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Research paper

Behaviour of reinforced stone columns subjected to static shear loading conditions

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Abstract

Stone columns, also known as granular piles, are an effective way of improving weak grounds which are having low bearing capacities, high compressibilities and low resistances to earthquakes. Stone column treatment is preferred to support low rise buildings or embankments on weak soils, which can tolerate some settlements. Stone columns mitigate liquefaction by providing shortest path for excess pore water to escape through the voids in stone columns. Another advantage of using stone column is that it can speed up consolidation process and the construction works can be started without much delay and thereby managing time and cost of construction.
The failure mechanism of stone column include bulging failure (long columns) or shear or punching failure. The failure mode depends on many parameters like strength, stiffness, length, diameter of column, reinforcement used, location, spacing, end condition, soft soil etc. Stone columns may fail by shear when it is subjected to horizontal load or movement. Columns mostly take vertical loads. When column supported embankments are huge, columns will undergo shear failure. It has been reported that the short end bearing and floating stone columns can fail in shear. Horizontal shear is also reported as one of the possible column failure mode under embankment.
In an embankment supported by stone columns, the columns in the middle is mostly subjected to vertical loading. But, the columns near to the toe of the embankment is subjected to lateral loading. The lateral load is predominantly acting on columns which are placed near to the toe of the embankment. The present study is focused on understanding the behaviour of porous concrete column improved ground subjected to static shear loading. Present study is aiming to study the behaviour of plain and reinforced stone columns under static shear loading conditions, with the help of numerical modelling using available software ABAQUS. The results of the study indicate that the porous concrete column improved soft/weak ground is able to take significantly more shear loads under less settlements under static lateral loading conditions and that porous concrete columns can withstand significant shear stresses.

Keywords: *Finite Element Modelling; Porous Concrete Columns; Stone Columns; Shear Strength; Shear Test Tank.*

1. Introduction

Stone columns are practiced all over the world for improving the vertical load carrying capacity and reducing settlement of soft soils and silty sands. Researchers across the world proposed various methods to improve vertical load carrying capacity of stone columns, but the behaviour under lateral loading is not well understood.
Barksdale and Bachus 1983 reported that the short end bearing stone columns fails in shear. They also reported that shear failure could occur for floating stone columns. In an embankment supported by stone columns, the columns in the middle is mostly subjected to vertical loading. But, the columns near to the toe of the embankment is subjected to lateral loading.
Le Ba 2013 reported that for end bearing columns, the actual failure mechanism may be of shear failure from the study conducted from finite element analysis. Kitazume 2007 and Han 2015 reported horizontal shear as one of the possible column failure mode under embankment. Kitazume and Maruyama 2007 evaluated the internal stability of Deep cement mixing (DCM) stone column improved ground using Rankine's theory of active and passive earth pressures. Shrestha 2015 reported that the current design methods consider the shear failure of DCM columns for internal stability below and stated that this kind of shear failure mechanism has not been verified experimentally and numerically.
Stone columns are subjected to lateral loading when it is placed below huge embankments and near to retaining wall. More research has to be carried out on stone columns under lateral loading to get an insight to the behaviour of improved ground. Recent researches suggested various reinforcements to ordinary stone columns in the form of providing geo-synthetic encasements(Murugesan and Rajagopal 2006; Wu and Hong 2007; Gniel and Bouazza 2008; Fattah and Majeed 2009; Hong et al. 2017; Castro 2016), geogrid encasements (Malarvizhi and Ilamparuthi 2006; Marto et al. 2013;),flexible sleeve(Wu et al. 2007),concrete plug(Black et al. 2007), random fibre (Partha and Samadhiya 2008),vertical circumferential nails (Shivashankar et al. 2010), horizontal strip (Ali et al. 2014), pervious stone columns (Suleiman et al. 2014) etc. Present study is aiming to study the behaviour of plain and porous concrete columns under static shear loading conditions.

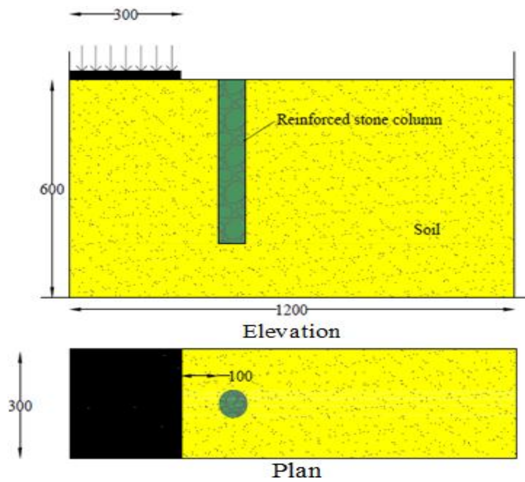

Fig. 1: Large Shear Test Tank.

2. Present study

2.1. Static loading using large shear test tank

In this study, series of three dimensional modelling of plain and reinforced stone columns were performed using Abaqus 3D software to understand the behavior of improved ground under static shear loading. The static shear is applied to the improved ground by generating lateral soil movement in plane strain tank by the application of vertical loading on the rigid plate. It has been reported by Murugesan and Rajagopal 2009 that the loading on the plane strain tank developed by them is very much similar to the lateral squeezing of soil bed between an embankment and relatively strong foundation below the soft clay. This plane strain tank setup is used in this study to evaluate the effect of diameter, effect of reinforced stone column and effect of depth of stone column (floating and end-bearing). The test setup used for modelling is shown in figure 1.

2.2. Validation and numerical modelling

Validation of numerical model was done by using the data from the experimental work reported by Murugesan and Rajagopal 2009. The results obtained from the numerical model is following the trends as reported in the experimental work.
The material parameters used in this study for validation as well as analysis is listed in Table 1 Porous concrete column is modelled as linear elastic material with Modulus of elasticity 15.4 GPa and a poisson's ratio of 0.20 as reported by Li Nu et al. 2014. The soil–stone column and soil-porous concrete interface is modelled with surface to surface contact with tangential and normal behavior and the coefficient of friction used is 0.36 and 0.3 respectively.
The analysis was carried out in two steps, geostatic step followed by displacement controlled loading given at the rate of 1.2 mm/min up to 50 mm vertical displacement. The loading rate and total time of 2520 s was adopted to simulate the laboratory work. The bottom part of the model is restrained in all directions and lateral vertical boundaries are restrained from displacement perpendicular to the respective surfaces. Following validation of the model, analysis was carried out in plain and porous concrete columns. The diameter of plain and reinforced stone column varied from 50mm, 70mm and 90 mm. Analysis of the effect of floating plain and reinforced stone columns are carried out for 90 mm diameter columns placed at a clear gap of 50 mm from the edge of the loading plate and depth of 4D and 6D are being documented.

Table 1: Material Properties Used in Simulation

Properties	Soft clay	Stone column
Model	Mohr-Coulomb	Mohr-Coulomb
Density(kN/m3)	17	20
Elastic modulus(kPa)	3000	45000
Poisson's ratio	0.45	0.3
Cohesion(KPa)	20	1
Friction Angle	0	42
Dilation Angle	0	10

3. Results and discussion

3.1. Effect of porous concrete column

This analysis is carried out for analyzing the shear resistance of porous column improved ground over unimproved ground. The analysis were carried out on soil, plain stone column and modified stone column using porous concrete. It can be seen from figure 2 that the performance of porous concrete column is very much higher than plain stone columns. While analyzing the deformed shape of model after analysis, the porous stone column has not undergone any shear failure and the behavior was similar to that of a flexible pile, whereas the plain stone column improved ground has seen to exhibit almost zero resistance and has undergone shear failure as shown in the figure 3. The porous concrete has higher modulus of elasticity and thereby the improved ground exhibits higher shear resistance than plain stone columns.

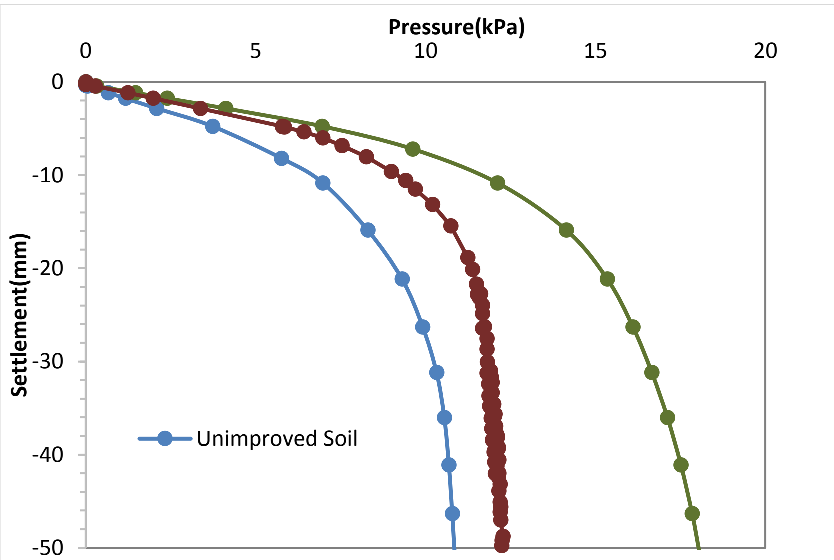

Fig. 2: Effect of Porous Concrete Column (Diameter of Column = 90 Mm, Length of Columns = 600 Mm and Distance from the Edge of Loading Plate = 50 Mm).

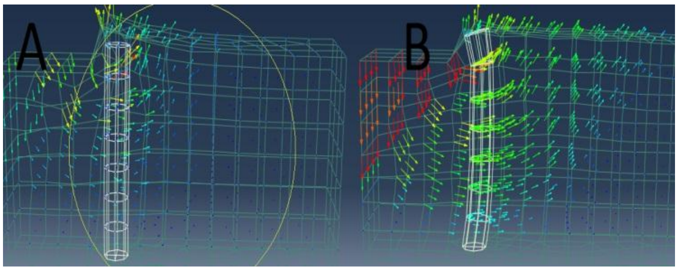

Fig. 3: Deformed Model A) Porous Concrete Column Improved Ground B) Plain Stone Column Improved Ground.

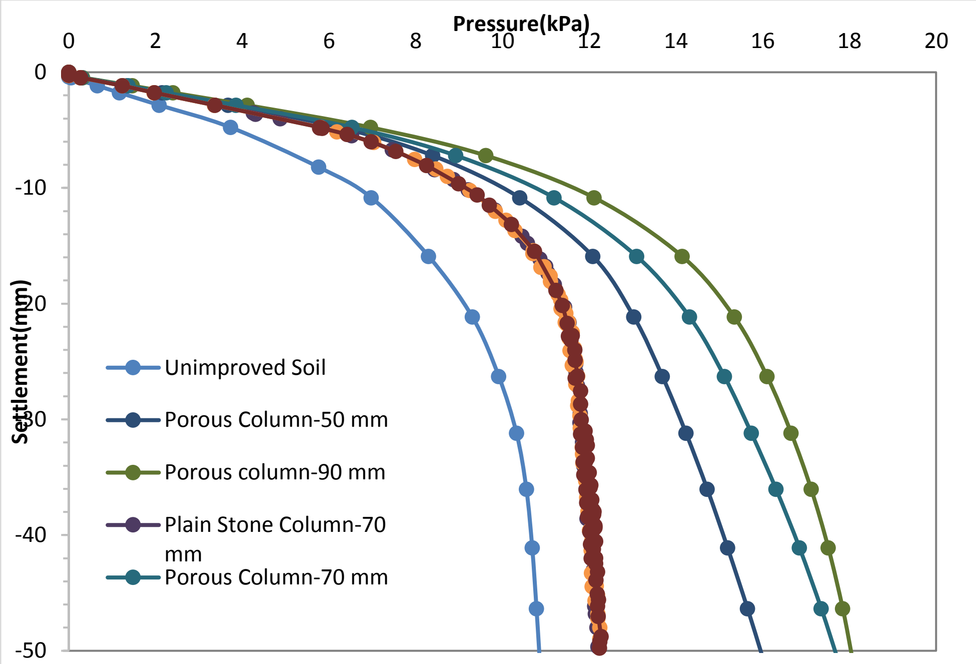

Fig. 4: Effect of Diameter (Length of Columns = 600 Mm and Distance from the Edge of Loading Plate = 50 Mm).

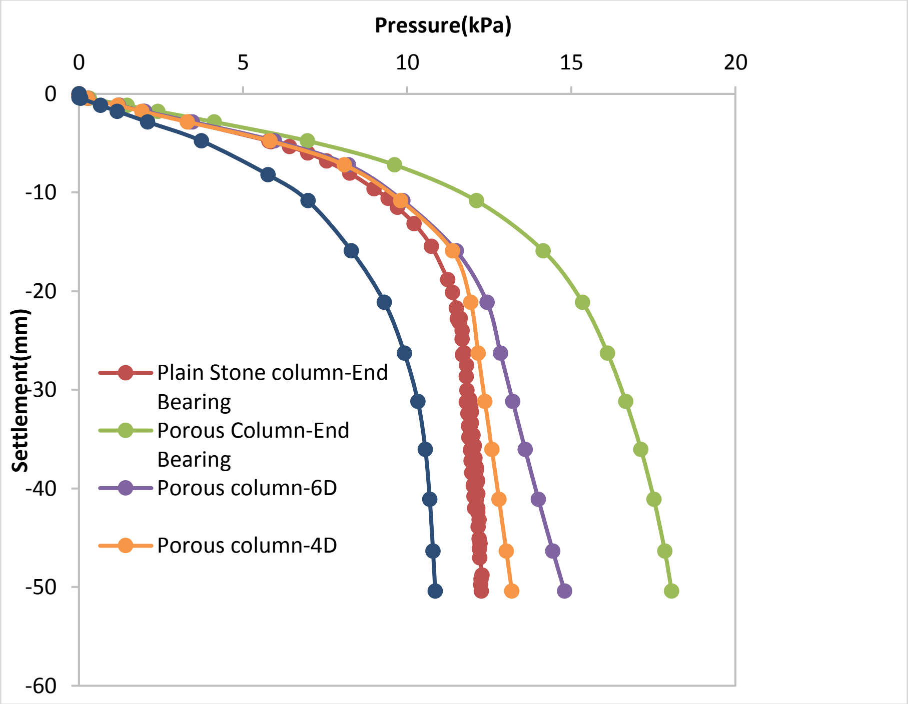

Fig. 5: Effect of Depth of Porous Concrete Columns (Diameter of Column = 90 Mm and Distance from the Edge of Loading Plate = 50 Mm).

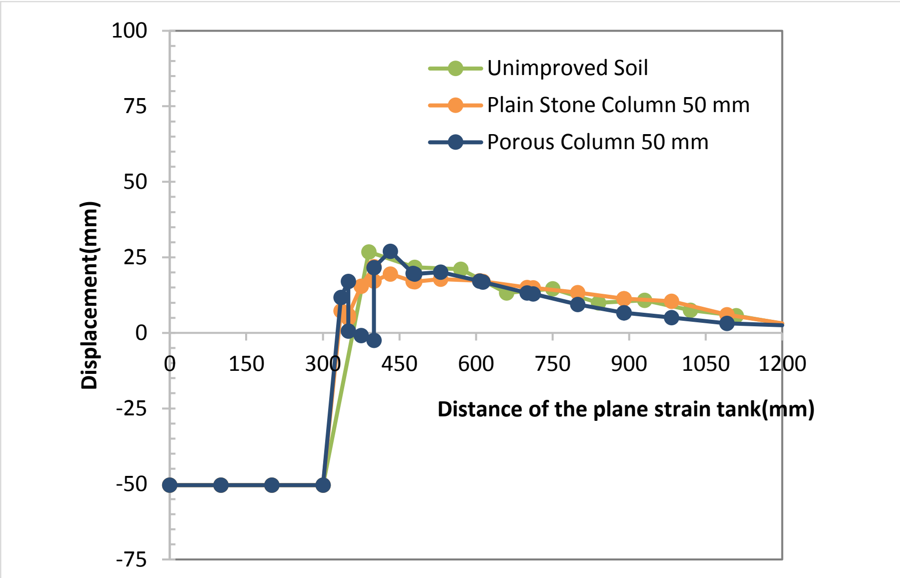

Fig. 6: Heave Profile of Clay.

3.2. Effect of diameter

Figure 4 shows the pressure settlement response of soil bed, plain stone columns and porous columns of diameters 50 mm, 70 mm and 90 mm respectively. The pressure settlement response under the loading plate for plain stone columns are almost same for all three diameters. But the response of porous column reinforced ground increased with increase in diameter. The increase in shear resistance of reinforced columns with larger diameter can be attributed to the resistance area offered by the rigid porous concrete along the full length of the column.

3.3. Effect of depth of porous concrete columns

Analysis were conducted on floating porous concrete columns and plain stone column improved ground with 90 mm diameter and columns placed at a clear gap of 50 mm from the edge of the loading plate for varying lengths 4D and 6D, D being diameter of stone column and to full length of 600 mm, i.e. end bearing. Porous column with end bearing condition showed maximum response than unreinforced ground and plain stone columns of varying depth. It can be also observed that the floating porous columns have better performance than untreated soil and plain stone columns.

3.4. Heave profile

Figure 6 represents the heave profile observed in the deformed model after analysis. The heave profile of the unimproved soil bed followed the same pattern as that of plain stone column. This shows that the plain stone column moved along with the soil without shear resistance. While the porous concrete column the upheaval in the column is very less when compared to plain and untreated ground. It can be also observed in the deformed figure 3 that the soil movement in porous concrete column is very limited near and beyond porous concrete column. This also indicates the better shear performance of porous concrete column over plain stone columns.

4. Conclusions

An attempt has been made to study the behavior of plain and porous concrete stone columns under static shear loading using plane strain model. It is observed that the porous concrete column has higher shear resistance than plain stone columns and unimproved foundation soil bed. The performance of porous stone column increased with increase in diameter of stone columns. The reinforced stone column improved ground with depth 6D has more shear resistance than 4D column. However, the performance of plain stone column with varying depths have almost similar resistance. The plain stone columns were found to have shear failure near to top and bottom ends along the length of stone columns and were having same failure pattern as that of unimproved ground. Shear resistance of improved ground can be increased by providing larger diameter reinforced columns near to the toe of the embankment.

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