COMPARATIVE STUDY OF EXPERIMENTAL AND THEORETICAL LOAD CARRYING CAPACITY OF STONE COLUMN WITH AND WITHOUT ENCASEMENT OF GEOSYNTHETICS

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ABSTRACT

The techniques for soil improvement have been changing and during the last three decades the concept of soil improvement by reinforcing it with tension resistant elements in various forms has received the attention. The reinforcement can be provided in vertical as well as in horizontal direction. The concept of introducing Geosynthetic Encased Column is found worth considering in Improvement of Load carrying capacity of soft clay ground intended to be treated by installation of Stone Column. In the present study a simple theoretical analysis is attempted to analyze a modified stone column treated ground and developed expressions to calculate the Ultimate Load Carrying capacities of Stone Column with and without encasement of geosynthetics. The correctness of these expressions is ratified by comparing the values obtained from the expressions with the observed results from tests on modeled stone column treated soil on a limited scale with and without encasement of geosynthetics.

KEYWORDS: Soil improvement, Stone column, Failure load, Geosynthetics, Encasement.

I. INTRODUCTION

Nowadays there are several techniques for soil improvement. Out of these techniques available for improving the weak strata, stone columns have been used to a large extent for several applications. The concept of soil improvement by reinforcing it with tension resistant elements in various forms has received the attention. This reinforcement can be provided in Vertical as well as in horizontal direction.

In the present study modifications to existing stone column technique are proposed. The modification is in the form of introducing marginally small percentage of Sand, Stone Dust and lime to the conventional granular material in addition to this the Encasement of Geosynthetic is suggested for enhancing the load carrying capacity of the Stone Column in treated ground.

In the conventional stone Column, the Bearing Capacity of the treated ground is mainly derived from the passive resistance offered by the surrounding soil due to lateral bulging of Stone Column material under axial load. Thus, logically if the Stone Column material is in the form adequately granular material, with small quantity of Lime, sand and Stone Dust, it is obvious that the effectiveness of the Stone Column treated ground is going to be enhanced. Also the introduction of Geosynthetic Encasement results in further enhancement of Load Carrying Capacity of Stone Column treated ground.

In order to improve the stiffness of the column material, it is necessary to provide some adhesion in the material matrix. This will prevent easy migration of particles readily outwards. Hence mixing of Sand and Stone Dust with combination of Lime of very insignificant quantity supplemented by filler material is used to induce certain bonding. The concept of Load transfer mechanism as it occurs in the pile is also considered for simplifying the analytical approach.
With the aforesaid considerations in view, the present study has been planned and carried out to develop the idealized load transfer mechanism. A simple theoretical analysis is attempted to analyze firstly, with a unit cell for untreated soft clay, secondly, unit cell for straight shafted stone column without encasement of geosynthetic, lastly, unit cell for straight shafted stone column with encasement of geosynthetic. Then mathematical expressions are developed for computing the ultimate load carrying capacities of stone column. The correctness of these expressions is ratified by comparing the values obtained from the expressions with the observed results from tests on modeled stone column treated soil on a limited scale. Different parameters length to diameter ratio \( r_L (L/d) \), shear strength of the surrounding soil and, the area replacement ratio \( r_a (a/A) \) and others were studied to show their effect on the bearing improvement and settlement reduction of the stone column.

II. LITERATURE REVIEW

Soft clays extending over large depths, stone columns could be the ideal choice from the point of view of technical feasibility and suitability. Improvement of strength and compressibility characteristics of soft and/or loose soil or heterogeneous fill by installation of stone column as load bearing member has been identified as an effective means of ground improvement technique. The beneficial effects of installation in weak or difficult subsoil deposits is manifested in the form of increased load carrying capacity, significant reduction in total and differential settlements, minimization of post construction settlements. Ranjan & Rao [19][20] utilized the analogy of expansion of cylindrical cavity in a homogeneous, infinite soil mass, a simple method of estimating the ultimate capacity of these piles both plane skirted has been developed. The analysis has been extended to pile group also. Mokashi et al [17] found that the passive restrained on the peripheral granular piles can also be increased by providing surcharge around the foundation. di Prisco, C et al [5] studied the mechanical behavior of sand columns reinforced by means of geosynthetics by performing small scale tests on single elements. Kameshwar Rao Tallapragada et al [11] found that the percentage reduction in settlement due to geosynthetic encasement decreased from 11.88% to 41.47% and the contribution of load carrying capacity due to geosynthetic encasement increased from 21.62% to 45.0% with smaller diameter and shorter length to larger diameter and longer length of stone column respectively.

Review of literature presented indicates, considerable attempts have been made to evolve a rational analysis and design procedure but most of them relied upon the basis that the Stone Column derives its capacity through the passive resistance offered by the surrounding soil. While many attempts were made to enhance the capacity by externally supporting the Stone Column in top portion or tried to improve the stiffness of the column material by additions. However some of them posed cost impediments, some constructional difficulties. However it is kept in view that, in addition to improve the Load Carrying Capacity, reduction in settlements of soft clays; the Stone Column serves the purpose of enhancement of time rate to consolidation. This functionality of Stone Column is most important as this can considerably reduce long term post construction settlements, which is a natural occurrence in soft clayey soils.

III. MATHEMATICAL FORMULATION FOR LOAD CAPACITY OF STONE COLUMN

3.1 Basic Assumptions

i) An approach of Static load equilibrium holds well.

ii) Unit cell concept is valid for estimating the performance of large layout of stone column.

iii) The soil to be treated is soft saturated clay.

iv) The effective length of the stone column for development of shaft surface resistance and the tip resistance is pertaining to length ratio \( (r_L) \) of 23.

v) The reduction in the ultimate tip bearing is assumed to vary linearly from zero percent at depth of \( 3d_c \) to 100 percent at depth of \( 23d_c \).

vi) Full mobilization of shaft surface resistance is assumed over the entire length of column \( (Le) \) and \( Le = 23d_c \).
Zone of depth of $3d_s$ is the zone of possible bulging. On reaching the failure of column under axial action, there cannot be possibility of bulging thereafter. If column of length $3d_s$ is constructed, it will act as a pile with full development of ultimate bearing resistance. Hence bearing capacity reduction factor $r_d$ is zero at this depth. In view of semi rigid nature of column material, and considering the vertical downward displacement of column, it is assumed that this vertical movement will cease to exist at a depth of $20d_s$ below the $3d_s$ depth level. At this level there will be no end bearing. Thus the value of $r_d = 100\%$. It can be expressed as

$$r_d = 0.05 \left( \frac{z}{d_s} \right) - 0.15 \quad \ldots \text{Eqn. (1)}$$

3.2 Notations used in the analysis

- $d_s =$ Diameter of Column Shaft
- $L =$ Length of Stone Column
- $a =$ Cross sectional area of column at ground surface
- $A =$ Area of Unit Cell
- $Z =$ Any depth below surface of ground
- $D_u =$ Diameter of Unit Cell
- $C_u =$ Undrained cohesion of untreated soil
- $C'_u =$ Undrained Cohesion for local shear
- $r_a =$ Area of Replacement ratio ($a/A$)
- $r_L =$ Length Ratio ($L/d_s$)
- $r_d =$ bearing capacity reduction factor at any depth $z$
- $Q_f =$ Load Capacity at failure of Unit Cell
- $q_f =$ Failure Load carrying Capacity of Unit Cell ($q_f/A$)
- $N_c =$ Bearing Capacity Factor for circular rigid load base untreated soft clay
- $N_{ct} =$ Bearing Capacity Factor for Stone Column treated soft clay
- $F_b =$ Bearing Capacity Improvement Factor.
- $R_t =$ Column tip resistance.
- $R_s =$ Soil resistance offered by tributary soil under ($A-a$) area at local failure of soft clay
- $R_{g1} =$ Resistance developed between Stone Column material and geosynthetic
- $R_{g2} =$ Resistance developed between geosynthetic and surrounding soil.

3.3 Unit Cell Analysis For Untreated Soft Clay

A Rigid Circular base of diameter $D_u$ (i.e. diameter of unit cell with area $A$) when loaded will cause local shear failure in soil. Shear Failure in soil occur up to a depth of $D_u$ below ground surface. This case is equivalent to rigid circular surface footing resting on soft clay for which Ultimate bearing capacity is expressed as,

$$q_u = c_u * N_c \quad \ldots \text{Eqn. (2)}$$

This equation is modified for circular area and local shear failure. Thus using the terminology considered in stone column system,

$$q_f = 1.2 * \left[ \frac{2}{3} (C'_u) \right] * N_c = \left[ 1.2 * \left( \frac{2}{3} \right) * 0.9 \right] C_u * N_c = 0.72 C_u N_c \quad \ldots \text{Eqn. (3)}$$

Different analysis viz. Prandtl, Terzaghi, Mayerhoff, Skempton have recommended different values $N_c$ for $\phi = 0$ case. In order to give appropriate weightage to all such values, the average of four theories is considered in the present analysis. Thus, $N_c = 5.61$ is decided as Bearing capacity factor. Hence Eqn.(3) of failure load carrying capacity of untreated clay becomes,

$$q_f = 0.72 * 5.61 C_u = 4.04 C_u \quad \ldots \text{Eqn. (4)}$$

$$N_c = \frac{(q_f / C_u)}{4.04} \quad \ldots \text{Eqn. (5)}$$

The failure load on the unit cell for untreated ground is obtained multiplying the failure load capacity with the bearing area.

$$Q_f = 4.04 C_u A \quad \ldots \text{Eqn. (6)}$$

3.4 Unit Cell Analysis For Straight Shafted Stone Column Without Geosynthetic

Fig.1 shows various resistances offered by the system under superimposed loads a single unit cell provided with a straight shafted stone column.
Static load equilibrium for this case is given by:

\[ Q_f = R_s + R_f + R_t \]  \hspace{1cm} \text{------- Eqn. (7)}

Now,

\[ R_s = [1.2 \times (2/3) \times 0.9 \times N_{ct} \times C_u \times (A-a)] \]
\[ = 4.0392 \times C_u \times (A-a) \]  \hspace{1cm} \text{------- Eqn. (8)}

\[ R_f = (\alpha \times C_u \times \frac{\pi \times d_s \times L}{2}) \]  \hspace{1cm} \text{------- Eqn. (9)}

For developing equation for \( R_t \), the Bearing Capacity, reduction factor for column tip level is required to be determined, hence, substituting \( z = L \) in Eqn.(1)

We get \( r_{dt} \) for tip as:

\[ r_{dt} = \left[ 0.05 \times \left( \frac{L}{d_s} \right) - 0.15 \right] \]

Hence, mobilized tip resistance, \( R_t \)

\[ R_t = (\alpha \times C_u \times \frac{\pi \times d_s \times L}{2}) \times C_u \]  \hspace{1cm} \text{------- Eqn. (10)}

Thus by dividing \( Q_f \) with area of unit cell ‘A’, we get expression for failure load carrying capacity \( q_f \) as under,

\[ q_f = \frac{[4.04(1-r_a)] + [(4 \alpha r_a r_t) + [(10.35-0.45r_L) r_a] C_u}{A} \]  \hspace{1cm} \text{-----Eqn. (12)}

Incorporating the following non dimensional Parameters \( r_a, r_t \) in Eqn.12

\[ r_a = (a/A) \text{ and } r_t = (L/d_s), \text{ L= L} \]
\[ d_s = (d_s/a) \text{ and } (a/a) = [(d_s 4 r_t)/(\pi d_s^3)] = (4 r_t)/(\pi d_s) \]
\[ q_t = [4.04(1-r_t)] C_u + [(4 \alpha r_t/\pi d_s) r_t d_s] C_u + [(10.35-0.45r_L) r_t] C_u \]
\[ q_t = [4.04(1-r_t)] C_u + [(4 \alpha r_t r_t) + [(10.35-0.45r_L) r_t] C_u \]
\[ q_t = C_u \times \left[ (4.04(1-r_t)) + [(4 \alpha r_t r_t) + [(10.35-0.45r_L) r_t] \right] \]  \hspace{1cm} \text{-----Eqn. (13)}

Now the failure load carrying capacity of soft clay treated material with straight shafted stone column can be expressed as

\[ q_f = C_u N_{ct} \]  \hspace{1cm} \text{-----Eqn. (14)}

Where \( N_{ct} \) = Bearing Capacity Factor of treated soft clay with straight shafted column system.

From Eqn. 12 & Eqn. 13

\[ N_{ct} = [4.04(1-r_3)] + [(4 \alpha r_3 r_t) + [(10.35-0.45r_L) r_t] \]  \hspace{1cm} \text{-----Eqn. (15)}

3.5 Bearing Capacity Improvement Factor (\( F_b \))
For identifying the extent of improvement occurring due to the treatments given by means of installation of stone column, the Bearing Capacity Improvement Factor \( F_b \) came into existence. The bearing capacity factor,

\[
F_b = \left( \frac{N_{ct}}{N_c} \right)
\]

----- Eqn. (16)

### 3.6 Unit Cell Analysis For Straight Shafted Stone Column With Encasement Of Geosynthetic.

Fig.2 shows various resistances offered by the system under superimposed loads a single unit cell provided with a straight shafted stone column.

\[
Q = R_S + R_t + R_{g1} + R_{g2}
\]

----- Eqn. (17)

\[
q_f = C_u \left\{ [4.04(1-r_a)] + [(10.35-0.45r_L) r_a] \right\} + R_{g1} + R_{g2}
\]

----- Eqn. (18)

Where, \( R_{g1} = (4 \alpha_1 r_a r_L) C_u \) \& \( R_{g2} = (4 \alpha_2 r_a r_L) C_u \)

\( \alpha_1 = \text{Adhesion Factor of Stone Column Material and Geosynthetic} = (C_{ug1}/C_u) \)

\( \alpha_2 = \text{Adhesion Factor of Geosynthetic and Surrounding Soil} = (C_{ug2}/C_u) \)

\( C_{ug1} = \text{Undrained Cohesion of Stone Column Material and Geosynthetic} \)

\( C_{ug2} = \text{Undrained Cohesion of Geosynthetic and Surrounding Soil}. \)

Hence Eqn.16 is modified as,

\[
q_f = \left\{ C_u \left[ [4.04(1-r_a)] + [(10.35-0.45r_L) r_a] \right] \right\} + (4 \alpha_1 r_a r_L) C_u + (4 \alpha_2 r_a r_L) C_u
\]

----- Eqn. (19)

\[
N_{ct} = [4.04(1-r_a)] + [(10.35-0.45r_L) r_a] + (4 \alpha_1 r_a r_L) + (4 \alpha_2 r_a r_L)
\]

----- Eqn. (20)

### IV. Parametric Study

The purpose is to study the effect of various parameters involved in the analytical treatment of systems considered in optimizing the benefits to be derived for stone column of soft clay treated soil. In addition to establishment of the effect of their variations on the performance of the system, they serve as general guiding tool. With the aforesaid considerations in view, the parametric study is undertaken for the different cases.

For a given soil state and its condition, the failure load carrying capacity depends on the non dimensional bearing capacity factor for treated ground. The non dimensional factor \( N_{ct} \) is given by,

\[
N_{ct} = [4.04(1-r_a)] + [(4 \alpha r_a r_L) + [(10.35-0.45r_L) r_a] \]

----- Eqn. (21)
From above Eqn. 20 it can be seen that the magnitude of $N_{ct}$ depends on Area Replacement Ratio ($r_a$) and Length ratio ($r_L$).

Hence, $N_{ct} = f(r_a, r_L)$

Therefore the parametric study is carried out by considering the different values of $r_a$ & $r_L$ and considering possible permutations and combinations.

The values of Area Replacement Ratio considered for this purpose are 0.05, 0.1, 0.15, 0.2, 0.25, and 0.3.

Considering floating type of stone column and from practical installation consideration, the length ratios considered are, 10, 12, 14, 16, 18 and 20.

The effect of these values of $r_a$ & $r_L$ on the non dimensional coefficients $N_{ct}$ and $F_b$ are presented in Table-1, Table-2 and Table-3.

### Table-1: the theoretical load carrying capacity, Q (Kg) without encasement of geosynthetic

<table>
<thead>
<tr>
<th>Length of stone column (L)</th>
<th>Dia. Of stone column (d_s)</th>
<th>$r_a$</th>
<th>$r_L$</th>
<th>$R_s$</th>
<th>$R_t$</th>
<th>$R_f$</th>
<th>$R_{eff}$</th>
<th>$N_{ct}$ = ($q_f/C_u$)</th>
<th>$q_f$ (kg/cm²)</th>
<th>Q (kg)</th>
<th>$F_b$ = ($N_{ct}/N_c$)</th>
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</thead>
<tbody>
<tr>
<td>30.0</td>
<td>2.5</td>
<td>0.062</td>
<td>12</td>
<td>3.79</td>
<td>2.62</td>
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<td>6.72</td>
<td>1.24</td>
<td>97.57</td>
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<td>0.034</td>
<td>15</td>
<td>3.90</td>
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<td>30.0</td>
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<td>20</td>
<td>3.95</td>
<td>1.55</td>
<td>0.03</td>
<td>5.53</td>
<td>1.02</td>
<td>80.34</td>
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<td>9</td>
<td>3.79</td>
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<td>15</td>
<td>3.95</td>
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<td>0.08</td>
<td>5.19</td>
<td>0.96</td>
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<tr>
<td>15.0</td>
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<td>4.85</td>
<td>0.90</td>
<td>70.53</td>
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### Table-2: Theoretical load carrying capacity, Q (Kg) with encasement of geosynthetic

<table>
<thead>
<tr>
<th>Length of stone column (L)</th>
<th>Dia. Of stone column (d_s)</th>
<th>$r_a$</th>
<th>$r_L$</th>
<th>$R_s$</th>
<th>$R_t$</th>
<th>$R_f$</th>
<th>$N_{ct}$ = ($R_s + R_t + R_f$)</th>
<th>$q_f$ (kg/cm²)</th>
<th>Q (kg)</th>
<th>$F_b$ = ($N_{ct}/N_c$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.0</td>
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<td>0.84</td>
<td>5.73</td>
<td>1.09</td>
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### Table-3: Direct Shear Test

<table>
<thead>
<tr>
<th>Material</th>
<th>Cohesion $C_u$ (Kg/cm²)</th>
<th>Friction angle $\phi$</th>
</tr>
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<tbody>
<tr>
<td>B.C SOIL and Geosynthetic</td>
<td>0.2</td>
<td>55</td>
</tr>
<tr>
<td>Stone column material and Geosynthetic</td>
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</table>
V. EXPERIMENTAL OBSERVATIONS

With the help of recorded load-settlement observations obtained while conducted the tests, curves were obtained for depicting the behavior of the unit cell under superimposed loads. The load settlement curves are developed for all the considered cases of:

- Untreated Soil
- Treated Soil:
  - Straight Shafted stone column without encasement of geotextile
  - Straight Shafted stone column with encasement of geotextile

Thus the introduction of geotextile confirms that the bulging phenomenon is the only governing criteria for failure of stone column and geotextile plays a vital role in its resistance to failure. The increased frictional resistance increases the load carrying capacity.

The failure load is obtained from the curves of load-settlement in the following manner. Tangents are drawn from the approximated initial straight line portion and from final straight portion of continuous yielding. The abscissa of point of intersection will represent the Experimental failure load. This is conventional and universally accepted method for evaluation of failure load for a continuously yielding type of plastic material. A sample of load-settlement curves are shown in Figure 5 and Figure 6 for the case of stone column having length $L = 15\text{cm}$ and diameter $d = 1.5\text{cm}$ and failure load is obtained. Failure loads were obtained for all the cases of study and the findings are presented in Table-4 and Table-5. The theoretical failure loads for all the cases which were computed and shown in the Table-1 and Table-2 are compared with experimental failure load in the Table-4 and Table-5.

![Figure 5](image1.png)

![Figure 6](image2.png)

Table-4: VARIATION OF LOAD CARRYING CAPACITY, $Q$ (Kg)
WITHOUT ENCASEMENT OF GEOSYNTHETIC

<table>
<thead>
<tr>
<th>Length of stone column ($L$)</th>
<th>Dia. of stone column (ds)</th>
<th>Load $Q$ (kg) (Theoretical)</th>
<th>Load $Q$ (kg) (Experimental)</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
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### Table-5: VARIATION OF LOAD CARRYING CAPACITY, $Q$ (Kg) WITH ENCASEMENT OF GEOSYNTHETIC

<table>
<thead>
<tr>
<th>Length of stone column (L)</th>
<th>Dia. of stone column (ds)</th>
<th>Load $Q$ (kg) (Theoretical)</th>
<th>Load $Q$ (kg) (Experimental)</th>
<th>% Error</th>
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### Table-6: THEORETICAL STRENGTH CONTRIBUTION OF GEOSYNTHETIC IN THE STONE COLUMN ENCASEMENT

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<tr>
<th>Length of stone column (L)</th>
<th>Dia. of stone column (ds)</th>
<th>Q (kg) Stone Column Material</th>
<th>Strength Contribution of Geosynthetic (Kg)</th>
<th>% Contribution of Strength due to Geosynthetic</th>
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<tbody>
<tr>
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<td>With Geosynthetic</td>
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### Table-7: EXPERIMENTAL STRENGTH CONTRIBUTION OF GEOSYNTHETIC IN THE STONE COLUMN ENCASEMENT

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<th>Dia. of stone column (d_s)</th>
<th>Q (kg) Stone Column Material</th>
<th>Strength Contribution of Geosynthetic (Kg)</th>
<th>% Contribution of Strength due to Geosynthetic</th>
</tr>
</thead>
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VI. DISCUSSION

By introducing Lime and Sand in the material Matrix for the column, the Rigidity of the Stone Column can be very easily improved. The semi rigid nature of Stone Column resulted in development of additional resistances like, Shaft Resistance and Tip Resistance in addition to the surface Resistance.

As compared to Conventional Stone Column, the Load Carrying Capacity of Stone Column by Treated material can be enhanced due to the development of these additional resistances. Additional resistance can be created by providing the Encasement of Geosynthetic to the Stone Column. The dual benefit of Treated material of Stone Column and Encasement of Geosynthetic are useful in deriving additional load carrying capacity as compared to Conventional Stone Column.

Experimental tests showed how the confining effect given by the geosynthetic improves the Load Carrying Capacity of Stone Column. The analysis for all cases of treated, untreated Stone Column Material with and without Encasement of Geosynthetic were carried out based on Unit Cell Concept.

VII. CONCLUSION

Load carrying strength of stone column improved by 20% to 66% and 42% to 124% because of treated material without and with encasement respectively as compared to untreated soil. The percentage difference in theoretical and experimental load carrying capacity of stone column without and with encasement respectively, varied from 2.47% to 8.79% and 1.12% to 6.56%. Results for the Experimental Investigations were found in close agreement with the analytical predictions. The theoretical values are lesser when compared to experimental values. For design of stone column the theoretical expressions can be used by multiplying them with 1.1.

From the parametric study it can be concluded that with very low area replacement ratios and length ratios, considerable improvement in the load carrying capacity can be achieved. The parametric studies also reveals longer lengths of columns can be replaced by shorter length of geotextile encased Stone column.

REFERENCES


Authors
