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Model Tests on Stone Columns Reinforced with Lateral Circular Discs

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Abstract

Stone columns have proven to be the most suited technique for improving the bearing capacity of weak or soft soils and are used worldwide for supporting flexible structures such as embankments, oil storage tanks, etc. Stone columns installed in very soft soils undergo excessive bulging on loading due to very low lateral confinement and consequently, failure occurs. The strength of stone columns in such conditions can be enhanced by reinforcing these with a suitable geosynthetic. In the present study, the stone columns were reinforced by providing lateral circular discs of geotextile within the column. The circular discs were placed at two different spacings (d and $d/2$) over varied column lengths ($l/4$, $l/2$, $3l/4$ and l). Small scale laboratory model tests have been carried out on floating and end-bearing single columns with and without reinforcements to evaluate relative improvement in the failure stress of the composite ground due to different configurations of the reinforcement. The tests indicate that the lateral circular discs distributed over full column length at d/2 spacing is the best configuration. The performance of reinforced end-bearing columns was much better than the reinforced floating columns. Both geotextile and geogrid were found to be equally effective for both floating and end-bearing stone columns.

Keywords: Geosynthetics; Soft Soil; Stone Column; Ground Improvement; Reinforcement.

1. Introduction

Due to rise in population and an increase in infrastructure growth in metropolitan areas, there is a dramatic rise in land prices and lack of suitable sites for development. Therefore, now-a-days construction is also being carried out on marginal sites having extremely poor ground conditions like soft clays that were earlier considered unsuitable due to their poor strength and high compressibility. Such soils when loaded cause excessive settlements and early failure of structures. It is a challenge to the geotechnical engineer to provide a suitable foundation with satisfactory performance at a reasonable cost in such soils. Stone columns have been used for both ground improvement and providing foundations to structures (Rao and Ranjan 1985). For low-rise buildings and structures such as liquid storage tanks, abutments, embankments, factories, etc. that can tolerate some settlement, stone columns provide an economical method of support in compressible and fine-grained soils (Mitchell 1981; Bergado et al. 1996). Stone column foundation is capped with a granular mat on the top. The granular mat helps in transmitting the load uniformly over the stone columns and drains out the water from the stone columns.

2. Literature Review

When the stone column reinforced ground is being loaded, the columns deform laterally into surrounding soft soil strata. For stone columns having lengths greater than critical length (i.e., about four times the diameter of the column), it is recognized that the bulging failure governs the load carrying capacity whether they bear on stiff layer or penetrate partially into the medium stiff soil (Madhav *et al.* 1994). When the stone columns are installed in extremely soft soils, the lateral confinement offered by the surrounding soil may not be adequate. Consequently, the stone columns installed in such soils will not be able to develop the required load-bearing capacity. In such situations, the bearing capacity of the stone column can be improved by providing circular lateral discs of a suitable geotextile as a reinforcing material along the length of the stone column at a regular spacing. In this case, the bulging of the columns is resisted by the frictional stresses mobilized on the surface of the geotextile owing to lateral movement of loose stone chips. Madhav et al. 1994; Sharma et al. 2004; Ayadat et al. 2008 have studied the behaviour of such reinforced stone columns. Most of the work done so far is limited to fully penetrating columns; therefore, in this paper experiments have also been conducted on floating columns.

3. Experimental Programme

3.1 Materials, Instrumentation and Test Programme

The model tests were conducted on soft soil bed reinforced with stone columns. The soft soil bed was made up of fully saturated remolded kaolin clay. The properties of the kaolin clay are given in Table 1. The columns were made up of stone chips of size varying from 2 mm to 4.75 mm compacted at a relative density D_r = 60% and having an angle of internal friction $\phi = 42^o$ as determined by the direct shear test.

Table 1: Properties of the clay used in the model tests.

Parameter	Value
Specific Gravity	2.64
Liquid Limit (%)	54
Plastic Limit (%)	23
Plasticity Index (%)	31
Saturated unit weight (kN/m^3)	18.59
Dry unit weight (kN/m^3)	14.5
Water content (%)	40±1
Shear strength (kPa)	6 – 7

A 20 mm thick mat was provided below the footing area in all model tests. The mat consisted of sub-angular Badarpur sand of predominantly quartz particles of sizes passing through 1 mm sieve and retained on 600 micron sieve having an angle of internal friction $\phi = 38^o$. A woven geotextile of tensile modulus = 97.5 kN/m was used to reinforce the model stone columns.

The model tests for floating columns were conducted in a perspex cylindrical tank of 300 mm diameter and 600 mm depth and for end bearing columns a tank of 300 mm diameter and 360 mm depth was used. The diameter and length of floating as well as end-bearing columns were kept as 30 mm and 360 mm respectively. A summary of the model tests is given in Table 2.

Table 2: Summary of the model tests conducted.

Test No.	*d* mm	*l* mm	Column Type	Reinf. Type	*s* mm	*x* mm	Test No.	*d* mm	*l* mm	Column Type	Reinf. Type	*s* mm	*x* mm
1.	-	-	Clay	-	-	-	11.	30	360	EB	UR	-	-
2.	30	360	FL	UR	-	-	12.	30	360	EB	LCD	30	90
3.	30	360	FL	LCD	30	90	13.	30	360	EB	LCD	30	180
4.	30	360	FL	LCD	30	180	14.	30	360	EB	LCD	30	270
5.	30	360	FL	LCD	30	270	15.	30	360	EB	LCD	30	360
6.	30	360	FL	LCD	30	360	16.	30	360	EB	LCD	15	90
7.	30	360	FL	LCD	15	90	17.	30	360	EB	LCD	15	180
8.	30	360	FL	LCD	15	180	18.	30	360	EB	LCD	15	270
9.	30	360	FL	LCD	15	270	19.	30	360	EB	LCD	15	360
10.	30	360	FL	LCD	15	360							

d = Diameter of column, *l* = Length of column, *s* = Lateral circular discs spacing, x = Reinforcement length, FL = Floating, EB = End-bearing, UR = Unreinforced, LCD = Lateral circular discs

3.2 Preparation of Soft Clay Bed

The soft clay bed was prepared for undrained shear strength of 6–7 kPa. The moisture content (40%) required for the desired shear strength was determined by conducting several vane shear tests on a cylindrical specimen of 76 mm height and 38 mm depth. After adding the water to the clay powder it was thoroughly mixed to a consistent paste and then left for 48 hours covered with wet gunny cloth for moisture equalization. This paste was then filled in the tank in 10 mm thick layers to the desired thickness by hand compaction such that no air voids are left in the soil. Before filling the soil in the tank, the inner surface of the tank wall was first coated with silicon grease and then covered with a polythene sheet to minimize the friction. The tank filled with soil was then again left for 48 hours for thixotropic gain.

3.3 Construction of Stone Columns

After finishing the top surface of the clay bed the position of column was marked and three vane shear tests were conducted at different depths within the column length for assessing the undrained shear strength of the clay bed. After conducting the vane shear tests, an open-ended perspex tube of external diameter of 30 mm and 1 mm thick was pushed to 15 mm into the soft soil at demarcated location. The soil from inside the casing pipe was then taken out with the help of an augur. The pipe was then again pushed into the soil by 15 mm and the soil was again removed from the pipe. The process was continued till the casing pipe to full column length is pushed into the soil. The inner surface of the casing pipe was then properly cleaned off and then the stone column was casted in steps by compacting the stone chips and withdrawing the casing pipe simultaneously. Stone columns reinforced with lateral discs were constructed by placing the lateral circular discs of reinforcing material at desired levels inside the column during the compaction of stone chips. The composite soil with the column inside was again left covered with a wet jute fabric in the controlled conditions for 24 hours to develop proper bonding between the stone chips of the column and the soft soil. Before loading, a sand mat of 20 mm thickness was then constructed by pouring Badarpur sand of required gradation over the footing area.

3.4 Test Procedure

After construction of stone column, sand mat of 60 mm diameter was compressed at a constant strain rate of 1 mm/min to ensure the undrained condition and the corresponding load was observed through a proving ring. The stone column and its tributary soft soil area were loaded through a 12 mm thick perspex plate of diameter double the column diameter, representing a 25% area replacement ratio (A_r). The composite soil was compressed to a maximum footing settlement of 60 mm. A complete test set up arrangement and schematic view of typical stone column foundation for test has been shown in Fig. 3.

Figure 1(a): Test set up ready for loading

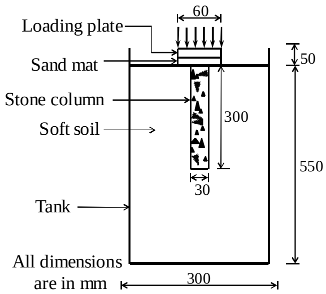


Figure 1(b): Schematic view of stone column

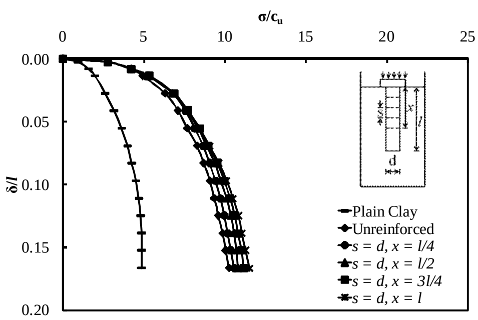
Figure 2. Deformed shapes of columns

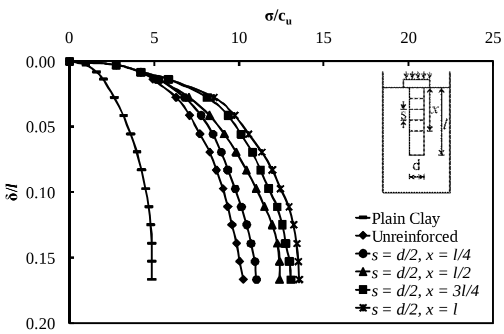
3.5 Post Test Analysis

After completion of the test, the stone chips from the column were carefully picked up and a thin paste of plaster of Paris was poured into the cavity to establish the deformed shape of the column. The hardened plaster of Paris representing the deformed column shape was isolated by removing the surrounding soft soil. Some of the photographs of deformed columns have been shown in Figure 2.

4. Results and Discussion

To study the relative performance of composite soil improved with reinforced stone columns, non-dimensional charts were prepared with the help of normalized applied vertical stress and footing settlement. The applied vertical stress (σ) was normalized by dividing it with undrained shear strength (c_u) of soft clay bed and footing settlement (δ) by dividing it with the column length (l). Thus in the ongoing text, the word "failure stress" stands for "normalized failure stress".

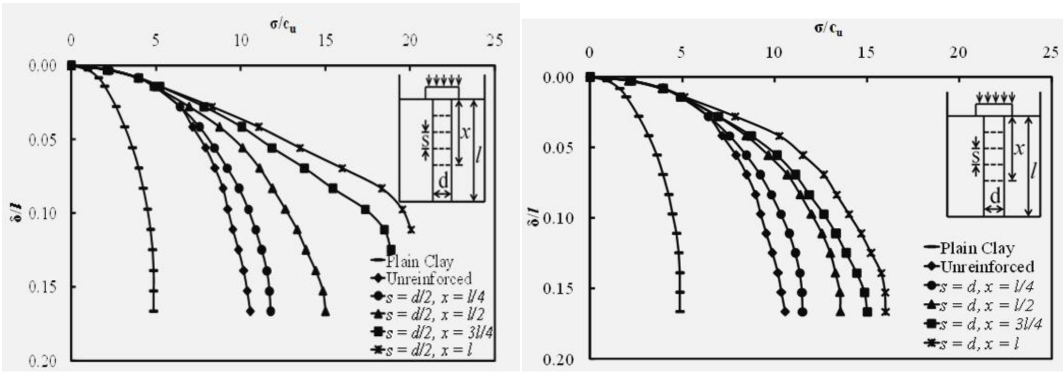




(a) (b)

Figure 3. Effect of reinforcement for the composite ground improved with floating columns (d = 30 mm, l = 360 mm, D_r = 60%, A_r = 25%).

Figures 3(a) and 3(b) show the effect of reinforcement on the failure stress of composite ground improved with floating columns having geotextile discs at "d" and "d/2" spacing respectively for different reinforcing lengths. The failure stress of the composite ground improved with reinforced columns increased by 12% for columns having discs at *d* spacing for full column length. In case of columns reinforced with discs at *d*/2 spacing for full column length, the failure stress increased by 32%. The reduced disc spacing increased the resistance against bulging and consequently bearing capacity improved. But the improvement was not significant because column terminates into soft soil; the increased stiffness due to reinforcement facilitates the penetration of column into the soft soil.



(a) **(b)**

Figure 4: Effect of encasement for the composite ground improved with end bearing columns (d = 30 mm, l = 300 mm, D_r = 60%, A_r = 25%).

Figures 4(a) and 4(b) show the effect of reinforcement on the failure stress of composite ground improved with end-bearing columns having geotextile discs at "*d*" and "*d*/2" spacing respectively for different reinforcing lengths. End-bearing columns exhibited more increase in failure stress as compared to floating column for all corresponding cases. The increase in bearing capacity of composite ground improved with end-bearing columns with disc spacing of "*d*" and "*d*/2" for full column length was found to be 52% and 90% respectively. In this case also, column reinforced at reduced spacing for full column length is more beneficial.

5. Conclusions

1. Whether floating or end-bearing, provision of reinforcement increases the bearing capacity of composite ground.
2. Bearing capacity of composite ground increases as the reinforcing length increases. .
3. Bearing capacity of composite ground increases as the discs spacing decreases.
4. End-bearing columns perform better than floating columns for each reinforcement configuration.
5. Whether floating or end-bearing, the best configuration for lateral discs of geotextile is the placement of the discs over full column length at *d*/2 spacing.

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