# Three-dimensional numerical analyses of pervious concrete column for soft soil improvement

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**Stone column (SC) or granular column is widely used as a soil improvement method for flexible foundations such as oil storage tanks, embankments and rigid foundations. The confining pressure exerted by the surrounding soil allows the SC to develop its bearing capacity. The soft soil surrounding a SC may not provide sufficient lateral confinement. So, the design bearing carrying capacity may not be achieved. In such soils, a pervious concrete column (PCC) may be applied which deals with reinforcement as well as drainage. PCC 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 study presents a parametric analysis of the performance of SCs, PCCs and composite columns (CCs) using three-dimensional numerical analyses. The parameters consider are: PCC diameter, PCC length in CCs surrounding soft clay cohesion, and full PCC length. Furthermore, the load transfer mechanism of pervious concrete is compared to that of a SC. In comparison to ordinary SCs, the findings of this study show that pervious concrete columns have a substantially better load carrying capacity and experience less lateral displacement. Furthermore, in a CC, the length of pervious concrete up to four times the column diameter may be sufficient to enhance the load carrying capacity of an ordinary SC.**

**Keywords:** Finite element analyses, land carrying capacity, pervious concrete column, soil improvement, stone column.

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 (SCs)[5,6]. Among the various ground improvement methods, the SC method is widely used as it provides 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 SC is calculated based on the lateral confinement pressure provided by the surrounding soil. Numerous researchers reported that the SCs increase the safe bearing capacity by four times[5,6]. Case studies of unsatisfactory behaviour of granular columns installed in soft soils have also been reported[8,9]. The reasons postulated for the unfavourable performance are squeezing of soft clay into SCs, greater lateral bulging and penetration of stone material into soft clay. This suggests that SCs have limited applications in soft clay soils. In these soils, it is necessary to strengthen SC 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 SCs; such as encasing the stone column peripherally with geosynthetics[7], reinforcing it by horizontal geogrid slice[10], skirting the SC with concrete[11], applying circumferential nail[12] and use of pervious concrete[13]. Although pervious concrete columns (PCCs) were applied in the field successfully, there are limited works reported in the literature.

Kim *et al.*[13] observed that the SC reinforced by pervious concrete at the top section of the granular column prevented 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 SCs. Based on laboratory model testing in clay, Kim *et al.*[13] found that pervious concrete piles might accelerate 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 the conventional SC.

In this study, a comprehensive parametric evaluation is carried out on single SCs, PCCs, and composite columns (CCs) using three-dimensional numerical analyses. The impact of variables such as column diameter, PCC length in CC, cohesion of soft clay around the column and full length of PCC are all considered in the study.

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**Table 1.** Properties of the benchmark case

| Parameters | Soft clay | Pervious concrete | Stone column | Sand |
|---|---|---|---|---|
| Unit weight $\gamma$ (kN/m$^3$) | 15 | 19 | 18 | 16.5 |
| Cohesion $C$ (kPa) | 15 ($C_u$) | – | 2 | 1 |
| Angle of internal friction $\varphi$ (deg) | 0 | – | 40 | 35 |
| Elastic modulus $E$ (kPa) | $250 \times C_u$ | $15 \times 10^6$ | 45,000 | 40,000 |
| Poisson ratio $\nu$ | 0.49 ($\nu_u$) | 0.15 | 0.3 | 0.3 |
| Dilatancy angle $\psi$ (deg) | – | – | 10 | 5 |

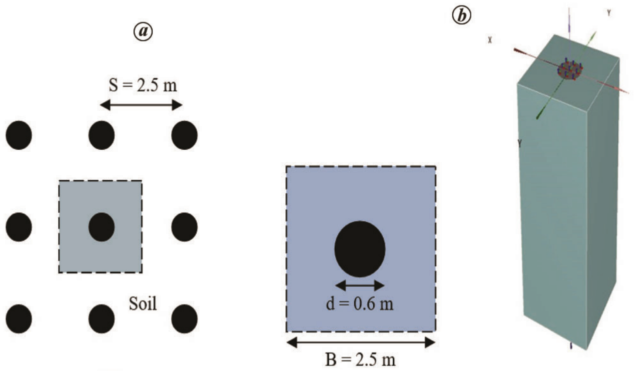

**Figure 1.** Three-dimensional column: ***a***, column layout; ***b***, 3D column.

## Numerical analysis

PLAXIS, a 3D finite element software was used to perform all numerical studies[16]. 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 the study. The soft clay was assumed to be underlain by a 2 m 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 used in the analysis was comparable to that used by other researchers in the past[17,18]. Both vertical and lateral settlements were restricted at the bottom of the model, whereas only vertical displacement was permitted and horizontal displacement was 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 behaviour of PCC is examined in the present study, focusing on short-term behaviour. Soft clay was analysed using undrained shear strength. Since 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 laboratory. The ideal elastoplastic Mohr Coulomb model was then regarded as a first approximation of soil behaviour for soft clay, sand and SC. Many previous studies have used the same constitutive model for soft clay[19,20], sand and SC[21,22].

Table 1 mentions the parameters for the benchmark case. Based on previous studies, the parameters of soft clay, sand, SC and pervious concrete were used (e.g. soft clay[19,20], sand and SC[21,22], and pervious concrete column[23,24]).

The undrained shear strength ($C_u$) is the basis for soft clay strength. As indicated in the literature[19,20], the undrained modulus of elasticity ($E_u$) was assumed (=250 Cu) and Poisson's ratio $\nu_u = 0.49$ (as it is widely known that the value 0.5 represents the case which there is no volume change, that produces major numerical complications). As suggested by 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 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 SC were used, as described by Brinkgreve and Vermeer[16].

For sand, stone and PCCs, a drain material behaviour was considered, as well as a short-term behaviour for soft clay. The pervious concrete was modelled using the linear elastic material model, which is characterized by two parameters: Young's modulus and Poisson's ratio. A drained material behaviour was assumed for the PCC having permeability $10^{-3}$ m/s. Several researchers have already adopted the same material model for 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 PCC. Table 2 summarizes the parameters varied for the study. Figure 2 shows a model with 114,888 nodes and 84,293 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 study 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.

**Table 2.** Parameters varied

| Parameters | Range |
|---|---|
| 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 $L_{pc}$ (m) | $2d$, $4d$, $6d$, $8.33d$* |
| Length of full pervious concrete column $L$ (m) | 2.5, 5*, 7.5, 10 |

*Parameters for the baseline case.

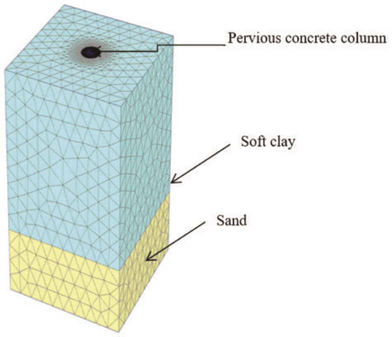

**Figure 2.** Three-dimensional model of the column.

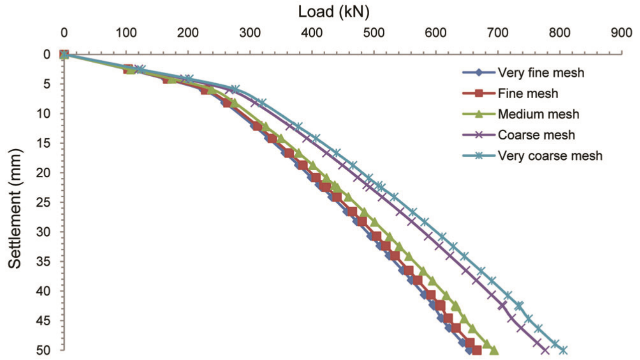

**Figure 3.** Convergence study for determining optimum mesh size.

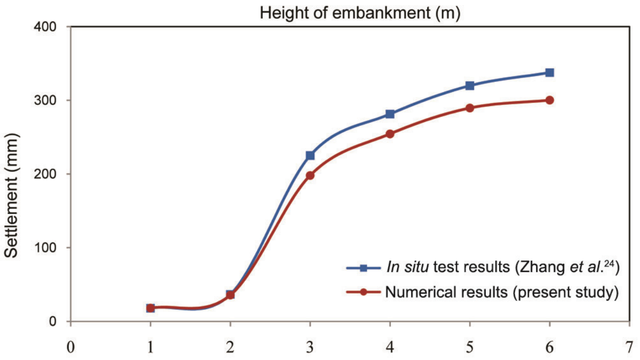

**Figure 4.** Comparison of results from validation analyses.

The present study deals with load–settlement behaviour of a pervious concrete column reinforced in soft clay. So, plastic analysis (mechanical behaviour) was 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 studies were carried out by applying the prescribed displacement directly over its surface. The vertical settlement of the surrounding soil must be considered for 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 the present study. Figure 4 depicts that the settlements derived from the numerical simulation are identical to those obtained from field experiments when the embankment height is less than 2 m. However, when the embankment height is more than 2 m, there is considerable variation 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, whereas the initial modulus established by the laboratory experiment is being used in the numerical solution; thereby, higher the embankment, larger is the difference between the settlement of an embankment attained by the computer model and 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 present numerical analysis with those of the reported experimental studies with soft clay as the surrounding soil[13,26,27], because the related soil properties (mainly undrained cohesion) are not available. In addition, the field works published[28,29] involving layered soil deposits, could not be correlated with the present study, as PCC behaviour was studied here by reinforcement in single soft clay layer.

## Results and discussion

### *Effect of pervious concrete*

To assess the axial load carrying capacity of SCs and PCCs, the displacement was applied entirely over the column area. The load–settlement response of SC and PCC is shown in Figure 5 illustrating a clear failure of SC, whereas

PCC does not show any signs of failure. It can be seen that the mobilized load on PCC is greater than that on SC. Moreover, the difference of mobilized load between SC and PCC increases with increase in settlement. For example, at a 25 mm settlement, the mobilized vertical load on top of a PCC is 6.3 times that of SC, while at a 50 mm settlement, the load on PCC is around 6.5 times that of SC.

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

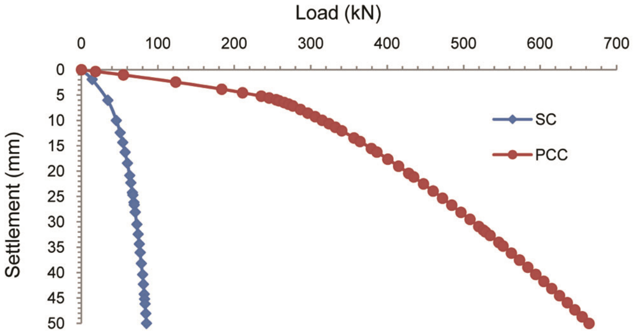

**Figure 5.** Load–settlement behaviour of a stone column (SC) and pervious concrete column (PCC).

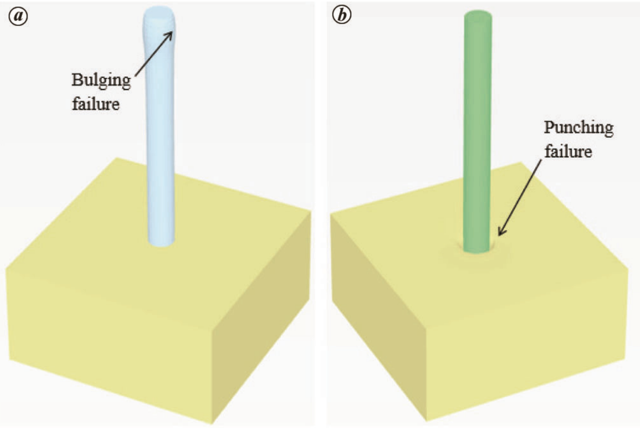

**Figure 6.** Deformed shapes: ***a***, SC; ***b***, PCC.

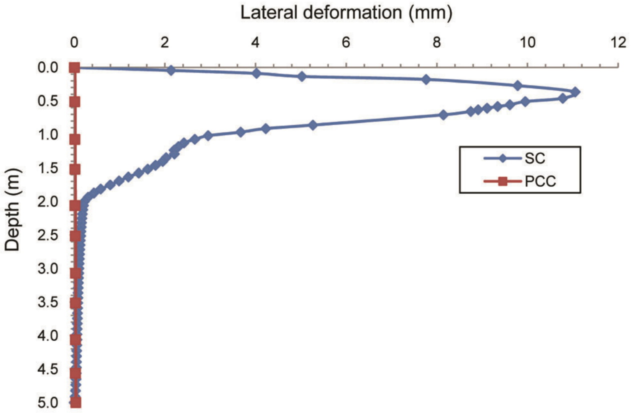

**Figure 7.** Lateral deformation of column along the length.

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

## *Effect of composite column*

The mobilized vertical loads at vertical settlement of 25 and 50 mm are presented in Figure 10 to better understand the behaviour of CCs. It can be observed that

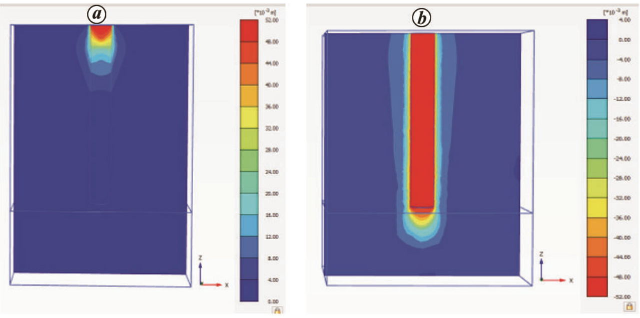

**Figure 8.** Shadings of vertical displacements: ***a***, SC; ***b***, PCC.

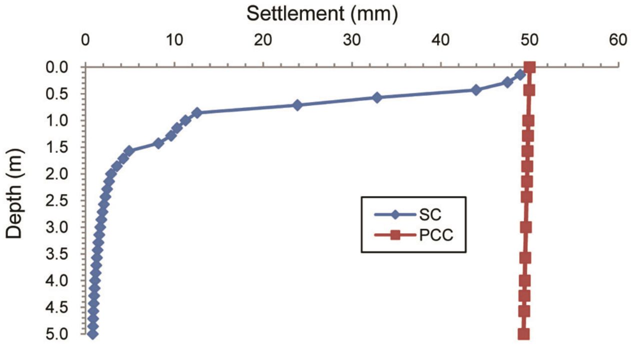

**Figure 9.** Vertical settlement versus depth of column.

pervious concrete up to four times the column diameter improves the SC's performance of SC for both 25 and 50 mm settlement. The mobilized vertical load in CC with PCC length of 4*d* was 140% more than that in SC at 50 mm settlement.

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

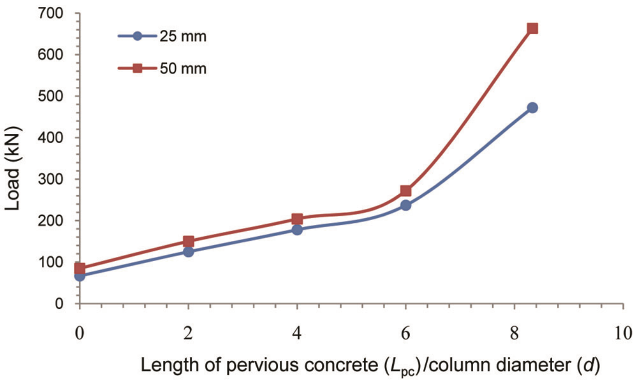

**Figure 10.** Mobilized vertical load in SC, PCC and composite column (CC) as a function of $L_{pc}$.

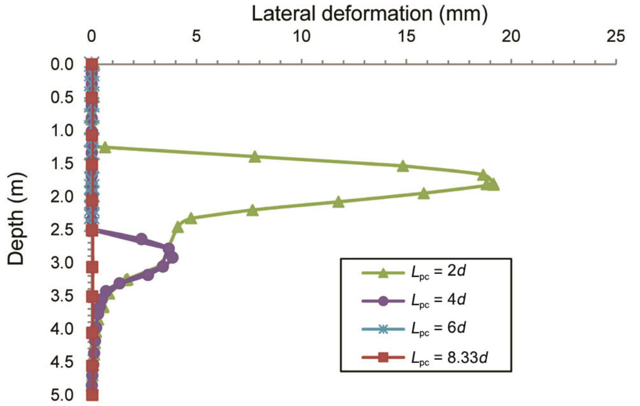

**Figure 11.** Lateral deformation versus depth at vertical stress of 625 kPa for CC and PCC with varying length of pervious concrete.

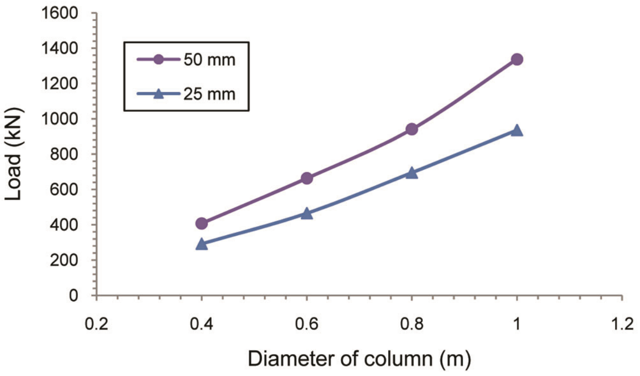

**Figure 12.** Load versus diameter of PCC for a settlement of 25 and 50 mm.

Lateral deformation of CCs having pervious concrete length 2*d*, 4*d* and 6*d* is presented in Figure 11 together with PCC (i.e. $L_{pc} = 8.33d$) for a vertical stress of 625 kpa. As the length of PCC increases from 2*d* to 6*d*, the maximum lateral deformation decreases. Moreover, for lengths more than 4*d*, the lateral deformation becomes negligible. This suggests that the reinforcement of SC with pervious concrete even up to a depth of 4*d* from the top of the column can considerably decrease the maximum lateral deformation.

## *Effect of column diameter*

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

## *Effect of PCC column length (i.e. PCC length up to full depth of soft clay)*

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

Figure 13 illustrates the vertical settlement at a load of 450 kN for different PCC lengths. It is seen that the PCC settlement decreases significantly as the length varies from 2.5 to 7.5 m. Thereafter, the decrease in settlement is marginal. As column length changes from 2.5 to 7.5 m, the settlement is reduced by 70% and as length changes from 7.5 to 10 m, the settlement is reduced by 29%.

## *Effect of strength of the soil surrounding the column*

The effect of soil surrounding the column was studied by varying cohesion of soft clay from 10 to 25 kPa. Figures 14 and 15 show the observed load-settlement results for SCs and PCCs respectively. It is can be observed that the load capacity of SC relies 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 SC and PCC increases by 127% and 31% respectively, when cohesion of the surrounding clay soil changes from 10 to 25 kPa.

## Conclusion

The following conclusions can be drawn from this study.

(i) A PCC has around 6.5 times the load-carrying capacity of a SC of the same diameter.

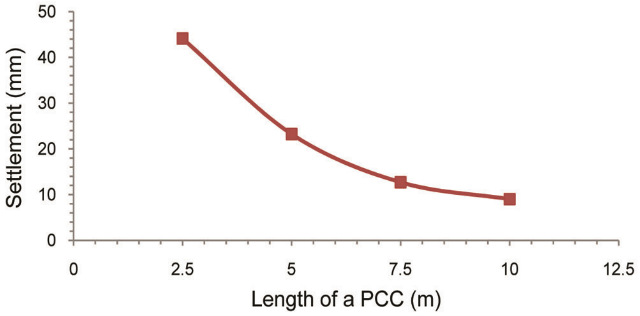

**Figure 13.** Settlement at a vertical load of 450 kN for different lengths of a PCC.

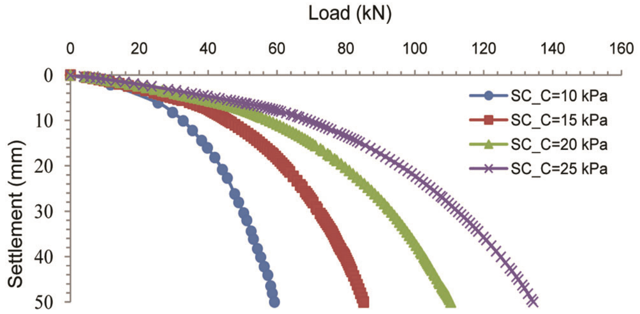

**Figure 14.** Load versus settlement of SC at a vertical settlement of 50 mm for different values of cohesion.

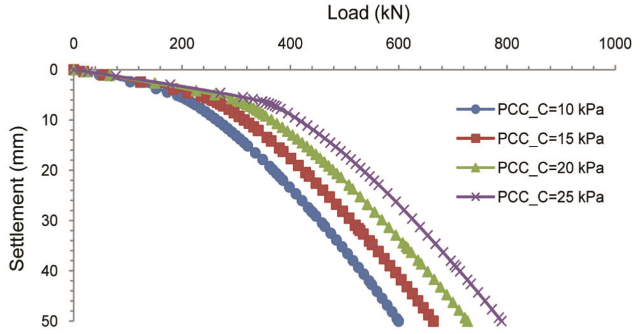

**Figure 15.** Load versus settlement of PCC at a vertical settlement of 50 mm for different values of cohesion.

(ii) SCs 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.

(iii) To effectively increase the load-carrying capacity of SCs, pervious concrete up to four times the diameter of the column (in composite column) may be provided near the top portion of the SC. The composite column also failed because of lateral bulging at the SC–PCC intersection.

(iv) The load-carrying capacity of PCC increases with increase in its diameter.

(v) As the length of the PCC 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 reduction in settlement becomes small.

(vi) In contrast to SCs, the load-carrying capacity of pervious concrete columns is not significantly influenced by the strength of the surrounding soil.

1. Indraratna, B., Khabbaz, H., Salim, W., Lackenby, J. and Christie, D., Ballast characteristics and the effects of geosynthetics on rail track deformation. In International Conference on Geosynthetics and Geoenvironmental Engineering, Bombay, India, 2004, pp. 3–12.
2. Rampello, S. and Callisto, L., Predicted and observed performance of an oil tank founded on soil cement columns in clayey soils. *Soils Found.*, 2003, **43**(4), 229–241.
3. Shen, S. L., Chai, J. C., Hong, Z. C. and Cai, F. X., Analysis of field performance of embankments on soft clay deposit with and without PVD-improvement. *Geotext. Geomembr.*, 2005, **23**(6), 463–485.
4. Rajasekaran, G. and Narasimha Rao, S., Permeability characteristics of lime treated marine clay. *Ocean Eng.*, 2002, **29**, 113–127.
5. Greenwood, D. A., Mechanical improvement of soils below ground surface. In Proceedings of the Ground Engineering Conference, London, UK, 1970, pp. 11–22.
6. Hughes, J. M. O., Withers, N. J. and Greenwood, D. A., A field trial of the reinforcing effect of a stone column in soil. *Geotechnique*, 1975, **25**(1), 31–44.
7. Murugesan, S. and Rajagopal, K., Geosynthetic-encased stone columns: numerical evaluation. *Geotext. Geomembr.*, 2006, **24**(6), 349–358.
8. McKenna, J. M., Eyre, W. A. and Wolstenholme, D. R., Performance of an embankment supported by stone columns in soft ground. *Geotechnique*, 1975, **25**(1), 51–59.
9. Greenwood, D. A., Load tests on stone columns. In *Deep Foundation Improvements: Design, Construction, and Testing* (eds Esrig, M. I. and Bachus, R. C.), American Society for Testing and Materials, Philadelphia, 1991, pp. 148–171.
10. Ayadat, T. and Hanna, A. M., Encapsulated stone columns as a soil improvement technique for collapsible soil. *Ground Improv.*, 2005, **4**(9), 137–147.
11. Ranjan, G., Ground treated with granular piles and its response under load. *Indian Geotech. J.*, 1989, **19**, 1–86.
12. Shivashankar, R., Dheerendra Babu, M. R., Nayak, S. and Manjunath, R., Stone columns with vertical circumferential nails: laboratory model study. *Geotech. Geol. Eng.*, 2010, **28**, 695–706.
13. Kim, S., Lee, D., Lee, J., You, S. and Choi, H., Application of recycled aggregate porous concrete pile (RAPP) to improve soft ground. *J. Mater. Cycles Waste Manage.*, 2012, **14**, 360–370.

14. Tandel, Y. K., Solanki, C. H. and Desai, A. K., Application of pervious concrete for strengthening of stone column for ground improvement. In Proceeding of National Conference on Structural Engineering Convention 2012 (8th Biennial Conference), Surat, 2012, pp. 177–181.
15. Suleiman, M., Ni, L. and Raich, A., Development of pervious concrete pile ground-improvement alternative and behavior under vertical loading. *J. Geotech. Geoenviron. Eng.*, 2014, **140**(7), 04014035.
16. Brinkgreve, R. B. and Vermeer, P. A., PLAXIS 3D-finite element code for soil and rocks analysis. AA. Balkema, Rotterdam, The Netherlands, 2010.
17. Yoo, C., Performance of geosynthetic-encased stone columns in embankment construction: numerical investigation. *J. Geotech. Geoenviron. Eng.*, 2010, **136**, 1148–1160.
18. Tang, L., Cong, S., Ling, X., Lu, J. and Elgamal, A., Geotextiles and geomembranes numerical study on ground improvement for liquefaction mitigation using stone columns encased with geosynthetics. *Geotext. Geomembr.*, 2015, **43**, 190–195.
19. De Sanctis, L. and Mandolini, A., Bearing capacity of piled rafts on soft clay soils. *J. Geotech. Geoenviron. Eng.*, 2006, **132**, 1600–1610.
20. Hossain, S. and Rao, K. N., Performance evaluation and numerical modeling of embankment over soft clayey soil improved with chemico-pile. *Transp. Res. Rec.*, 1952, **2006**, 80–89.
21. Zahmatkesh, A. and Choobbasti, A. J., Settlement evaluation of soft clay reinforced with stone columns using the equivalent secant modulus. *Arab. J. Geosci.*, 2012, **5**, 103–109.
22. Abusharar, S. W. and Han, J., Two-dimensional deep-seated slope stability analysis of embankments over stone column-improved soft clay. *Eng. Geol.*, 2011, **120**, 103–110.
23. Shafee, A., Ghodrati, M. and Fahimifar, A., Numerical investigation on load bearing capacity of pervious concrete piles as an alternative to granular columns. *Int. J. Geotech. Geol. Eng.*, 2018, **12**, 501–507.
24. Zhang, J., Cui, X., Huang, D., Jin, Q., Lou, J. and Tang, W., Numerical simulation of consolidation settlement of pervious concrete pile composite foundation under road embankment. *Int. J. Geomech.*, 2016, **16**, B4015006.
25. Bolton, M. D., The strength and dilatancy of sands. *Géotechnique*, 1986, **37**, 219–226.
26. You, S., Lee, J. and Gabr, M. A., Experimental evaluation of recycled aggregate porous concrete piles (RAPP) for soft ground Improvement. *Mar. Georesour. Geotechnol.*, 2016, **38**, 712–720.
27. Munaga, T., Khan, M. M. and Gonavaram, K. K., Axial and lateral loading behaviour of pervious concrete pile. *Indian Geotech. J.*, 2019, 1–9.
28. Kim, H. T., Yoo, C. H., Hwang, J. S. and Sim, Y. J., Application of porous concrete to a structural foundation in soft ground. *Adv. Mater. Res.*, 2007, **28**, 895–898.
29. Qing, J. *et al.*, *In situ* evaluation and analysis of improvement effects of pervious concrete pile on alluvial silt ground. *Geomech. Geoeng.*, 2019, **16**(3), 212–222.

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