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# Stone Columns and Reinforced Sand Bed for Performance Improvement of Foundations on Soft Clay

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## ABSTRACT

being one of the most erratic soils with very low bearing capacity and high compressibility. Many techniques, such as stone columns and geosynthetic reinforced sand bed, are effective means of performance improvement of foundations on soft clay soil. Although their individual applications have been studied extensively, the combined application of both has remained unexplored. Stone columns develop their load carrying capacity from the circumferential confinement provided by the surrounding soils. In very soft soils, an important problem which should be taken into account for designing stone column is bulging as the circumferential confinement offered by the surrounding soft soil may not be sufficient to develop the required load carrying capacity. Hence a confinement by geosynthetics would yield a better result and prevents squeezing of stones into the surrounding clay. The load carrying capacity is further increased and settlement is decreased with the addition of a sand bed over the stone columns, also this layer of sand is used to let the foundation distribute its load uniformly. In the current research, a series of numerical model tests on an unreinforced sand bed (USB) and a geogrid reinforced sand bed (GRSB) placed over a vertically encased stone column (ESC) floating in soft clay. Three dimensional finite difference numerical models were performed using a finite difference package FLAC3D. In the finite difference analysis, geosynthetics were modeled as an elasto-plastic material

***Keywords***: Soft clay, Ground improvement, Stone column, Geosynthetic, Sand Bed.

## INTRODUCTION

Due to the ever increasing demand for land space because of increased construction activity worldwide, there is an increasing need to improve soft soil grounds which otherwise are unsuitable for adopting the conventional shallow foundations. Using deep foundations, such as pile, to bypass the weak soil is often costly. Ground improvement technique is a potential alternative to mitigate this problem. Amongst the various ground improvement techniques used for improving the in-situ ground conditions, geosynthetics reinforcement and stone column technique are probably the most versatile ones. This is primarily due to their simplicity, ease of construction and overall economy that finds favor with the practicing engineers.

Historically, research studies have been designed to investigate the behavior of ordinary and encased stone column-reinforced clay systems in the laboratory tests and numerical studies that are conducted by (Bergado et al. 1987, El Sawwaf 2007, Elsawy et al. 2009, Black et al. 2011, Ramadan et al., 2015, 2016, Ghazavi et al. 2017 and Ramadan et al. 2018 (a & b)). The concept of using geosynthetics reinforced sand bed has been acknowledged by several researchers (Guido et al. 1989, Latha et. al. 2009, Azzam and Nazir 2010, Laman et. al. 2012, 2014, Das et. al. 2015, 2016 and Infante et. al. 2019). There are very limited experimental investigations or three- dimensional numerical studies to show the combined effect of geogrid reinforced sand bed (GRSB) with encased stone columns (ESC) such as (Thakare and Tanveer 2016, Debnath and Dey 2017, Wu et al. 2019).

The present research main aim is to show the beneficial use of unreinforced or geosynthetic reinforced sand bed over encased stone columns in terms of increasing in bearing capacity and minimizing the settlement. The analysis is carried out using a three dimensional finite difference numerical model FLAC3D and the results of the numerical study conducted for the effect of multilayer geosynthetic-reinforced granular fill over soft soil with encased stone columns on settlement response, bearing capacity and bulging of the stone column were reported.

## NUMERICAL MODEL

Finite difference analyses were carried out by the FLAC3D program to create a three dimensional model of foundation on soft clay soil improved with unreinforced or geosynthetic reinforced sand bed and encased stone columns. This program uses an explicit finite difference technique to solve problems with initial and boundary conditions. By default the model is assumed to be in equilibrium when the maximum unbalanced force ratio (i.e. the ratio between the magnitude of the maximum unbalanced force and the magnitude of the average applied mechanical force within the mesh) falls below 1×10-5. FLAC3D supports various constitutive models and structural elements that are utilized to model various geotechnical and structural materials, such as soil reinforced with geosynthetic. At the bottom boundary of the finite difference mesh, the displacements were set to zero in the z direction. The displacements in the x and y directions were set to zero on the circumferential boundary of the soft soil zone.

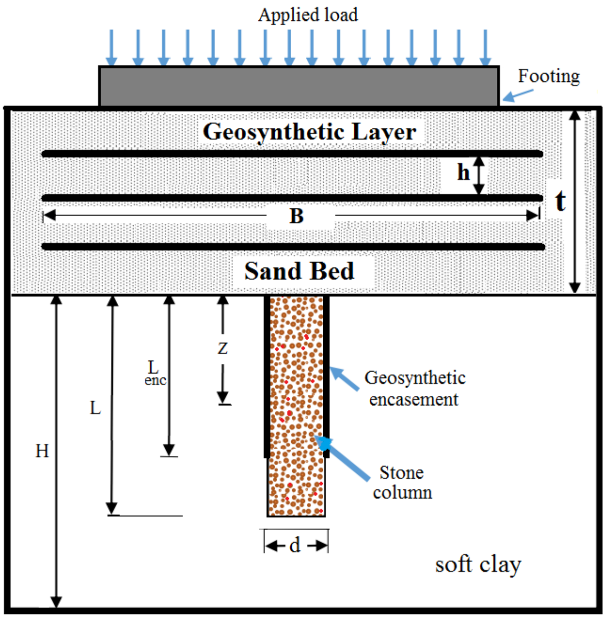
## MODEL DETAILS

A model was developed containing soil, sand bed, stone columns, footing and geosynthetic encasement as shown in Figure 1. Both the infill material used for the sand bed, encased stone columns and the weak surrounding soil, which was soft clay, were modeled as a linear elastic perfectly plastic material using Mohr-Coulomb criterion. Brick elements were used to model the soil. The stone column is modeled as a massive circular element with outside interface with soil. The column was divided in the radial direction to four parts. It is modeled to behave as a conventional elastic-perfectly plastic model based on Mohr-Coulomb failure criterion in FLAC3D software. The footing is modeled as square brick elements with 0.7 m thickness, its length and width depend on the stone column diameter. Interfaces element is used to represent the connection between footing, sand bed, column, geosynthetics and soil.

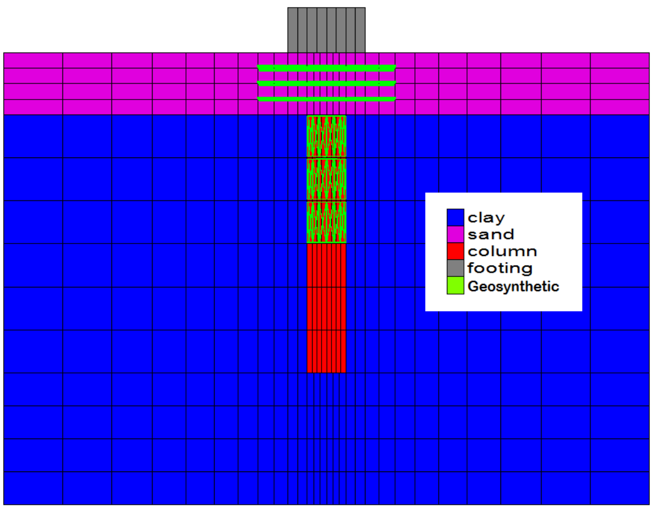
In FLAC3D, the Mohr Coulomb constitutive model requires wet density (γ), angle of internal friction (φ), cohesion (c), bulk modulus (K) and shear modulus (G). The bulk and shear moduli are both functions of the Young's modulus (E) and Poisson's ratio (v) and are calculated using the following equations:

$$K = \frac{E}{3(1-2\nu)} \tag{1}$$

$$G = \frac{E}{2(1-\nu)} \tag{2}$$




**(a) Geometry Model.**




**(b) Finite difference mesh for the model**

**Figure 1. FLAC3D model.**

A summary of the physical and elastic material properties are provided in Table 1. The groundwater table was assumed to be located at the surface of the soft clay layer.

**Table 1. Physical Properties of used materials**

| Parameter / Material | $\gamma$ ($kN/m^3$) | E MPa | $\nu$ | c kPa | $\varphi$ deg. |
|---|---|---|---|---|---|
| Soft clay | 17 | 4 | 0.45 | 20 | 0 |
| Sand | 19 | 32 | 0.3 | 0 | 30 |
| Stone column | 18 | 55 | 0.3 | 0 | 40 |
| Footing | 0 | 25000 | 0.2 | 0 | 0 |

## CASES OF STUDY

The main factors taken into consideration were: side length of square footing (D), stone column diameter (d), length of stone column (L), encasement length (Lenc), axial stiffness of stone column encasement (Jsc), internal friction angle of stone column material (φsc), thickness of unreinforced sand bed (t), vertical distance between geosynthetic layers (h), friction angle of sand bed material (φSB), number of geosynthetic layers (N), length of geosynthetic (B), axial stiffness of sand bed (JSB). The soft clay soil has a depth (H) =10 m according to the case study and undrained cohesion (Cu) = 20 kN/m2.

In all cases, the footing is supported by sand bed over single stone column. The effective stone column length (L) to diameter (d) ratio was (L/d) = 10 (Malarvizhi et al., 2007; Fattah et al., 2012; Ramadan et al., 2015). The effective projection of the footing was (C) = 0.5d (Ramadan et al., 2015). The encasement length to diameter ratio (Lenc/d) = 5.0 (Ramadan et al., 2018b). The encasement axial stiffness of stone column (Jsc) = 2000 kN/m (Chungsik Yoo 2015 and Ramadan et al., 2018b).

**Table 2. The general plan of the parametric study**

<table>
<tr><th>Case of study</th><th>D (m)</th><th>d (m)</th><th>L (m)</th><th>$L_{enc}/d$</th><th>$\varphi_{SC}$</th><th>$J_{SC}$ kN/m</th><th>t/D or h/D</th><th>$\varphi_{SB}$</th><th>N</th><th>B/D</th><th>$J_{SB}$ kN/m</th></tr>
<tr><td>Clay Only</td><td rowspan="5">1.2</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>OSC</td><td rowspan="4">0.6</td><td rowspan="4">6.0</td><td>-</td><td rowspan="4">40°</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>ESC</td><td rowspan="3">5.0</td><td rowspan="3">2000</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>ESC + USB</td><td>t/D = 1.5</td><td rowspan="2">30°</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>ESC + GRSB</td><td>h/D = 0.30</td><td>3</td><td>2</td><td>2000</td></tr>
</table>

## RESULTS AND ANALYSIS

A model was run which simulated the construction of footing rest on soft clay without any improvements and then it was run with stone column with and without encasement installed in soft clay. Also, the model was run with unreinforced and geosynthetic reinforced sand bed over encased stone column

Figure 2 shows a typical axial stress versus settlement of footing relationship for different improvement cases. Settlement was calculated at the top of the soft clay at the center of footing under applied axial stress. For comparing and expressing results to show the effect of using ordinary, encased stone columns, unreinforced and geosynthetic reinforced sand bed to increase the bearing capacity of soft clay, a dimensionless parameter called BCR (Bearing Capacity Ratio) is used. The BCR was defined as:

$$BCR = \frac{\text{Ultimate bearing capacity of improved soil}}{\text{Ultimate bearing capacity of soft soil only}} \qquad (3)$$

Figure 3 shows the variation of BCR with different improvement cases. As compared to unreinforced clay bed, a 1.83 fold increase in bearing capacity was observed with the provision of ordinary stone column (OSC) and 2.58 fold increase in bearing capacity with the provision of encased stone column (ESC). Also, in case of clay bed provided with combination of unreinforced (ESC+USB) and geosynthetic reinforced sand bed (ESC+GRSB) over encased stone column, 3.59 and 8.07 fold increase in bearing capacity, respectively.

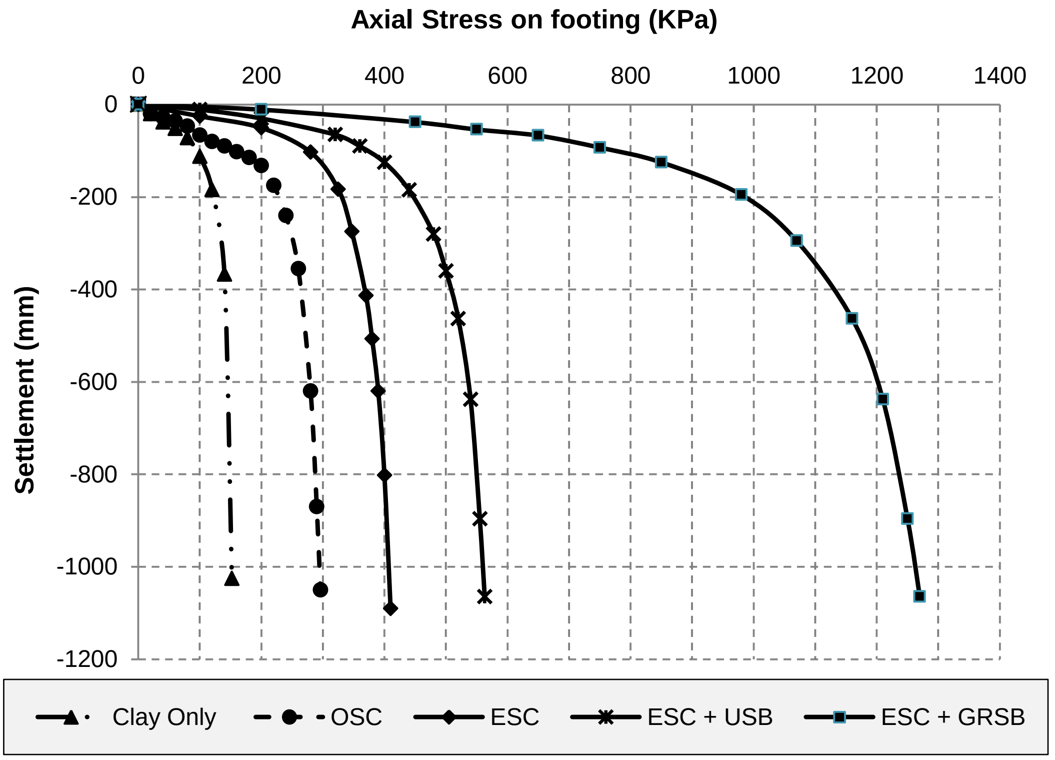



**Figure 2. Axial stress on footing versus settlement for different improvement cases**

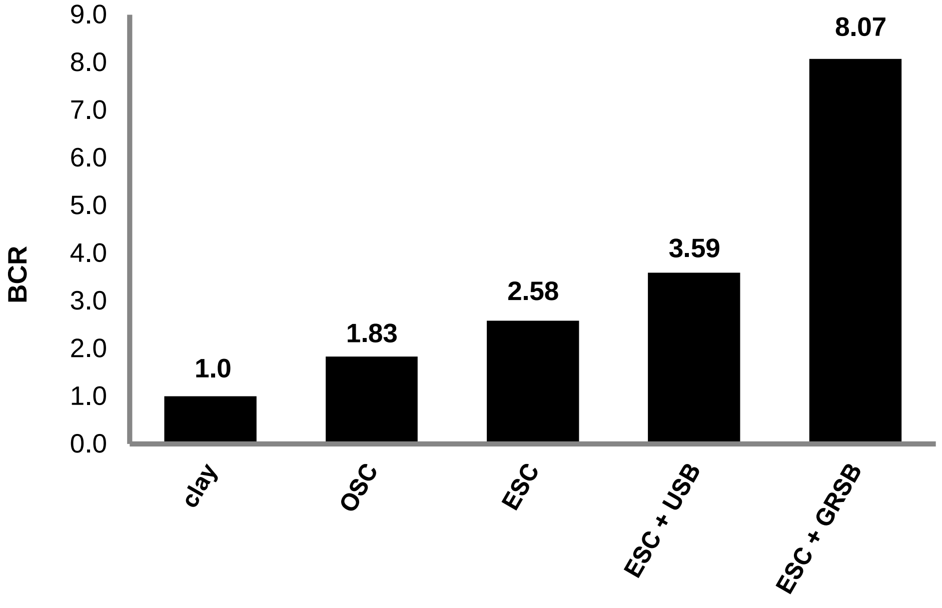



**Figure 3. BCR for different improvement cases**

Figure 4 shows the lateral displacement to diameter of stone column ratio, Ux/d, at different improvement cases. The lateral deformation increased as the depth from the top of soft clay layer (Z) increases to reach the maximum lateral deformation then decreasing to reach small value of deformation. The maximum bulge has been observed at a depth of 2, 2.5 and 3.0 times the diameter of stone column in case of soil improved by stone column alone and by placing of unreinforced and geosynthetic reinforced sand bed over encased stone column, respectively.

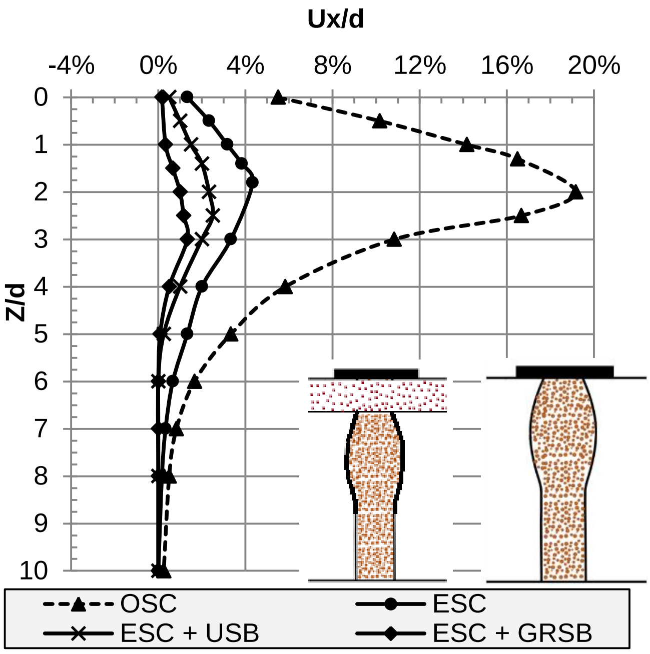



**Figure 4. Lateral displacement to diameter ratio vs. Z/d for different improvement cases**

## CONCLUSIONS

Based on the results the following conclusions can be drawn:

- When encasing the stone column, the lateral bulging is considerably decreased due primarily to the added confinement by the encasement.
- With provision of OSC, the bearing capacity of soft clay bed can be increased by 1.83 fold and with ESC it is of the order of 2.58 fold.
- It has been observed that the placement of unreinforced sand bed over encased stone column-improved soft clay (ESC+USB) increases the load carrying capacity by 3.59 fold .
- The stiffness and load carrying capacity of the clay bed with composite reinforcement (ESC + GRSB) is much higher as compared to that with the (ESC) alone. It is noted that BCR increased by 8.07 fold with combination of geosynthetic reinforced sand bed over encased stone column (ESC+GRSB).
- Decrease in bulge diameter and increase in depth of bulge have been observed due to placement of sand bed over encased stone column improved soft clay. Further decrease in maximum bulge diameter and increase in depth of bulge have been observed due to application of geosynthetic reinforced sand bed .
- The maximum bulge has been observed at a depth of 2, 2.5 and 3.0 times the diameter of stone column in case of soil improved by stone column alone and by placing of unreinforced and geosynthetic reinforced sand bed over encased stone column, respectively.

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