EXPERIMENTAL AND NUMERICAL INVESTIGATIONS ON THE BEHAVIOUR OF GEOSYNTHETIC ENCASED STONE COLUMNS

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ABSTRACT: Stone columns are being widely used as ground reinforcing elements for the construction of flexible structures on soft soils. When they are installed in extreme soft soils, the possible squeezing of the stones in to the surrounding soil and intrusion of the clay in to the stone aggregate will result in poor performance of the stone column. In such situations confining the individual stone columns within a geosynthetic encasement would help in preserving the functions of the stone column as well as improving its strength and stiffness by many folds. In this paper the performance of the encased stone column has been evaluated through experimental studies and numerical simulations. The results have brought out the benefits of encasing the stone columns with geosynthetic, particularly in terms of enhanced load capacity. The influence of the geometry of the stone column, material properties like stiffness of the geosynthetic used for the encasement has been investigated. The numerical simulations generally agreed reasonably well with the experimental results.

1. INTRODUCTION

Among different ground reinforcement techniques, insertion of stone columns (otherwise called as granular pile) is being widely used for the construction of flexible structures over soft soils. When such columns are installed in very soft clays, we may encounter the following problems. (i) Loss of Stones: The stones charged in to the column may squeeze out of the column due to low lateral confinement from the surrounding soft clay. Due to this squeezing, the quantity of stone required to form the stone column may be much higher than anticipated. (ii) Contamination of Stone Aggregate: The surrounding soft clay soil may intrude or penetrate into the stone aggregate leading it to the reduction in frictional strength of the aggregate besides impeding the drainage function of the stone column. (iii) Limited Bearing Capacity: As the stone columns largely depend on the lateral passive support from the surrounding soil, the load carrying capacity of the stone column can not be improved more than 25 times the strength of the soft clay and the control over settlement is also limited (Chummar 2000). Hence, it may not be possible to design economical spacing for stone columns in case of very heavy loads.

Nevertheless the performance of the stone columns can be considerably improved by encasing the individual stone columns with suitable geosynthetics. Among various methods of enhancing the load capacity of the stone columns such as introducing horizontal layers of reinforcements, vertical reinforcing rods, grouting the column, skirting the stone column treated area etc., encasing the column with geosynthetic would be an ideal form since it also offers other benefits as follows (Raithel et al. 2002, Alexiew et al. 2005) i) Additional lateral confinement ii) Making the stone column to act as a semi-rigid element enabling the load transfer to deeper depths. (iii) Preventing the lateral squeezing of stones in to surrounding soft clays thereby minimising the loss of stones. (iv) Enabling higher degree of compaction compared to the conventional stone columns. (v) Promoting the vertical drainage function of the column by acting as a good filter (if encased by geotextile) (vi) Preserving the frictional properties of the aggregates (vii) Increasing the shear resistance of the stone column (Murugesan & Rajagopal 2009). In spite having all these benefits of there has not been enough application of this technique in the field. There is good amount of research being carried out on this technique both by model experiments (Ayadat & Hanna 2005, Murugesan And Rajagopal 2007, Malarvizhi & Ilamparuthi 2007, Gniel & Bouazza 2008) as well as analytical investigations (Murugesan & Rajagopal 2006, Wu et al. 2009). This paper explains about the laboratory model tests performed on the stone columns with and without geosynthetic encasement and subsequently the numerical simulation of the results using Finite Element Method.
2. LABORATORY EXPERIMENTS

In the present study the load tests were conducted on the stone columns installed in unit cell tank which would represent a typical stone column and contributory in a grid of columns. The cylindrical unit cell tank used in this study was of 210 mm diameter and 500 mm height. The plan area of the tank is equivalent to a typical unit cell area of stone columns installed at a centre to centre spacing of 200 mm in square pattern and 186 mm spacing in triangular pattern. The clay bed in the unit cell tank for the installation of stone columns was prepared by consolidating the slurry clay in a laboratory controlled condition. The stone column of the required diameter was installed at the centre of the tank with displacement method. The readers can refer Murugesan (2007) for further details.

2.1 Material Properties

The properties of clay bed formed in the unit cell tank are listed in Table 1. For every test, fresh clay bed was prepared with consistent properties to have proper comparison between tests. The stone aggregates used to form the stone columns were granite chips of size 2 to 10 mm and having uniform gradation. The peak angle of internal friction of stone aggregates determined from the direct shear test data is 41.5º within a normal pressure range up to 300 kPa. The density of the stone aggregate in all the tests was maintained close to 1.6 g/cc.

Table 1: Properties of Clay Bed

<table>
<thead>
<tr>
<th>Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid limit</td>
<td>49%</td>
</tr>
<tr>
<td>Plastic limit</td>
<td>17%</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>2.59</td>
</tr>
<tr>
<td>In-situ Moisture</td>
<td>47±1%</td>
</tr>
<tr>
<td>In-situ vane shear strength</td>
<td>2.5 kPa</td>
</tr>
<tr>
<td>In-situ void ratio</td>
<td>1.25</td>
</tr>
<tr>
<td>Consistency Index</td>
<td>0.06</td>
</tr>
<tr>
<td>Dry unit weight</td>
<td>11.56 kN/m³</td>
</tr>
<tr>
<td>IS Soil Classification Symbol</td>
<td>CH</td>
</tr>
<tr>
<td>Degree of Saturation</td>
<td>96%</td>
</tr>
</tbody>
</table>

In the present study woven and nonwoven geotextiles were used as encasement for the stone column. As the geosynthetics were stitched to form the tube for encasing the stone column, the seam strength of the geosynthetic was also determined with geosynthetic specimens having a horizontal seam at mid length. The tensile strength properties are listed in the Table 2.

Table 2: Properties of Geosynthetics Used for the Encasement

<table>
<thead>
<tr>
<th>Strength properties</th>
<th>Woven geotextile</th>
<th>Nonwoven geotextile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate tensile strength (kN/m)</td>
<td>20</td>
<td>6.8</td>
</tr>
<tr>
<td>Ultimate seam strength (kN/m)</td>
<td>4.7</td>
<td>5.1</td>
</tr>
<tr>
<td>Initial modulus (kN/m) (based on seam strength)</td>
<td>17.5</td>
<td>12</td>
</tr>
</tbody>
</table>

2.2 Load Tests on the Stone columns

The stone columns thus formed were subjected to vertical loading at a constant strain rate of 1.2 mm per minute through a loading plate of diameter equal to that of the stone column. The loading plate was placed concentrically over the stone column. All the load tests were performed by loading only the stone column, in order to directly compare the improvement in the load capacity due to encasement. The loads corresponding to different displacements (in the stone column) were measured using a proving ring (having accuracy of 0.01 kN). Figure 1 shows the schematic of the load test set up. Three series of tests were conducted by varying the diameter of the stone column, viz. 50 mm, 75 mm and 100 mm. The first series of tests were performed on the virgin clay bed without any stone columns. A second series of tests were performed on ordinary stone columns of different diameter without any encasement (referred to as OSC). The third series of tests were performed on geosynthetic encased stone columns (referred to as ESC) with woven and nonwoven geotextiles and different diameters.

3. NUMERICAL ANALYSIS

The results from the laboratory tests of the present work were back-predicted through numerical simulations with relevant material properties used in the experiments. All the analyses in this investigation were performed using the finite element program 'GEOFEM' which was originally developed at the Royal Military College of Canada (Rajagopal & Bathurst, 1993) and subsequently modified at IIT Madras. In finite element models, the cylindrical unit cell was idealised as axisymmetric case with radial symmetry around a vertical axis passing through the centre of the stone column. As the problem can be modelled as axisymmetric case, one half of a
typical vertical section passing through the central vertical axis is considered for the analysis. This area is discretised using 8-node quadrilateral elements for all the components in the system as shown in Figure 2.

![Typical Finite Element Mesh Used in the Analyses](image)

In the current investigations the stone columns and the soft soil are modelled using hyperbolic non-linear elastic equation given by Duncan & Chang (1970), Equation 1.

$$E_t = \frac{1}{K \left(1 - \sin \phi \right) \left(\sigma_1 - \sigma_3\right)^2} \left(\frac{\sigma_3}{p_a}\right)^m$$

where $E_t$ is the tangent modulus, $K$, $m$, $\eta$, $R_f$, $c$, $\phi$, $\gamma$ are Young’s modulus number, Young’s modulus exponent, Poisson’s ratio, Failure ratio, cohesion, angle of internal friction and unit weight respectively. The geosynthetic used for encasement of stone columns are assumed as linear elastic and modelled as a continuum element whose Young’s modulus ($E$) was derived from the relation $J = E \times t$. Where $J$ is the secant modulus of the geosynthetic and $t$ is the thickness of the geosynthetic.

The shear strength parameters were considered as that of clay soil and aggregates as reported in the details of laboratory experiments in section 2. The hyperbolic parameters considered are listed in Table 3. In order to reduce the number of parameters in the investigation, it is assumed that the contact between the different materials is perfect thus avoiding the need for interface elements. However, the elements immediately adjacent to the geosynthetic encasement are given lower shear strength values equal to 2/3rd of the strength of the parent material in order to allow the relative deformation between the encasement and adjacent materials. Further, the effects of stone column installation on the development and dissipation of the pore pressures are not considered in the analysis.

### Table 3: Hyperbolic Material Properties Used in the Numerical Simulation of the Experiments

<table>
<thead>
<tr>
<th>Materials</th>
<th>$K$ (kPa)</th>
<th>$m$</th>
<th>$\eta$</th>
<th>$R_f$</th>
<th>$c'$ (kPa)</th>
<th>$\phi'$ ($^\circ$)</th>
<th>$\gamma$ (kN/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stone column</td>
<td>250</td>
<td>0.7</td>
<td>0.3</td>
<td>0.7</td>
<td>0</td>
<td>41.5</td>
<td>16</td>
</tr>
<tr>
<td>Foundation soil</td>
<td>15</td>
<td>0.5</td>
<td>0.45</td>
<td>0.7</td>
<td>2.5</td>
<td>0</td>
<td>17</td>
</tr>
<tr>
<td>Geosynthetic encasement</td>
<td>Linear Elastic</td>
<td>$\nu = 0.3$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4. RESULTS AND DISCUSSIONS

Figure 3 shows the pressure settlement curve obtained from laboratory tests for the case of virgin clay bed, OSCs and ESCs encased with non woven geotextile, of three diameters, 50, 75 and 100 mm. The loading on clay bed and OSCs show clear catastrophic failure. Whereas the ESCs have shown elastic behaviour, and there is no remarkable failure. The load carrying capacity of individual stone column for a settlement of 10 mm is increased by 3 to 5 folds because of encasement. The ESCs behaved like elastic semi-rigid flexible piles. In the case of ESCs the compression of the stone column was mainly due to the readjustment of the particle within the stone column and the elongation of the geosynthetic encasement. In the present study the failure was not observed even for the settlement of 50 mm (i.e. 10% of the column length). Figure 4 shows the load settlement response of the stone columns encased with woven geotextile for the three diameters (50 mm, 75 mm and 100 mm) of the column. ESCs with woven geotextile show stiffer response than that of ESCs with nonwoven geotextile. This is because of higher modulus of the geotextile.

![Pressure Settlement Response of the OSCs and ESCs with the Nonwoven Geotextile](image)
In both the cases, it is observed that the load capacities of OSCs are almost same for all the diameters. Whereas for the ESCs it could be observed that as the diameter increases the load capacity of encased stone column decreases. The load capacity is found to depend very much on the diameter of the stone column.

The load settlement responses obtained from experiments and numerical analysis are compared for different cases in Figures through 5 to 7. In general there has been a reasonably good agreement between the responses from model tests and that from the numerical analyses. From Figure 5 it is observed that the hyperbolic model is predicting well the load settlement responses of the stone column and virgin clay bed. The discrepancy in comparison could be due to the total stress analysis assuming fully undrained response while in reality the drainage may take place due to small size of the test set up. Hence a part of the measured settlements could be due to consolidation of soil which was not simulated in the numerical investigations.

5. CONCLUSIONS

Encasing the stone column with suitable geosynthetic has emerged as one of the attractive techniques to improve the performance of stone columns, especially which are installed in very soft soils. In this paper the individual load capacity of this type of the stone columns were investigated through laboratory model experiments and the same has been simulated through numerical modeling. The behaviour of the geosynthetic encased stone columns was compared with the ordinary stone columns and clear improvement is observed because of encasement. The major conclusions drawn from this study are as follows.

1. Pressure settlement response of geosynthetic encased stone columns generally shows linear behaviour not indicating any catastrophic failure unlike the conventional stone columns.
2. The improvement in the load capacity due to encasement depends upon the diameter of the stone column. Lesser
the diameter more would be the improvement. This is in line with the findings from earlier published literature.

3. The numerical simulation with hyperbolic mode for the soil and stone columns has predicted reasonably well, the laboratory responses. In general the numerical modeling of the ESCs compared well with that of the model experiments to a reasonable degree.

REFERENCES


