EFFECT OF VARIATION OF SOIL PARAMETERS ON STONE COLUMN IMPROVED GROUND

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ABSTRACT: The performance of geotechnical structures is often affected by the uncertain behavior of geotechnical parameters, if they are not properly accounted for. Reliability analysis takes into account the effect of these variations. In the present study, the effect of variation of geotechnical random variables on consolidation and bearing capacity of stone column improved soft ground is studied. Seven geotechnical parameters are considered as random variables. Probability of failure (P_f) is calculated for stability against consolidation and bearing capacity by Monte Carlo Simulation for a target degree of consolidation and a target safe load. Sensitivity analysis by F-test shows that apart from coefficient of radial consolidation (c_r) and cohesion of soil (c_s), internal angle of friction of stone column (φ_s) and soil (φ_f) also influence P_f. If the coefficient of variation of c_r exceeds 20%, P_f exceeds the safe value of 0.001 according to US Army Corps of Engineers. As the spacing between the stone column increases, the probability of reaching a target degree of consolidation decreases. Finally, design guidelines are provided for different spacing and diameter of the stone column corresponding to different variations of geotechnical random variables.

KEYWORDS: Uncertainty, Reliability Analysis, Stone Columns, Bearing Capacity, Consolidation

1 INTRODUCTION

Stone columns increase the shear strength and decrease the compressibility of soft soil. Greenwood (1970) first proposed the theory of load transfer and estimated the ultimate bearing capacity and settlement of stone columns. Ambily and Gandhi (2007) indicated that ultimate capacity of stone column was governed primarily by maximum radial reaction of soil against the bulging.

However, most of the reported studies are based on deterministic approach. Soil, being a natural material, uncertainties in geotechnical engineering is unavoidable. Factor of Safety (FS) does not consider the amount of uncertainty associated with the system. Alonso and Jimenez (2011) observed that radial coefficient of consolidation has the highest influence on the reliability results for stone column-improved ground. Douglas and Schaefer (2012) concluded that Priebe’s Method is found to have approximately 89% probability that the measured settlement will be smaller than the estimated settlement. Deb and Majee (2014) suggested probability based design charts for estimating diameter and spacing for stone column improved ground by considering c_r and c_s as the random variables.

A sensitivity analysis by F-test method is carried out in the present study to identify the relative contributions of seven geotechnical random variables on P_f for the bearing capacity and consolidation settlement. Probability of failure (P_f) is computed for a target degree of consolidation and a target safe load by Monte Carlo Simulation (MCS) in commercially available software Matlab 2015a. Design guidelines, considering both consolidation and bearing capacity of improved ground, are proposed for different spacing and diameter of stone columns, corresponding to different variations of geotechnical random variables and time frames of achieving target consolidation.

2 ANALYSIS OF STONE COLUMNS

2.1 Bearing Capacity

The bearing capacity of a stone column is obtained by summing up the resistance of the soil surrounding the column against bulging, due to surcharge effect and bearing support by intervening soil between the columns (IS 15284 (Part 1): 2003):

For c - φ soils, the bearing capacity is determined by Bell’s formula which is:
\[ \sigma_{sl} = P_p = \gamma z k_p + 2c_u \sqrt{k_p} \]  \hspace{1cm} (1)

where, \( P_p \) = passive pressure, \( z \) = average bulge depth = 2\( d_c \), \( d_c \) = diameter of stone column, \( D_e \) = equivalent diameter = 1.05 and 1.13 times the spacing (S) for triangular and square pattern of arrangement of columns respectively.

Limiting axial stress in the column is given by

\[ \sigma_v = \sigma_{sl} K_{pcol} = \sigma_{sl} \left( 1+ \frac{\sin \phi}{1-\sin \phi} \right) \]  \hspace{1cm} (2)

Where, \( \phi_c \) = angle of internal friction of column. Therefore, safe load on column is

\[ Q_1 = \frac{\sigma_{sl} \pi d_c^2}{4} \]  \hspace{1cm} (3)

Safe bearing pressure of soil \( q_{safe} = c_u N_c \)  \hspace{1cm} (4)

The increase in the mean radial stress due to surcharge,

\[ \Delta \sigma_{rr} = q_{safe} \left( 1+\frac{2K_p}{3} \right) \]  \hspace{1cm} (5)

The increase in safe load of column,

\[ Q_2 = \left( \frac{K_{pcol} \Delta \sigma_{rr} \pi d_c^2}{4} \right) \]  \hspace{1cm} (6)

The area of intervening soil is \( A_s = S^2 - \left( \frac{\pi d_c^2}{4} \right) \)

Safe load taken by the intervening soil is \( Q_3 = q_{safe} A_s \)  \hspace{1cm} (7)

The overall safe bearing capacity of each stone column is given by \( Q_{allowable} = Q_1 + Q_2 + Q_3 \)  \hspace{1cm} (8)

### 2.2 Consolidation

The radial rate of consolidation of stone column improved ground is more effective compared to the vertical rate of consolidation. The radial rate of consolidation \( (U_r) \) is (Han and Ye, 2000) as follows:

\[ U_r = 1 - \left( \frac{8}{\pi^2} \exp \left( \frac{-s_x}{s(N)} \right) \right) \]  \hspace{1cm} (9)

where, \( F(N) = \frac{N^2}{N^2 - 1} \ln(N) - \frac{3N^2 - 1}{4N^2} \)

Diameter Ratio \( N = \frac{D_e}{d_c} \), \hspace{1cm} (10)

Modified Time Factor \( T_r = \frac{C_r \times t}{D_r^2} \) \hspace{1cm} (11)

Modified Coefficient of Radial Consolidation \( C_r = C_r (1 + \frac{n_s}{N^2 - 1}) \) \hspace{1cm} (12)

Modular Ratio \( n_s = \frac{E_c}{E_s} \) \hspace{1cm} (13)

\( E_c \) and \( E_s \) are the elastic moduli of stone column and soft soil respectively.

\[ \xi = \frac{(1+\mu_c)(1-2\mu_s)(1-\mu_s)}{(1+\mu_s)(1-2\mu_c)(1-\mu_c)} \] \hspace{1cm} (14)

\( \mu_c \) and \( \mu_s \) are the elastic moduli of stone column and soft soil respectively.

### 3 DETERMINISTIC ANALYSIS

The diameter ratio \( (N) \) of stone columns is considered in the range of 2-6, (Mitchell, 1981). 6m deep stone columns are considered with spacing (S) varying from 1m - 4m. Table 1 summarises the different cases considered in the present study. In the present study, the target safe superstructure load is considered as 200kN, 300kN and 400 kN (Mitchell, 1981). The target degree of consolidation \( (U_{target}) \) is considered is 85% in a time frame of 0.5 and 1 year.

\[ FS (bearing) = \frac{Q_{allowable}}{Q_{superstructure}}; FS (consolidation) = \frac{U_{achieved}}{U_{target}} \]

<table>
<thead>
<tr>
<th>Case</th>
<th>( S/d_c )</th>
<th>( S (m) )</th>
<th>( d_c (m) )</th>
<th>( D_e = 1.05S )</th>
<th>( N = D_e/d_c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>2.38</td>
<td>1.0</td>
<td>0.42</td>
<td>1.05</td>
<td>2.5</td>
</tr>
<tr>
<td>II</td>
<td>3.33</td>
<td>1.5</td>
<td>0.45</td>
<td>1.58</td>
<td>3.5</td>
</tr>
<tr>
<td>III</td>
<td>4.29</td>
<td>2.0</td>
<td>0.47</td>
<td>2.10</td>
<td>4.5</td>
</tr>
<tr>
<td>IV</td>
<td>5.55</td>
<td>2.5</td>
<td>0.45</td>
<td>2.63</td>
<td>5.5</td>
</tr>
<tr>
<td>V</td>
<td>4.54</td>
<td>3.0</td>
<td>0.66</td>
<td>3.15</td>
<td>4.5</td>
</tr>
<tr>
<td>VI</td>
<td>3.33</td>
<td>3.5</td>
<td>1.05</td>
<td>3.68</td>
<td>3.5</td>
</tr>
<tr>
<td>VII</td>
<td>2.38</td>
<td>4.0</td>
<td>1.68</td>
<td>4.20</td>
<td>2.5</td>
</tr>
</tbody>
</table>

The mean, coefficient of variation (COV) and statistical distribution of the geotechnical random variables are summarized in Table 2.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Mean</th>
<th>COV (%)</th>
<th>Distribution</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>( c_r ) (kN/m2)</td>
<td>25</td>
<td>20-50</td>
<td>Log-Normal</td>
<td>Duncan (2000)</td>
</tr>
<tr>
<td>( \gamma_s ) (kN/m3)</td>
<td>20</td>
<td>7</td>
<td>Gaussian</td>
<td>Mitchell (1981)</td>
</tr>
<tr>
<td>( \phi_s ) (°)</td>
<td>38</td>
<td>5-20</td>
<td>Log-Normal</td>
<td>Zhou et al. (1999)</td>
</tr>
<tr>
<td>( c_s ) (m2/yr)</td>
<td>2</td>
<td>10-90</td>
<td>Log-Normal</td>
<td>Alonso and Jimenez (2011)</td>
</tr>
<tr>
<td>( E_s ) (kN/m2)</td>
<td>300</td>
<td>20-50</td>
<td>Log-Normal</td>
<td>Alonso and Jimenez (2011)</td>
</tr>
<tr>
<td>( E_c ) (kN/m2)</td>
<td>30000</td>
<td>30</td>
<td>Log-Normal</td>
<td></td>
</tr>
</tbody>
</table>
FS obtained by deterministic analysis corresponding to different target safe loads and target degrees of consolidation show that FS against bearing capacity increases with increase in spacing and diameter ratio. The FS is found to be minimum for a spacing of 1m and diameter ratio of 2.5. However, the target degree of consolidation is not achieved within a target period of time if the spacing and diameter ratio of the stone columns increase.

4 PROBABILISTIC ANALYSIS

$P_f$ is calculated by Monte Carlo Simulation in commercially available software Matlab R2015a by generating 50,000 random data points.

4.1 Sensitivity Analysis

Sensitivity analysis of different geotechnical random variables is carried out on different failure modes by $F$-test method in Matlab R2015a. Sensitivity analysis shows that cohesion of soil ($c_s$) is the major parameter affecting $P_f$, followed by internal angle of friction of stone column ($\phi_r$).

4.2 Effect of variation of $\phi_r$

From Fig. 1, it is observed that when $S = 1m$ and $N = 2.5$, $P_f$ is above the acceptable limit for any variation of $\phi_r$. With increase in $S$ and $D_e$, $P_f$ decreases. For the assumed mean values of geotechnical random variables, the stone column can sustain a maximum safe load of 200 kN, considering any variation of the random variables and any arrangement of the stone columns.

![Fig.1. $P_f$ with variations of $\phi_r$](image)

4.3 Effect of variation of $c_s$ and $E_s$

The cohesion of soil ($c_s$) affects the bearing capacity as well as consolidation of a stone column improved ground. Variation of $c_s$ from 20% to 50% has no effect on the consolidation settlement when $S < 1.5m$ and $N < 3.5$ for 85% target degree of consolidation in 3 months. If the time frame is extended to 6 months, there will be no effect on consolidation for stone columns having $S < 2m$ and $N < 4.5$. However, beyond a time span of 1 year, the target degree of consolidation tends to be achieved for all variations of $c_s$ and for any spacing and diameter ratio.

![Fig.2. $P_f$ for different variations of $c_s$](image)

4.4 Effect of variation of $c_r$

The effect of variation of coefficient of radial consolidation ($c_r$) has a significant effect on $P_f$ of stone columns against consolidation settlement. Two extreme cases (I and VII) are shown in Fig. 4. It may be observed from Fig. 3 that, unlike bearing capacity, $P_f$ increases for higher values of $S$ and $N$.

![Fig.3. $P_f$ with variations of $c_r$](image)
4.5 Combined Probability of Failure

Table 4a. Design Guidelines for $t = 6$ months

<table>
<thead>
<tr>
<th>$COV$ of $c_r$ (%)</th>
<th>$U_r = 85%$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$20$</td>
</tr>
<tr>
<td>$10$</td>
<td>$S = 1.5 - 2m$, $N = 3.5 - 4.5$</td>
</tr>
<tr>
<td>$20$</td>
<td>$S = 1.5m$, $N = 3.5$</td>
</tr>
<tr>
<td>$30$</td>
<td>$S = 1.5m$, $N = 3.5$</td>
</tr>
<tr>
<td>$40$</td>
<td>$S = 1.5m$, $N = 3.5$</td>
</tr>
<tr>
<td>$50$</td>
<td>$S = 1.5m$, $N = 3.5$</td>
</tr>
<tr>
<td>$60$</td>
<td>$S = 1.5m$, $N = 3.5$</td>
</tr>
<tr>
<td>$70$</td>
<td>$S = 1.5m$, $N = 3.5$</td>
</tr>
<tr>
<td>$80$</td>
<td>$S = 1.5m$, $N = 3.5$</td>
</tr>
<tr>
<td>$90$</td>
<td>$S = 1.5m$, $N = 3.5$</td>
</tr>
</tbody>
</table>

$P_f (combined) = P_f (bearing \cup \text{consolidation})$
$= P_f (bearing) + P_f (cons) - P_f (\text{bearing} \cap \text{cons})$
$= P_f (\text{bearing}) + P_f (\text{cons})$ \quad \text{[\because \text{events are independent]}

5 CONCLUSIONS

In the present study, the effect of variation of seven geotechnical random variables on bearing and consolidation of stone column improved ground are studied. It is observed that $\phi_r$ and $c_r$ have maximum effect on bearing capacity of stone column improved ground, while $c_r$ plays an important role in consolidation. Design guidelines for spacing and diameter ratio are provided for different target degrees of consolidation in varying time frames.

References


