Influence of Stone Column Length on the Settlement of Soft Clayey Layer

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Abstract: Currently, geotechnical engineers use stone columns to strengthen weak soils. The usage of stone columns to strengthen soft soil has proven successful, increasing their bearing capacity, reducing the settlement and decreasing the consolidation time. The present study was carried out to investigate the impact of the length of stone columns on the behaviour of soft soils and determine the effective length of stone columns, within which they have the greatest impact on the process of settlement of the soft clay layer. The analysis was performed utilizing a three-dimensional limited distinction numerical model FLAC3D. The results of the study confirmed that with the increase in the length of the stone columns, the settlement of the clay layer decreases. This decrease in settlement is significant to a depth corresponding to the relative length of the piles (L/d) = 10, after that the decrease in settlement practically stops.

1. Introduction

Soft clay soil is a saturated soil that has low values of shear strength parameters, likewise has high estimation of pressure. One method for solving this issue is boring a few openings at specified intervals and filling them with granular material, henceforth they have the term stone column. Stone columns as semi-inflexible inclusions are utilized to reduce settlements under foundation loads in compressible soils. It might viably expand the general bearing capacity and decrease the settlement of foundation soil by moving loads from the weak soil to the relatively stiffer stone columns and combining the in-situ weak soil to a stronger inclusion, the stone column.

A lot of researches that examine the stone column technique as an improvement method for soft soil have been published in the past. The stone columns provide the visible improving on the behaviour of the soft ground. The increase of the bearing capacity of the soft soil with stone columns depends mainly on the geometric conditions of columns. The stone columns with smaller spacing distances and smaller diameters have a greater bearing capacity and show smaller settlement as well as low lateral bulging than wider spacing and larger diameters of stone columns [1-3].

Furthermore, some of researches performed tests for investigating the effect of length stone column at the improving method. These researches confirmed that the settlement decrease with increasing column lengths and the improving of bearing capacity of improved soil increase with also increasing column lengths [4-6]. From these results, researcher move to find the optimal normalized column length, which gives the optimal performance of columns. [5], concluded with expanding of (L/d), the bearing
improvement ratio increases and keeps on expanding at the same rate and when \((L/d)\) turns out to be
more than 8 the bearing improvement ratio are being steady. Also, expressed the compelling length
stone columns that give significant settlement improvement under the footings, [6]. Settlement reduction
factors decrease with expanding column lengths. These elements along the column are similar to the
factors underneath the segments for lengths \(L/B > 1.0\).

The main aim of the present work is to study the length effects of stone columns on the behaviour of
soft soils improved by stone columns. The analysis was carried out using a three dimensional finite
difference numerical model FLAC3D. The main investigated relationships are stress-settlement
relationships and Vertical displacement distributions.

2. Model details
The analysis was performed by using a three dimensional finite difference model FLAC3D. The
computation scheme performed by FLAC3D takes an enormous number of estimation steps, each
progressively redistributing an unbalanced force caused by changes to stress or displacement boundaries
through the mesh [7].

The soil was modelled to behave as elastic-perfectly plastic model based on Mohr-Coulomb failure
criterion in FLAC3D software. Brick elements are used to model the soil. The parameters of soft clay
are given in Table 1. The depth of soil layer \((H)\) was assumed in all cases of study equals 10 m. Also,
the width and the length of the soil model \(\geq 10 \, \text{B}\), where the \(B = \text{width of the footing, to be}
ensured there are no effect of the boundary on the model. Moreover, the groundwater table was assumed to be
located at the surface of the soft clay layer. The stone column is modelled as a massive circular element
with an outside interface with soil. The column was divided in a radial direction to four parts. The stone
column is modelled to behave as a conventional elastic-perfectly plastic model based on Mohr-Coulomb
failure criterion in FLAC3D software. The parameters of stone column are given in Table 1. The footing
is modelled as square brick elements with 0.7 m thickness, width and length is depended in the spacing
between columns. Interface element is used to represent the connection between footing, columns and
soil. A summary of the physical and elastic material properties are provided in Table 1. Also, Figure 1
shows the model details and dominations.

The main factors taken into consideration were: depth of soil layer \((H)\), Length of stone column \((L)\),
stone column diameter \((d)\) and width of booting \((B)\). In all cases, the footing is supported by four circular
stone columns. The canter to the canter distance of the stone columns \((S)\) to column diameter \((d)\), spacing
ratio \((S/d)\) is 2.0 in all studies. Length to diameter ratio of stone columns was changed from 0 to 15.
Column diameter \(d=0.4 \, \text{m and } d=0.6 \, \text{m. Area replacement ratio is 19.6% in all studies.}

Table 1. Physical and mechanical material properties

| parameter       | \(\gamma \, (\text{kN/ m}^3)\) | \(E \, (\text{kPa})\) | \(\nu\) | \(\varphi \, (^\circ)\) | \(c \, (\text{kPa})\) |
|-----------------|-----------------------------|---------------------|-------|----------------|------------------|
| Soft clay       | 17                          | \(4\times10^3\)     | 0.45  | 0             | 20               |
| Stone column    | 18                          | \(55\times10^3\)    | 0.30  | 40            | 0                |

3. Results and discussions
This section presents the results of the numerical performed in the form of relations:

\[
\Delta/B = f(P); \beta = f(L/d); (\Delta/B) = f(L/d).
\]

3.1. Effect of length stone columns on axial stress
The main objective of this section is to investigate the effect the height to diameter of stone column
\((L/d)\) on the behaviour of stone column- soft clay soil system. Eight cases are carried out with different
values of diameter \((d)\) of the stone column. Figures (2, 3), show comparison between \((P)\) versus \((\Delta/B)\)
for the ratio between the length to diameter of stone column (L/d). It is observed that the axial stress increases with the increasing of stone column length (L/d). The difference in the behaviour of stone column is very small when L/d > 10. The practical ratio of L/d ranges from 10 to 15.

**Figure 1.** Model geometry

**Figure 2.** \((\Delta/B) = f(P)\) at \(d = 0.4m\)
3.2. Effect of stone length on the improvement ratio $\beta$

For comparing and expressing results to show the effect of $L/d$ at the behaviour of soft clay improvement, a dimensionless parameter ($\beta$) known as the ratio between the values of $(p2)$ for improved soil to the value $(P1)$ for clay without columns. The values ($\beta$) obtained from Figures (2, 3) at a $P$ value corresponding to values of $\Delta/B = 5\%$, 10\%, 15\% and 20\%. From Figures (4-7), with the increase of $L/d$ from 0 to 15 the $\beta$ increases from 100\% to 140\% of stone column diameter 0.4 m and from 100 \% to 145\% for stone column diameter 0.6 m. The $\beta$ increase with the increase of ratio $L/d$ till reach $L/d = 10$ then the $\beta$ become steady. The rate of increase in $\beta$ equal about (1.5-2\%) from $L/d = 10$ to $L/d = 15$ at $d = 0.4$ m and from $L/d = 8$ to $L/d = 15$ at $d = 0.6$ m.

From the current result and the other results, it may be concluded that, the $\beta$ increases with the increase in $L/d$. For $L/d$ values more than 10, the rate of increase in $\beta$ is small. The effective length to diameter ratio of stone column is found to be $L/d = 10$.

![Figure 3. $(\Delta/B) = f(P)$ at $d = 0.6m$](image)

![Figure 4. $\beta = f(L/d)$ at $\Delta/B = 5\%$](image)
3.3. Effect of stone length on the vertical displacement
As seen in Figure (8 – 13), the vertical displacement distribution with difference depth clay layer under the footing, under the stresses (P = 100, 150 & 200 kPa) for d = 0.40 & 0.60 m. Similar results have been found in columns both in d = 0.4 m and d = 0.6 m. From these figures, the vertical displacement decreases with increasing L/d. When L/d = 10 displacements are quite similar to the displacement at L/d = 15. Also, the vertical displacement decreases with increasing the depth below surface.
It can be divided these relations to 3 parts. First part, it is a zone from under the footing to depth equal 6d. At this part occurred the maximum displacement. Through this part at all cases, the rate of change of displacement is significantly reduced with the depth to reach approximately half his value under the footing at depth equal 6d. The second part, it is a zone from depth equal 6d to a depth equal 10d. In this part, the shape of displacement has a curve shape through this part. The rates of change of displacement are reduced with the depth to displacement at 10d reach approximately quarter his value at 6d. Finally, the third part is a part deeper than 10d. Through this part the displacement gradually reduces with depth, but the rate of change is small. And at depth = 10d the value of displacement reaches the small value it is about (1.5% at d = 0.4 m and 1% at d = 0.6 m) of footing width.

It can be concluded that, at depth = 10d the value of displacement reaches small value, after that the decrease in settlement practically stops. The effective length to diameter ratio of stone column is found to be L/d =10 and thereafter there is no effect on displacement value.

![Diagram](image)

**Figure 8.** $(\Delta/B) = f(L/d)$ at $P = 100$ kPa
Figure 9. $(\Delta/B) = f(L/d)$ at $P = 150$ kPa

Figure 10. $(\Delta/B) = f(L/d)$ at $P = 200$ kPa
4. Conclusion
From the results of the research, several conclusions have been drawn and are summarized as follows:

- The settlement of footing decreases with increasing of stone column length to reach the length to stone column diameter ratio $L/d=10$, then the decrease is very small or virtually has no effect.
- $\beta$ increases with the increasing $L/d$. At $L/d$ values more than 10, the rate of increase in $\beta$ is small.
- At depth = 10 d from the surface, the vertical displacement reaches a negligible value.
- The effective length of stone column was found $L/d = 10$ and after that does not affect the amount of displacement.

5. Reference
[1] S. Christoulas, G. Bouckovalas and C. Giannaros, An experimental study on model stone columns, 2000 Soils and Foundations, vol. 40 (6), pp. 11-22, 2000.
[2] A. Ambily and S. Ganghi, Behavior of stone columns based on experimental and FEM analysis, 2007 J Geotech. Geoenviron. Eng. ASCE, vol. 133(4) pp. 405–415, 2007.
[3] M. Elsawy, K. Lesny & W. Richwien, Behavior of ordinary and encased stone columns studied by FEM analysis, 2009 Proc. of the 17th Int. Conf. on Soil Mechanics and Geotechnical Engineering, Alexandria, 2009.
[4] J. T. Shahu and Y. R. Reddy, Clayey soil reinforced with stone column group: model tests and analyses, 2011 J Geotech Geoenviron Eng ASCE, vol. 137(12), pp. 1265-1274, 2011.
[5] M. Y. Fattah and Q. G. Majeed, Finite element analysis of geogrid encased stone columns, 2012 Geotechnical and Geological Engineering, vol. 30 (4), pp. 713-726, 2012.
[6] M. Tekin and M.U. Ergun, A model study of strains under footings supported by floating and end-bearing granular columns, Proc. of the 18th Int. Conf. on Soil Mechanics and Geotechnical Engineering, Paris, 2013.
[7] Itasca, FLAC3D: Fast Lagrangian Analysis of Continua, User's manual, 2006 Itasca Consulting Group, Minnesota, (2006).