Numerical analysis of a stone column group

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ABSTRACT

This paper presents numerical analyses of a group of stone columns penetrated in a 10m deep soft clay stratum. A rigid raft transfers the super-structure's loading to the stone columns and the parent soft soil. The columns group comprises five columns with a symmetric configuration. The analyses are performed on a plane strain idealization of the structure, using an elasto plastic constitutive behavior for the materials. Two main types of analyses are carried out: (a) the stone columns are all end bearing and (b) the stone columns are floating in the soft clay layer. For case (b) analyses, (i) once the length of all of the columns are considered equal and then (ii) they are considered to be unequal, i.e., central columns are shorter than the side ones. This paper presents major findings of the analyses.

RÉSUMÉ

Ce document présente l'analyse numérique d'un groupe de colonnes de pierre percé de 10m de profondeur dans une couche d'argile molle. Un radeau rigide transferts super-structure de charge à la pierre des colonnes et le parent de sol souple. La colonne comprend cinq colonnes avec une configuration symétrique. Les analyses sont effectuées sur un plan de souche idéalisation de la structure, au moyen d'un comportement constitutif élastoplastique pour les matières. Deux grands types d'analyses sont réalisées: (a) les colonnes de pierre sont tous munis fin et (b) les colonnes de pierre flottant dans la couche d'argile molle. Foa cas (b) analyse, (i) une fois la longueur de l'ensemble des colonnes sont égaux et puis (ii) ils sont considérés comme l'inégalité, c'est-à-dire, colonnes centrales sont plus courtes que celles du côté. Ce document présente les principaux résultats des analyses.

1 INTRODUCTION

Stone columns are recognized as an efficient, cost effective, and environment friendly method for increasing bearing capacity (Etezad et al. 2005, Sivakumar et al. 2004, Shroff et al. 2005, Hu et al. 1997, McKelvey et al. 2004) and rate of consolidation (Acharya et al. 2005, Jie Han et al. 2001), decreasing settlement (Fessi et al 2005, Maurya et al. 2005, Sivakumar et al. 2004, Pulko et al. 2005, Shroff et al. 2005, McKelvey et al. 2004), and liquefaction potential of soft soils (Shenthan et al. 2004). Stone columns constructed with replacement methods have two advantages: 1) the strength and stiffness of the parent soil are increased through its substitution by granular materials (sand, gravel, cobbles) and 2) materials of the columns provide radial drainage, leading to an increase of the consolidation rate in the soil. Similar to piles, stone columns are divided into two groups: end bearing columns and floating columns. The aim of this paper is to present numerical analyses of a stone column group with (a) end bearing and then (b) floating length in a clayey soil.

2 NUMERICAL ANALYSES

In order to evaluate the effect of constructing stone columns in reducing settlement of a rigid footing laid on a clayey ground reinforced with stone columns a number of numerical analyses are carried out, for which ABAQUS finite element computer code was employed.

The Mohr-Columb elasto-plastic model with a non-associated flow rule was employed for representing behavior of both the stone columns and clay soil materials; The linear elastic model was used for the rigid footing in the analyses.

2.1 Verification Analysis

Numerical analyses are carried out on one of the Wood et al (2000) experiments [TS17] and then the numerical and experimental results are compared. Table 1 shows specifications of TS17 test. Figures 1 and 2 present deformed shape of the stone columns in TS17 test and the deformed mesh resulted from the numerical analyses, respectively. It is seen that the numerical analyses' result are in reasonable agreements with the result of TS17.

Table 1. Specifications of TS17 test (Wood et al. 2000)

Characteristic	Stone column	Clay
Undrained shear strength (kPa)	--	14
Radius (mm)	5.5[1]	150[2]
Length (mm)	160[3]	300[4]
Distance (mm)[5]	19.8	--
Area replacement ratio (%)	24	--
Bulk modulus (MPa)	100	10
Shear modulus (MPa)	50	5
Drained friction angle (º)	30	23

[1] Stone column's radius
[2] Radius of the tank in which TS17 was carried out
[3] Stone column's length
[4] Tank's length
[5] Distance = centre to centre distance between two adjacent stone columns

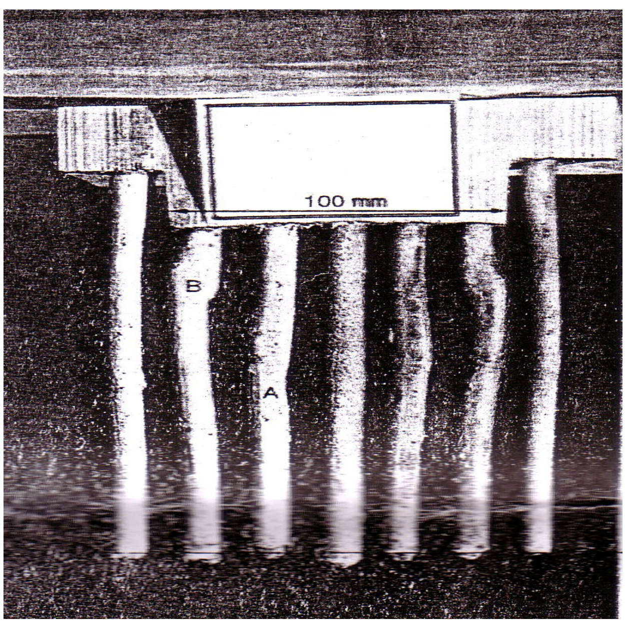

Fig 1- Stone columns' deformation in TS17 (Wood et al 2000)

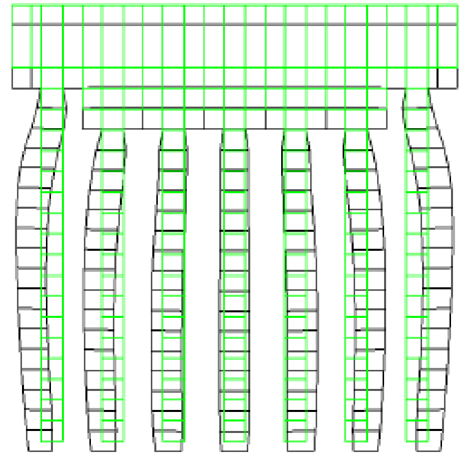

Fig 2- Deformed mesh of TS17 test resulted from numerical model

2.2 Stone column group analysis

In order to evaluate the effect of constructing stone columns in reducing settlement of a rigid footing laid on a clayey ground, first the ground without the stone columns was numerically simulated and analyzed. Then the ground reinforced by five end bearing stone columns, each with 0.6 m diameter and 10 m length, was analyzed. The geometry of the ground and the columns is presented in Figure 3.

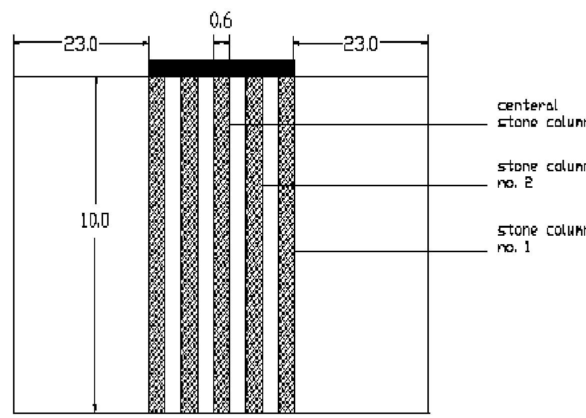

Fig 3- Geometry of the clay layer reinforced with stone columns

A load of 100kN/m^2 in 100 increments was applied via the rigid raft on the soil and stone columns group. The magnitude of the load was chosen based on the bearing capacity of the ground before the reinforcement. The mechanical characteristics of the stone columns and soil materials are presented in Table 2.

Figure 4 shows settlement profiles of the footing on the clay layer with and without the stone columns reinforcement. Since the raft on top of the columns is rigid and the load is uniform, the settlement for all of the columns is equal.

Figure 5 presents the computed deformed shape of the columns. Variations of bulging (i.e., lateral deformation) of the stone columns with depth are shown in Figure 6. Because of the symmetry of the columns group and the loading, only three (out of five) of the columns are included in Figure 6. This figure shows that the maximum bulging occurs in the side columns and relates to a depth of about 4D from the column's top. Also it is evident that the bulging of the central column is less than the bulging of the side columns. Moreover in the central column, the maximum bulging occurs comparatively in a lower elevation.

Table 2. Mechanical characteristics of stone columns and soil materials

Characteristic	Stone column	clay
Density (kg/m^3)	2040	1830
Young Modulus (MPa)	30	10
Poisson Ratio	0.35	0.45
Friction angle (º)	40	10
Dilatancy angle (º)	10	0
Undrained shear strength (kPa)	0	5

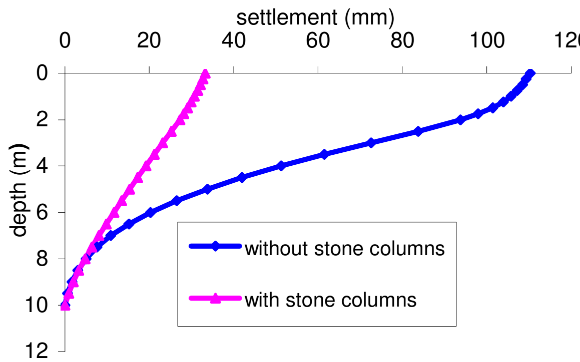

Fig 4- Settlement profiles of the ground with and without stone columns

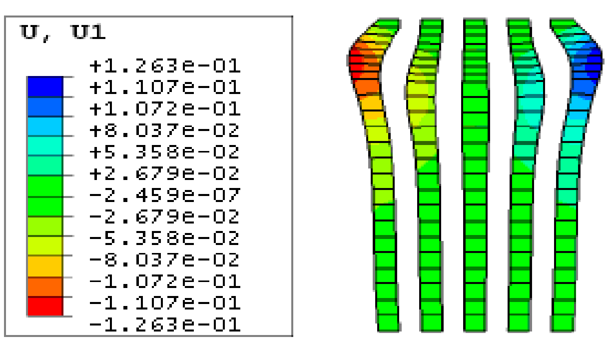

Fig 5- Deformed mesh of the columns after loading

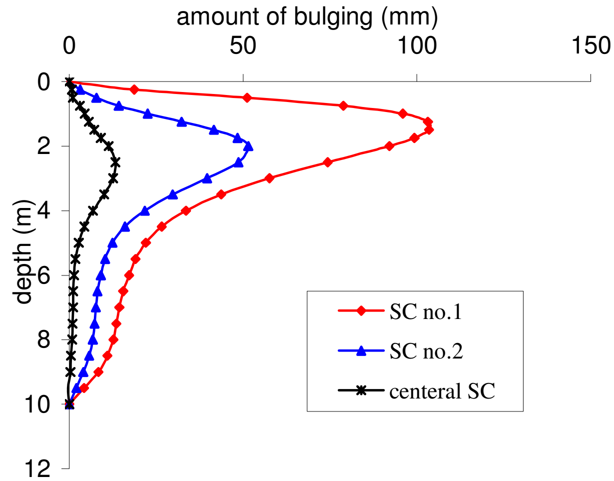

Fig 6- Variations of bulging with length of stone columns of Figure 3

2.2.1 End bearing versus floating columns

Stone columns from a length point of view may be divided into long columns and short columns. If the column's length is higher than three times of its diameter, it is named a long stone column; otherwise, it is a short stone column. The failure mode of a stone column depends on its length and its end bearing conditions.

For a floating, short stone column, a punching failure mode occurs under excessive loading. An end bearing short stone column faces usually local and general shear failure. A long stone column, either floating or end bearing, undergoes a bulging failure mode. The bulging occurs generally in a depth of 2D to 4D from the column's top. Both laboratory tests (Hu et al. 1997, Wood et al. 2000, McKelvey et al. 2004, Sivakumar et al. 2004) and field tests (Hughes et al. 1975, Maurya et al. 2005) confirm the above failure modes.

In order to study the effect of end bearing conditions of the columns and their length on the settlement, a series of numerical analyses were carried out on a group of stone columns, including 5 columns with 0.6 m diameter and varying length (2 to 10 m). All columns, except for the columns of 10 m long, are floating. General geometrical and mechanical specifications of the soil and the stone columns are the same as shown in Figure 3 and Table 2, respectively. For each of the analyses, the columns are of equal length.

Figure 7 shows settlements at the top and end of the columns for different columns length. It is seen that the settlement of the top and tip of the columns decrease by increasing the columns' length. The settlement of the 10 m long columns is 6.66 cm, which is almost equal to the settlement of the 9 m long columns.

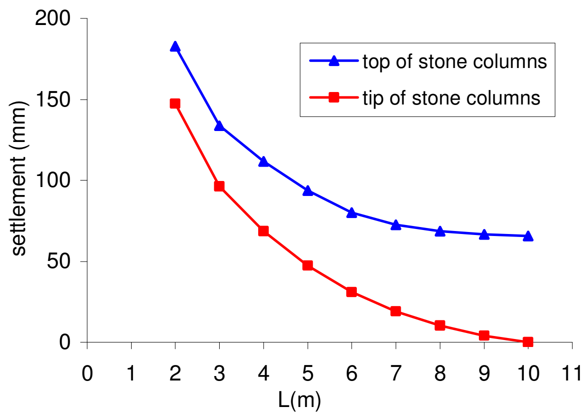

Fig 7- Settlements of the top and tip of stone column groups for different columns length

Figure 7 interestingly shows that by increasing the columns' length from 6 m to 10 m, the settlements values, especially at top of the columns, have decreased very slightly.

Figure 8 illustrates maximum bulging values for the stone column groups with different lengths of the columns. It is obvious that the central columns suffer less bulging, as a result of confinement due to the presence of the adjacent columns. Bulging of the columns is caused due to increases of average vertical stresses within the stone columns. With increasing of the column's length, the amount of exerted load to the tip of the columns decreases and as a result, the average vertical stress within the columns decreases; as a result, the bulging of the columns decreases; this issue is presented clearly in Figure 9.

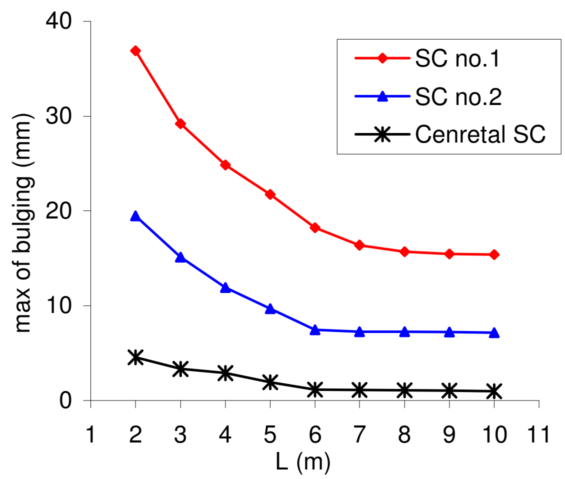

Fig 8- Bulging in the columns with different length (Figure 3 is the reference)

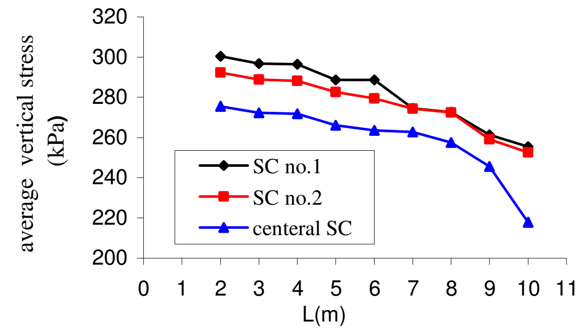

Fig 9- Average vertical stress versus stone columns length (Figure 3 is the reference)

The decrease of the average vertical stress results in the decrease of columns bulging and their deformation. In other words, the amount of bulging in a column indicates the amount of load transferred to it.

With an attention to the fact that the central columns (compared with the side columns) suffer less bulging, one can come to the conclusion that the transmitted loads to the central columns are less than those to the side columns. Therefore, we can take into consideration that the length of the central columns may be designed shorter than the side columns, without causing any increase in the total settlement.

2.2.2 Design implications

In order to evaluate the above notion, two types of numerical analyses on a number of hypothetical stone column groups with varying columns length were carried out. In the first type of analysis, with assuming equal settlement, consumption of minimum total volume of materials for the columns was aimed. In the second type of analyses, assuming equal total volume of materials for the stone columns, the aim was to reach a minimum settlement.

In the first type, the analyses were carried out on a stone column group once with two end-bearing side columns, as shown in Figure 10, and then assuming all columns floating, as shown in Figure 11.

The geometrical specifications of the stone columns in the first type of analyses are presented in Table 3. Mechanical parameters of the columns and the parent soil materials are the same as presented in Table 2.

Table 3. Geometrical Specifications of column's group

Type of Column's Group	Length of SC[1] No.1 (m)	Length of SC No.2 (m)	Length of central SC (m)
1	10	10	10
2	10	9	8
3	10	8	7
4	10	7	6

[1]SC= Stone Column

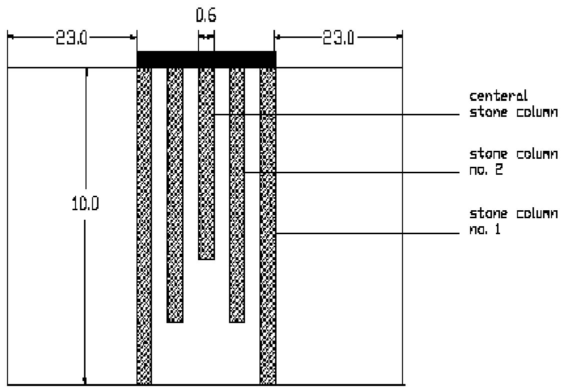

Fig 10- Stone column group with unequal length (end bearing side columns)

The second type of analysis was performed in recognition of stone columns' material with the same total volume, but with different arrangements in terms of the columns' length. In the second type, the analyses were carried out only on floating stone column groups, as shown in Figure 11.

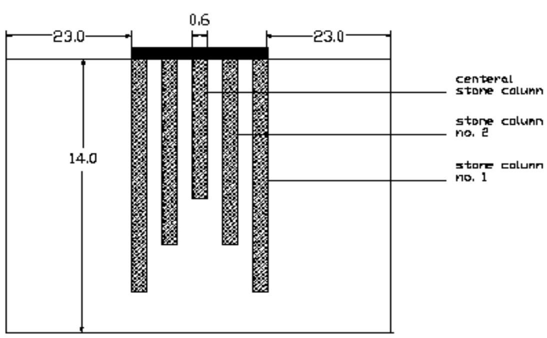

Fig 11- Stone column group with unequal length (all floating columns)

The results of the analyses in the form of columns' settlements for the four type of column's group of Table 3 are shown in Figure 12. This figure indicates that by reducing the length of the central columns (central sc and sc No.2), the settlement of the footing increases. Figure 12 also shows that this increase is less for the group of stone columns with end-bearing side columns. It is of interest that for the latter, the settlements of the columns arrangement of group No.1 and group No.2 are almost the same. In the stone column group No.2, the central columns are 9 m and 8 m long; while in the stone column group No.1, all columns are 10 m long. It means that the lengths of the stone columns could be unequal (i.e., inside columns be shorter), without causing any tangible increase in the settlement of the columns group.

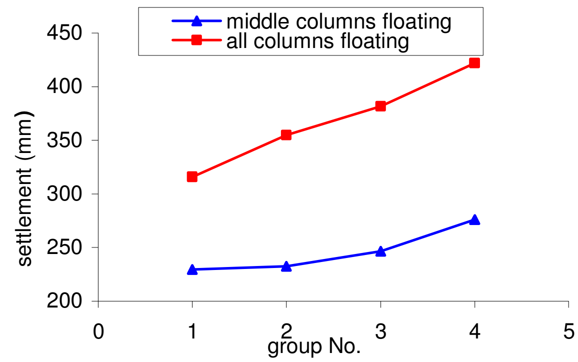

Fig 12- Column's settlement versus the type of column's group

Nine series of analyses on the floating stone column groups, based on the geometrical specifications of Table 4 and mechanical specifications of the materials of Table 2, were carried out; the only exception was E of stone columns materials which here was 90MPa, instead of 30MPa. As mentioned, the total volume of materials for the stone columns is equal for all the stone column groups of Table 4. The load of 90 KN/m^2 during 100 increments was applied through a rigid footing.

The results of these analyses in the form of raft and columns settlement versus the type of columns group (based on Table 4) is shown in Figure 13. Figure 13 indicates that the settlement of the column group depends on the columns configuration. This figure also shows that the column's settlement in group 6, in which lengths of the columns are unequal, is less than their settlement in group 1, in which lengths of the columns are all equal (8 m). Therefore, one may conclude that group 6 is preferred from a low settlement point of view. On the basis of the above results and comparison, one may suggest optimization of the columns length and arrangement in designing of stone column groups.

Also the results show that settlements in groups 7, 8 and 9 are comparatively high. The reason can be the existence of comparatively shorter central stone columns in groups 7 and 8 and missing of central column in group 9.

Table 4- Geometrical specifications of column’s group

Type of Column’s Group	Length of SC[1] No.1 (m)	Length of SC No.2 (m)	Length of central SC (m)
1	8	8	8
2	8.5	8	7
3	9	8	6
4	9.5	8	5
5	10	8	4
6	10.5	8	3
7	11	8	2
8	11.5	8	1
9	12	8	-

[1] SC= Stone Column

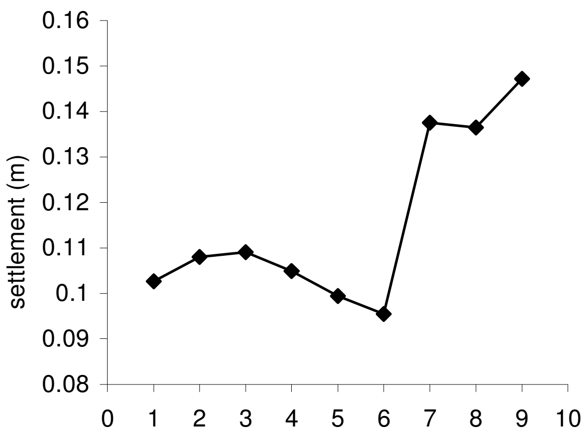

Fig 13- Columns settlement versus the type of columns group

3 CONCLUSION

The results of the numerical analyses show that:

– Bulging occurs in the upper parts of the columns, between 2D to 4D from the top, and that bulging is comparatively higher for the side columns. The columns' bulging are caused due to the increase of average vertical stresses in stone column's length. With increasing of the column's length, the amount of exerted load to the tip of the columns decreases and as a result, the average vertical stress within the columns decreases. The decreasing of average of vertical stress results in the decreasing of columns maximum bulging and their deformation. It is clearly obvious that central columns as a result of confinement stress resulted from the adjacent columns, have less bulging.

– The top and tip of columns settlements decrease by increasing of the columns length.

– The lengths of the stone columns in a group could be designed unequal, i.e., inside columns is shorter, without increasing settlements of the column group.

– Also in recognition of constant volume of stone columns materials, the numerical analyses showed that columns length in a group can be designed optimally to minimize the ground settlement.

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