Behaviour of Reinforced Stone Columns in Soft Soils: 
An Experimental Study

Ali, K.  
Research Scholar  
e-mail: kausarali786@rediffmail.com

Shahu, J.T.  
Associate Professor  
e-mail: shahu@civil.iitd.ac.in

Sharma, K.G.  
Professor  
e-mail: kgsharma@civil.iitd.ac.in

Department of Civil Engineering, Indian Institute of Technology Delhi, India

ABSTRACT

In coastal areas, due to non-availability of suitable sites for infrastructure development, construction is being carried out on sites having extremely poor ground conditions like soft clays which pose serious problems like excessive settlements. For rigid structures such as multi-storeyed buildings, pile foundation is the best but for low rise buildings and structures such as liquid storage tanks, bridge abutments, road/rail embankments, factories etc. that can tolerate some settlement, provision of stone columns has proved safe and economical method of ground improvement. In the present study, laboratory model tests have been carried out on floating and fully penetrating single piles with and without geotextile to find out the effect of encasement, l/d ratio and diameter of column on bearing capacity. Encasement increases the ultimate bearing capacity substantially whereas columns having l/d ratio more than six do not contribute further. For constant l/d ratio, the bearing capacity of the composite ground decreases as the column diameter increases.

Keywords: Soft Clay, Stone Column, Ground Improvement, Geosynthetic.

1. INTRODUCTION

Sufficient infrastructure of buildings, roads, tunnels, bridges and other civil engineering works is the prime requirement for all round development of any country. Earlier, there was no crisis of suitable land for the construction sites but now-a-days due to rapid increase in infrastructure growth, particularly in metropolitan cities, there is lack of suitable sites and consequently a dramatic rise in land prices. Therefore, construction is now also being carried out on sites having extremely poor ground conditions like soft clays, which cover a vast area all along the Indian coast and some parts of Indo Gangetic plains. Pile foundation is the best solution for almost all the problems posed by soft soils but the use is limited to only rigid structures such as multi-storied buildings due to its very high cost. For low rise buildings and the structures such as liquid storage tanks, road/rail embankments, factories etc. that can tolerate some settlements, ground improvement techniques are normally considered as economical and stone columns is one of the most suited technique and used worldwide.

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). Alamgir et al. (1996) proposed an elastic approach to predict the load sharing and resulting settlement of ground improved by stone columns assuming free strain condition. Shahu et al. (2000) brought out the effect of a granular mat over the improved ground on its overall response within the frame work of equal strain theory and unit cell concept. 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. McKenna et al. (1975) have reported cases where the stone column was not restrained by the surrounding soft clay which led to excessive bulging and squeezing of the soft clay into the voids of the aggregate. In such situations, the bearing capacity of the stone column can be improved by imparting additional confinement to the stone column by...
encasing the individual stone columns using a geosynthetic. Malarvizhi & Ilamparuthi (2004), Ayadat & Hanna (2005), Murugesan & Rajagopal (2007) have studied the behaviour of reinforced stone columns. Most of the work done so far is limited to fully penetrating columns; therefore, in this paper more emphasis has been given to floating columns.

3. EXPERIMENTAL PROGRAMME

The laboratory model tests for fully penetrating and floating stone columns were conducted in a cylindrical tank of 300 mm diameter and 600 mm deep filled with fully saturated remoulded kaoline soil. All experiments were carried out on 40, 50 and 70 mm diameter by loading column area only. Rest of the details of laboratory tests are as follows:

Materials

Very fine powder of kaoline soil was used for preparing the test bed. The properties of the clayey soil are given in Table 1. Crushed stone chips of size varying from 1 mm to 4.75 mm having an angle of internal friction of 40°, as determined from direct shear test were used for construction of stone columns. Badarpur sand of size ranging from 600 micron to 1 mm was used to provide the mat on the foundation area. The dry density of the sand used was 16 kN/m³. The angle of internal friction of the sand was 38° as determined by conducting direct shear tests. For accurate representation of the model behaviour, it is necessary that the stiffness and strength of the reinforcing material (i.e., geosynthetic) should also be suitably scaled. Therefore, a cotton fabric was used as the reinforcing material in the model tests to satisfy the similitude ratio. The tensile strength of the cotton fabric as determined by wide strip tensile test (ASTM D 4595–05) was 4.48 kN/m. The tensile strength of woven geotextile generally used in the field varies from 35 to 65 kN/m (Cheung 1998). Hence the use of cotton fabric was considered satisfactory because its similitude ratio (0.09) is almost same as that of model and material dimensions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Gravity</td>
<td>2.64</td>
</tr>
<tr>
<td>Liquid Limit (%)</td>
<td>54</td>
</tr>
<tr>
<td>Plastic Limit (%)</td>
<td>23</td>
</tr>
<tr>
<td>Plasticity Index (%)</td>
<td>31</td>
</tr>
<tr>
<td>Saturated unit weight (kN/m³)</td>
<td>18.59</td>
</tr>
<tr>
<td>Dry unit weight (kN/m³)</td>
<td>14.5</td>
</tr>
<tr>
<td>Water content (%)</td>
<td>38</td>
</tr>
<tr>
<td>Unconfined compressive strength (kPa)</td>
<td>10</td>
</tr>
</tbody>
</table>

Preparation of Soft Clay Bed

The clay bed was prepared for shear strength of 8 – 10 kN/m². To determine the moisture content required for the desired strength, several unconfined compression tests were carried out on a cylindrical specimen of 38 mm diameter and 76 mm height with different water contents and based on these results, the required water content of 38% was adopted. The clay was air-dried and initial moisture content was determined. Additional water was then added to maintain the required moisture content (38%) and the clay was thoroughly mixed to a consistent paste. This paste was then filled in the tank in layers each of 50 mm thick by hand compaction so that no air voids are left in the soil. Before filling the soil in the tank, inner surface of the tank wall was coated with a thin film of silicon grease and the same was also covered with a smooth polythene sheet to minimize the friction between soil and the tank wall.

Construction of Stone Columns

Before construction of the columns, shear strength of the prepared bed was judged by conducting vane shear test at the centre of the test clay bed at three different depths in the same vertical line. All model stone columns were constructed by the replacement technique. An open-ended seamless perspex pipe of required outer diameter having 1 mm wall thickness was pushed into the clay at the required place to a depth of 1/5th of the total length of the column and soil was scooped from inside of the pipe. After scooping out the soil, the pipe was pushed further to the same depth as before and soil was again scooped out in the same fashion. The process was repeated till the required depth of column was achieved. For construction of columns reinforced with geotextile, the procedure was same except that the geotextile was wrapped around the pipe before inserting it in the clay bed. The stone chips were then poured into the hole in 50 mm thick layers and compacted as the pipe was withdrawn in stages of 50 mm. To achieve a uniform density, compaction was given with a 2 kg circular steel rod with 10 blows of 100 mm drop to each layer. A sand mat of 20 mm thickness was then placed on the column top.

Test Procedure

After preparing the stone column, sand mat was compressed at a constant strain rate of 1 mm/min to ensure the undrained condition and the corresponding applied load was observed through a proving ring. The column area was loaded through a perspex loading plate of 12 mm thickness and of same diameter as that of the column. The load was observed at equal intervals of settlement (1mm). The load was applied up to a settlement of 50 mm or till failure whichever was earlier. To measure the stresses at bottom of the column and at other locations, earth pressure cells (Fig.1) were placed at the required locations during the model preparation. The earth pressure cells were connected to an electronic data logger (Fig.1) for recording the data. The data was retrieved by an instant print out during loading and by a floppy disc at the end of the experiment.
A complete test set-up ready for test has been shown in Fig. 2. After completion of the test, the deformed shape of column was established by pouring a thin paste of plaster of Paris into the cavity created by careful removal of the stone chips of the column. The hardened plaster of Paris representing the deformed column structure was isolated by scooping out the surrounding soil. The photographs of deformed shapes of some columns after different tests are shown in Figure 3.

**Model Tests Performed**
A total of seven model tests in two series were conducted. The first series consisted of three model tests conducted on different column diameters, keeping the length to diameter ratio as six for each test. In the second series, a total of three tests were conducted with different length to diameter ratio but keeping the column diameter the same (= 50 mm). The seventh test was carried out on a plain clay bed by loading it with a 50 mm diameter loading plate for comparison purposes. A summary of all tests is given in Table 2. A 20 mm thick sand mat was used to transfer the applied loads.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Dia. of Column (mm)</th>
<th>Length of Column (mm)</th>
<th>Applied Stress (kPa)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40</td>
<td>240</td>
<td>122</td>
<td>Ordinary Column</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>300</td>
<td>111</td>
<td>Ordinary Column</td>
</tr>
<tr>
<td>3</td>
<td>70</td>
<td>420</td>
<td>85</td>
<td>Ordinary Column</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>450</td>
<td>108</td>
<td>Ordinary Column</td>
</tr>
<tr>
<td>5</td>
<td>50</td>
<td>550</td>
<td>106</td>
<td>Reinforced Column</td>
</tr>
<tr>
<td>6</td>
<td>50</td>
<td>300</td>
<td>140</td>
<td>Reinforced Column</td>
</tr>
<tr>
<td>7</td>
<td>–</td>
<td>–</td>
<td>40</td>
<td>Soft Clay Only</td>
</tr>
</tbody>
</table>

Thickness of soft clay bed = 550 mm
Thickness of sand mat = 20 mm

4. **RESULTS AND DISCUSSION**

Figure 4 shows the applied vertical stress-settlement curves for plain clay, ordinary stone column and reinforced stone column. Plain clay was loaded by a loading plate of 50 mm diameter at its centre whereas a column of 50 mm diameter and 300 mm length was used for ordinary and reinforced stone columns. The loading on plain clay bed shows clear failure. Ordinary and reinforced stone columns exhibit an
elastic behaviour. The ultimate bearing capacity of the model increases in the following order: plain clay, ordinary stone column and reinforced stone column. For 30 mm settlement, the corresponding vertical stresses are 40, 110 and 140 kPa, respectively. Thus the ultimate bearing capacity increases 2.7 times and 3.5 times, respectively, for the ordinary stone column and the reinforced stone column as compared to the plain clay.

The effect of column diameter on bearing capacity was also investigated by conducting laboratory tests on 40, 50 and 70 mm diameter ordinary columns with constant length to diameter ratio as six. All the columns used for the purpose were of floating type. It is clear from the Figure 5 that the bearing capacity of the composite ground decreases as the column diameter increases.

5. CONCLUSIONS
1. Since stone columns having lengths more than six times their diameter do not contribute much to bearing capacity therefore, floating columns should be preferred in situations where hard strata is at a depth more than this length.
2. As far as possible, columns of smaller diameter should be provided because these are stronger than large diameter columns.
3. The columns should be wrapped around with some geosynthetic material, by doing so the bearing capacity of improved ground is increased by manifolds.
4. Since bulging of stone columns takes place only in upper portion due to lack of lateral pressure, hence providing geosynthetic in that portion may also be equally beneficial.

REFERENCES