CHAPTER 8

THEORETICAL PREDICTIONS OF BEARING STRENGTH
OF STABILISED BEDS

8.1 INTRODUCTION

The design methods for predicting bearing strength of stone column stabilised bed are few and among the methods, the method based on combined resistances of stone column due to bulging and the bearing strength of clay around the column is widely used in design offices. The Indian Standards code of Practice (IS 15284 Part 1, 2003) also recommends this method. From the experimental observations and numerical analyses of current research it is shown that the stone column bulges and the soil around the column provides lateral resistance and also shares the part of the load as a bearing support. The stress condition in the column is in passive state and the passive pressure coefficient is more or less equal to $K_{pcol}$. Thus the method recommended in IS 15284 Part 1 (2003) is used to determine the bearing strength of stone column stabilised bed and compared with the experimental results of the present study.

In the case of encased stone column stabilised bed there is no accepted design method in practice since this technique is still at the research stage. The experimental observations and numerical studies of this research has thrown some light on interaction between three components of encased stone column stabilised bed. From the results of the analysis it is understood that the encased column behaves as a right cylinder. The encasement (i.e. reinforcement) provided to the stone column controls the bulging of the
column by providing confinement to the column material. The reinforcement provided offers strength to the column as a reinforcing compression shell and local buckling, which provides hoop tension (i.e. confining pressure) associated with circumferential strains in the reinforcement. Similar effect is brought out by Henkel and Gilbert (1952) in their research study on the effect of the rubber membrane on the strength of clay. This idea has been extended here to determine bearing strength of encased column stabilised bed. In this method compression shell theory and hoop tension theory of Henkel and Gilbert (1952) are used in combination with the method of IS 15284 Part 1 (2003) for the estimation of bearing capacity of encased stone column stabilised bed. The bearing capacities determined for the encased stone column by the methods are verified with the values obtained from the experiments conducted in this study.

8.2 PREDICTION OF BEARING STRENGTH OF A STONE COLUMN

Load carrying capacity of single stone column treated clay bed is obtained by using the method given in IS 15284 Part 1 (2003). The total load a stone column can bear is calculated by summing up the three components as given below.

1. Capacity of stone column resulting from the resistance offered by the surrounding soil against its lateral deformation (bulging) under axial load.

2. Capacity of the stone column resulting from increase in resistance offered by the surrounding soil due to surcharge over it, and

3. Bearing support provided by the intervening soil between the columns.
This method is applied here with the assumptions that the column is yielded adequately to satisfy plastic deformation so as to mobilise passive condition fully and the effective area of stone column including intervening soil is equal to the loading area of rigid circular plate (i.e. model footing). The surcharge effect on the stone column is taken as zero.

The limiting axial stress in the column is determined using the equation given below.

\[
\sigma_v = (\sigma_{r0} + 4c_u)K_{p,\text{col}}
\]  

(8.1)

In the above equation \(\sigma_{r0}\) is the initial effective radial stress at an average depth of two times the diameter of the column from the column head, which is computed using relation \(\sigma_{r0} = K_0\sigma_{v0}\), where \(K_0 = 0.6\) and \(\sigma_{v0}\) is the effective vertical stress. \(K_{p,\text{col}} = \tan^2(45 + \phi_e/2)\), where \(\phi_e\) is the angle of internal friction of granular column material.

The bearing resistance offered by the clayey soil in contact with the loading plate with is determined from the equation, \(q_u = c_uN_c\), where \(N_c\) is bearing capacity factor taken as 6.2 based on the experimental results of this study. Thus the limiting bearing capacity of a stone column \(q_{\text{col}}\) is determined from the following relation.

\[
q_{\text{col}} = \sigma_vA_c + q_u(A - A_c)
\]  

(8.2)

where \(A_c = \text{area of column}\)
\(A = \text{area of loading plate}\)

The limiting capacity of column obtained from the above equation is compared with the bearing pressure (i.e. pressure for a settlement of 10mm) obtained from experimental load – settlement curve in Table 8.1. The
predicted capacity of the column compared well with experimental results except for the column in a clay of very low consistency (0.05) wherein the difference between the values is around 25%. Thus the study supports that the design method recommended in IS 15284 Part 1 (2003) can be used for the estimation of load carrying capacity of stone column stabilised bed.

Table 8.1 Comparison of bearing strength predicted with experimental results for a stone column

<table>
<thead>
<tr>
<th>Test Id</th>
<th>Diameter of column (mm)</th>
<th>Area of loading (mm²)</th>
<th>Ic</th>
<th>Bearing resistance of column (kN/m²)</th>
<th>Exptl. at 10mm settlement</th>
<th>Predicted values</th>
</tr>
</thead>
<tbody>
<tr>
<td>T101</td>
<td>30</td>
<td>2827</td>
<td>0.25</td>
<td></td>
<td>47.78</td>
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<td>5027</td>
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<td>39.73</td>
<td>39.29</td>
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<tr>
<td>T109</td>
<td>60</td>
<td>11310</td>
<td>0.25</td>
<td></td>
<td>34.56</td>
<td>37.69</td>
</tr>
<tr>
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<td></td>
<td>30.69</td>
<td>34.23</td>
</tr>
<tr>
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<td>60</td>
<td>25447</td>
<td>0.25</td>
<td></td>
<td>28.36</td>
<td>31.35</td>
</tr>
<tr>
<td>T119</td>
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<td>11310</td>
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<tr>
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<td>11310</td>
<td>0.45</td>
<td></td>
<td>77.17</td>
<td>78.32</td>
</tr>
</tbody>
</table>

8.3 PREDICTION OF BEARING STRENGTH OF AN ENCASED STONE COLUMN

As stated, the bearing strength of an encased stone column is estimated by combining compression shell and hoop tension theories with the equation used for predicting capacity of stone column (as in IS 15284 Part 1 2003). The resistance offered by the column due to reinforcement is determined by the following equations [Henkel and Gilbert (1952) approach of right cylinder behavior of the encasement].
(i) Compression Shell theory

\[ \sigma_{1g} = \frac{\pi d M \varepsilon (1 - \varepsilon)}{A_0} \]  

(8.3)

(ii) Hoop Tension theory

\[ \sigma_{3g} = \frac{2M (1 - \sqrt{1 - \varepsilon})}{d (1 - \varepsilon)} \]  

(8.4)

where  
\[ \sigma_{1g} \] = resistance of the column due to compression shell  
\[ \sigma_{3g} \] = confining stress in the column due to hoop tension effect  
\[ d \] = diameter of column  
\[ M \] = compression modulus of encasing material  
\[ \varepsilon \] = axial strain of the column  
\[ A_0 \] = initial area of the column

The above equations are used in three different ways (methods) to determine the bearing capacity of encased stone column.

(a) Method I

In the first method both compression shell and hoop tension effect of reinforcement are considered along with the bearing support offered by the clayey soil in contact with the loading plate. In this method it is assumed that (i) the core (i.e. stone column) and the encasement are acting as a single unit, (ii) the bending stiffness of encasement is negligible, (iii) creep of encasing material is not considered since the test is not a slow test, (iv) the lateral resistance of soil is far less than the hoop tension developed, and (v) the compression modulus of reinforcement is assumed to be equal to tension modulus. Based on the above assumptions, the combined strength of encased column is obtained by the following equation. In this the bearing strength is
referred as bearing pressure, since the strength is determined for different settlements of the column.

\[
q_b = \frac{\left[ \sigma_{1g} A_c + \sigma_{3g} K_{pcol} A_c + N_c c_u (A - A_c) \right]}{A}
\]  

(8.5)

where 
- \(q_b\) = bearing pressure for a given settlement
- \(\sigma_{1g}\) = resistance of the column due to compression shell
- \(\sigma_{3g}\) = confining stress in the column due to hoop tension effect
- \(A_c\) = area of the column
- \(N_c\) = bearing capacity factor equal to 6.2\(c_u\)
- \(c_u\) = undrained shear strength of clay
- \(A\) = area of the loading plate

(b) **Method II**

In the second method the bearing strength of encased column is determined as a sum of contribution of the following three components.

(i) Increase in the capacity of stone column due to compression shell effect,

(ii) Capacity of stone column resulting from the resistance offered by the surrounding soil (confining effect due to hoop tension is ignored), and

(iii) Bearing support provided by the clay in contact with loading plate.
Based on the above, the bearing resistance of an encased stone column is

\[
q_b = \frac{[\sigma_{1g} A_c + \sigma_r A_c + N_c c_u (A - A_c)]}{A}
\]  

(8.6)

where

- \(q_b\) = bearing pressure for a given settlement
- \(\sigma_{1g}\) = resistance of the column due to compression shell
- \(\sigma_r\) = limiting axial stress of the stone column
- \(N_c\) = bearing capacity factor taken as 6.2
- \(c_u\) = undrained shear strength of clay
- \(A_c\) = area of the column
- \(A\) = area of the loading plate

(c) Method III

In this method, the compression shell effect is completely ignored and the effect of hoop tension is considered as the additional confinement to the stone column. Thus the bearing capacity of an encased stone column is obtained by summing the contribution of the following three components.

(i) The additional resistance to the stone column by means of increase in confining pressure (i.e. due to hoop tension, \(\sigma_{3g}\)),

(ii) Capacity of the stone column resulting from the resistance offered by the clay surrounding the column, and

(iii) Bearing support provided by the clay in contact with loading plate.
From the above, the bearing resistance of column for a given settlement is expressed as

\[
q_b = \frac{[\sigma_{3g} K_{p, col} A_c + \sigma_v A_c + N_c c_u (A - A_c)]}{A}
\] (8.7)

where

- \( q_b \) = bearing pressure for a given settlement
- \( \sigma_{3g} \) = confining stress in the column due to hoop tension effect
- \( K_{p, col} = \tan^2(45 + \phi/2) \)
- \( \sigma_v \) = limiting axial stress on the stone column
- \( N_c \) = bearing capacity factor taken as 6.2
- \( c_u \) = undrained shear strength of clay
- \( A_c \) = area of the column
- \( A \) = area of the loading plate

The assumptions made in method I are valid for methods II and III also. In method II, the hoop tension effect is ignored. This is one possible situation where the deformation in the column is not sufficient enough to buckle the reinforcement or little buckling, hence hoop tension is not effective. The other condition is that the reinforcement is not held firmly against the column, hence buckling is predominant. This case is considered in method III. In all the methods it is assumed that column deforms without volume change.

### 8.4 COMPARISON OF THE EXPERIMENTAL RESULTS WITH THE PREDICTED VALUES

The bearing pressure of end-bearing columns tested are predicted using the three methods suggested above for the column settlement of 10mm
and 20mm and are compared with experimental results. These two settlements represent the axial strain of 3.33% and 6.67% respectively.

The bearing pressures predicted using method I are compared with the respective experimental values in Figure 8.1. In Figure 8.1(a) the bearing pressure corresponding to 10mm settlement is compared and it shows that the predicted value from the equation of method I is higher than the experimental value particularly for the column with net3. However, the maximum variation is around 20%. In the case of 20mm settlement, the comparison is very good irrespective of the column diameter and the method I predicts the capacity of column reasonably well particularly for the axial strain of 6.67% (i.e. 20mm settlement). The comparison confirms that the reinforcement provides resistance to the column by the combined action of compression shell and buckling particularly at higher settlement.

The values obtained from the theory are in consistence with experimental values with coefficient of determination of 0.82 and 0.92 for the bearing pressures at 10mm and 20mm settlements respectively. The respective coefficient of correlation values are 0.91 and 0.92, which confirms strong correlation between the values of experiment and theory.

The bearing pressure determined from the method II for the column of different diameters encased with three different nets are compared in Figure 8.2 with experimental results. Figure 8.2(a) presents the comparison for 10mm settlement and for the 20mm settlement the comparison is presented in Figure 8.2(b). The bearing pressures obtained both for the 10mm and 20mm settlements compare well with the experimental results. For both the settlements the difference in bearing pressure between the theory and experiment is less than 10%. Further the theoretically predicted values are consistent with the experimental values. The coefficient of determination is 0.94; it implies that more than 90% of the variation in bearing pressure values
predicted from the theory (method II) is explained by the bearing pressures of experiments. The coefficient of correlation is 0.96 for the data compared, which is close to unity indicating strong correlation between the bearing pressure values of theory and experiment.

In method III the confining effect of reinforcement alone is considered to the stone column and the bearing pressures obtained by this method for the settlement of 10mm and 20mm are compared in Figure 8.3 with the experimental values. Though theoretically predicted values are in consistence with experimental results, they are away from the perfect fit line (i.e. dotted line) indicating that the method III underestimates the bearing pressure of the column irrespective of the settlement and the degree of underestimation is high if the column strength is high. Hence the method III is considered as highly conservative in predicting the capacity of encased stone column.

8.5 SUMMARY

Among the three methods considered in this study, method I wherein the effect of reinforcement to the column is included by the combined action of compression shell and buckling (hoop tension) compares well for the bearing pressure corresponding to axial strain of 6.67%. However there is marginal overestimation of capacity. Method II wherein the resistance due to compression shell alone is considered compares well with the experimentally predicted bearing pressures irrespective of the axial strain of the column considered in this study for comparison. Method III which includes only the buckling effect of column resulted in conservative estimation of bearing pressure.
Figure 8.1  Comparison of bearing pressure predicted by method I (combined effect of compression shell and hoop tension) and experimental results
Figure 8.2 Comparison of bearing pressure between compression shell theory (method II) and experimental results

(a) 10mm settlement (3.33% strain)

(b) 20mm settlement (6.67% strain)
Figure 8.3  Comparison of bearing pressure between hoop tension theory (method III) and experimental results