A Numerical Study on the Shear Strength of Pervious Concrete Column in Weak Ground

Rashma R.S.V[1], Jayalekshmi B.R[2], and R. Shivashankar [2]
[1]*Former Research Scholar, Department of Civil Engineering, National Institute of Technology Karnataka, Surathkal, India*
[2] *Professor, Department of Civil Engineering, National Institute of Technology Karnataka, Surathkal, India*
E-mail: rashmarsv@gmail.com

ABSTRACT: In this study, the response of pervious concrete column-treated ground under shear loading is examined by employing a series of numerical analyses. The shear behaviour of pervious concrete column-treated ground is compared with stone column-treated ground and weak ground. Two types of analyses were carried out to assess shear strength of the composite ground. Conventional direct shear test model and large shear test models were evaluated using ABAQUS software. The pervious concrete column-treated ground is observed to have greater shear strength than the mere stone column-treated ground. The lateral deflection pattern of the pervious concrete column is also noticed to be very much lesser than conventional stone columns under static shear loading. The overall shear performance of the pervious concrete column-treated ground is found to be improved than the typical stone column-treated ground.

KEYWORDS: Pervious concrete columns, Stone columns, Treated ground, Shear resistance, Numerical analysis.

1. INTRODUCTION

Stone columns, also known as gravel piles, are used as a ground improvement technique to improve the load bearing of weak grounds. It also provides an effortless path for the pore-water to flow across the pores of extremely porous gravel and prevents the surrounding soil from losing its shear strength and hence mitigates liquefaction. The shear strength of the soil is one of the factors which can be improved by reinforcing the weak soil with the inclusions such as employing geo-synthetic encasements (Murugesan and Rajagopal, 2006, 2009; Gniel and Bouazza, 2009; Lo et al., 2010; Chen et al., 2015; Mohapatra and Rajagopal, 2016, 2017; Castro 2017; Hong et al., 2017) and deep cement mixing columns (Barksdale and Bachus, 1983; Kitazume and Maruyama 2007; Nguyen et al., 2016) which are generally employed in the weak ground. Recently, Ni et al. (2016) suggested pervious concrete column as a substitute to typical stone column. The shear behavior of weak ground with stone columns and geo-synthetic encased stone columns are available in literature (Barksdale and Bachus, 1983; Murugesan and Rajagopal, 2006, 2009; Mohapatra and Rajagopal, 2016, 2017; Mohapatra et al., 2016, 2017, 2018). However, the shear behavior of the pervious concrete column inclusion in the weak ground is not well explored. Thus, the present research considered pervious concrete column in lieu of typical stone column to examine the shear strength of the treated ground. The pervious concrete column has a vertical load-carrying capacity of 4.4 times more than ordinary stone column (Ni, 2014; Suleiman et al, 2014). It is additionally stated that the pervious concrete column has comparable drainage characteristics as that of conventional stone column (Ni, 2014; Suleiman et al., 2014). The comparable permeability characteristics of pervious concrete column, along with high load-bearing capability and the performance of the pervious concrete column (rigid column) being independent of the bordering soil property, establishes it as a viable solution in very weak clays (Barksdale and Bachus, 1983; Ni 2014; Suleiman et al., 2014)

Stone columns are generally used to support huge embankments in weak soils. The present study focusses on the columns staged under the toe of the embankment where lateral loading is significant. In a stone column-supported embankment construction, the stone columns positioned proximate to the toe of the embankment undergoes prevalent shear loading when evaluated with the stone columns positioned beneath the centerline of the embankment. The single column modelled in the study represents column adjacent to the toe of the embankment, where shear loading is predominant. In this study, the shear capacity of weak soil, ordinary stone column-treated ground, and pervious concrete column-treated soil are compared and presented. The shear resistance of the treated ground with ordinary stone columns and pervious concrete columns in terms of shear strength is considered. Numerical analyses of direct shear and large shear tests were used, and the analysis procedures are discussed in the subsequent sections.

2. METHODOLOGY

Numerical simulation of the direct shear test and large shear tests were carried out with various parameters to evaluate the shear resistance of pervious concrete column-treated ground. In both analyses, the weak ground was made up of weak clay.

2.1 Direct Shear Test Model

In direct shear test model numerical analysis (Figure 1(a)), the upper box was moved relative to the lower box, and the shear stress corresponding to the shear displacement of the upper box was reflected as the ratio of summing the corresponding horizontal force components, which causes shear displacement, to the plan area of the shear box (305×305 mm^2). Direct shear test using model dimensions of 305 mm × 305 mm according to ASTM-D3080 (1998) was modelled in the software. The direct shear test analysis was conducted for several average pressures differing between 0 kPa - 75 kPa, which represents the pressure on columns positioned below the toe of the embankment and the centerline of the embankment, respectively. The pressure of 75 kPa represents a 5 m high embankment with a density of 15 kN/m^3.

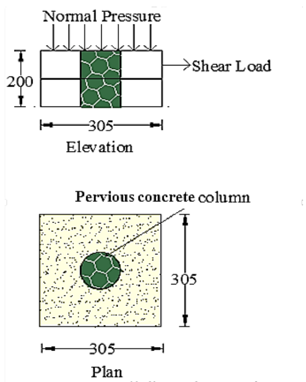

Figure 1(a) Direct shear test for pervious concrete column-treated ground

Three steps were used in the analysis for direct test simulation. In the first geostatic step, gravity loading was employed, and all translations were established to zero. Normal pressure was applied in the second step. Then displacement-controlled loading was employed to the vertical lateral borders of the top box for a total time of 200000 seconds at the rate of 2×10^{-4} mm/sec to achieve 40 mm horizontal translation. A similar rate of translation was used by Mohapatra et al. (2017). The lower box in the model remains fixed at all the stages of loading. The numerical analysis of direct shear test was conducted for weak soil, stone column-treated weak soil, and pervious concrete column-treated weak soil considering varying normal pressures. The total depth of the shear box modelled was 200 mm, and it clearly indicates the depth limitation. To overcome this limitation, a large shear test model analysis was carried out, as explained in Section 2.2.

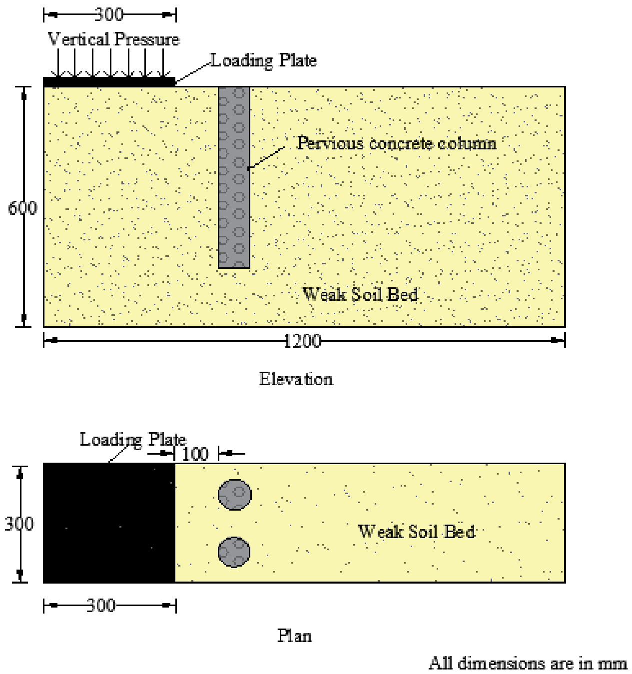

Figure 1(b) Large shear test model with two columns at 200 mm c/c arrangement

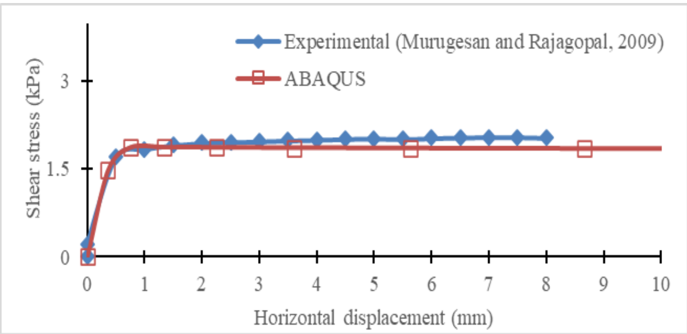

Figure 1(c) Validation of ABAQUS model.

2.2 Large Shear Test Model

In numerical modelling of large shear test modelling, shear loading was employed to the improved ground by simulating vertical movement on the loading plate and shear strength of improved ground was assessed indirectly from the increased pressure-settlement response on loading plate. This procedure for shear loading was developed by Murugesan and Rajagopal (2009) and similar dimensions were used in the present study. The model used for numerical analysis is shown in Figure 1(b). The vertical loading on the loading plate of large shear test tank is very much like the lateral squeezing of soil bed between an embankment and relatively strong foundation below the soft clay, thereby generating shear load in the large tank (2009). The loading was simulated till the vertical settlement of the top plate reached 50 mm. Two steps were used in the analysis for large shear test simulation. In the first geostatic step, gravity loading was employed, and all translations were established to zero. Then displacement-controlled loading was applied for a total time of 2500 seconds at the rate of 1.2 mm/min to achieve a settlement of 50 mm. The lateral borders of the shear test model were restricted from the translation at right angles to the corresponding planes. The base of the large shear test model was fixed during all the phases of loading.

The large shear test simulation was also carried out for weak soil, stone column-treated soil, and pervious concrete column-treated soil. The depths of floating pervious concrete columns were varied from 1D to 8D (D-diameter of the column studied), and the results were compared with the performance of end-bearing columns. The impact of pervious concrete columns, the impact of the depth of the stone column and pervious concrete column, lateral deformation of the columns, and heave profile were studied.

3. NUMERICAL MODELLING

ABAQUS student edition 2016 has been used for numerical modelling. The numerical model was validated by using the laboratory experimental data described by Murugesan and Rajagopal (2009). Clay was used as weak soil in the experimental setup. Therefore, for validation, direct shear test was modelled for the improved clay reinforced with stone column of diameter 100 mm under normal pressure of 13.3 kPa. The dimensions of the direct shear test box used were 300 mm × 300 mm × 200 mm. Displacement-controlled loading was applied to the upper shear box, although the displacement was given to the lower shear box in their experimental setup. The results obtained from the ABAQUS model and reference experimental data were found to be in good agreement and follow the same pattern. The validation results in terms of the shear stress-horizontal displacement plot are shown in Figure1(c).

The material properties employed in the numerical analysis are presented in Table 1. Modified cam clay was utilized for modelling weak soil, and a well-established Mohr-Coulomb model was utilized for modelling stone columns. Linear elastic material with young's modulus of 15.4 GPa and Poisson ratio of 0.20, as indicated by Ni et al. (2014), was used for modelling pervious concrete columns. The properties of weak soil and stone columns were adopted from Shahu and Reddy (2011) and Ambily and Gandhi (2007), respectively. The soil–stone column interface was demonstrated with surface-to-surface contact with tangential and normal behavior, and the coefficient of friction used was 0.621, calculated as 2/3 tan ø, where ø is the angle of internal friction of the stone column. The soil-pervious concrete interface was also modelled with surface-to-surface contact with tangential and normal behavior, and the coefficient of friction used was 0.3, considered as tan ø, ø being the angle of internal friction of soil. Eight noded brick elements were used for simulating weak soil, stone column, and pervious concrete column. Finite element mesh was generated automatically, and most of the default values for computation parameters were used as suggested in ABAQUS manual (2016).

Table 1 Material Properties

Weak soil (Shahu and Reddy 2011)	
Constitutive model	Modified Cam-Clay
Density (kN/m^3)	17
Logarithmic hardening constant for plasticity	0.11
Poisson's ratio	0.33
Bulk modulus	0.025
Critical state stress ratio	0.703
Gravel (Ambily and Gandhi 2007)	
Constitutive model	Mohr-Coulomb
Density (kN/m^3)	16.62
Modulus of elasticity (kPa)	55000
Poisson’s ratio	0.3
Cohesion (kPa)	1
Angle of friction (Degrees)	43
Dilation angle (Degrees)	10
Pervious concrete (Ni 2014)	
Constitutive model	Linear Elastic
Modulus of elasticity (GPa)	15.4
Poisson’s ratio	0.2

In direct shear analysis, normal pressures were differed from 0 kPa-75 kPa at a difference of 15 kPa, that relates to the embankment altitude between 0 m - 5 m for a density of 15 kN/m^3. The shear failure is generally expected near the toe of the embankment. Therefore, the column placed below or adjacent to the toe of the embankment experiences significant shear loading. To evaluate the shear performance for a minimum normal pressure, lower value of embankment fill density was considered. The normal pressures related to 0 kPa and 75 kPa exemplify columns laid underneath the toe and center of the embankment, respectively. The clayey soil, soil treated with stone columns, and with pervious concrete columns were analyzed by changing the normal pressures differing between 0 kPa - 75 kPa.

In a large shear test model, displacement-controlled loading to achieve a settlement of 50 mm was applied for all the cases considered. In order to investigate the impact of the diameter of the stone columns and pervious concrete columns, analyses were carried out for 50 mm, 70 mm, and 90 mm columns. To study the significance of the depth of the pervious concrete columns, the depth of column was varied from 1D to 8D (D-diameter of the column) and was compared with end-bearing condition. Lateral deflection of 50 mm, 70 mm, and 90 mm diameter end-bearing columns were studied under shear loading. The two-column group performance of pervious concrete columns was compared with a single column. The heave profile of weak soil was also studied and reported. After numerical analysis, the deformed mesh of stone column and pervious concrete columns was assessed, and distortion profile was studied.

4. RESULTS AND DISCUSSIONS

4.1 Impact of Pervious Concrete Column

Firstly, numerical analysis of direct shear test was conducted for analyzing the shear strength of pervious concrete column treated soil over unimproved weak soil. The direct shear test analysis was conducted on weak soil, ordinary stone column (OSC) treated soil, and pervious concrete column treated soil (PCC) for differing normal pressures from 0 kPa to 75 kPa. The diameter of the stone column and pervious concrete column considered was 70 mm for all the normal pressures considered. The results of the direct shear analysis are shown in Figure 2(a).

The shear performance of the weak soil, typical stone column, and pervious concrete column-treated soil increased with surge in the normal pressure (Figure 2(a)). While analyzing the deformed shape of model after direct shear model analysis (Figure 2(b)), the pervious concrete column was not seen to undergo any shear failure, and the behavior was like that of a rigid pile, whereas the ordinary stone column improved ground had shown least resistance and had undergone shear failure. The diameter of column shown in Figure 2(b) is 70 mm subjected to a normal pressure of 45 kPa. The pervious concrete has higher modulus of elasticity, and thereby the treated soil exhibited higher shear endurance than the typical stone column treated soil.

Secondly, large shear test model analyses were conducted on weak soil, ordinary stone column (OSC) treated soil, and pervious concrete (PCC) treated soil. The diameter of the column studied was 90 mm, with a length of the column as 600 mm (i.e., end-bearing condition), and a clear gap between the edge of the plate and the column is 50 mm. The results are given in Figure 3(a). It can be seen from Figure 3(a) that the shear endurance of pervious concrete column is significantly higher than the typical stone column. From Figure 3(a), the shear performance of ordinary stone column and pervious concrete column treated soil increased by 9% and 57% compared to unimproved weak soil.

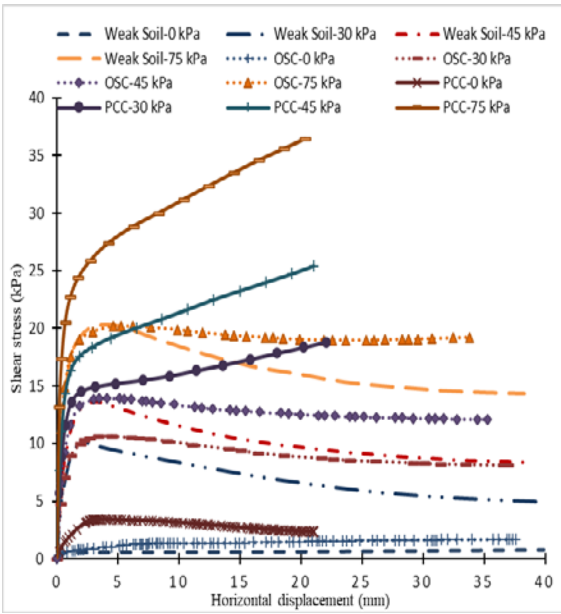

Figure 2(a) Effect of pervious concrete column (direct shear test model analysis)

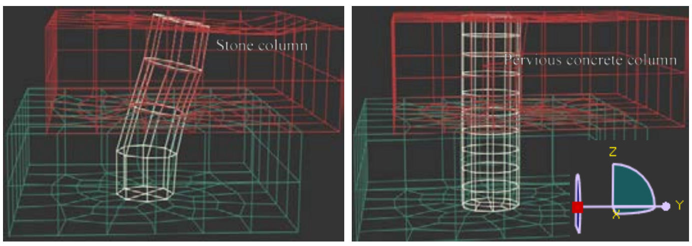

Figure 2(b) Deformed stone column and pervious concrete column after direct shear analysis

The deformed pattern of two pervious concrete column groups from large shear test analysis is shown in Figure 3(b). The two columns considered have a diameter of 70 mm. The displacement contours seen in Figure 3(b) are very less compared to that of unimproved ground, and the columns are seen to reduce the shear movements. This high shear resistance is credited to the higher rigidity of pervious concrete columns.

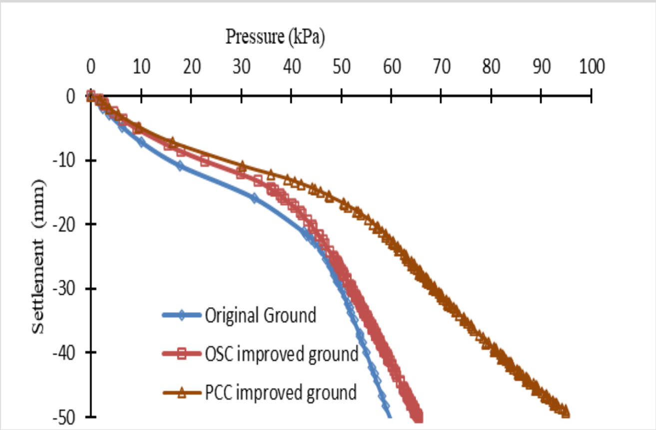

Figure 3(a) Impact of pervious concrete column (from large shear test model)

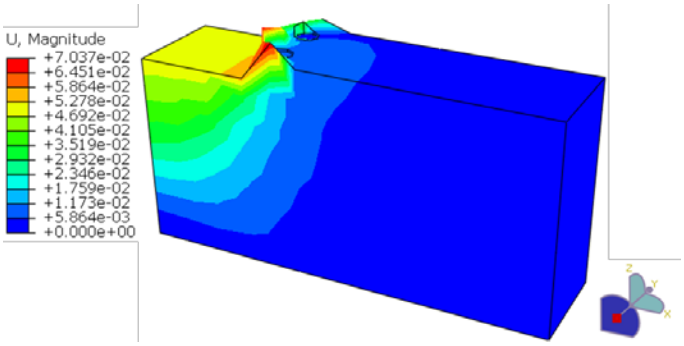

Figure 3(b) Deformed pervious concrete column treated ground with two columns from large shear test analysis

4.2 Impact of the Depth of Pervious Concrete Column

To explore the impact of the depth of the pervious concrete column, the length of the column was altered (from 1D to 8D) for 50 mm diameter column and compared with end bearing column, and results are presented in Figure 4. The clear gap between the edge of the plate and the column considered was 50 mm.

It is noticed that the pressure-settlement response of the floating pervious concrete column-treated ground is like that of the typical stone column-treated ground. This could be due to insufficient anchorage length of columns in the analysis. The pressure-settlement response of the end-bearing pervious concrete column (45%) is significantly higher than the floating columns (19%) and end-bearing stone column. Hence, it is expected to keep the depth of the pervious concrete column to rock layer for attaining superior shear endurance.

4.3 Lateral Deflection of the Pervious Concrete Column

Figure 5 shows the lateral deflection of pervious concrete column and ordinary stone column. The lateral deflection at the top end of the pervious concrete column is very less than that of ordinary stone column. The study was conducted for three diameters of 50 mm, 70 mm, and 90 mm end-bearing columns. The end-bearing columns were selected for evaluating the lateral deflection of columns due to their significant performance than floating columns. The clear gap between edge of loading plate and column was taken as 50 mm. The lateral defection at the top end of stone columns of all three diameters has almost similar pattern. This behavior is due to the size of the aggregate and property being considered the same for all three diameters. However, in the field, the aggregate size is different for different diameter columns. The lateral deflection of 90 mm pervious concrete column is lesser than that of 70 mm and 50 mm diameter columns. This lesser deflection of 90 mm pervious concrete column could be due to the shear endurance posed by the higher diameter pervious concrete column along the circumference of column.

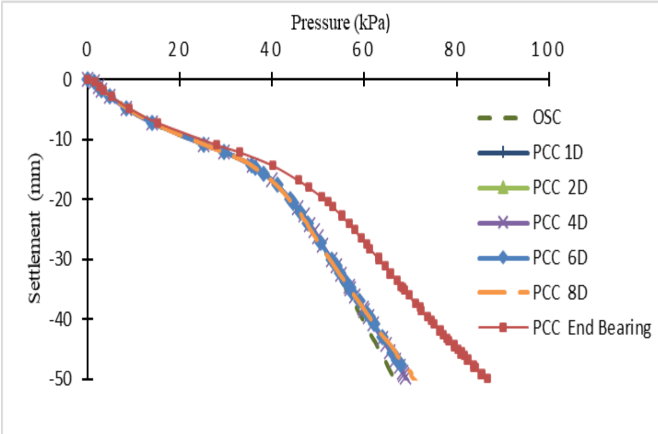

Figure 4 Impact of the depth of the pervious concrete column

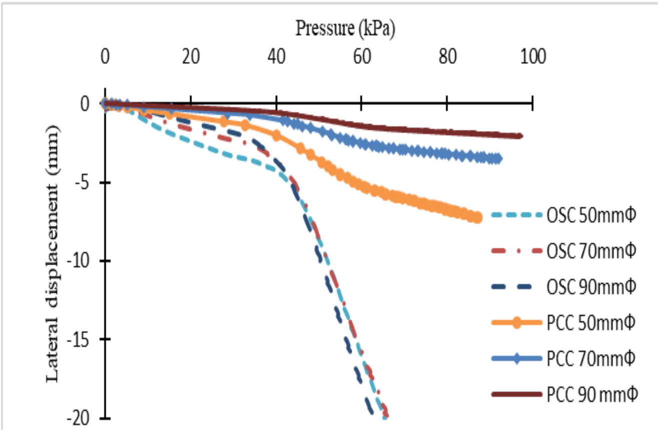

Figure 5 Pressure versus lateral deflection of the top end of the end-bearing columns

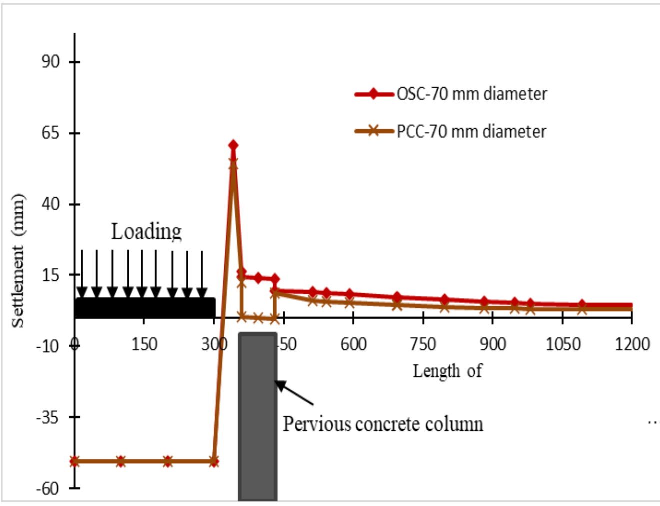

Figure 6 Heave profile observed for weak soil

4.4 Heave Profile

After large shear test analysis, the heave profile of the weak soil was noted as shown in Figure6. It is noticed that the pervious concrete column completely resisted the shear movements, and the behavior could be compared with rigid pile by undergoing very less deformations. It is interesting to note that the soil movement beyond pervious concrete column is very less. The less clay movement beyond the pervious concrete column is attributable to the superior shear endurance posed by unyielding pervious concrete columns.

5. CONCLUSIONS

An effort has occurred to analyze the endurances of stone column-treated ground and pervious concrete column-treated ground under static shear loading using FEM of direct shear test and large shear test simulations. It is noticed that the pervious concrete column-treated soil has greater shear endurance than the typical stone column-treated soil and unimproved soil. The shear performance of pervious concrete column heightened with rise in the number of columns, as anticipated. The performance of ordinary stone column with varying depths has almost similar resistance. However, the endurance of the end-bearing pervious concrete column is noticed as considerably elevated than the floating pervious concrete columns. Consequently, it is recommended to require the depth of the pervious concrete column to reach the rock layer for attaining superior shear endurance. The lateral deflection of pervious concrete column is also observed as very much smaller than typical stone column for all the diameters studied.

It can be determined that the pervious concrete-treated ground has elevated shear endurance and could perform well during shear-induced movements. Also, the shear resistance of pervious concrete column-treated clay could prevent damages to a greater extent owing to its rigid behavior as that of concrete piles. Therefore, it can be concluded that pervious concrete column-treated ground has superior shear execution than the typical stone column-treated ground.

The effect of consolidation and permeability of inclusions were not considered in the analysis. Therefore, coupled phenomena were not modelled, which is a limitation of this study. Hence, the advantage of column inclusions for the drainage of excess pore-water pressure in soft clay during shearing is not reflected in the present study. However, the performance of pervious concrete column-treated soil is found to have better shear performance than conventional stone column-treated soil.

6. ACKNOWLEDGEMENT

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