Theme T 6
Recent Developments in Experimental Geotechnics
Load Deformation Behaviour of Floating Stone Columns in Soft Clay

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ABSTRACT

A series of model footing load tests were carried out on floating stone columns reinforced clay bed to understand the load deformation behavior. All the experiments were carried out on stone columns in groups to understand the group effects and interactions. The parameters varied in this experimental investigation were length and spacing of the stone column without changing the undrained shear strength of the clay. The undrained strength of clay bed was kept constant as 5kPa in all the tests. In this paper the results obtained from experimental investigations were analysed in terms of load carrying capacity, deformation behaviour of stone column and the interaction amongst the stone columns. It was observed that the bearing capacity of the stone column reinforced clay bed can withstand a load more than 4 times that of the soft clay bed alone. The optimum length and spacing of the stone column were obtained from experimental results and strong interaction has been observed for too small spacing of stone column.

1. INTRODUCTION

Stone columns or a Granular pile (as it sometimes called as) is one of the most versatile method of improvement of clay and silty clay where there is a requirement for moderate increase in bearing capacity. Earlier stone columns were used for supporting flexible structures like tank foundations but nowadays stone columns are increasingly being used in small groups to support isolated footings in soft soils when conventional foundations are considered uneconomical. The load carrying capacity of the stone column is a function of the rate of application of the load and as well as the confinement provided by the surrounding soil. The use of floating stone column may be one of the best options for improvement of soft clay where the depth of supporting hard stratum is at large depth. Numerous reporting have been found in the literature regarding the load deformation behaviour of end bearing stone column but very few are there in the area of floating stone column.

The research work on the load deformation behavior of end bearing stone column on clay bed was studied by various researchers in triaxial testing apparatus and with model plate load test. The few of the reported work are of Juran and Guermazi (1988), Alamgir et al. (1996) Porooshashb and Meyerhof (1997), Rao et al. (2000), Wood et al. (2000) used theoretical and model tests to determine the mechanism and response of beds of clay reinforced with stone columns. Bae et al. (2002) studied the failure mechanism and influence of various parameters responsible for the behaviour of end-bearing column groups through loading tests and unit cell consolidation tests. McKelvey et al. (2004), Ambily and Gandhi (2007), Black et al. (2007) reported the results of experimental investigation on sand columns carried out in model stone columns and loaded under triaxial conditions.

The above literature reveals that the research work on stone column is only limited to the case of end bearing columns and hence a comprehensive experimental investigation was carried out to know the load deformation behaviour of floating stone columns in soft clay bed.

Experimental Investigation

Materials Used

A locally available natural silty clay soil was used to prepare the clay subgrade in the present study. The specific gravity of this soil is found to be 2.63. The liquid limit, plastic limit and plasticity index of the soil are found to be 40%, 21% and 19% respectively. As per the Unified Soil Classification System (USCS), the soil can be classified as clay with low plasticity (CL).

The stone columns formed are of 100mm diameter and constructed by crushed stone aggregate with particle size varying in the range of 2mm to 10mm. The average particle size of the material (D_{50}) is 4.9mm. The crushed stone aggregate used has Coefficient of uniformity (C_u) of 2.32 and Coefficient of curvature (C_c) of 0.88 and is classified
as poorly graded gravel (GP) as per Unified Soil Classification System (USCS). The specific gravity, maximum dry density ($\gamma_{dmax}$) and minimum dry density ($\gamma_{dmin}$) of the aggregate are found to be 2.69, 16.83 kN/m$^3$ and 14.17 kN/m$^3$ respectively. The peak friction angle of the aggregate is found to be 48°. The grain size distribution of clay and the stone aggregate used in this experimental investigation is depicted in Fig.1.

![Fig. 1: Grain Size Distribution of Materials Used in this Investigation](image)

**Experimental Setup**

The model tests were conducted in a test bed-cum-loading frame assembly in the laboratory. The soil beds were prepared in a steel tank with inside dimensions of 1000 mm x 1000 mm x 1300 mm (depth). The four sides of the tank are made of thick mild steel sheet and are braced laterally on the outer surface with steel channels to avoid yielding during the tests. The model foundation used is made of a steel plate of 150mm in diameter and 30 mm in thickness. It is rigidly attached to the load cell assembly system. A rough-base condition was achieved by cementing a thin layer of sand on to the base of the model foundation with epoxy glue. In all tests the footing was placed at the centre of the tank. The footing was loaded with a computer controlled motorised hydraulic system supported against the upper cross head of the reaction frame.

The depth of the test tank is 8.6 times the diameter of the footing and the minimum distance from the centre of the footing to the side walls of the tank is 3.3 times the footing diameter and it found to be free from boundary effect provided by the tank wall.

**Details of Test Series**

Three series of model tests were carried out on unreinforced and on stone columns reinforced soft clay bed. The test series 1 was conducted on soft clay bed alone. The details of the test series and the in-situ properties of the test clay bed are summarised in table 1 and 2.

<table>
<thead>
<tr>
<th>Table 1: Details of Test Series</th>
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<tbody>
<tr>
<td><strong>Test Series</strong></td>
</tr>
<tr>
<td>1</td>
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<tr>
<td>2</td>
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<tr>
<td></td>
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<td>3</td>
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</table>

**Note:** SC: Stone column, $L$ and $d_{sc}$ are the length and diameter of the stone column

**Table 2: Properties of Clay in Test Bed**

<table>
<thead>
<tr>
<th>Property</th>
<th>Range</th>
<th>Average Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture Content</td>
<td>35.8-36.5 %</td>
<td>36 %</td>
</tr>
<tr>
<td>Bulk Unit weight ($\gamma_b$)</td>
<td>18-18.1 kN/m$^3$</td>
<td>18.05 kN/m$^3$</td>
</tr>
<tr>
<td>Vane shear strength ($c_u$)</td>
<td>4.8-5.2 kPa</td>
<td>5 kPa</td>
</tr>
</tbody>
</table>

**2. RESULTS AND DISCUSSION**

Tests under series 2 and 3 were carried out to study the behaviour of the stone column reinforced foundation system for different length and spacing of stone columns. In each series only one parameter was varied while others were kept constant. The bearing pressure and settlement responses of the footing, with and without stone columns in the clay beds are depicted in Fig.2 and 3.

![Fig. 2: Pressure Settlement Response of Stone Column Reinforced Clay Bed for Different Lengths of Stone Columns](image)
the deformed stone column and \( r_o \) is the radius of the original undeformed stone column. A typical plot of the radial strain in the stone column at different depth of stone column \( (L/d_{sc}) \) is shown in Fig. 3.

![Fig. 3: Variations of Radial Strain on Central Stone Column with Length](image)

**Effect of Length of Stone Column**

Fig. 2 depicts the bearing pressure versus footing settlement responses for different lengths of stone column, expressed in non dimensional form with respect to its diameter \( (L/d_{sc}) \). It could be observed that even with stone column of length as small as its diameter \( (L/d_{sc} = 1) \), in the clay bed, the performance of the footing (both in terms of increase in bearing capacity and reduction in settlement) can be increased substantially. The performance improvement continues to increase with increase in length of stone column. It is of interest to note that the stone column length varying from \( 3d_{sc} \) to \( 5d_{sc} \) there is substantial improvement in terms of increase in bearing capacity and reduction in settlement of the foundation bed beyond which further improvement is marginal. It could be observed that with provision of stone column the bearing capacity can be increased by 3.5 times that of the clay alone.

For all cases, initially the value of increase in bearing pressure is high but it reduces with increased footing settlement. However for settlement \( (S/D) \) beyond 3% it again continues to increase with increase in settlement. The initially high value of bearing pressure is due to stiffening effect of the stone column under the footing. This effect reduces as the stone column deforms under footing penetration.

After a threshold limit of deformation, the shear resistance of the soil starts getting mobilized leading to increased load carrying capacity.

With increased length of stone column, its punching reduces therefore it bulges more leading to increased mobilization of soil passive resistance and hence increased load carrying capacity. However, beyond certain length \( (i.e. L = 5d_{sc}) \) though the resistance against punching continues to increase but the stone column reaches its maximum bulging capacity and hence further improvement in bearing pressure is marginal (Fig. 2). Hence length of stone column \( (L) \) giving maximum performance improvement is 5 times its diameter \( (d_{sc}) \).

The maximum deformed shape of the stone columns depicted in Fig.3 indicates that bulging dies down to a practically negligible value for length of stone column greater than \( 4d_{sc} \). Similar observations have been reported by Rao et al. (1997) and Sharma et al. (2004).

**Effect of Spacing of Stone Column**

Fig. 4 shows the bearing pressure-footing settlement responses for different spacing of stone columns \( (S/d_{sc}) \). It could be observed that as the spacing of the stone column decreases the bearing pressure of the foundation bed increases. The increase in bearing pressure, when the spacing \( (S) \) reduces from \( 3.5d_{sc} \) to \( 2.5d_{sc} \) is substantially high beyond which further increase in bearing capacity is marginal. Hence the optimum spacing of the stone columns can be taken as \( 2.5d_{sc} \).

![Fig. 4: Variations of Bearing Pressure with Footing Settlement for Stone Column Reinforced Clay with Different Spacings of Stone Columns](image)

3. CONCLUSIONS

From the above discussion the following major conclusions may be drawn:

1. With the provision of stone column in soft clay bed the bearing capacity of the foundation bed can be improved by 3.5 times.
2. The length of stone column providing maximum performance improvement is equal to 5 times its diameter.

3. Maximum increase in bearing pressure is observed for the reduction in spacing of stone column from 3.5 - 2.5 times the diameter of the stone column. The radial strain on the stone column dies down to zero beyond the length of stone column equal to 4 times its diameter.

4. Bulging of the stone column under the application of load is essential for mobilization of the load carrying capacity of the stone column in groups. But excess bulging leads to decrease in load carrying capacity.

5. Stone columns of length less than 3 times its diameter shows negligible or no bulging and hence it simply punches to the soft clay under the application of load.

6. As the stone column in this present investigation were tested in undrained conditions and the load carrying capacity could be further more in case of field application where drainage will be allowed to occur.

7. Radial strain on the stone column is maximum at a depth \( d_{sc} \) from the top of the stone column due to the lateral restrained offered by the rough footing base.

REFERENCES


