa and 100 kPa pressure intensity.

One-dimensional consolidation experiment was carried out on PC samples, subjecting them to a particular overburden pressure intensity. Subsequently, the specimen was unloaded, and its shear strength was assessed by performing a vane shear test (VST). The entire sample was then carefully removed and manually remolded. This RM sample was backfilled into the consolidation ring, and the pressure intensity was applied, ranging from 12.5 kPa to 200 kPa, using an incremental loading ratio of one. The sample underwent consolidation in its undisturbed condition for comparative analysis of the strength and consolidation properties of both preconsolidated (PC) and remolded (RM) samples. Notably, remoulding was not performed in the case of the preconsolidated sample.

Radial consolidation test was conducted by adopting the same procedure as 1-D consolidation, with the exception of the inclusion of sand drains. The loading process involved applying pressure to the preconsolidated (PC) samples until the intended pressure intensity was reached. Subsequently, the samples were unloaded and the shear strength was assessed using a vane shear device. The sample was then properly remolded and reinstated in the consolidation ring with central drainage facilitated by sand drain. After the preparation of the sample with radial drainage, the loading was progressively increased from 12.5 kPa to 200 kPa. In an undisturbed radial consolidation test, the sample was not remolded, and after applying a

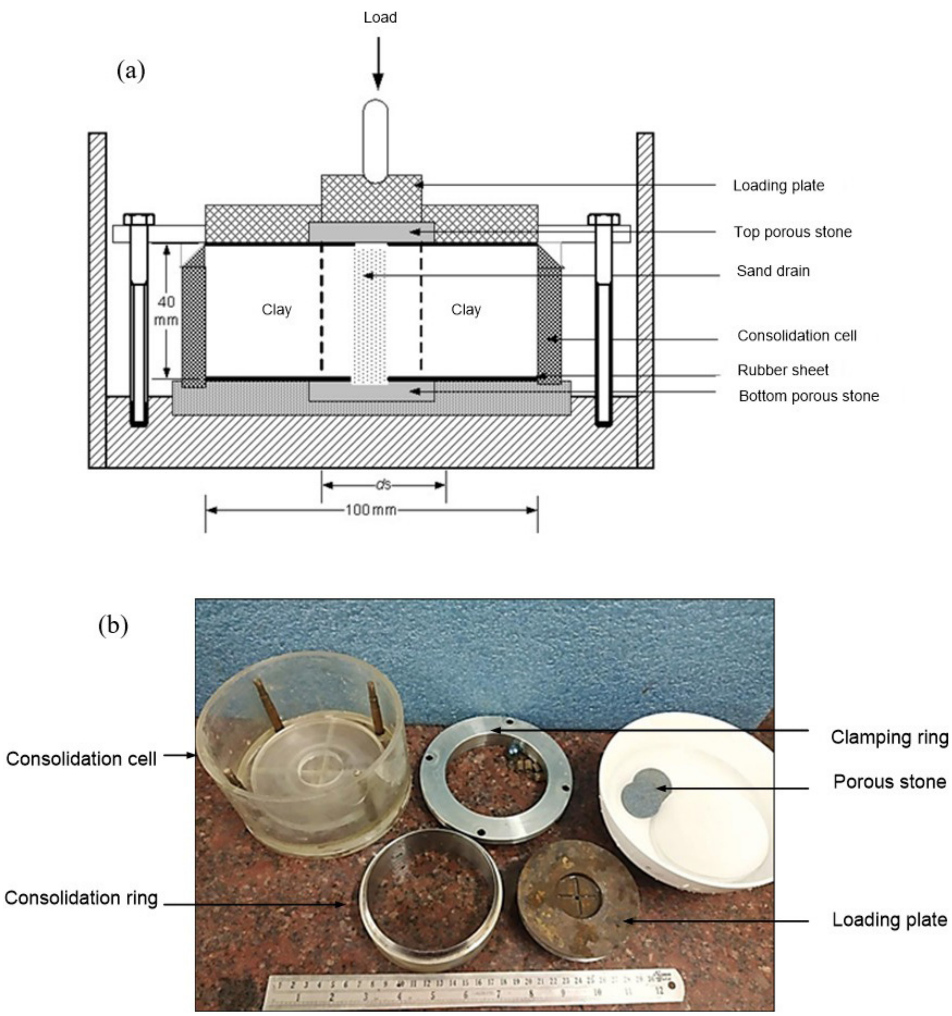


Figure 1. (a) schematic (Aparna et al., 2023); (b) photograph of the 100 mm consolidation cell utilized to perform the consolidation test.

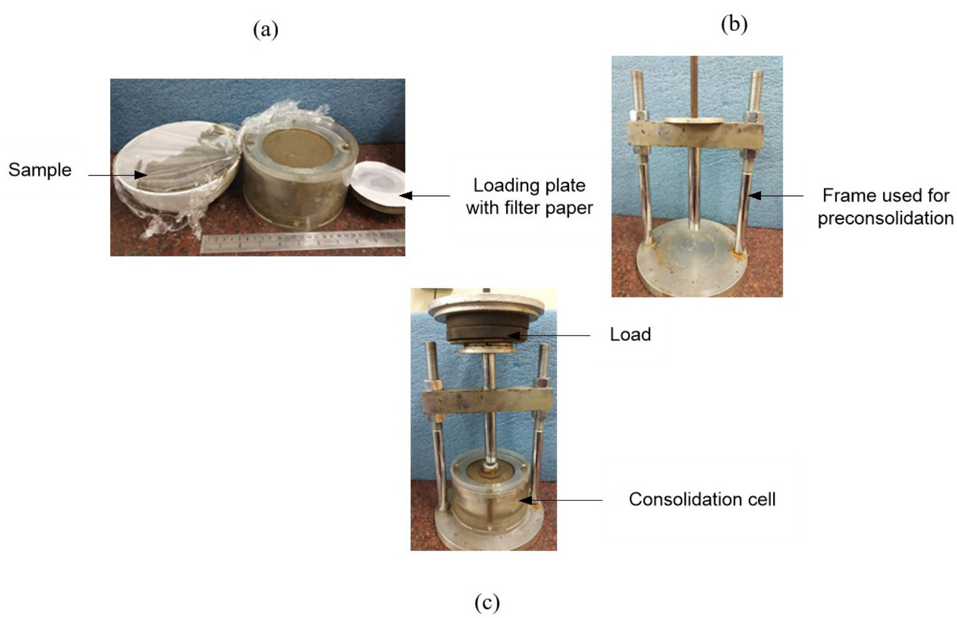


Figure 2. Photograph for preconsolidating the specimen: (a) cell with slurry sample; (b) frame used; (c) final set up.

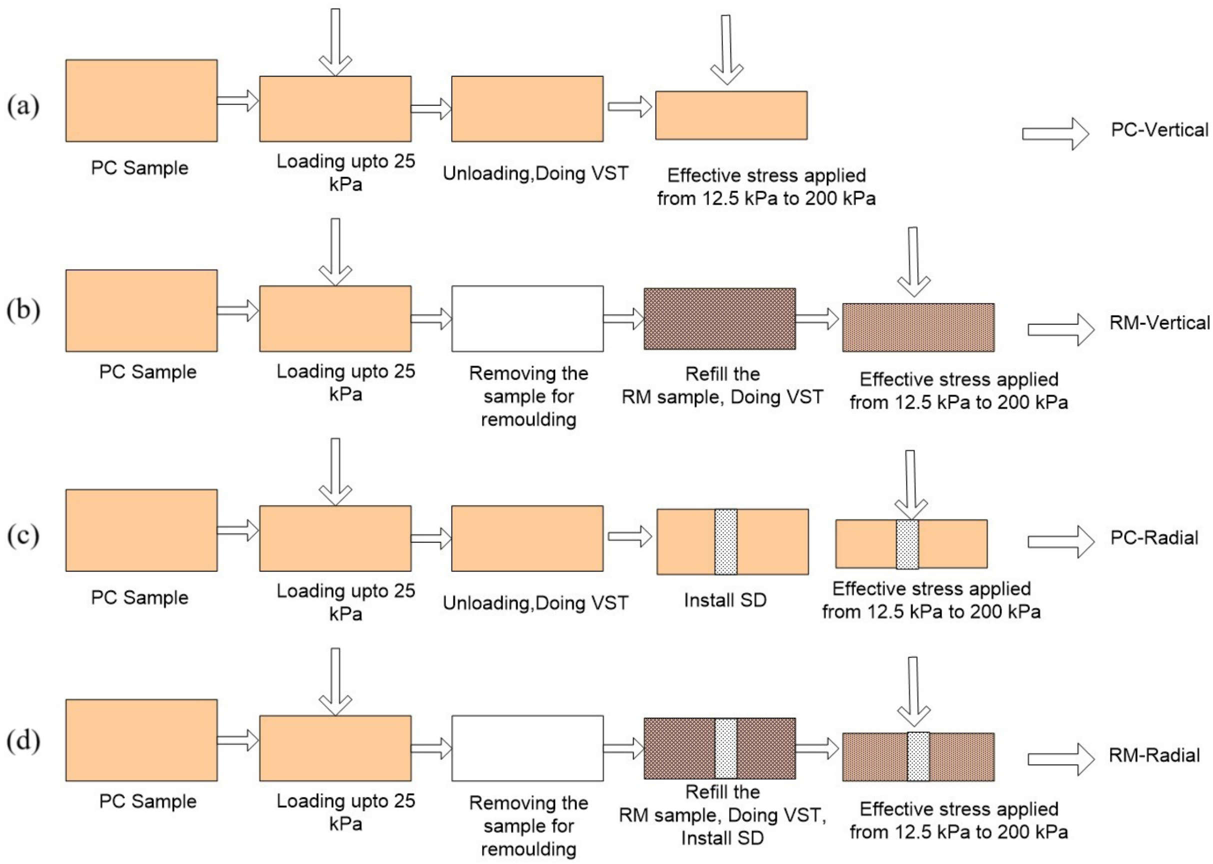
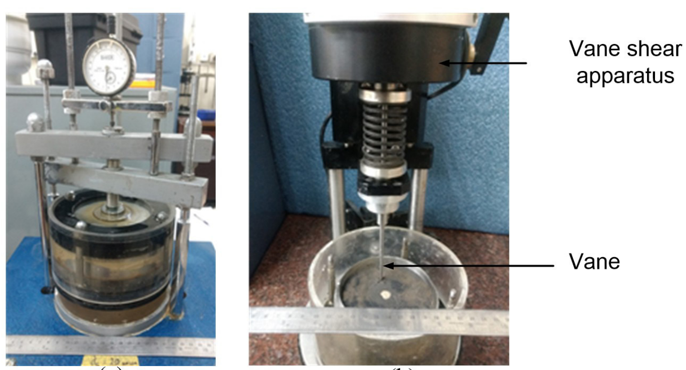


Figure 3. Methodology implemented for: (a) PC-vertical; (b) RM-vertical; (c) PC-radial; (d) RM-radial samples with an overburden pressure of 25 kPa.



(a) (b)

Figure 4. Photograph of: (a) consolidation setup; (b) vane shear test after consolidation of soil.

specific pressure intensity, unloading was performed, followed by the installation of a sand drain. Subsequent loading was conducted, ranging from 12.5 kPa to 200 kPa. The VST was performed at the start and end of the test. A photograph of the consolidation set-up and the vane shear test setup is shown in Figure 4. Thus, the initial and final shear strengths can be found.

From this study, the consolidation coefficient for preconsolidated samples under vertical drainage ($c_{v\_(PC)}$) and radial drainage ($c_{h\_(PC)}$) conditions can be found. Additionally, the consolidation coefficient for the remolded sample under vertical drainage ($c_{v\_(RM)}$) and radial drainage ($c_{h\_(RM)}$) conditions can be determined. The shear strength of both preconsolidated and remoulded samples can be

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Table 2. Reduction percentage of shear strength with PC and RM samples.

Overburden stress (kPa)	s_u of PC sample (kPa)	s_u of RM sample (kPa)	$\Delta s_u = (s_{u\_PC} - s_{u\_RM})$ (kPa)	Reduction percentage $(s_{u\_PC} - s_{u\_RM})/s_{u\_PC}$ (%)	α
25	8.4	5.3	3.1	36.9	0.25
50	13.9	9.5	4.4	31.7	0.2
100	24.6	16.4	8.2	25.3	0.2

observed at various overburden pressure intensities. Through systematic analysis, the variation of the PC/RM ratio with respect to the coefficient of consolidation and shear strength for different overburden pressure intensities was determined and compared.

3. Results and discussion

The impact of smearing under specific overburden stress conditions was assessed by averaging the coefficient of consolidation at various effective stresses beyond the designated overburden stress. For instance, to determine the c_{v_RM} value at overburden stress of 50 kPa, the sample was subjected to staged loading until reaching the targeted overburden stress of 50 kPa. Following consolidation, the specimen was unloaded, carefully extracted, remolded and then carefully backfilled into the consolidation cell. Despite the initial loading of 50 kPa, during the subsequent reloading phase, effective stress was applied in the range of 12.5 kPa to 200 kPa. The primary focus in this case is on the coefficient of consolidation beyond the effective stress value of 50 kPa, and its average value was subsequently derived. Figure 5 illustrates the plot of c_v and c_h values with overburden stress intensities for both PC and RM specimens. It can be observed from the figure that the c_h values of the PC and RM specimens are higher than the c_v values for the entire range of overburden stresses considered. The figure also shows that the c_h values of both PC and RM specimens exhibit a declining pattern as overburden stress intensifies. The reduction in c_h values of RM specimens in response to the increase in overburden stress is more intense compared to the PC specimens. The plot also indicates that the c_v values of both PC and RM specimens are relatively insensitive to the change in the applied overburden stress. This insensitivity implies that the vertical consolidation characteristics of the samples exhibit a degree of stability across the considered range of overburden stresses.

Figure 6 shows the variation of c_{v_PC}/c_{v_RM} and c_{h_PC}/c_{h_RM} with overburden stress. From the graph, it can be observed that both the c_{v_PC}/c_{v_RM} and c_{h_PC}/c_{h_RM} ratios increase with the increase in overburden stress. Hence, it can be inferred that the remolding increases with depth. While conflicting findings exist in the literature, the current experimental study confirms the observation reported by Akagi (1981) and Bergado et al. (1993) that the smearing increases with depth. The c_{v_PC}/c_{v_RM} and c_{h_PC}/c_{h_RM} at 2.5 m, 4.5 m and 7 m depths were reported by Akagi (1981), who observed that the smearing effect rises with depth.

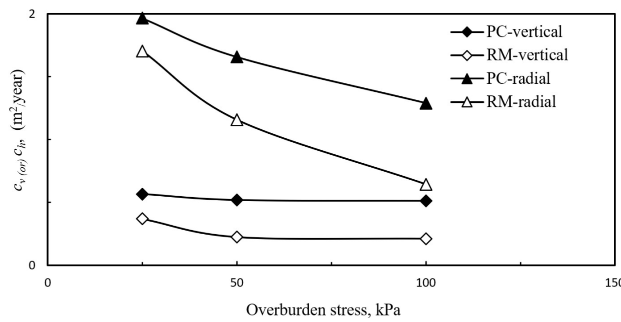

Figure 5. c_v and c_h values at different overburden stress.

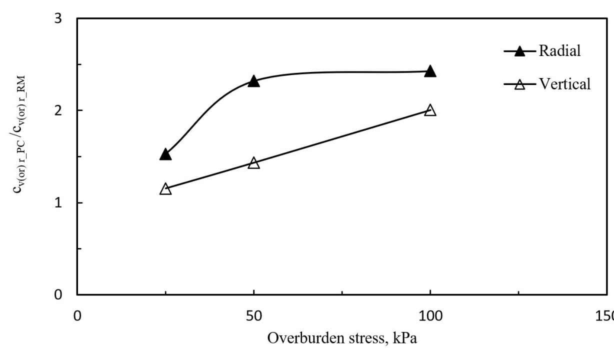

Figure 6. c_{v_PC}/c_{v_RM} and c_{h_PC}/c_{h_RM} with the overburden stress.

The undrained shear strength of the PC and RM samples at various overburden stresses are reported in Table 2. The shear strength of the PC sample is higher than the shear strength of the RM sample. Upon remolding, the s_u value of the RM samples was reduced due to the damage of the soil structure caused by mechanical disturbance. It can be noted that the reduction in the percentage of shear strength due to remolding decreases with an increase in overburden stress. The *'α'* value ($\Delta s_u/\Delta\sigma'_v$) of the soil for different overburden stress remains almost constant, and it ranges from 0.22 to 0.25. A similar observation was reported by Remy et al. (2011).

4. Conclusion

In the present study, an experimental analysis of the smearing effect of soil under varying overburden stress was conducted. The observed trends in the c_{v_PC}/c_{v_RM} and c_{h_PC}/c_{h_RM}, which exhibited an increase with higher overburden stress, strongly suggest a corresponding rise in the remolding

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effect with depth. As anticipated, the shear strength of the PC sample is higher than that of the RM sample, underscoring the impact of mechanical disturbance on the undrained shear strength of the latter. This study contributes to a deeper understanding of the consolidation characteristics of soil under different stress conditions and highlights the importance of considering overburden stress in evaluating soil stability and strength characteristics.

Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Radhakrishna P. Aparna: conceptualization, data curation, visualization, writing – original draft. Retnamony G. Robinson: conceptualization, methodology, supervision, writing – review & editing. Shailesh R. Gandhi: formal analysis, methodology, supervision, writing – review & editing.

Data availability

All data produced or examined in the course of the current study are included in this article.

Declaration of use of generative artificial intelligence

No assistance of Generative Artificial Intelligence (GenAI) has been used for the preparation of this paper.

List of symbols and abbreviations

1-D	One – dimensional
c_h	Coefficient of consolidation under radial drainage
$c_{h\_(PC)}$	Coefficient of consolidation for preconsolidated samples under radial drainage
$c_{h\_(RM)}$	Coefficient of consolidation for remolded sample under radial drainage
c_v	Coefficient of consolidation under vertical drainage
$c_{v\_(PC)}$	Coefficient of consolidation for preconsolidated samples under vertical drainage
$c_{v\_(RM)}$	Coefficient of consolidation for remolded sample under vertical drainage
r_w	Radius of the drain
s_u	Undrained shear strength
s_{u_PC}	Undrained shear strength of preconsolidated sample
s_{u_RM}	Undrained shear strength of remolded sample
ASTM	American society of testing materials
IIT	Indian Institute of Technology
IS	Indian Standard
PC	Preconsolidated
PC/RM	Preconsolidated/Remolded
PVD	Prefabricated vertical drain
RM	Remolded
SCP	Sand compaction pile
VST	Vane shear test
α	Change in undrained shear strength to the change in overburden stress
Δs_u	Change in undrained shear strength
$\Delta\sigma'_v$	Change in overburden stress

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