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Centrifuge model studies on the performance of soft clay improved with pervious concrete piles

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ABSTRACT: Pervious Concrete Piles (PCPs) are gaining traction as a promising alternative for soft soil improvement, especially, where conventional granular piles face installation challenges due to low confinement. The objective of the present study is to understand the influence of PCPs in improving the soft clay through centrifuge model tests conducted in a 1.1 m radius balance beam centrifuge facility available at IIT Bombay, India. The present study focusses on the behaviour of PCP reinforced soft ground under flexible loading, which is like embankment loading / loading due to an oil storage tank as the interface between the structure and underlying soft soil deposit is flexible. PCPs, essentially made of uniform sized aggregate, provide higher strength while being permeable, independent of the soil surrounding the piles. This study presents the deformation and consolidation behaviour under a uniform distributed pressure of the order of 100 kPa, which is applied all over the model surface. For comparison purposes, results of centrifuge model tests of PCP improved ground are compared with densely packed granular pile reinforced ground. The results of this study lead to understand the efficacy of using PCPs for improving consolidation characteristics of soft clayey soils.

1 INTRODUCTION

Limited availability of competent ground for construction purposes has led to the development of various innovative ground improvement techniques. For soft clay, extensively used ground improvement techniques are improving undrained shear strength by preloading and vacuum consolidation or inclusions such as granular columns can be provided to create an extra drainage path (Chu et al. 2000; Black et al. 2006). However, the strength and stiffness of granular columns depend on the properties of surrounding soil. Thus, for very soft soil (c_u < 15 kPa) which cannot provide sufficient lateral confinement to develop strength and stiffness, granular column is not suitable. They get squeezed into the surrounding soil and fail in bulging (McKenna et al. 1975; Barksdale and Bachus 1983; McKelvey et al. 2004). This led to the need of development of a new ground improvement technology which is independent of confinement provided by surrounding soil while still offering a drainage path to accelerate consolidation similar to granular columns.

Pervious concrete is a special type of concrete which is made of uniform sized aggregate with little fines. Pervious concrete has been widely used in pavements for controlling storm water runoff and recharges groundwater levels. The inherent drainage properties and strength of pervious concrete make it highly suitable for geotechnical applications. Pervious concrete piles (PCPs) provide higher strength when compared to granular piles while possessing permeability in the same range. Research by Suleiman et al. (2014), Munaga et al. (2020), and Umaiyan and Muthukkumaran (2022a, 2022b) explored the use of PCPs in ground improvement.

Furthermore, the utilization of centrifuge-based physical model investigations, which offer the closest approximation to field conditions, are lacking in assessing the behaviour of PCP reinforced soft clay. The present study focusses on the behaviour of pervious concrete pile reinforced soft ground under flexible loading which is similar to embankment loading or loading due to an oil storage tank as the interface between the structure and underlying soft soil deposit is flexible. However, the reinforced soft ground is loaded at 1g and then taken to higher gravity level, similar to the speed – up method, where the embankment is constructed at 1g and taken to high gravities. This study presents the deformation and consolidation behaviour under a distributed pressure which is applied all over the model on the soil surface, representing central area under an embankment which is quite far from the side slopes. This study compares the behaviour of unreinforced soft clay, soft clay improved with stone columns at 85% relative density and soft clay imrpoved with pervious concrete piles under flexible surcharge loading.

2 DETAILS OF CENTRIFUGE MODEL TESTS

2.1 Model materials used in the present study

The model clay used in the present study was kaolin, procured from M/s Ashapura Minechem Ltd., Mumbai, India in powder form. The specific gravity of the kaolin was measured as 2.54 using the density bottle method. The Liquid limit (LL), Plastic limit (PL) and Plasticity index (PI) of kaolin were observed to be 43.1%, 25.1% and 18% respectively, based on which the kaolin sample tested was classified as CL, indicating an inorganic clay of medium to low plasticity as per (USCS).

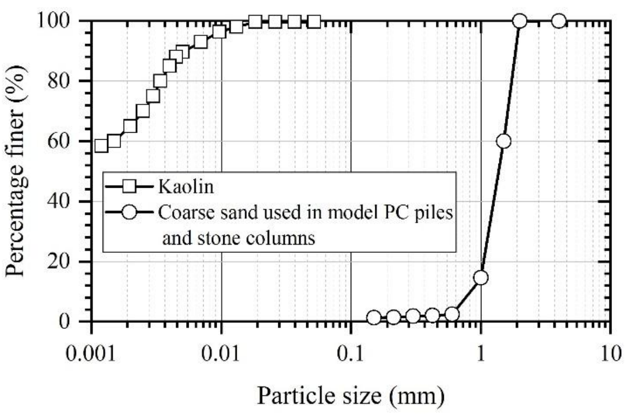

Fig 1. Particle size distribution curves of model materials

The commercially available Grade I Ennore sand was procured and utilized for modelling the aggregates in pervious concrete piles. The graded fraction of Grade I Ennore sand passing through 2 mm and retained on 1 mm sieve was segregated and used in the present study. This specific size range was deliberately chosen to ensure compatibility with small scale laboratory experiments, where scaling laws necessitate precise control of material properties. The particle size distribution curves of model materials are given in Fig1. Ordinary Portland Cement (OPC) Grade 53, with a specific gravity of 3.1, was employed as the binding material. The design of pervious concrete is guided by the selection of a target porosity (n), which dictates the void content required in the hardened concrete to achieve the desired permeability and drainage characteristics, according to the formula given by Cai et al. (2021). After conducting characterizations tests on many trial mixes, the pervious concrete mix with 0.2 cement-aggregate ratio and 0.4 water-cement ratio which met the requirements, was chosen to prepare pervious concrete piles. The moulds for casting pervious concrete piles are made from thick transparent polythene sheets. The pervious concrete mix is prepared in the required proportions and poured into the mould in three layers by giving 25 blows for each layer with a tamper. The piles are demoulded after 24 hours and kept for curing. After curing the piles for 14 days, they can be used in the centrifuge model experiments. The pervious concrete mix had average 28 day compressive strength of 14 MPa, coefficient of permeability of 1.5 x 10^{-4} m/s (from constant head permeability test), elastic modulus of 12 GPa, Poisson's ratio of 0.2 and a porosity of 26%.

2.2 Model test package

The 1.1 m radius small balanced beam centrifuge that has a capacity of 10 g -tonnes and can carry a maximum payload of 50 kg has been used in the present stsudy (Viswanadham 2025).

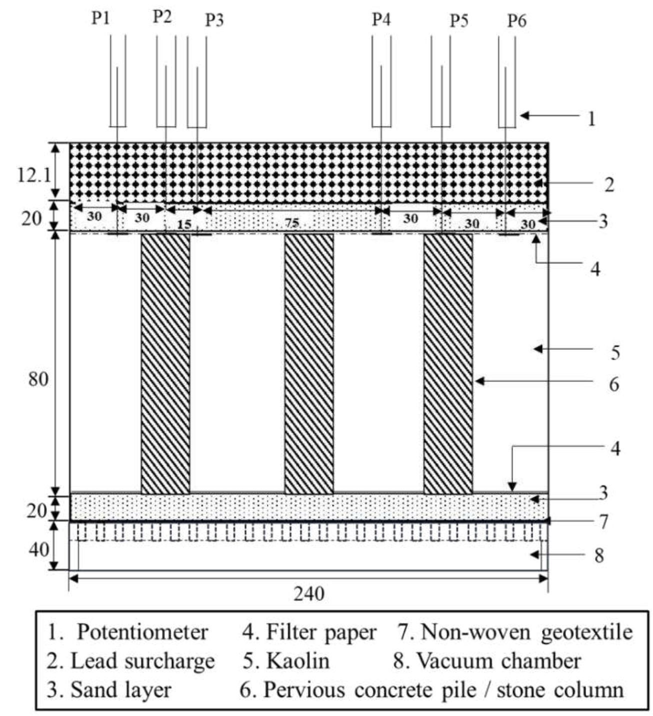

Fig 2. Schematic representation of model test setup used in the present study. All dimensions are in mm (Not drawn to scale)

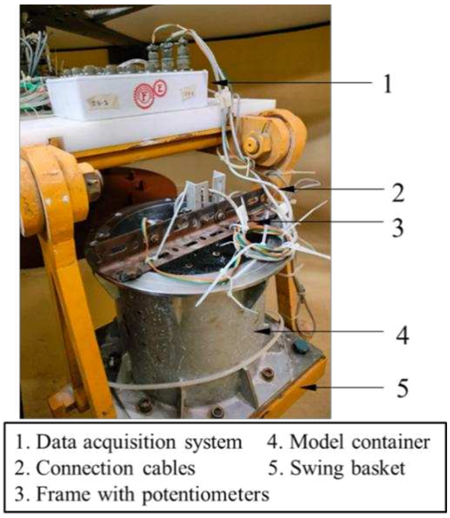

Fig 3. Perspective view of the test setup mounted on centrifuge swing basket

Considering a gravity level of 60g (ω = 24.988 rad/s) in the present case, the variation of g-level with model depth denoted by N_{top} and N_{bottom} are equal to 58.3g and 63.39g respectively, thereby indicating an error magnitude of 2.83% and 5.65% respectively generated at the top and bottom of the soil model due to the above variation. Both of these errors are found to be well within the limit of 10% prescribed by Taylor (1995).

The error arising due to variation of g-level with horizontal distance of the model is 0.774%, which is negligible and assumed to be insignificant for all practical purposes. The height of model H_{m} is 0.08 m, and the effective radius (R_{m}) is 0.9427 m, thereby producing an error of H_{m} / 6R_{e} = 1.414%, which is less than 3% prescribed by Taylor (1995). The model test package used for conducting model tests includes model container, instrumentation and data acquisition system. The model container made of stainless steel and having 240 mm diameter and 240 mm length was employed for conducting model tests. A schematic representation of the model test package adopted along with instrumentation details is presented in Fig. 2. The instrumentation adopted primarily includes potentiometers placed at different locations to record the settlement data during the centrifuge experiment. The view of model test package mounted on the swing basket is shown in Fig 3.

2.3 Test procedure and test program

In the present study, model clay bed was prepared through vacuum consolidation. Initially, clay slurry was mixed at 1.5 times liquid limit which is around 64.5 % water content. A non-woven geotextile layer is placed on the perforated plate to avoid clay particles in the chamber and a dense sand layer of 20 mm is formed. The inner walls of the container are coated with grease to reduce side wall friction. After pouring the slurry into the container, one more geotextile layer is laid and a perforated plate is placed above it to facilitate settlement measurement that causes 0.5 kPa surcharge; with a water level of about 10 mm on it. Initial height of slurry was 185 mm. And the vacuum pressure was applied in three stages: -30 kPa, -60 kPa and -90 kPa, the first two stages maintained for 24 hours each and the third stage is maintained for 120 hours. This is termed as Stage 1 vacuum consolidation.

Piles are installed in the clay bed for reinforced model after stage 1 consolidation. The positions where piles are to be installed according to the desired pattern are marked and the soil in those marked positions is removed with the auger custom designed and fabricated for this purpose. The pervious concrete pile is then installed with a guide that ensures verticality. In the case of stone column improved model tests, the process of installation is similar till the removal of clay using auger. After that pre calculated amount of sand required to fill the hole is poured into it through a funnel. It is poured in three lifts by compacting to achieve the required relative density. Later, vacuum pressure is applied through the piles. As the pile is porous it sucks in water from the surrounding soil and allows it to consolidate. Top of the pile is covered with kaolin slurry to avoid the escape of vacuum pressure from top. A surcharge of 5 kPa is placed on the model and vacuum pressure of -90 kPa is applied for 24 hours. This is termed as Stage 2 vacuum consolidation. This also helps to reduce the gap between pile and soil.

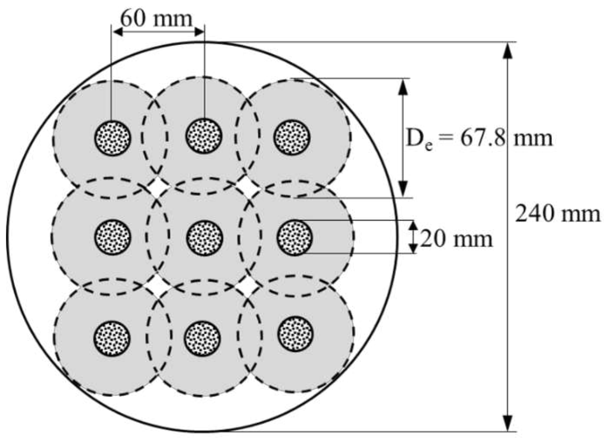

Fig 4. Plan view of soft clay improved with pervious concrete piles / stone columns in a square grid pattern

The clay model is trimmed to 80 mm after the completion of stage 2 vacuum consolidation. A non-woven geotextile is placed above it and a 20 mm thick sand layer is created. It is intended to create a 100 kPa surcharge on the models to test in a centrifuge. Sand layer creates a flexible surcharge, but the height of sand layer required to create a 100 kPa surcharge is restricted due to space constraint in the container dimensions. Therefore, lead balls of 2 mm diameter were used to cause the surcharge load.

Table 1. Details of centrifuge tests

Test ID	Type of pile	D_p (mm)	S (mm)	L_p (mm)	A_r (%)
T1	-	-	-	-	-
T2	Stone column	20 (1200)	60 (3600)	80 (4800)	10
T3	PCP	20 (1200)	60 (3600)	80 (4800)	10

Note: Parentheses indicate corresponding values in prototype scale; D_p: Diameter of pile; S: Spacing between piles; L_p: Length of pile; A_r: Area replacement ratio

Lead has a specific gravity of 11.6, thus requiring less space for 100 kPa surcharge. Also, since the lead balls are discrete particles, they allow for flexible loading on the model. A 12.1 mm thick layer of lead balls is placed above the sand layer which can create a pressure of 100 kPa on the model at 60g. Upon completion the model preparation, model the test package is mounted on the swing basket of the centrifuge. The centrifuge was rotated at a constant angular velocity of 236 rpm, corresponding to 60g. The selection of the gravity level of 60g was made as it is the minimum g level where the centrifuge arm becomes horizontal for the centrifuge modelling principles to be applicable. Figure 4 shows the square pattern of piles / stone columns adopted for the experiments where dotted lines indicate their influence zones with an effective diameter D_e = 67.8 mm and area replacement ratio a_s = 8.72%. In this study, a comprehensive analysis of three model tests, excluding the pilot and calibration tests, is presented, assessing the performance of unreinforced clay, stone column reinforced clay and pervious concrete pile reinforced clay subjected to a flexible loading of 100 kPa (i.e. about 5 m height of embankment), along with their deformation patterns. The details of centrifuge model tests are presented in Table 1.

3 RESULTS AND DISCUSSION

The variation of settlement (on the pile and on the soil) with time for models T1, T2 and T3 is shown in Fig 5. The settlement behaviour of the models was investigated based on the potentiometer readings during the centrifuge tests. Model T1, which is unreinforced, displayed a gradual settlement trend throughout the test. The model experienced a maximum settlement of 200 mm (in prototype dimensions) which is the highest of all the models, that progressed over a duration of 700 days. However, the soil settled uniformly as there was no reinforcement.

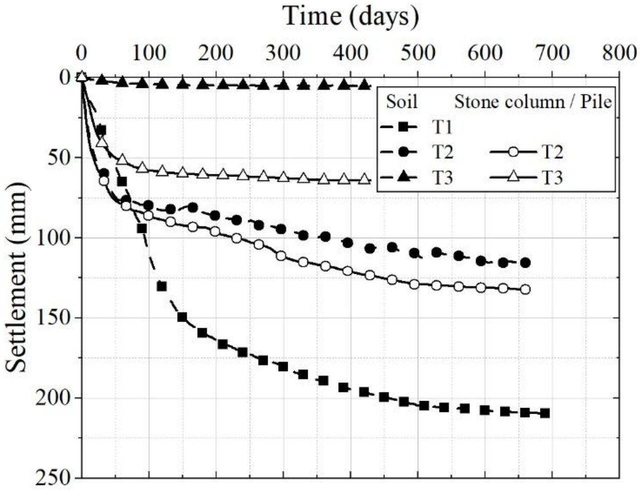

Fig 5. Variation of settlement with time for models T1, T2 and T3(Prototype dimensions)

The deformation profiles of models T1, T2 and T3 are presented in Figs 6, 7 and 8 respectively. Model T2, reinforced with stone columns of 85% relative density, experienced a maximum settlement of 116 mm and 141 mm on the stone columns and the clay respectively. As stone columns are compressible, the model settled in a uniform manner initially, however, it indicated a differential settlement at later stages owing to the stiffness difference between soil and stone column. Model T2 exhibits nearly equal strain condition due to compressible stone column. However, a maximum differential settlement of 25 mm was caused due to the flexible nature of loading.

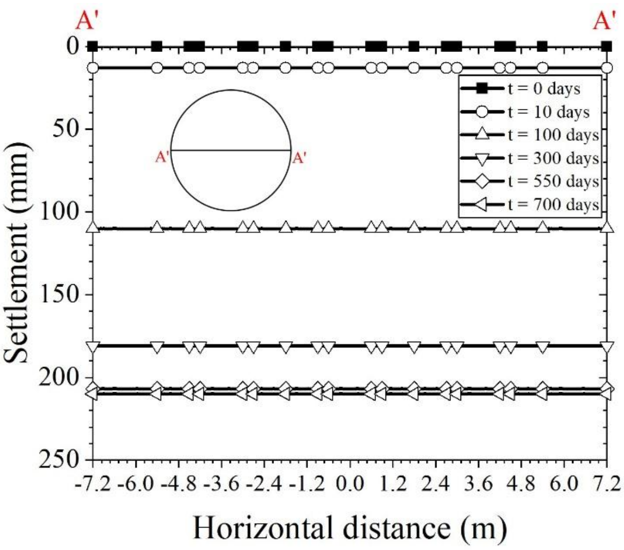

Fig 6. Deformation profile of model T1 during centrifuge test (unreinforced model)

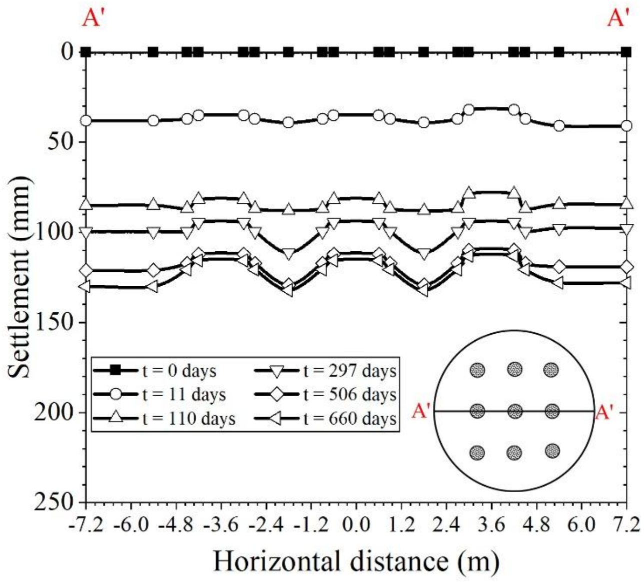

Fig 7. Deformation profile of model T2 during centrifuge test (model improved with stone columns)

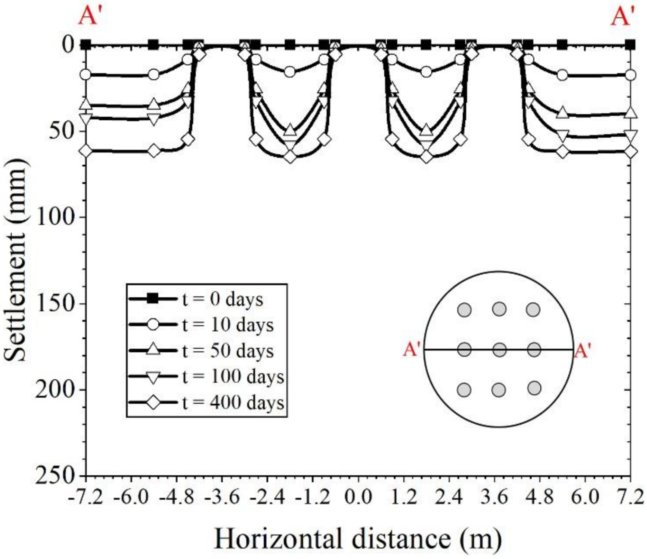

Fig 8. Deformation profile of model T3 during centrifuge test (model improved with pervious concrete piles)

Table 2. Comparison of t_{90} and c_v values obtained for centrifuge model tests

Model test	**t_{90} (days)**	**c_v (m^2/yr)**
T1	327.6	5.367
T2	75.7	23.22
T3	44.9	39.16

The maximum settlement of clay between the piles is 57 mm for model T3 (reinforced with pervious concrete piles) and equilibrium was attained at around 400 days whereas for unreinforced model T1, settlement occurred till 700 days in prototype dimensions. The potentiometers located on the piles showed a settlement of less than 4 mm, indicating minimal settlement of piles. The model experienced differential settlement as the pile deformations is extremely less due to its high stiffness. The flexible nature of applied load allowed the differential settlement to occur, which progressed over time. It is observed that models T3 indicates significant differential settlement between the pile and soil, due to the large difference in the stiffness of piles and surrounding soil, however, model T2 showed minimal differential settlement due to the less difference in stiffness of stone column and clay.

Table 2 presents the value of t_{90} calculated by Taylor's square root of time method from settlement data and c_v for all the model tests. The settlement data of potentiometer located on clay between the piles was taken to calculate t_{90}. The t_{90} value for unreinforced model T1 is 327.6 days which is the highest of all the models. For model T3, t_{90} value is 44.9 days, which is the least of all. This is because the settlement in clay occurred at a faster rate due to the additional drainage provided by the piles. The drainage capability of piles was confirmed during the post-test investigations as the water content of clay near the piles decreased. As the loading is flexible, stress is distributed over the pile and soil, however, piles take larger portion of the applied load due to higher stiffness. For model T2, t_{90} value was 75.7 days which is greater than that of model T3, because the stress concentration ratio is lower due to low stiffness of stone columns as compared to pervious concrete piles. This causes the clay to carry more load in the case of stone column reinforced clay as compared to pervious concrete pile reinforced clay. Though the coefficient of permeability of stone columns (0.6×10^{-3} m/s) is slightly higher than that of pervious concrete piles (1.5×10^{-4} m/s), the stress transfer is lower in the case of stone columns leading to longer time required to attain high degree of consolidation. The high stiffness and high permeable nature of pervious concrete piles facilitates quicker settlement of the improved soft soil model, thereby resulting in lower t_{90} value and higher c_v value.

4 CONCLUSIONS

In this study, an attempt has been made to understand the behaviour of unreinforced and reinforced soft clay under flexible loading condition. Lead balls were used to simulate flexible surcharge. A total of three model tests were presented in this study. The experimental setup, test procedure and results are discussed through parametric studies, wherein, the effect of stiffness of pile was studied. The findings from the conducted study are listed below.

- Pervious concrete piles were quite effective in reduction of the settlement of soft clay. The settlement of clay reduced by 68% with PCPs.
- The deformation behaviour of the model is significantly influenced by the stiffness of the pile. Model T3 reinforced with higher stiffness piles showed minimal settlement of clay. However, the settlement of pile and surrounding clay was not equal. Model T2 improved with stone columns which are compressible settled in a rather uniform manner.
- The stress transfer resulted in differential settlement due to the flexible nature of load. Model T3 with higher stiffness piles showed high differential settlement. Model T2 reinforced with low stiffness piles showed less differential settlement comparatively.

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