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Reliability Based Performance Evaluation of Stone Column Improved Soft Ground

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***Abstract*—**The present study considers the effect of variation of different geotechnical random variables in the design of stone column-foundation systems for assessing the bearing capacity and consolidation settlement of highly compressible soil. The soil and stone column properties, spacing, diameter and arrangement of stone columns are considered as the random variables. Probability of failure (P_f) is computed for a target degree of consolidation and a target safe load by Monte Carlo Simulation (MCS). The study shows that the variation in coefficient of radial consolidation (c_r) and cohesion of soil (c_s) are two most important factors influencing Pf. If the coefficient of variation (COV) of c_r exceeds 20%, P_f exceeds 0.001, which is unsafe following the guidelines of US Army Corps of Engineers. The bearing capacity also exceeds its safe value for COV of c_s > 30%. It is also observed that as the spacing between the stone column increases, the probability of reaching a target degree of consolidation decreases. Accordingly, design guidelines, considering both consolidation and bearing capacity of improved ground, are proposed for different spacing and diameter of stone columns and geotechnical random variables.

***Keywords*—**Bearing capacity, consolidation, geotechnical random variables, probability of failure, stone columns.

I. Introduction

EVALUATION of the stability of foundations resting on weak soil layers requires prediction of settlement. The provision of stone columns increases shear strength and decreases compressibility of the composite soil consisting of the stone column and the surrounding soil.

The theory of load transfer, estimation of ultimate bearing capacity and prediction of settlement of stone columns was first proposed by Greenwood [1]. Research showed that the maximum radial soil reaction against bulging was one of the major factors for determining ultimate bearing capacity of soil. It was also shown that the vertical movement of stone column was limited to four times the diameter of the column [2]. A mathematical model for consolidation rate was proposed considering the clogging effect [3]. However, most of the reported studies are based on deterministic approach. Since soil is a natural material, its properties are bound to vary from place to place. A Factor of Safety (FS) is applied to design of structures, based on past experience to take into account this natural soil variability. This does not consider the amount of uncertainty associated with the system. For stone column-improved ground radial coefficient of consolidation has the highest influence on the reliability results [4]. The reliability of Priebe's Method is also carried out for estimating settlement of stone columns [5]. A simplified probabilistic method was proposed in which the inherent variability of the coefficient of consolidation of the soil is considered [6]. Probability based design charts were suggested for estimating diameter and spacing for stone column improved ground [7]. A qualitative and quantitative improvement in soft clay by stone columns is carried out using finite element method considering a drained analysis of Mohr-Coulomb failure criteria [8]. A numerical model is proposed to analyse elastic and elasto-plastic behavior of stone-column reinforced foundations and implemented in an axi-symmetric finite element code [9].

From the above literature, it is observed that most of the reliability analysis of soil consolidation via vertical drain is conducted on PVD-improved ground. Limited studies are conducted on stone column-improved ground. The present paper studies the effect of variation of six different geotechnical random variables on bearing capacity and consolidation settlement of stone columns. Probability of failure (P_f) is analysed for two target degrees of consolidation of 85% and 95% and three target safe loads of 200 kN, 300 kN and 400 kN. The analysis is carried out by MCS in commercially available software MATLAB R2015a. Finally design guidelines are proposed for different dimension of stone columns and variations of geotechnical random variables, which may lead to a safe and economic design.

II. Bearing Capacity of Stone Columns

The triangular and square arrangements of stone columns are shown in Figs. 1 (a) and (b). The bearing capacity of stone columns is calculated in accordance with IS 15284 (Part 1): 2003 [10]. The overall bearing capacity of a stone column is obtained by summing up the contribution of

a) Capacity of the column resulting from the resistance of the soil surrounding it against bulging.
b) Capacity due to the resistance offered by the soil due to the surcharge effect.
c) Capacity due to the bearing support given by intervening soil between the columns.

For soils having cohesion, c and angle of internal friction, φ, the bearing capacity is determined by Bell's formula which is:

$$\sigma_{rL} = P_p = \gamma z k_P + 2c_u.\sqrt{k_P} \tag{1}$$

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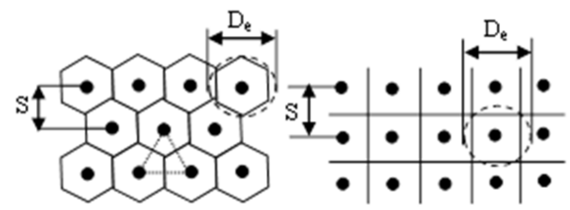
where, P_p = passive pressure, z = average bulge depth = $2d_c$, d_c = diameter of stone column, D_e= equivalent diameter of stone column, which is 1.05 and 1.13 times the spacing for triangular and square pattern of arrangement of columns respectively. k_p = coefficient of passive pressure and φ_g = angle of internal friction of stone column.



(a) (b)

Fig. 1 (a) Triangular and (b) Square Arrangement of Stone Columns

Limiting axial stress in the column is given by

$$\sigma_v = \sigma_{rL}.K_{pcol} = \sigma_{rL}\left(\frac{1+\sin\phi_c}{1-\sin\phi_c}\right) \tag{2}$$

where, φ_c = angle of internal friction of granular column material. Therefore, safe load on column considering a FS 2, is

$$Q_1 = \left(\frac{\sigma_y.\pi.d_c^{\,2}}{4}\right).\frac{1}{2}$$

Safe bearing pressure of soil with a FS = 2.5, is

$$q_{safe} = \left(\frac{C_u.N_c}{2.5}\right)$$

Considering the surcharge effect, the increase in the mean radial stress due to surcharge,

$$\Delta\sigma_{ro} = q_{safe}\left(\frac{1+2.K_p}{3}\right) \tag{3}$$

By considering a FS of 2, the increase in safe load of column,

$$Q_2 = \left(\frac{K_{pcol}.\Delta\sigma_{ro}.\pi.d_c^{\,2}}{4}\right).\frac{1}{2} \tag{4}$$

Considering bearing support provided by the intervening soil, the area of the intervening soil is $A_g = 0.866\left(S^2\right) - \left(\frac{\pi.d_c^{\,2}}{4}\right)$ for triangular arrangement and $A_g = S^2 - \left(\frac{\pi.d_c^{\,2}}{4}\right)$ for square arrangement. Safe load that can be taken by the intervening soil is

$$Q_3 = q_{safe}.A_g \tag{5}$$

Therefore, the overall safe bearing capacity of each stone column is obtained by

$$Q_{allowable} = Q_1 + Q_2 + Q_3 \tag{6}$$

III. Consolidation of Stone Columns

In the present study, the radial rate of consolidation (U_r) is considered for analysis and is calculated as) [11].

$$U_r^{'} = 1 - \left(\frac{8}{\pi^2}\exp^{\left(\frac{-8T_r^{'}}{F(N)}\right)}\right) \tag{7}$$

where

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

Diameter Ratio (N) is

$$N = \frac{D_e}{d_c},$$

Modified Time Factor ($T_r^{'}$) is

$$T_r^{'} = \frac{C_r^{'} * t}{D_e^2}$$

Modified Coefficient of Radial Consolidation ($C_r^{'}$)

$$C_r^{'} = C_r\left(1 + \frac{n_s}{N^2-1}\right)$$

Modular Ratio (n_s)

$$n_s = \xi\frac{E_c}{E_s}$$

E_c and E_s are moduli of elasticity of stone column and soil respectively.

$$\xi = \frac{(1+\mu_s)(1-2\mu_s)(1-\mu_c)}{(1+\mu_c)(1-2\mu_c)(1-\mu_s)}$$

μ_c and μ_s are Poisson's ratio of stone column and soil respectively.

IV. Deterministic Analysis

The diameter ratio (N) of stone columns is considered in the range of 2-6, depending upon the arrangement of stone columns (square or triangular) [12]. A constant depth of 6 m is considered with spacing (S) varying from 1 m to 4 m. Tables I and II summarise the different cases considered depending on the values of N and S for triangular and square pattern of arrangement respectively.

TABLE I
CASES FOR TRIANGULAR PATTERN

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

TABLE II
CASES FOR SQUARE PATTERN

Case	S/d_c	S (m)	d_c (m)	$D_e = 1.13S$	$N = D_e/d_c$
I	2.22	1.0	0.45	1.130	2.5
II	3.13	1.5	0.48	1.695	3.5
III	4.00	2.0	0.50	2.260	4.5
IV	4.90	2.5	0.51	2.825	5.5
V	4.00	3.0	0.75	3.390	4.5
VI	3.10	3.5	1.13	3.955	3.5
VII	2.21	4.0	1.81	4.520	2.5

TABLE III
STATISTICS OF INPUT PARAMETERS

Variables	Mean μ	*COV* (%)	Distribution
φ_s (°)	15	5-20	Log-Normal [13]
c_s (kN/m^2)	25	20-50	Log-Normal [14]
γ_s (kN/m^3)	20	7	Gaussian [15]
φ_c (°)	38	5-20	Log-Normal [12]
c_r(m^2/yr)	2	10-90	Log-Normal [12]
E_s(kN/m^2)	300c_s	20-50	Log-Normal [4]
E_c(kN/m^2)	30000	30	Log-Normal [4]
μ_s	0.4	-	- [16]
μ_c	0.2	-	- [16]

According to Mitchell [12], the safe superstructure load ($Q_{superstructure}$) for stone columns in soft to medium stiff clays lies in the range of 200 – 300 kN. In the present study, three different target safe superstructure loads are considered (200, 300 and 400 kN). Two target degrees of consolidation (U_{target}) considered are 85% and 95% in a time frame of 3, 6, 9 and 12 months. The factors of safety against bearing and consolidation are defined as:

$$FS\,(bearing) = \frac{Q_{allowable}}{Q_{\text{superstructure}}} \text{ and } FS\,(consolidation) = \frac{U_{\text{achieved}}\,(=U_r')}{U_{\text{target}}}$$

The mean values of the geotechnical random variables, their COV and statistical distribution are considered from past research works, in absence of any site data, and are summarized in Table III. FS obtained by deterministic analysis for different cases of triangular and square arrangements corresponding to different target safe loads and target degrees of consolidation are summarized in Tables IV and V. It can be seen from Table IV that FS against bearing capacity increases with increase in spacing and diameter ratio. Minimum FS is observed for a spacing of 1 m and diameter ratio of 2.5. However, it is difficult to achieve the target degree of consolidation within a target period of time with increase in the spacing and diameter ratio of the stone columns.

TABLE IV
DETERMINISTIC FACTORS OF SAFETY FOR BEARING CAPACITY

Cases	*FS* for Triangular Arrangement			*FS* for Square Arrangement		
	Q=200 kN	*Q*=300 kN	*Q*=400 kN	*Q*=200 kN	*Q*=300 kN	*Q*=400 kN
I	2.22	1.48	1.11	2.57	1.71	1.29
II	4.09	2.72	2.04	4.73	3.15	2.37
III	6.59	4.39	3.29	7.63	5.09	3.82
IV	9.78	6.52	4.89	11.31	7.54	5.66
V	14.98	9.98	7.49	17.34	11.56	8.67
VI	22.99	15.33	11.49	26.69	17.79	13.34
VII	39.46	26.31	19.73	46.10	30.73	23.05

TABLE V
DETERMINISTIC FACTORS OF SAFETY FOR CONSOLIDATION SETTLEMENT

Cases	U_{target} = 85%				U_{target} = 95%			
	t=0.25	0.5	0.75	1.0	*t*=0.25	0.5	0.75	1.0
I	1.17	1.17	1.17	1.17	1.05	1.17	1.17	1.17
II	1.12	1.17	1.17	1.17	1.01	1.05	1.05	1.05
III	0.88	1.08	1.14	1.16	0.79	0.97	1.02	1.04
IV	0.65	0.89	1.02	1.09	0.58	0.79	0.91	0.97
V	0.61	0.84	0.98	1.06	0.54	0.75	0.87	0.94
VI	0.62	0.86	0.99	1.07	0.56	0.76	0.89	0.95
VII	0.76	0.99	1.09	1.14	0.68	0.89	0.98	1.02

V. PROBABILISTIC ANALYSIS

A. Probability of Failure

The random variables φ_s, γ_s, c_s, φ_c and c_r (Table III) are considered statistically independent of each other. For the probabilistic analysis of the stone column improved ground, a performance function is defined as $g_i(x) = (FS)_i - 1$, where i denotes the two different failure modes. Failure occurs when $g_i(x) < 0$. In the present study, the limit equilibrium equations are coded in commercially available software MATLAB R2015a and P_f is obtained by MCS by generating 50,000 data points.

Case 1: Effect of Variation of φ_c

P_f for bearing capacity failure obtained for different spacing and diameter ratio of stone columns, corresponding to different variations of φ_c, are shown in Fig. 2 (a). Since φ_c does not directly affect the consolidation settlement, hence this section only deals with P_f for bearing capacity failure. From the figure, it is quite evident that when S = 1 m and N = 2.5, the P_f is above the acceptable limit for any variation of φ_c. Fig. 2 (b) shows the variations of P_f for the three different target loads for S = 1 m and N = 2.5. It may be concluded that for the assumed mean values of the 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.

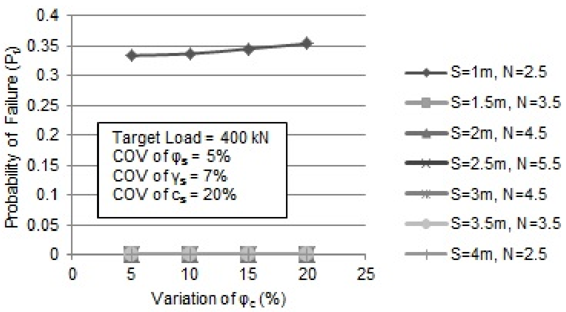


Fig. 2 (a) P_f for different variations of φ_c for different spacing and diameter ratios

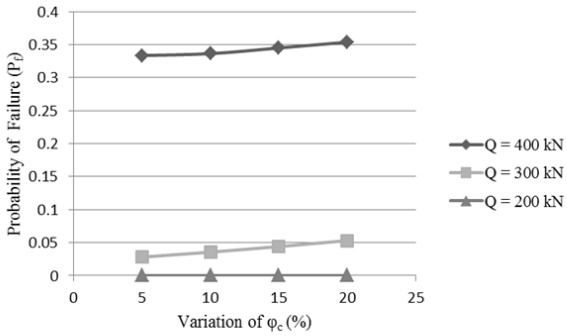


Fig. 2 (b) P_f for different variations of φ_c for different target loads

Case 2: Effect of Variation of φ_s

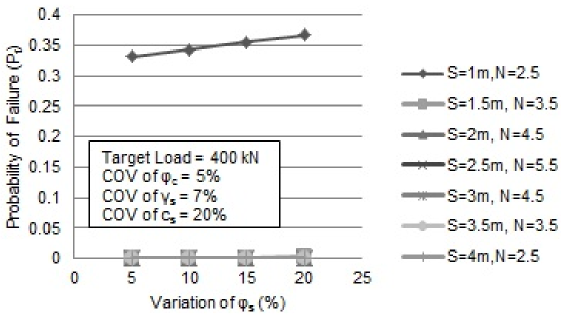


Fig. 3 P_f for different variations of φ_s for different spacing and diameter ratios

Secondly, the effect of variation of internal angle of friction of soil (φ_s) on bearing capacity failure is analyzed (Fig. 3). It is noted from the figure that the P_f shows a similar variation as in Case 1. This shows that φ_s and φ_c have almost similar effect on the bearing capacity of a stone column improved ground.

Case 3: Effect of Variation of c_s

The cohesion of soil (c_s) affects the bearing capacity as well as the consolidation settlement characteristics of a stone column improved ground. Fig. 4 demonstrates the P_f for different spacing and diameter ratios corresponding to different variations on c_s. It can be inferred from the figure that when *COV* of c_s exceeds 20%, the P_f crosses the acceptable limits when the spacing and diameter ratio of stone columns are less than 1.5 m and 3.5 respectively.

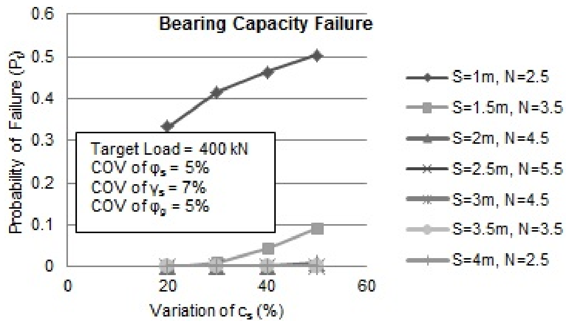


Fig. 4 P_f for different variations of c_s for different spacing and diameter ratios

The effect on *FS* due to variation of c_s and in consequence, E_s, on consolidation settlement of stone column improved ground is relatively small. Variation of c_s from 20% to 50% has no effect on the consolidation settlement when spacing and diameter ratio of stone columns are less than 1.5 m and 3.5 respectively 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 spacing and diameter ratio less than 2 m and 4.5 respectively. For 85% consolidation to be achieved in 9 months, the same may be considered as 2.5 m and 5.5 respectively. However, it may be observed that the target degree of consolidation can be achieved for any variation of c_s and for all spacing and diameter ratios when the time span exceeds 1 year. For a target degree of consolidation of 95% and time frame of 3 months, spacing and diameter ratio of stone columns should be less than 1 m and 2.5 respectively, while for 6 months, it should be restricted to 1.5 m and 3.5 respectively. For a target time between 6 and 12 months, the spacing and diameter ratio should be limited to 2 m and 4.5 respectively.

Case 4: Effect of Variation of c_r

The variation of coefficient of radial consolidation (c_r) has a significant effect on the probability of failure of the stone columns against consolidation settlement. Figs. 5 (a) and (b) show the P_f against consolidation settlement for variation of c_r, time, spacing and diameter ratio of stone columns corresponding to 85% and 95% target degree of consolidation. It may be observed from Fig. 5 that, unlike bearing capacity, P_f increases for higher values of spacing and diameter ratios.

From Figs. 5 (a) and (b), it can be inferred that, in order to achieve 85% target degree of consolidation in a time period of 3 months, the spacing and diameter ratio needs to be restricted within 1.5 m and 3.5 respectively. When the target degree of consolidation is 95%; keeping all other conditions same, the spacing and diameter ratio needs to be limited within 1 m and 2.5 respectively. To achieve the target degree of consolidation within 1 year, the spacing and diameter ratio should always be limited to 1.5 m and 3.5, for any values of *COV* of c_r. Only one case is shown in Figs. 5 (a) and (b).

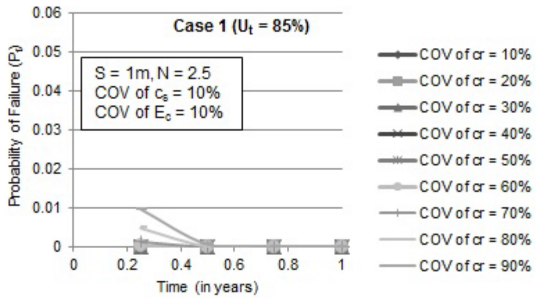


Fig. 5 (a) P_f for different variations of c_r for S = 1 m and N = 2.5

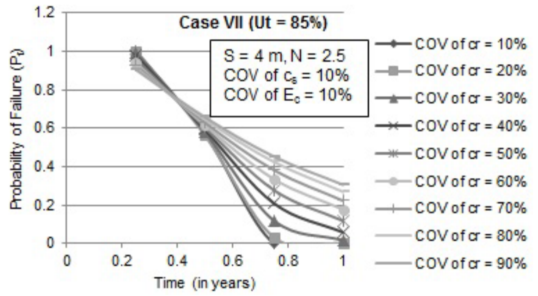


Fig. 5 (b) P_f for different variations of c_r for S = 1 m and N = 2.5

B. Combined Probability of Failure

Considering bearing and consolidation failure as independent events, failure will occur if the stone columns fail either in bearing or consolidation. Mathematically,

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

The design guidelines for 85% and 95% consolidation in a time frame of 6 months are provided in Table VI.

TABLE VI
DESIGN GUIDELINES FOR T = 6 MONTHS

	U_t = 85%				U_t = 95%			
COV	*COV* of c_s				*COV* of c_s			
of c_r	20	30	40	50	20	30	40	50
10	S=1.5 - 2m, N=3.5 – 4.5	S=2m, N=4.5	S=2m, N=4.5		S=1.5m, N=3.5			
20	S=1.5m, N=3.5				S=1.5m, N=3.5			
30	S=1.5m, N=3.5				S=1.5m, N=3.5			
40	S=1.5m, N=3.5				S=1.5m, N=3.5			
50	S=1.5m, N=3.5				S=1.5m, N=3.5			
60	S=1.5m, N=3.5				S=1.5m, N=3.5			
70	S=1.5m, N=3.5							
80								
90								

VI. CONCLUSIONS

In the present study, the effect of variation of geotechnical random variables on bearing and consolidation of stone column improved ground are studied. It is observed that the variation of internal angle of friction of soil (φ_s) and stone column (φ_c) have maximum effect on bearing capacity of stone column improved ground, while for consolidation settlement, the effect of variation of the coefficient of radial consolidation (c_r) is found to be most significant. In order to achieve 85% target degree of consolidation in a time period of 3 months for a target reliability index of β = 3 and *COV* of c_r within 20%, the spacing and diameter ratio needs to be restricted within 1.5 m and 3.5 respectively. Accordingly, design guidelines for spacing and diameter ratio are provided for different target degrees of consolidation in varying time frames.

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