Behavior of Rigid Footing Rested on a Group of Stone Column

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Abstract. Raft foundation often adopted for structures constructed on highly compressible soil. Sometimes raft footings are preferred on stone column-improved ground. The current FEM-based numerical study investigated the behavior of a rigid square footing model resting on the surface of a soft ground improved with a group of stone column. To analyze the behavior of the rigid footing, a group of fully penetrating stone columns was constructed beneath the rigid footing. Various parameters such as area replacement ratio, column spacing and relative position of column have been studied. Performance of rigid footing enhances with the increment of area replacement ratio. Bearing capacity improvement was found to be higher at lower settlement level. And a better settlement improvement was observed when footing is acted upon by a higher loading. For larger size raft footing, stone columns arrangements have a significant effect on load-settlement behavior. When stone columns are placed near to the center of the footing, shows a better improvement in term of settlement and load carrying capacity. A single stone column of equivalent area ratio constructed at the center, shows similar behavior as a group of stone column. Different types of failure mechanism were observed for the stone columns placed at different position. Stone columns constructed near the edge of the footing failed by the combined action of bulging and buckling. Whereas, central columns mainly failed by bulging near the top.

Keywords: Stone column, Rigid footing, Bearing capacity improvement, Stone column arrangement.

1 Introduction

Ground improvement using vibro stone column is one of the most widely accepted techniques adopted in improving soft soil deposit like marine clay [6-10]. It provides a relatively stiffer medium that improves the load carrying capacity of soft soil and accelerates the consolidation settlement by reducing the drainage path. The structures (like embankment, storage tank, lightweight structure, etc.) that can tolerate a few amounts of settlement are preferred to construct on stone column improvement ground. Recently, stone columns are also employed beneath a rigid footing [2-5, 7, 14, 15]. Further, rigid foundation for oil storage tanks is often constructed on stone column improved ground near the seashore [4]. In these cases, the ground is subjected to a uniformly distributed load. The performance of the stone columns depends upon all round confinement of the surrounding soil. Sometimes the function of the stone column become limited due to low confinement. When stone columns are installed in a large area, one single stone column can be idealized as a unit cell. But, the individual behavior of stone columns beneath a rigid footing is different. The footing near the edge of the raft tends to shift outwards upon loading [5]. Das and Deb [4] presented an analytical solution to understand the behavior of circular rigid raft footing constructed on stone column improved ground. They idealized the surrounding soil and stone column as a Pasternak shear layer and non-linear spring system. Castro [2] performed a numerical 2D and 3D analysis on the performance of a group of stone column beneath a rigid square footing. Configuration and arrangement of stone column with different area ratio were studied in this study. A new simplified model suggested where a group of stone column can be replaced with a single central stone column of equal area replacement ratio. Zhou et al. (2017) evaluated the failure modes and ultimate bearing capacity of strip footing constructed on stone column reinforced ground. A parametric analysis is conducted by varying aspect ratio, area replacement ratio, and surcharge load. Elsawy and Garhy (2017) also carried out a 3D finite element analysis to investigate the influence of various parameters on the load-settlement behavior of a rigid footing constructed on the granular pile. The settlement improvement achieved and bending moment generated in the rigid raft by the various configuration of stone columns. Castro [3] studied the performance of a group of encased stone column beneath a rigid footing. A 2D and 3D finite element analysis is carried out and presented the concept of critical length of encasement as well as column length. The influences of several parameters such as length of the column, length of the encasement, column arrangement, etc. are investigated in the load-settlement response of the rigid raft footing.

However, a scarce of information is available on the performance of raft footing on stone column improved ground. This numerical study presents a 3D finite element model to investigate the influence of various parameters on the bearing capacity improvement as well as settlement improvement.

2 Numerical models

A 3D finite element model was developed using FEM program PLAXIS 3D. A rigid square footing was assumed to be constructed over a soft clay layer of 20m thickness. A sand blanket was provided on the top surface of the clay layer. For the sake of simplicity, water table was considered at the top of the clay layer. A 50m×50m clay surface was taken to avoid boundary constraint on the load-settlement behavior of footing. A schematic diagram of the used model is presented in Fig (1). Finite element discretization was done using ten noded tetrahedral elements. To avoid the complexity of the model and to reduce calculation time, the load-settlement analysis was carried out with an axisymmetric part of the rigid footing (Fig.2). Only the vertical movement was allowed along the side of the model and the movement of the base was kept restrained. Raft footing was idealized as a plate element available in the program.

Long term behavior of clay can be modelled by two methods: (i) drained analysis using effective stress parameters, (ii) using undrained condition and effective stress parameters followed by consolidation [7]. The study was carried out after a sufficient time lapsed after loading and considering the consolidation of the clay layer already occurred by drainage of excess pore water through stone columns. A drained analysis was carried out by assuming all the pore pressure was dissipated. Considering the elasto-plastic behavior of the materials, Mohr-coulomb failure criteria was adopted [1, 3, 11-13]. Assuming perfect bonding between the column and soil, no interface element was considered.

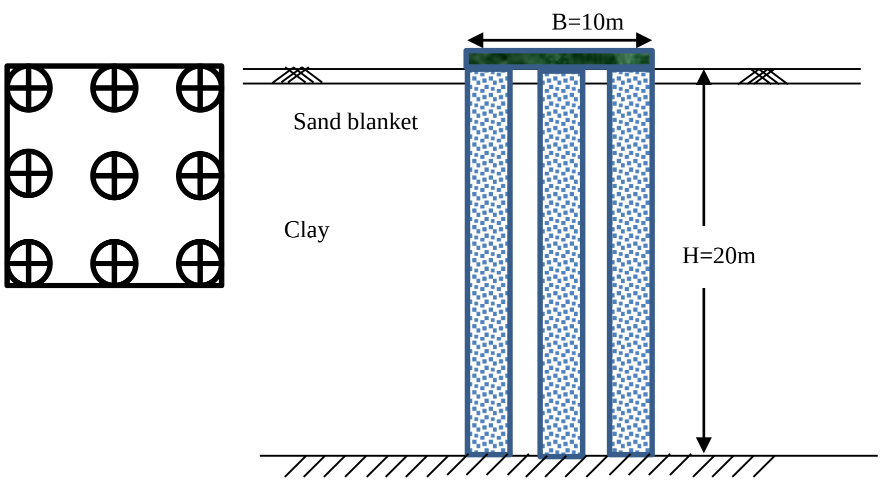

Fig. 1. Layout of a rigid footing on a group of stone columns in the clay layer of 20m thickness

3 Reference case

Loading was applied through a rigid footing of size 10m×10m. Table 1. shows the properties of the clay layer and column material adapted from well-established literature. In the case of stone and sand, a small value of cohesion was assumed to avoid calculation difficulty. A 0.5 m thick sand layer was provided at the top of the clay layer. In this reference case, the stone columns are extended through the clay layer. Although stone column having length more than critical length doesn't indicate any further significant improvement in load carrying capacity, it may be effective as a vertical drain to accelerate consolidation. As this numerical analysis is based on the long term behavior of surrounding soil, both the stone column (floating type and end bearing) of length more than the critical length will not affect the results discussed here. Stone columns of diameter 1m were constructed in a square grid pattern beneath the rigid raft.

Table 1. Material properties [1]

Materials	E (kPa)	Cu (kPa)	Φ (^{O})	Ψ (^{O})	μ	Υ_{dry} (kN/m3)	Υ_{bulk} (kN/m3)
clay	2,150	7	0	0	0.47	13.6	18.3
Sand	20,000	0.3	30	5	0.3	15.5	18.5
Stone	55,000	0.3	43	10	0.3	16.62	20.1

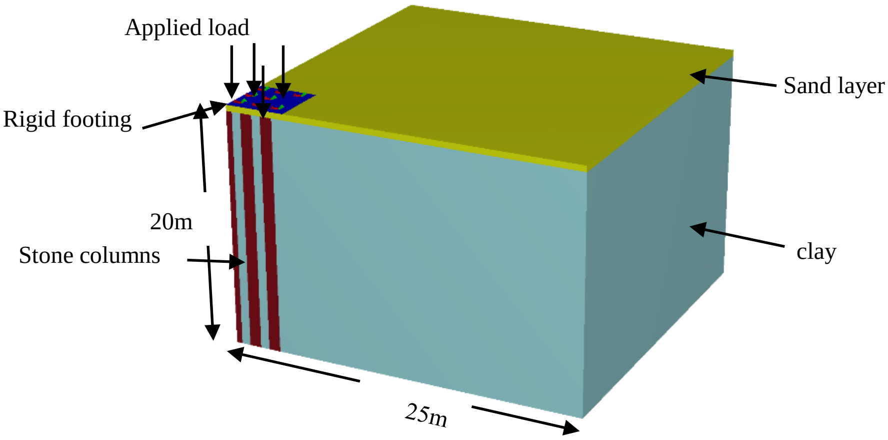

Fig. 2. Layout of the 3D reference model

4 Result and discussion

The load-settlement behavior of rigid raft on unreinforced soil and reinforced with group of end bearing stone column was studied using FEM program PLAXIS 3D. The influence of area replacement ratio, column configuration, column spacing and modes of failure of individual stone columns in the group has been investigated.

4.1 Area replacement ratio (A_r)

Area replacement ratio(A_r) i.e. the quantity of soil replaced by granular materials is a very significant parameter to control the degree of improvement. Here, *Ar* is calculated as the ratio between the sum of area of columns to the area of raft footing. As, uniformly distributed load was applied on the footing, the loaded area and the raft area is same. The effect of area replacement ratio on both bearing capacity improvement and settlement improvement was studied. Bearing capacity improvement is presented here as the ratio of bearing capacity of reinforced ground to that of the unreinforced one. Further, settlement improvement was calculated at different loading level as well as at ultimate load carrying capacity of footing on unreinforced soil. Settlement improvement ratio is presented as the ratio between the settlement of unreinforced ground and settlement of reinforced ground at that load. To study the effect of area replacement ratio stone column of group 2×2, 3×3, 4×4, 5×5, 6×6, 7×7 were constructed beneath the footing. Fig (3) shows the column arrangements for which the improvement factors were calculated and in all cases diameter of column was same.

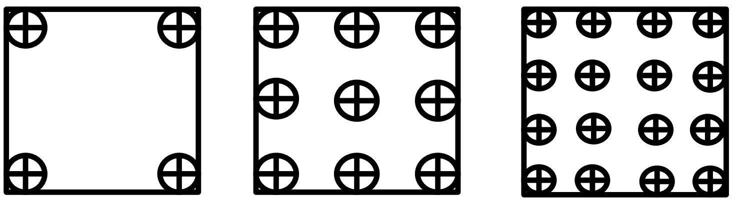

Fig. 3. Column configuration adopted to study the effect of area ratio

Fig (4) presents the bearing capacity improvement with inverse area ratio. Here improvement was calculated at different settlement level (i.e. 50, 100, 150 and 200mm). A rapid change of improvement was observed when inverse area replacement ratio is less than 15. Further, the bearing capacity improvement was found to be higher at lower settlement. Fig (5) presents the variation of settlement improvement with inverse area ratio at different applied stress (i.e. 25, 30, 35 kPa and ultimate load carrying capacity of unreinforced ground). Settlement improvement decrease with the increase of inverse area replacement ratio. Further, the rate of reduction is higher when inverse area replacement ratio is less than 15. It was observed that the settlement improvement was higher at higher loading. In all cases, stone columns are equally distributed beneath the rigid footing. Although this improvement depends upon the arrangement of the stone column also and this phenomenon has been discussed in the following section.

4.2 Column position

When large numbers of stone columns are constructed in a group, then the behavior of interior columns is nearly same and they can be approximated as a single stone column in a unit cell. But when stone columns are constructed beneath a rigid footing, the all-around confinement generated due to the overburden pressure is not identical except the central column. The load-settlement performance of the footing significantly depends upon the increased confinement around the stone columns during loading. So, in this case, relative position of column is more meaningful than the spacing of stone columns. In this study, a group of 4, 9, 16, 25 and 36 numbers of stone columns were taken. In each case, relative column position was shifted towards the center by keeping area ratio constant. The details information of the study is shown in Table 2.

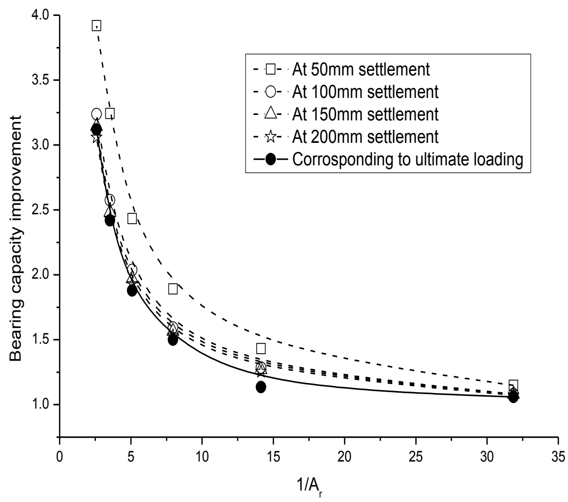

Fig. 4. Variation of bearing capacity improvement with inverse area ratio

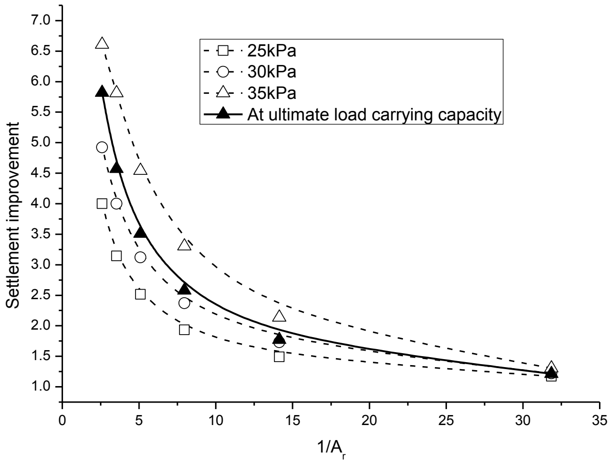

Fig. 5. Variation of settlement improvement with inverse area ratio

Table 2. Detailed information of the studied case

Case no.	Number of column	A_r (%)	*s/d*	D_c (m)	Edge distance (m)
1	4	0.031	9	4.5	0.5
			7	3.5	1.5
			6	3	2
			4	2	3
			2	1	4
			0	0	5
2	9	7.07	4.5	4.5	0.5
			3.5	3.5	1.5
			3	3	2
			2	2	3
			0	0	5
3	16	12.57	3	4.5	0.5
			2.33	3.5	1.5
			2	3	2
			1.67	2.5	2.5
			0	0	5
4	25	19.63	2.25	4.5	0.5
			1.75	3.5	1.5
			1.5	3	2
			1.25	2.5	2.5
			0	0	5
5	36	28.27	1.8	4.5	0.5
			1.4	3.5	1.5
			1.2	3	2
			0	0	5

Where, *s/d* spacing to diameter ratio, *Dc* distance of the exterior column from the center of the raft.

Relative bearing capacity improvement and settlement improvement of reinforced ground was calculated over an unreinforced ground. The position of the columns was shifted towards the center of the raft from the edge by reducing their center to center spacing and finally, one single stone column was constructed at the center of equivalent area replacement ratio. Fig (6) shows the studied relative column positions beneath the rigid footing.
Fig (7,8) shows the performance of the footing gets improved when stone columns are placed near to the center. Two main criterion plays behind this characteristic: (1) as the rigid footing constructed on the granular layer, then the stress accumulation will be there near to the center, so the presence of stone column near to the center improve the performance. (2) on the other hand, stone columns near to the center experiences higher lateral confinement increased due to overburden pressure of the rigid footing. By maintaining constant area ratio, spacing between the columns were subsequently decreased and column group shifted towards the center. A clear enhancement of the performance was found when columns are towards center. For this particular case, this increment was observed up to a distance between the exterior column and center of the raft decreased to 3m. So, a minimum edge distance of 1-1.5 times the diameter of column is effective for a constant area replacement ratio. The bearing capacity and the settlement of a group of stone column was compared with the single central column of equivalent area ratio and the results were found to be similar in both case.

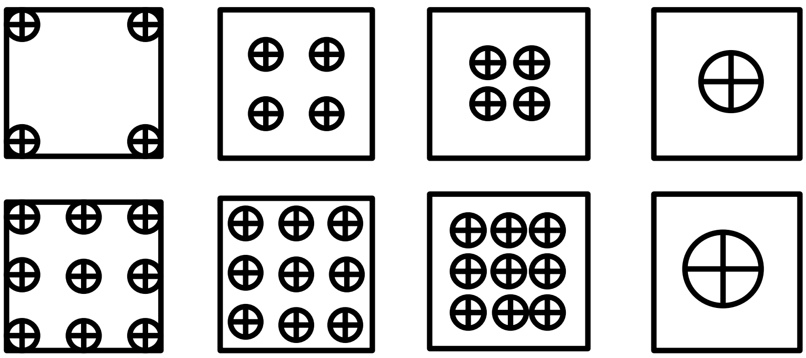

Fig. 6. Column arrangement for 2×2 and 3×3 group of stone column

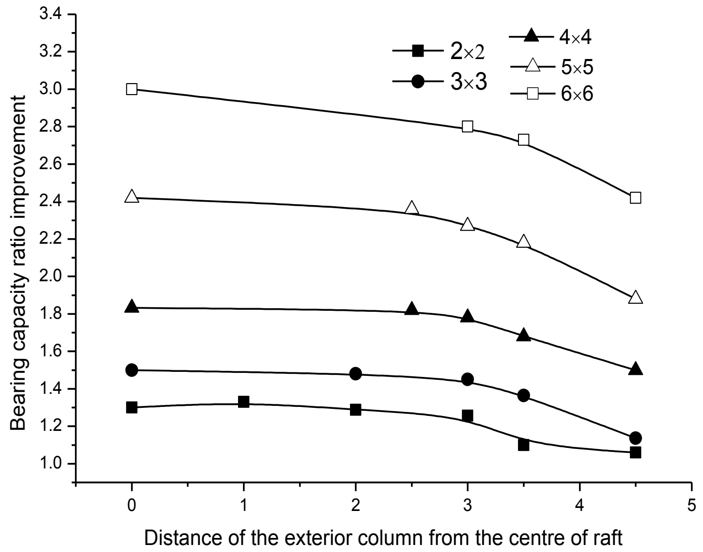

Fig. 7. Bearing capacity improvement at different column arrangement

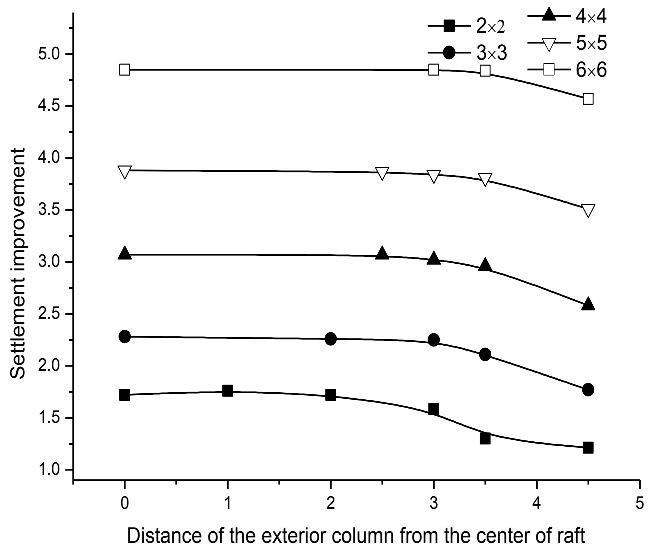

Fig. 8. Settlement improvement factor at different column arrangement

4.3 Failure mechanism

Failure mechanism of stone columns beneath a rigid footing is quite different than the stone columns constructed in an infinite group. Although, bulging type failure is predominant in both cases. Only the central column senses symmetrical all-round confinement developed due to overburden pressure from raft footing. And the columns other than the central column, are acted upon a higher lateral pressure inside the footing area. As a result, bulging and buckling happens simultaneously in the peripheral columns. And this phenomenon is more predominant in the stone columns near the edge. Fig (9) shows the different failure pattern of the individual stone columns placed at different position. Again when columns are constructed more close to center, load bearing capacity also increase due to better confinement.
Bulging depth of the individual stone columns also differ with the relative position. A central column experiences bulging at higher depth than the columns away from the center.

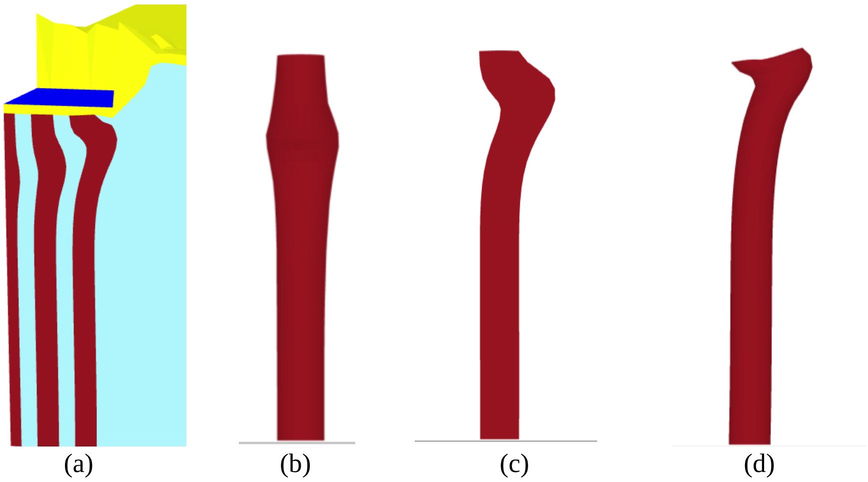

Fig. 9. Failure pattern of stone columns : (a) at group, (b) central column, (c) intermediate column, (d) column near edge.

5 Conclusions

The performance of a square rigid footing on a stone column reinforced soft ground have been studied in this analysis. A full scale 3D finite element analysis of the stone column treated soil and untreated soft ground was investigated using Plaxis program. A series of parametric study was conducted to examine the effect of various design parameters such as area replacement ratio (A_r), spacing and different arrangement of granular pile, edge distance from the exterior column, dimeter of stone column (d). Influence of these parameters on settlement improvement and load carrying capacity improvement of the rigid raft was investigated. Based on the results obtained, following conclusions can be drawn:

Settlement improvement as well as load carrying capacity improvement was observed to be increased with area replacement ratio. A higher load carrying capacity improvement was found at lower settlement level. Further, a better settlement improvement of the reinforced ground was observed when higher loading is applied on the footing. A rapid change of the improvement factor is noticed when inverse area ratio is less than 15. Relative column position has a significant effect on performance of rigid footing. Stone columns placed closer to the centre shows better improvement in performance than placed near the edge. For a group of stone columns, a minimum edge distance of 1-1.5*D* is found to be more effective for a particular area replacement ratio. Failure mechanism of individual stone columns depends upon their relative position. Only the central column failed by uniform bulging near the top. Whereas the stone columns other than central column, failed by non-uniform bulging, due to uneven lateral pressure. Therefore, stone columns near the edge mainly failed by combined action of bulging and buckling.

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