Three-dimensional numerical analyses of

pervious concrete column for soft soil improvement

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Abstract Stone column or granular column is widely used as a soil improvement method, for flexible foundation such as oil storage tanks, embankments and rigid foundation. The confining pressure exerted by the surrounding soil allows the stone column to develop their bearing capacity. The soft soils surrounding stone column may not provide sufficient lateral confinement. So, the design bearing carrying capacity may not be achieved. In such soils, a pervious concrete column may be applied which deals with the purpose of reinforcement as well as drainage. Pervious concrete column can be constructed up to the full depth of soft soil or on the upper portion of a stone column up to which bulging is predominant. This paper presents the parametric investigation of the performance of stone column, pervious concrete column, and composite column through three dimensional numerical analyses. The parameters consider are: pervious concrete column diameter, pervious concrete length of in composite column, surrounding soft clay cohesion, and full pervious concrete column length. Furthermore, pervious concrete's load transfer mechanism is compared to that of a stone column. In comparison to ordinary stone columns, the findings of the analyses show that pervious concrete columns have a substantially better load carrying capacity and experience less lateral displacement. Furthermore, in a composite column, a length of pervious concrete up to four times column diameter may be sufficient to enhance the load carrying capability of an ordinary stone column.

Keywords: Soil Improvement; stone column; pervious concrete column; finite element analyses.

1 Introduction

To improve soft soils; a number of ground improvement methods are available. These include, vacuum pre-consolidation[1], soil cement column[2], pre-consolidation using pre-fabricated vertical drains[3], lime treatment[4], and stone columns[5,6]. Among the various ground improvement methods, the stone column method is widely used as it gives the advantages of increasing bearing capacity, reduced settlements and accelerates the consolidation settlements and ease in construction[7]. The ultimate load-carrying capacity of a stone column is calculated based on the lateral confinement pressure provided by surrounding soil. Numerous researchers reported that the stone columns increase the safe bearing capacity by four times[5-6]. Contradictory to some researchers, case studies of unsatisfactory behavior of granular columns installed in soft soils were also reported[8-9]. The reasons postulated for the unfavorable performance are squeezing of soft clay into stone column, greater lateral bulging, and penetration of stone material into soft clay. This suggests that the stone columns have limited applications in soft clay soils. In these types of soils, it is necessary to strengthen the stone column either up to critical length (i.e., maximum bulging depth) or fully[10].

Many techniques were applied in the past to enhance the load-carrying capacity of stone columns; such as encasing the stone column peripherally with geosynthetic[7], reinforcing the stone column by horizontal geogrid slice[10], skirting the stone column with concrete[11], applying circumferential nail[12], and use of pervious concrete[13]. Although the pervious concrete columns were applied in the field successfully, there are limited works reported in the literature.

Kim et al.[13] observed that the stone column reinforced by pervious concrete at the top section of the granular column had the effect of preventing bulging collapse and settlement reduction in laboratory and full-scale field testing. Tandel et al.[14] found through numerical simulations that the reinforcing effect of the upper portion of the granular column significantly increases the bearing capability of the stone columns. Based on laboratory model testing in clay, Kim et al.[13] found that pervious concrete piles might speed up the consolidation of soft clay formation by acting as a vertical drain. Suleiman et al.[15] used a laboratory model test in sand to examine the performance of pervious concrete piles and found that the bearing capacity of pervious concrete column is around four times more than conventional stone column.

In this work, a comprehensive parametric analysis is carried out on single stone columns, pervious concrete column, and composite columns using three-dimensional numerical analyses. The impact of variables such as the column diameter, the pervious concrete column length in the composite column, the cohesion of the soft clay around the column, and the full length of the pervious concrete column are all taken into account in this research.

2 Numerical Analysis

The PLAXIS[16], a 3D FE software, was used to perform all of the numerical studies. As illustrated in Figure 1(b), a 3D column model was used to explore the performance of PCCs. The thickness of soft clay was maintained constant throughout all of the studies. The soft clay was assumed to be underlain by a 2m thick layer of sand. A square pattern was chosen for column arrangement. Figure 1(a) depicts a common column configuration. The distance between columns was maintained constant at 2.5 m. The boundary condition employed in the analysis is comparable to what other researchers have used in the past[17-18]. Both vertical and lateral settlements are restricted at the bottom of the model, while only vertical displacement is permitted and horizontal displacement is restricted at the vertical boundary.

For all materials, the finite element mesh utilized in the numerical study was created with 10 nodded tetrahedral elements.

The mechanical behavior of pervious concrete column is examined in present study, with a focus on short-term behavior. Soft clay was analyzed using undrained shear strength. Because qualitative rather than quantitative analysis is more common, the numerical analysis should be based on a basic model like Mohr Coulomb, whose parameters can be tested easily in the lab. The ideal elastoplastic Mohr Coulomb model was then regarded as a first approximation of soil behavior for soft clay, sand, and stone column. Many studies used the same constitutive model for soft clay[19-20], sand, and stone column in the past[21-22].

The parameters for benchmark case are mentioned in Table 1. Based on previous studies, the parameters of soft clay, sand, stone column, and pervious concrete were used. (e.g. soft clay[19-20]; sand, and stone column [21-22], and pervious concrete column[23,24]).

The undrained shear strength (C_u) is the basis for the soft clay strength property. Since previously indicated in the literature[19-20], the undrained modulus of elasticity (Eu) was assumed (=250 Cu) and the Poisson's ratio vu = 0.49 (as it is widely known that the value 0.5 represents a circumstance in which there is no volume change, which produces major numerical complications). As suggested in Brinkgreve and Vermeer[16], for soft clays, the angle of dilatancy is typically taken zero. The dilatancy angle for coarse soils was calculated based on correlation ($\psi=\phi-30°$)[25]. PLAXIS performs well enough for non-cohesive soils; however, instead of using the value of cohesion zero to reduce numerical instability, 1 kPa for sand and 2 kPa for stone column were used, as described by Brinkgreve and Vermeer[16].

For sand, stone, and pervious concrete columns, a drain material behavior was considered, as well as a short-term behavior for soft clay. The pervious concrete was modeled using the linear elastic material model, which is characterized by two parameters: young 's modulus and Poisson ratio. A drained material behavior was assumed for the pervious concrete column having permeability 10^{-3} m/s. Several researchers have already adopted the same material model for the simulation of previous concrete piles. Shafee et al.[23] concluded that strength properties of pervious concrete do not have significant effects on ultimate vertical load bearing of piles. So, further in the analysis, linear elastic material model was adopted for a pervious concrete column. In the analysis parameters varied for parametric study is summarized in Table 2. Figure 2 shows a model with 114888 nodes and 84293 elements.

A mesh convergence analysis was performed to determine the best meshing configuration for the numerical model. Figure 3 illustrates the findings of the convergence investigation for load bearing capacity of a full-length PCC, which reveals that the results are almost equivalent beyond the fine mesh. Furthermore, when the mesh is changed from medium to extremely coarse, the load capacity of a PCC changes dramatically. As a result, for the current numerical model, a fine meshing approach is used. Meshes are refined locally in the location of the stress concentration.

To make the analysis simple, the interface between different materials was not considered in the analyses.

The present study deals with load-settlement behavior of a pervious concrete column reinforced in soft clay. So, plastic analysis (mechanical behavior) is carried out. Only consolidation analyses and groundwater flow calculations need the input of permeability parameters[16].

To establish the vertical load-carrying capability of the pervious concrete column, all investigations were carried out by applying prescribed displacement directly over the top of its surface. The vertical settlement of the surrounding soil must be taken into consideration when doing a group analysis of pervious concrete columns.

Zhang et al.[24] reported in-situ test results of an embankment supported on pervious concrete columns, which were used to verify the numerical approach used in current work. Figure 4 depicts that the settlements derived from the numerical simulation are identical to those obtained from field experiments when the embankment height was lesser than 2 m. But, with embankment height is more than 2 m, there is a considerable variation that rises with embankment height. This is most likely because settlement is related to the young's modulus of the soil. The elastic modulus decreases with embankment height, implying the level of stress encountered by the foundation, while the initial modulus established by the laboratory experiment is being used in the numerical solution; thereby, the higher the embankment, the larger the difference between the settlement of an embankment attained by the computer model and the test results in the field. Another factor contributing to the difference is that in situ constructed PCCs are often weaker than laboratory specimens. Despite this, the patterns of settlements derived from numerical methods and observed in the field are similar.

It is difficult to compare the findings of the current numerical analysis with those of the reported experimental study with soft clay as surrounding soil[13,26,27], because the related soil properties (mainly undrained cohesion) were not available. In addition, the field works published[28-29] involving layered soil deposits, could not be correlated with the present study as in the current study, pervious concrete column behavior was studied by reinforcement in single soft clay layer.

Table 1. Properties of the bench mark case

Parameters	Soft clay	Pervious concrete	Stone column	Sand
Unit weight: γ (kN/m^3)	15	19	18	16.5
Cohesion: C (kPa)	15 (C_u)	-	2	1
Angle of internal friction: φ (deg)	0	-	40	35
Elastic modulus: E (kPa)	250 × C_u	15 × 10^6	45000	40000
Poisson ratio: ν	0.49 (ν_u)	0.15	0.3	0.3
Dilatancy angle: ψ (deg)	-	-	10	5

Table 2. Parameters varied

Parameters	Variation
Soft clay cohesion: C_u (kPa)	10, 15*, 20, 25
Diameter of column: d (m)	0.4, 0.6*, 0.8, 1.0
Length of pervious concrete in composite column: Lpc (m)	2d, 4d, 6d, 8.33d*
Length of full pervious concrete column: L (m)	2.5, 5*, 7.5, 10

* Parameters for base line case

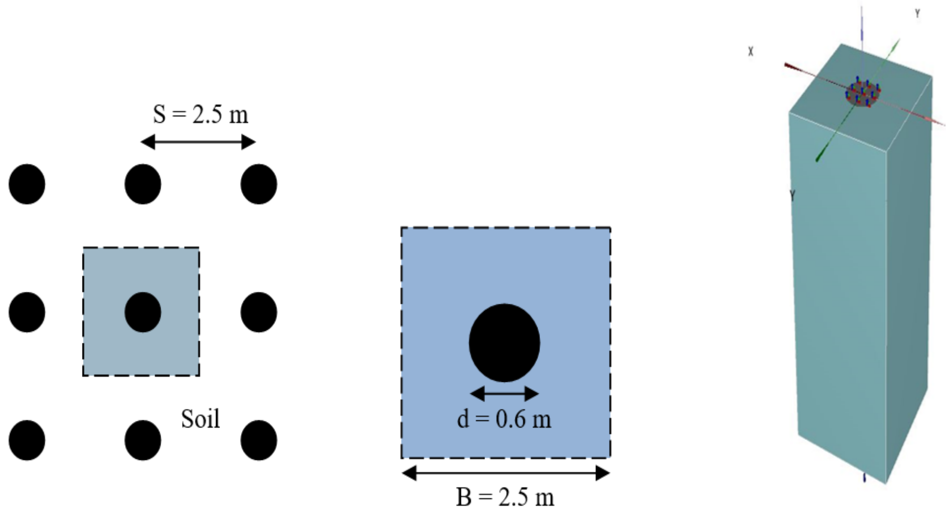


Figure 1. Three-dimensional column: (a) column layout; (b) 3 D column.

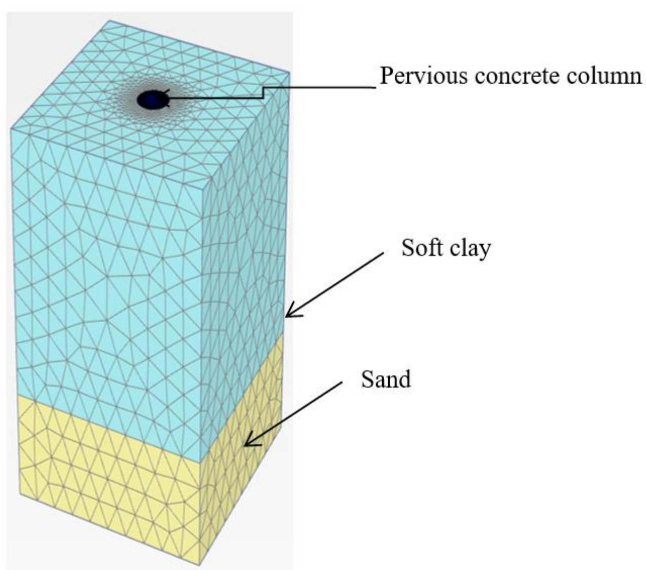


Figure 2. Three-dimensional model of the column.

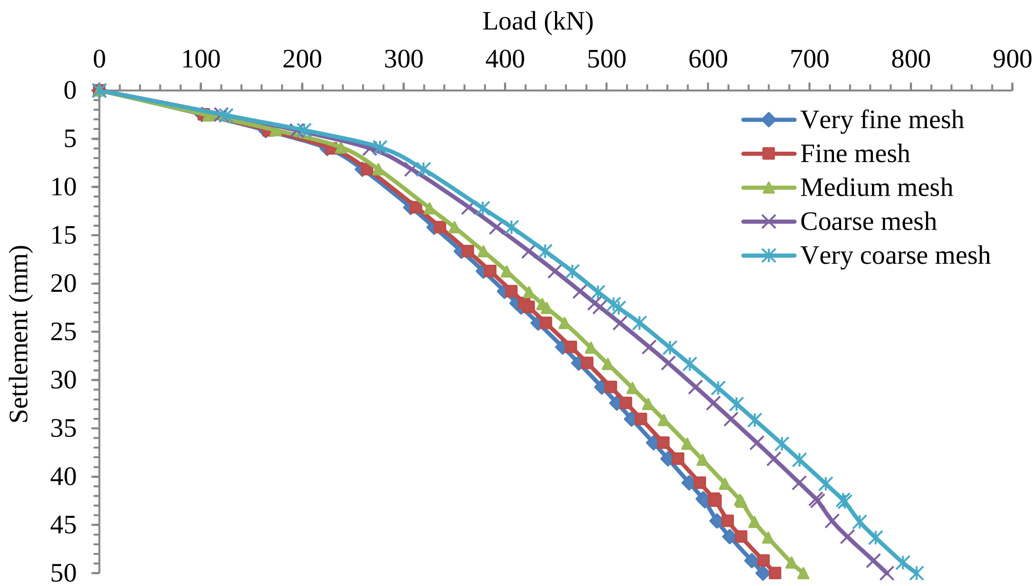


Figure 3. Convergence study for determining the optimum mesh size.

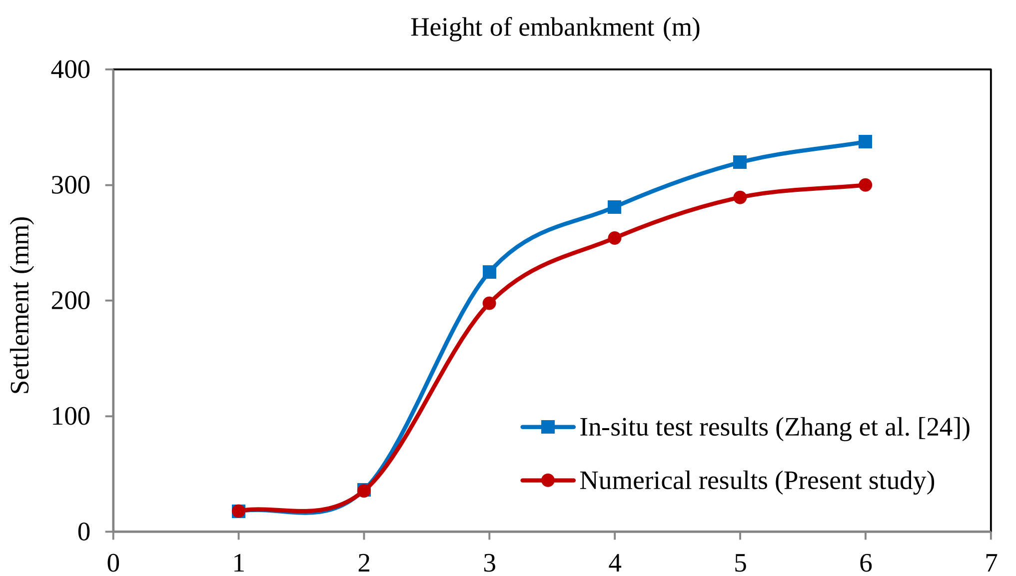


Figure 4. Comparison of results from validation analyses.

3. Results and Discussion

3.1 Effect of pervious concrete

To assess the axial load carrying capacity of stone columns (SC) and pervious concrete columns, the displacement was applied entirely over the column area. The load-settlement response of the SC and PCC are shown in Figure 5 illustrating a clear failure of SC, whereas the pervious concrete column does not show any sign of failure. It can be seen that the mobilized load on PCC is greater than the SC. Moreover, the difference of mobilized load between SC and PCC is increased with increase in settlement. For example, at a 25mm settlement, the mobilized vertical load on top of the PCC is 6.3 times that of the stone column, and at a 50mm settlement, the load is around 6.5 times that of the SC.

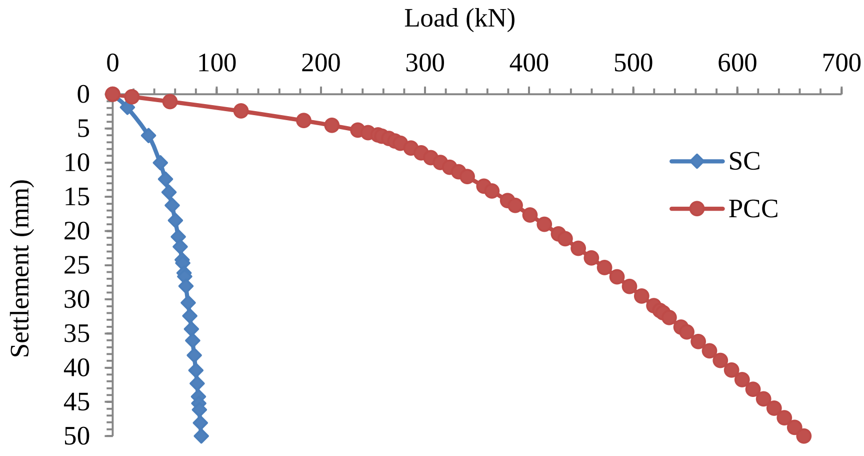


Figure 5. Load-settlement behavior of a SC and PCC.

Figure 6 illustrate the deformed shapes of a SC and a PCC. The lateral deformations of a SC and a PCC obtained from the numerical analyses are plotted against depth at a vertical settlement of 50mm in Figure 7. It can be observed that in SC maximum lateral deformation occurred up to a depth of 2m (3.33d) and at greater depths, the lateral deformation becomes negligible. In SC, maximum lateral deformation is observed about 11.05 mm, whereas in PCC, no appreciable amount of lateral deformation is seen.

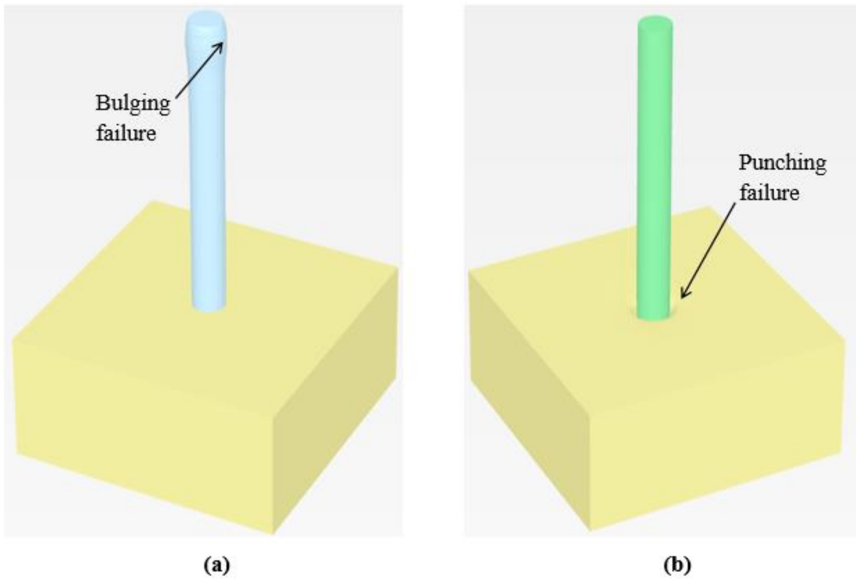


Figure 6. Deformed shapes: (a) SC; (b) PCC.

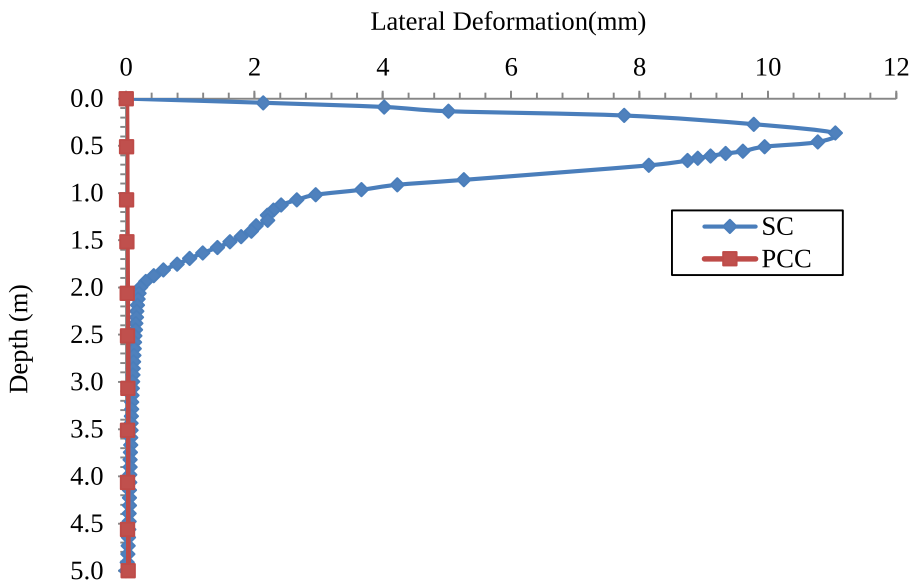
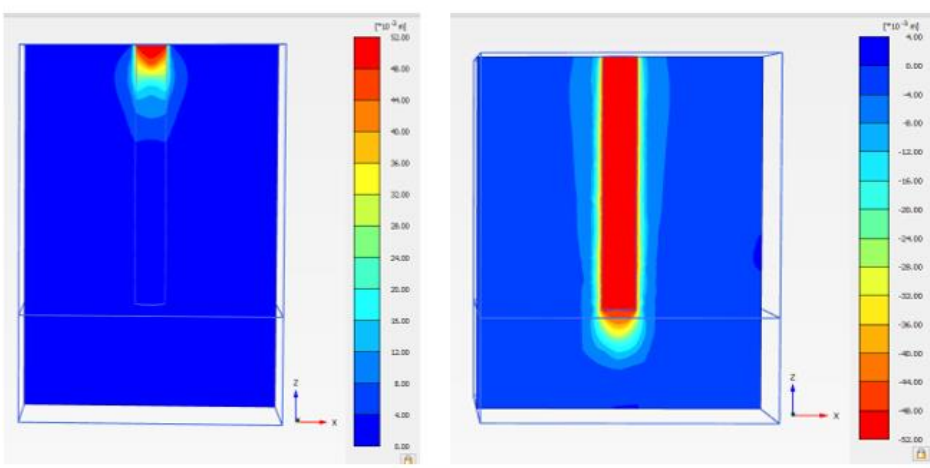


Figure 7. Lateral deformation of column along the length.

It's useful to look at the load transfer mechanisms of both the SC and the PCC. Figures 8a and 8b depict vertical settlement shadings for a SC and a PCC, respectively. Figure 9 shows the vertical settlements versus depths for a SC and PCC. After a depth of 2.5 m (i.e., 4.17d) from the top of the column, vertical settlements in the SC are minimal. This is caused by the SC's lateral deformation failure mechanism, which occurs at the top of the column. In fact, the vertical settlements seen in the SC seem to be mostly due to lateral column material displacement rather than vertical settlements due to column material compression under load. The vertical settlements in the PCC, on the other hand, are evenly distributed over the length of the column, indicating punching failure.



(a) **(b)**

Figure 8. Shadings of vertical displacements: (a) SC; (b) PCC.

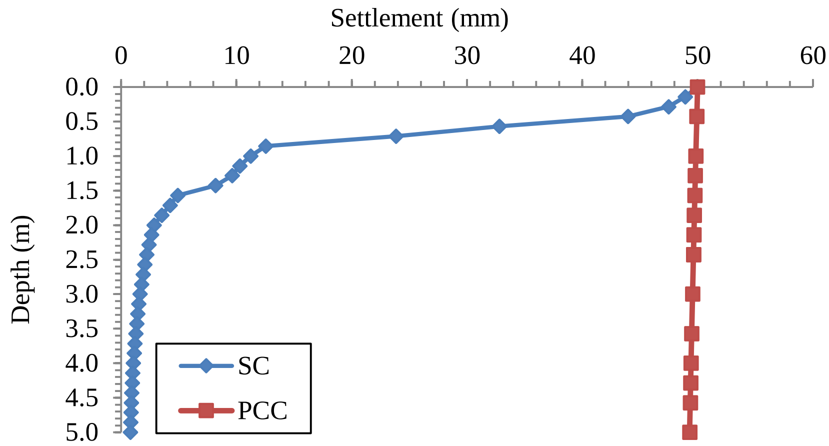


Figure 9. Vertical settlement vs. depth of column.

3.2 Effect of composite column

The mobilized vertical loads at vertical settlements of 25 and 50 mm are presented in Figure 10 to better understand the behavior of CCs. It can be observed that pervious concrete up to four times the column diameter improves the SC's performance for both 25 and 50 mm settlement. The mobilized vertical load in the CC with pervious concrete column length of 4d was 140 % more than that in the SC at 50 mm settlement.

It is seen from Figure 10 that mobilized vertical load on the top of the CC more or less remain same for both 25 and 50mm settlement for length of PCC upto 6d, but for a length of pervious concrete column of 8.33d (i.e. full length PCC) the mobilized load at a 50mm settlement is more than at a 25 mm settlement. This is attributed to compression of the SC material, indicating punching of pervious concrete in the SC material.

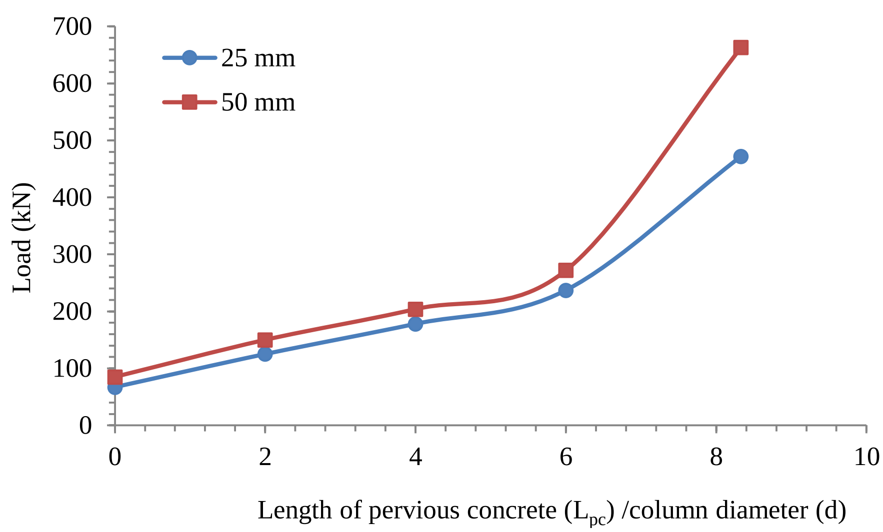


Figure 10. Mobilized vertical load in a SC, PCC, and CC as a function of L_{pc}.

Lateral deformation of CCs having pervious concrete length; 2d, 4d and 6d are presented in the Figure 11 together with the PCC (i.e. L_{pc} =8.33d), for a vertical stress of 625 kpa. As the length of PCC increases from 2d to 6d, the maximum lateral deformation decreases. Moreover, after length of 4d, the lateral deformation becomes negligible.

This suggests that the reinforcement of the SC with pervious concrete even up to a depth of 4d from the top of the column can considerably decrease the maximum lateral deformation.

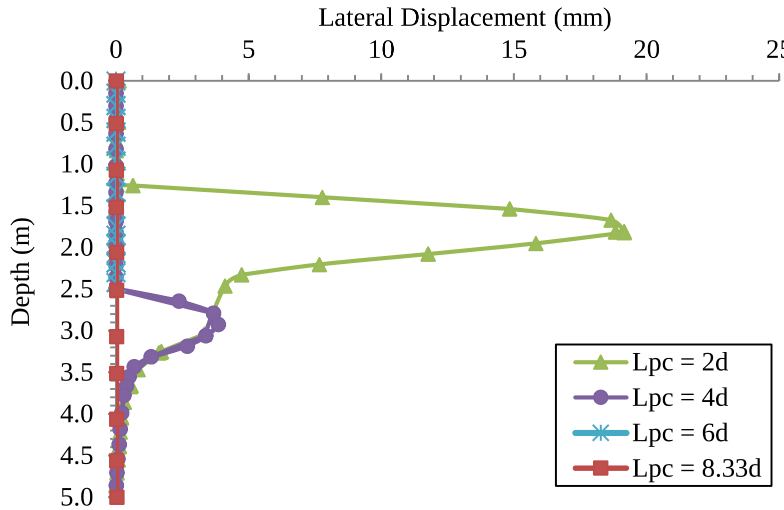


Figure 11. Lateral deformation vs. depth at a vertical stress of 625 kPa for a CC, and PCC with varying length of pervious concrete.

3.3 Effect of column diameter

Figure 12 illustrate the mobilized loads at vertical settlement of 25 and 50 mm for pervious concrete column at varying diameter. It is seen that mobilized load for pervious concrete column improves with increase in column diameter. For example, at a 50 mm settlement, increasing the pervious concrete diameter from 0.6 to 1m increases the mobilize load by 102%. Moreover; the effect of column diameter increases with increasing vertical settlements. For example, as settlement increases from 25 to 50 mm, loads increases by 43% for a column dimater of 1 m. This phenomenon is reasonable as larger settlement corresponds to larger loads in the column

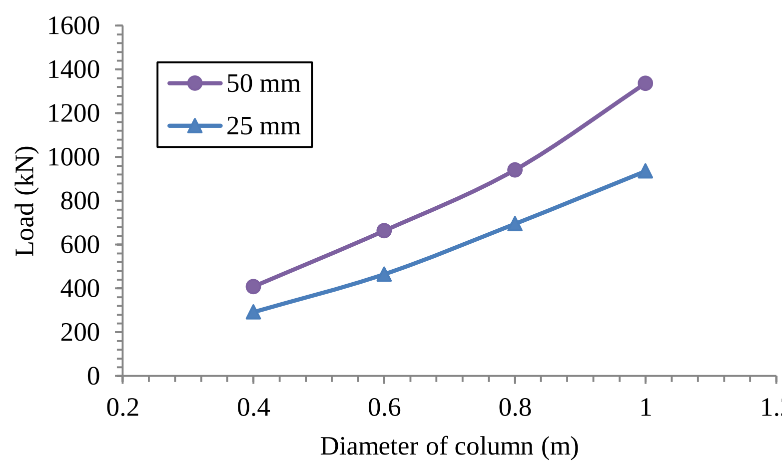


Figure 12. Load vs. diameter of a PCC for a settlement of 25 and 50 mm.

3.4 Effect of pervious concrete column length (i.e. pervious concrete clumn length upto full depth of soft clay)

To study the effect of the PCC length, four analysis were performed by varying column length from 2.5 to 10 m. In this section, length of pervious concrete was assumed upto the full depth of soft clay. It should be noted that PCCs are rested on the firm sand layer and could not be considered as floating column.

The vertical settlement at a load of 450 kN for the different PCC length are illustrated in Figure 13. It is seen that pervious concrete column settlement decrease significantly as the length varies from 2.5 to 7.5m, thenafter decrease in settlement is marginal. As column length change from 2.5 to 7.5m, the settlement is reduced by 70% and as length changes from 7.5 to 10m settlement is reduced by 29%.

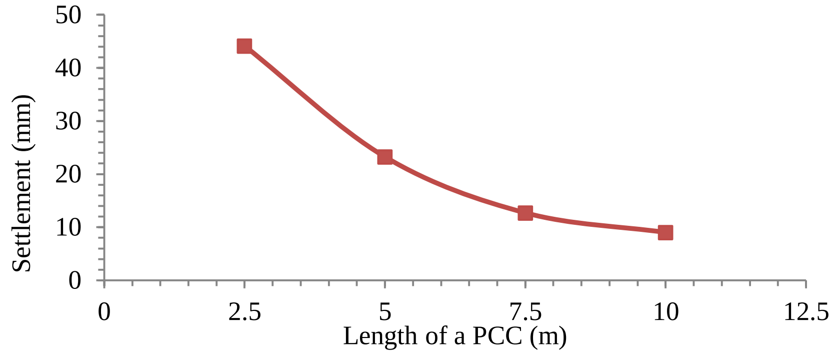


Figure 13. Settlement at a vertical load of 450 kN for different length of a PCC.

3.5 The effect of strength of the soil surrounding the column

The effect of the soil surrounding the column was studied by varying cohesion of soft clay from 10 to 25kPa. The observed load-settlements results for SCs and PCCs are shown in Figures 16 and 17, respectively. It is can be observed that the load capacity of SC is relied on the surrounding clayey soil cohesion. The influence of surrounding clay cohesion on PCC performance, on the other hand, is not significant. The load-carrying capacity of the SC and PCC increases by 127 % and 31 %, respectively, when the cohesion of the surrounding clay soil changes from 10 to 25 kPa.

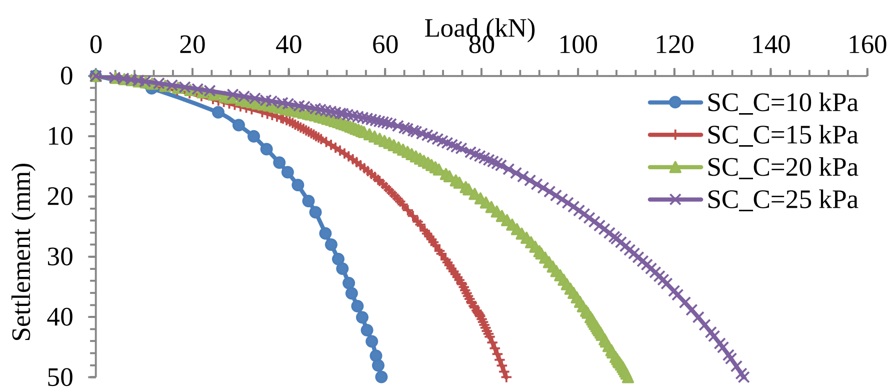


Figure 14. Load vs. settlement of SCs at 50 mm vertical settlement considering different values of cohesion.

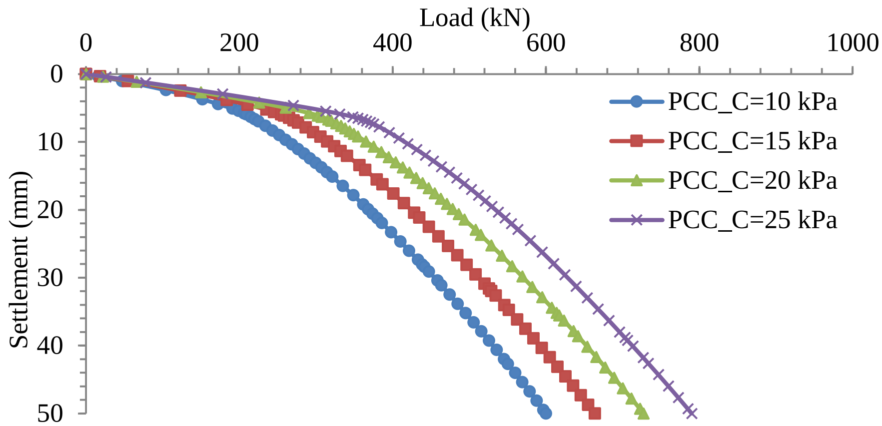


Figure 15. Load vs. settlement of PCCs at 50 mm vertical settlement considering different values of cohesion.

4 Conclusions

The following conclusions have been withdrawn as an outcome of the investigation's findings.

1. A pervious concrete column has around 6.5 times the load - carrying capacity of a stone column of the same diameter.
2. Stone columns failed by bulging (i.e. lateral deformation) into the surrounding soil, while pervious concrete column failed by directly punching into the end bearing soil at the pile base.
3. To effectively increase the stone column's load-carrying capacity, pervious concrete up to four times the diameter of the column (in composite column) may be provided near the top portion of the stone column. The composite column also failed because of lateral bulging at the stone column-pervious concrete column intersection.
4. A pervious concrete column's load-carrying capacity increases as its diameter increases.
5. As the length of the pervious concrete column increases, so does the mobilized load. Furthermore, the settlement of pervious concrete reduces with increasing column length. However, at a length of 7.5 m, i.e., a length to diameter ratio of 12.50, the amount of reduction in settlement becomes minor.
6. In contrast to stone columns, pervious concrete columns' load-carrying capacity is not remarkably influenced by the strength of the surrounding soil.

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