The Effect of Geometric Parameters on the Strength of Stone Columns

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Abstract-Many geotechnical sites are unsuitable for construction due to their low bearing capacity. In the present study, stone column technique has been analyzed for the ground improvement of soft clayey soil. The change in bearing capacity of stone columns with variation in static parameters has been estimated using Indian Standard Code 15284 (IS Code) - 2003, Bouassida's method (1994), and Afshar's and Ghazavi's method (2014). From the analytical solution of the expression by the IS Code method for bearing capacity of the stone column, it is found that with the increase in diameter of the column, the bearing capacity of the stone column increases. Comparison of the results from the three methods has been conducted and it was found that values obtained from IS Code are very close to those obtained by the other two analytical methods. Also, the critical interpretation of the results shows that the IS Code gives safer design values for a wide range of the static parameters. The results of the IS Code were compared with the experimental findings to evaluate the ability of the method to design the actual load carrying capacity of the stone column.

Keywords-ground improvement; clay; bearing capacity; reinforced soil

I. INTRODUCTION

The stone column is one of the most important techniques used for improving ground quality. The construction technique for stone column comes under vibro - replacement. It increases the bearing capacity of the ground to remarkable extent and also reduces the post construction settlement of weak soils [1–11]. The first use of stone columns was done in Europe in 1834 [12]. Stone columns act as reinforcement and vertical drains for the soft clayey soils. They increase the bearing capacity of the ground by enhancing the horizontal component of effective stress [13-14]. Drainage function of stone columns is very useful in the mitigation of damages due to liquefaction. Stone columns are constructed by filling cylindrical cavities in soil stratum with granular material that increases the rate of consolidation. Consolidation is highly affected by the compressibility in the smear zone for smaller diameter to spacing (S/D) ratio of the stone columns [15, 16]. The techniques used for installing stone columns in Indian subcontinent are explained in [17]. The authors concluded that stone columns can be installed by both displacement and non-displacement methods. Due to the reinforcement of soil by highly compacted granular material, the settlement of the soil also decreases [18, 19]. Greater stiffness of stone columns compared to that of the surrounding soil causes a large portion of the vertical load to be transferred to the columns. Therefore, the entire soil below the foundation behaves as a reinforced soil with higher load carrying capacity. A group of stone columns gives better stability than a single stone column of huge diameter [20, 21]. Spacing and diameter of the stone columns are two critical parameters that affect their bearing capacity. Several researchers have studied the deformation pattern of groups of stone columns keeping in view factors like depth and spacing [22, 23].

A lower bound solution for the estimation of the bearing capacity of a foundation resting on reinforced soil using rigorous analytical results of the yield design theory was proposed in [24]. Coulomb's lateral earth pressure theory was used to predict the stone column ultimate bearing capacity in [27]. Researchers regarded an imaginary retaining wall to develop a simple analytical solution for estimating the bearing capacity. They analyzed the effect of parameters such as column diameter, friction angle of the column material, and column spacing on the ultimate bearing capacity of the stone column [24-29]. The present study deals in finding the optimum spacing of the stone columns when they are provided in group to achieve maximum bearing capacity. For different values of diameter and spacing of the columns, bearing capacity has been calculated using IS 15284 Part-I [30], by varying the angle of internal friction of granular column material. The estimated values of bearing capacities of the reinforced soil from IS Code method have been compared with the bearing capacity values obtained in [24] and [27] and finally conclusions have been drawn regarding the effect of these parameters on the ultimate bearing capacity of a stone column.

II. METHODOLOGY

The major materials used in the analysis of stone columns are clay (soft soil) and aggregates (stones). The range of physical parameters used in this study for the prediction of the bearing capacity of the stone columns are shown in Table I.

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TABLE I. PARAMETERS USED IN THE ANALYSISS

Parameter	Range	Reference
Diameter, D	0.5m –1.5m	[16]
Spacing, S	$2D$ – $3D$	[2]
Angle of internal friction, φ	35° – 45°	[20]
Critical length	$3D$ – $5D$	[15]
	$2D$	[24]

A. Bearing Capacity Using the IS Code Method

IS:15284 Part I [30] is a simple analytical method for calculating the ultimate bearing capacity of a stone column which uses Coulomb's lateral earth pressure theory.

1) Capacity Based on the Bulging of the Column

Considering that the foundation soil is at failure when stressed horizontally due to the bulging of the stone column, the limiting (yield) axial stress in the column is given by the sum of the following:

$$\sigma_v = \sigma_{rl} K_{pcol}$$

$$\sigma_v = (\sigma_{ro} + 4C_u)\, K_{pcol} \quad (1)$$

where σ_v is the limiting axial stress in the column when it approaches shear failure due to bulging, σ_{rl} is the limiting radial stress, which is equal to σ_{ro} + $4C_u$, C_u is the undisturbed undrained shear strength of the clay surrounding the column, and σ_{ro} is the initial effective radial stress = $K_o\,\sigma_{vo}$, where K_o is the average coefficient of lateral earth pressure for clays equal to 0.6, K_o is the average initial effective vertical stress considering an average bulge depth twice as the diameter, i.e. $\sigma_{vo} = \gamma\ (2D)$, γ is the effective unit weight of soil within the influence zone, and $K_{pcol} = \tan^2(45° + \frac{\Phi}{2})$, where φ_c is the angle of internal friction of the granular column material. The safe load on column alone is given by:

$$Q_1 = \frac{\sigma_v\ x\ \frac{\pi}{4}D^2}{2} \quad (2)$$

where $A_c = \frac{\pi}{4} D^2$ is the cross-sectional area of stone column and 2 is the factor of safety.

2) Surcharge Effect

Initially, the surcharge load is carried completely by the rigid column. As the column dilates, some load is shared by the intervening soil. Consolidation of soil under this load results in an increase in its strength which provides additional lateral resistance against bulging. The increase in capacity of the column due to surcharge may be computed in terms of increase in mean radial stress of the soil as follows:

$$\Delta\sigma_{ro} = \frac{q_{safe}}{3}(1 + 2K_o) \quad (3)$$

where $\Delta\sigma_{ro}$ is the increase in mean radial stress due to surcharge and q_{safe} is the safe bearing pressure of soil with a factor of safety of 2.5:

$$q_{safe} = \frac{C_u N_c}{2.5}$$

So, the increase in the safe load of column, Q_2 is given by:

$$Q_2 = \frac{K_{pcol}\,\Delta\sigma_{ro} A_s}{2} \quad (4)$$

3) Bearing Support Provided by the Intervening Soil

This component consists of the intrinsic capacity of the virgin soil to support a vertical load which may be computed as follows:

The effective area of stone column including the intervening soil for triangular pattern is equal to $0.866S^2$. The area of intervening soil for each column, A_g *is* given by:

$$A_g = 0.866S^2 - \frac{\pi D^2}{4} \quad (5)$$

The safe load taken by the intervening soil is:

$$Q_3 = q_{safe} A_g \quad (6)$$

Therefore, the overall safe load on each column and its tributary soil is:

$$Q_{safe} = Q_1 + Q_2 + Q_3 \quad (7)$$

B. Bearing Capacity by Bouassida's [24] Method

The Bouassida's formula [24] for the estimation of bearing capacity is:

$$\frac{Q_{cc}}{A} = 4C + 2\eta\ [C(K_p - 2) + C\sqrt{K_p} \quad (8)$$

where Q_{cc} is the lower-bound estimate for the foundation bearing capacity, C is the cohesion of the reinforcing material, η the proportion of reinforcement, K_p is the coefficient of passive stress of the reinforcing material.

C. Bearing Capacity by Afshar's and Ghazavi's [27] Design Method

To calculate the ultimate bearing capacity of stone columns, an imaginary retaining wall is assumed that extends from the edge of the columns in the vertical direction. The center to center spacing of the columns is S and the entire system is analyzed using plane strain condition by converting the stone columns into equal sized vertical strip walls. The lateral distance between the walls is estimated to be 0.866 times S. The width W of the continuous strip wall is related to spacing as: $W = \frac{A_s}{S}$, where A_s is the cross section area of the stone column (in the horizontal direction). The ultimate bearing pressure is given by:

$$q_{ult} = C_c\left(\frac{2\cos\frac{\varphi_c}{2}\sqrt{K_{pc_c}}}{\cos\frac{\varphi_s}{2}K_{as}}\right) + \overline{q}\left(\frac{K_{pc}\cos\frac{\varphi_c}{2}}{K_{as}\cos\frac{\varphi_s}{2}}\right) + \frac{1}{2}W\gamma_c\left(\frac{K_{pc}\cos\frac{\varphi_c}{2}}{K_{as}\cos\frac{\varphi_s}{2}} - \frac{\gamma_s}{\gamma_c}\right)\tan\eta_a \quad (9)$$

where C_c is the cohesion of the soil, φ_c is the angle of internal friction, K_{pc} is the lateral passive earth pressure coefficient, K_{as} is the lateral active earth pressure coefficient, $\overline{q}$ is the surcharge pressure on passive region surface, γ_c is the unit weight of the column material, γ_s is the unit weight of the soil material, and η_a is the angle of active wedge with horizontal direction.

III. RESULTS

A. Parametric Study Using the IS Code Method

The results of IS Code method [30] have been obtained for soft clays of different area ratios. The ratio of center to center spacing between the columns and the diameter of the column are taken as *S/D* = 1.5, *S/D* = 2 and *S/D* =3. The effect of the angle of internal friction of the stone column material (φ), unit weight (γ), and soil cohesion (C_u) on the bearing capacity of stone column is studied. The bearing capacity obtained by varying the above-mentioned parameters is presented in Figures 1-6. To study the effect of variation of φ on the bearing capacity of the stone columns, the value of bearing capacity is calculated for *S/D* ratio equal to 2, 3, and 1.5 for 2 sets with diameters: *D* = 0.5 and *D* = 1.5. It was observed that bearing capacity increases with decrease in *S/D* ratio and diameter of the stone column plays an important role in its bearing capacity. When the friction angle varied from 35° to 45°, there has been continuous increase in the value of bearing capacity. Also, the percentage change in bearing capacity is 44.80% for *S* = 1.5 *D*, 34.57% for *S* = 2*D*, and approximately, 21% for *S*= 3*D* for D = 0.5m. Similarly, for *D* = 1.5 m, when friction angle varied from 35° to 45°, the percentage change in bearing capacity is 46.42% for *S* = 1.5 *D*, 36.88% for *S* = 2*D* and 23.23% for *S*= 3*D*. Figures 1 and 2 show the variation of bearing capacity (*q*) with the angle of internal friction (φ), at D = 0.5m and 1.5m respectively. It is observed that, bearing capacity shows direct relation with angle of internal friction.

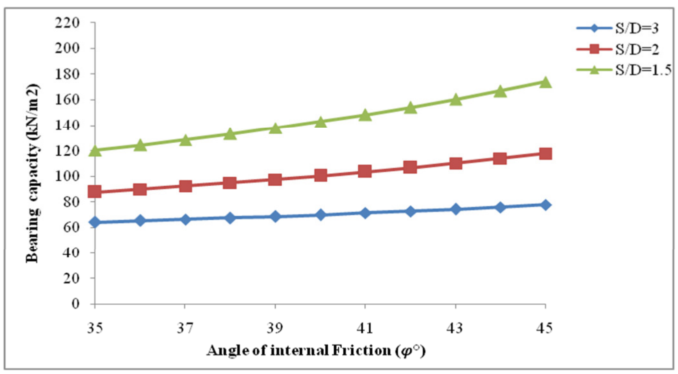

Fig. 1. Variation of bearing capacity with angle of internal friction φ (*D*=0.5m).

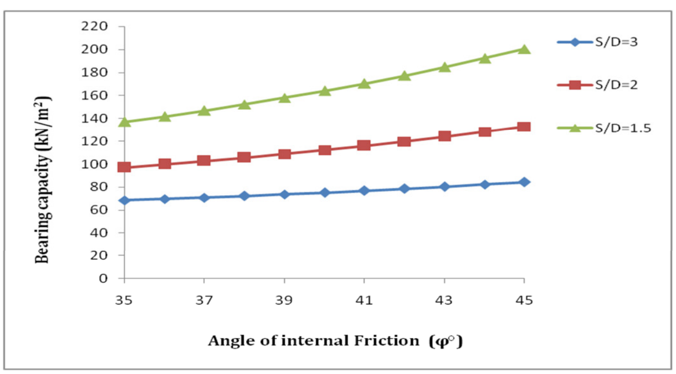

Fig. 2. Variation of bearing capacity with angle of internal friction φ (*D*=1.5m).

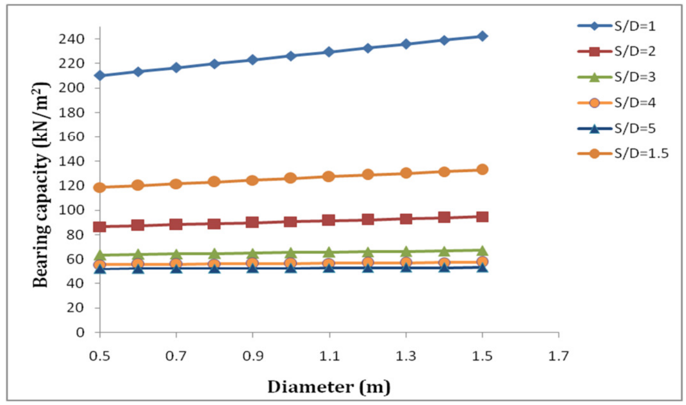

Fig. 3. Variation of bearing capacity *q* with diameter *D*.

The second geometric parameter responsible for affecting the bearing capacity of the stone column is the column diameter. To study the effect of diameter (*D*) on the bearing capacity (*q*) of the stone column, the diameter was varied from 0.5 to 1.5m for 6 sets of *S*/*D* ratios = 1, 1.5, 2, 3, 4 and 5. It can be clearly seen from Figure 3 that as the S/D ratio increases, the bearing capacity of the stone column decreases. When the diameter increases from 0.5 to 1.5m, the percentage change in bearing capacity is 15.26% for *S* = 1*D*, 12.01% for *S* = 1.5*D*, 9.27% for *S* = 2*D*, 5.54% for *S* = 3*D*, 3.55% for *S* = 4*D*, and 2.42% for *S* = 5*D*. It is observed that when spacing is less than two times the diameter of the column, there is higher increase in values of bearing capacity.

The third parameter whose effect is studied on the bearing capacity of stone columns is the unit weight of the soil (γ). The change in bearing capacity with different values of γ is studied with two sets of diameter, *D* = 0.5 and 1.5m at center to center spacing, *S* = 1.5D, 2*D*, and 3*D*. Cohesion (C_u) of the soft soil and the angle of internal friction of the column material (φ) are taken as 20kN/m^2 and 38° respectively. When the values of unit weight vary from 14 to 19kN/m^3 at *D* = 0.5m, the percentage change in bearing capacity is 1.95% for *S* = 1.5*D*, 1.53% for *S* = 2*D*, and 0.94% for *S*= 3*D*. Similarly, when the values of unit weight increase from 14 to 19kN/m^3 at *D* = 1.5m, the percentage change in bearing capacity is 5.27% for *S* = 1.5*D*, 4.23% for *S* = 2*D*, and 2.71% for *S* = 3*D*. Therefore, the conclusion is that while designing the stone column, the unit weight of the native soil has very less significance.

B. Comparison between the IS Code and Bouassida's Method

The IS Code method basically depends upon diameter, angle of internal friction of column material, and the unit density of the native soil. The range of these parameters for the study is taken as 0.5m to 1.5m, 35^o to 45^o, 14kN/m^3 to 19kN/m^3 respectively. A comparison between the predictions made by the IS Code method and Bouassida's method [24] follows.

The IS Code uses the shear strength parameter of stone column and native soil materials for the prediction of bearing capacity, whereas the important parameter in [24] is area replacement ratio. From Figure 5, it can be stated that at spacing ≥ 2*D*, the IS Code method gives conservative values of bearing capacity in comparison with Bouassida's method [24]. The difference in bearing capacity values by IS Code method and Bouassida's method increases as the spacing of the columns increases. It was found that the bearing capacity value by IS Code method is higher than the value obtained through Bouassida's method for $S = 1.5D$ (Figure 5).

The percentage deviation in the values of bearing capacity by using IS Code method and Bouassida's method was calculated for every 10% increment in design parameters. Figure 4 shows that for $S = 2D$ and $S = 3D$, the IS Code method gives lower value of bearing capacity for every 10% increase in the design parameters, i.e. D, φ, and γ.

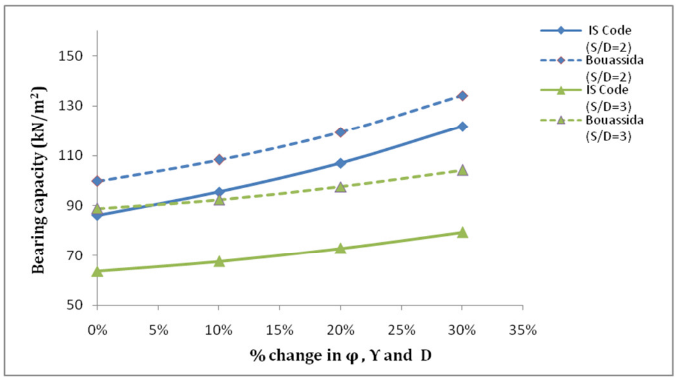

Fig. 4. Comparison of the bearing capacity by IS Code and Bouassida's method.

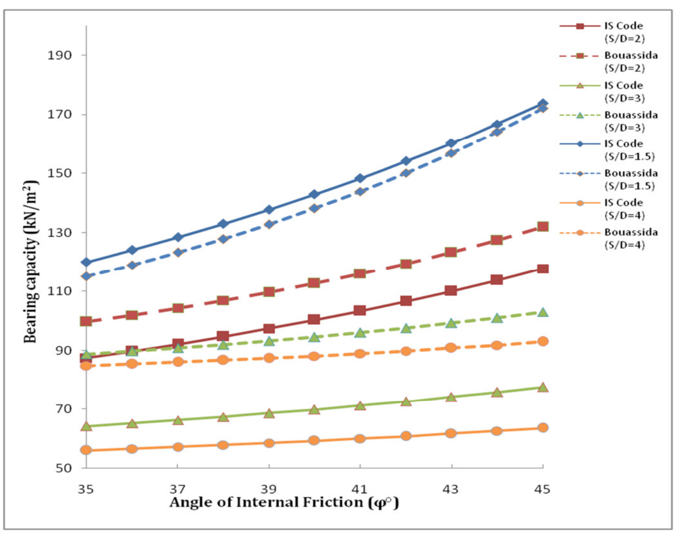

Fig. 5. Comparison of bearing capacity vs φ by IS Code and Bouassida's method.

C. Comparison between IS Code Method and Afshar's and Ghazavi's Design Method [27]

The analytical solution given by Afshar and Ghazavi [27] was used for the same soil conditions as used in the IS Code method and the bearing capacity has been calculated for $\varphi = 35°$, $\gamma = 14\text{kN/m}^3$, and $D = 0.5\text{m}$. The values of bearing capacity were calculated for two sets of spacing and diameter ratio, i.e. $S/D = 2$ and 3. Figure 6 shows the graph comparing bearing capacity obtained by the IS Code method [30] and the Afshar – Ghazavi method. It is clearly visible that for $S = 2D$ and $S = 3D$, the IS Code method gives lower values of bearing capacity than the Afshar -Ghazavi method.

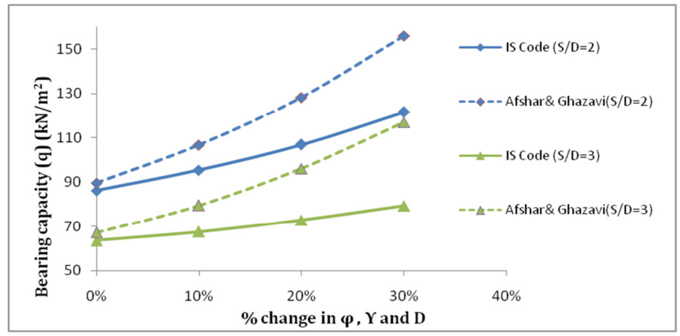

Fig. 6. Comparison of bearing capacity by the IS Code method Afshar - Ghazavi method.

D. Result Comparison of the IS Code Method and Experimental Findings

The ultimate bearing capacity of stone columns calculated analytically is compared with the experimental results observed from model tests by [31, 19].

The bearing capacity of soft clay reinforced with a single stone column was investigated using small-scale physical model test in [31]. The test tank used in their experiment had 650mm diameter. A stone column having a diameter of 25mm and a length of 225mm was constructed at the center of the clay bed. The undrained shear strength of the clay was 20kN/m^2 and the internal friction angle (φ) of the stone column material was 38°. The ultimate load of the single load column was found to be 450N. Implementing the soil parameters in IS Code method, the ultimate load calculated from analytical method was about 420N, which is quite close to the result obtained in [31].

A large-scale test on stone columns was conducted in [20]. The stone columns were installed in triangular pattern with $S = 4\text{m}$, $D = 0.9$ m, and length $L = 6.6\text{m}$. The ultimate bearing capacity of native soil was 34kN/m^2 and field load tests were carried out on stone columns using real Reinforced Concrete (RC) footing. Considering the average cohesion of the soft soil, $C_u = 12\text{kN/m}^2$, Maurya's model test [20] gave an ultimate load of about 800kN. For the same soil and load conditions the IS Code method gave stone column ultimate bearing capacity $q = 36\text{kN/m}^2$ and ultimate load of about 770kN, therefore, both results are close to each other.

IV. Discussion

After the analysis of the stone columns from the three considered analytical methods of stone column design, it has been found that the friction angle φ of the stone column material increases the interlocking between particles, thus affecting the strength of columns. It was observed that bearing capacity increases with decrease in S/D ratio and the diameter of the stone column plays an important role in its bearing capacity. IS Code Method [30] gives conservative values of bearing capacity compared to Bouassida's method [24], whereas the Afsar - Ghazavi method [27] gives the highest values.

V. CONCLUSIONS

Based on the above results, the following conclusions can be drawn:

- The bearing capacity of a stone column mainly depends on the angle of internal friction of column material (φ), the diameter of the stone column (D), the length of the stone column (L), the spacing between the stone columns (S), the unit density of the surrounding soil (γ), and the undrained cohesion (Cu) of the surrounding soft soil.
- Upon varying the first geometrical parameter, i.e the spacing of stone column, it was seen that stone column capacity decreases by increasing the center to center spacing to 3D. Beyond this value, the decrease of the stone column capacity is negligible. If the spacing between the stone columns is less than twice the diameter, then the design of the stone column is not feasible from the construction point of view. Therefore, spacing greater than 2D is suggested.
- The analytical result suggests that the bearing capacity of the stone column increases with the increase in the friction angle of the stone material and the diameter of the column due to the high interlocking between the stone particles.
- It was found that the variation of bearing capacity with respect to diameter is more with smaller values of S/D ratio.
- The variation of stone column bearing capacity with the unit weight of the soil shows a nearly constant graph, which means that the stone column bearing capacity remains almost the same with variation in unit weight.
- The IS Code method gives conservative results for bearing capacity when compared to Bouassida's design method for $S/D = 2$ and above. Likewise, it is found that for $S = 2D$ and 3D, the IS Code method gives lower values of bearing capacity than Afshar's and Ghazavi's method [31].
- The study shows that among the 3 design methods, lower bearing capacity values are obtained from the IS Code method, intermediate values are obtained from Bouassida's method, and the highest values are obtained from Afshar's and Ghazavi's method.
- The values of ultimate bearing capacity of the soil and stone column capacity observed from the model tests in [20, 31] are close to the values obtained from the IS Code method [30].

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