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# THREE-DIMENSIONAL MODELING OF A GROUP OF STONE COLUMNS IN "BOUREGREG VALLEY" SOFT GROUND

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## ABSTRACT

With the evolution of computer technology in geosciences, finite element modeling can be easily applied to the treated areas by stone columns, which are a method of improving the soil having low geotechnical properties and likely to deform significantly under load action , by incorporating granular material (commonly called ballast) compacted by remounting passes. This numerical modeling is a simple and effective alternative to approach the real behavior of soils reinforced by stone columns, it allows settlement analysis, lateral deformation, vertical and horizontal stresses in order to understand the behavior of columns and soil. It also has the advantage of integrating the settlements of the underlying layers, especially those of least resistance. This paper aims to study the behavior of column groups by establishing the relationship between the columns spacing, columns properties, columns length and the settlement improvement. Based on the finite element modeling of the "ground / Columns" and taking as a case study the reinforcement of "Bouregreg Valley" ground.

**Keywords:** finite element, groups, columns, modeling.

## INTRODUCTION

The increasing use of floor surfaces available, sometimes with weak mechanical characteristics and low bearing capacity, poses a real challenge for the geotechnical to overcome these defects [9]. Various soil-building techniques have been developed and applied over the last years ; stone columns are used as a soil-improvement technique to reduce settlement and to increase the bearing capacity of foundations on soft clay soil, the benefits arise from the fact that there is a partial replacement of the compressible soil by a more competent material (compacted stone aggregates). Moreover the stone columns are highly permeable and act as vertical drains facilitating consolidation of the soft soil improving the performance of the foundation.

The paper presents, in the first part, soil conditions and the parameters associated with columns, is then presented 3D finite element analyses that study the performance of groups of stone columns [3].

Wehr (1999) and Muir Wood *et al* (2000) studied the performance of the column groups ballasted using finite element analysis [10-2-1]. To clarify the most important parameters and the influence of the number of columns and their position, 3D numerical analyses using the "Plaxis 3D Foundation" software were carried out, the study presents the finite element (numerical) models, the parametric study and their results.

## SITE CHARACTERISATION AND COLUMNS PROPRETIES:

A campaign for recognition was implemented at the site of the "Bouregreg valley".

**Figure-1.** Soil reinforcement of the Bouregreg valley by stone columns technique.

Core drilling, with removal intact and reshaped samples allowed making laboratory tests (identification and characterization of soils) and establishing a detailed section of land. Pressumeter tests were realized to determine soil pressumeter characteristics [12].

These tests show that up to 11m generally there are soft clay formations low consistent and that beyond this depth we have consistent sand.

**Figure-2.** Removal of intact and altered samples for laboratory tests.

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We are interested in this layer of low geotechnical properties, its characteristics are as follows:

$\gamma$=18 kN /m$^3$, E= 2585 kPa, $\phi$=15°, c=25 kPa and $\nu$=0,33.

For the calculation of Young's modulus, the following formulas are used:

$E = E_{oed} \frac{(1-2\nu)(1+\nu)}{1-\nu}$ With $\nu$ : poisson's ratio and $E_{oed}$ : œdometric modulus calculated based on the pressuremeter modulus by the relationship: $E_{oed} = \frac{E_M}{\alpha}$ in which $\alpha$ is a rheological coefficient that depends on the type of soil and the limit pressure.

Due to low geotechnical propreties of the soil, it is absolutely necessary to treat this soil by stone columns technique of improvement.

We have performed a series of three-dimensional modeling of stone columns with isolated column in the center and then to column groups, using the PLAXIS 3DF software [4].

## NUMERICAL MODEL OF AN ISOLATED COLUMN

The finite element method is a powerful tool for analyzing complex engineering problems, Plaxis 3DF is a three-dimensional FE program which is ideal for capturing the complex behavior of groups of stone columns.

The interactions between the different columns of groups and those between soil and columns have been detailed. The effects of columns spacing and length on the efficiency of groups were considered, and parametric studies were performed.

In accordance with standard practice for numerical modeling of stone columns, column-soil interface elements are not used (Shabu and Reddy, 2011) [13].

A uniform vertical pressure of P=100 kPa is applied on the rigid square footing, the ground water level is at the surface ($\gamma$w=10 kN/m3).

We discuss in this part the behavior of an isolated column. For this, we take a soil mass with dimensions (36mx36mx10,5m). The column follows the linear-elastic constitutive rule while the soil follows the Mohr coulomb one. Typical values of Ec=70 MPa, $\phi_c$ =45°and $\psi_c$ =15° were chosen.

As a first approach (for the isolated column model), the footing width (B=s), and the column diameter, dc=0,8m, The column is considered to reach consistent soil, and it has a length of 10.5m (L=H).

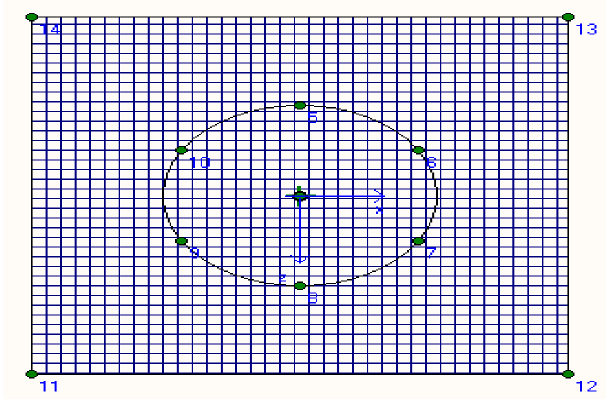


**Figure-3.** Numerical modeling (Plaxis 3DF) of an isolated stone column.

## COMPARISON OF FINITE ELEMENT AND ANALYTICAL METHODS (SETTLEMENT IMPROVEMENT FACTOR)

This section analyses the settlement performance of an isolated column, which is determined by The settlement improvement factor, $\beta$, that factor of end bearing stone column deducted from Plaxis 3DF [4] analyses is compared with various analytical methods. $\beta$ is defined as the ratio of the settlement of an untreated soil to that of treated soil. That factor corresponds to the application of a 100 kPa uniform pressure.

The area ratio is defined as the ratio of the footing area (A) to the area of the column beneath the footing:

$\frac{A}{A_c} = \frac{B^2}{\pi {R_c}^2} = \frac{s^2}{\pi {R_c}^2}$ With

B: rigid footing width

s: column spacing

Rc: the radius of the column

In this part the area ratio is varied from 2 to 18 while varying the width of the rigid footing B ( B=s ) from 1m to 3m, we obtain variations in the settlement improvement factor, as shown in the following figure.

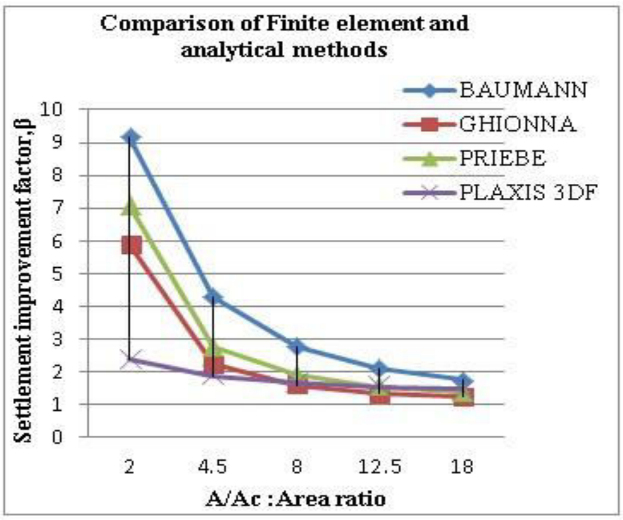


**Figure-4.** Comparison of finite element (Plaxis 3DF) and analytical methods.

The graphs (Figure.2) illustrate for different values of area ratio the settlement improvement factor, β estimated by different analytical methods: Priebe (1995), Baumann and Bauer (1974), Ghionna and Jamiolkowski (1981). For the same data as the 3D numerical modeling [5-15-16].

The examination of the results permits to note:

The 3D numerical model leads to values of β between 1,47 et 2,38 for 2<A/Ac<18.

For low area ratio, the results obtained by numerical method move away from those obtained by analytical methods.

For 8<A/Ac<18, The calculation by the method of Priebe and Ghionna gives values close to those obtained by the numerical calculation.

It can be seen in figure.2 that Baumann and Bauer over estimate β values, which due to the fact that the method of Baumann and Bauer (1974) has a weaker theoretical basis than Priebe and is believed to give poorer settlement predictions for clayey soils (Slocombe, 2001) [5-15-14].

This analyzes give early confidence in the ability of Plaxis 3D foundation to capture stone column behavior.

## NUMERICAL ANALYSES OF A GROUP OF COLUMNS

The numerical modeling of a group of stone columns has predominantly been the focus of several studies: Shahu and reddy (2011) , Wehr (1999) and Muir Wood *et al* (2000) investigated the performance of groups of stone columns using finite-element analysis, and Kaliakin *et al.* (2012) conducted a numerical model to study the behavior of stone columns in soft soil [13-2-10-17].

The parametric study was carried out varying several properties:

- Column position
- Material properties : The friction angle of the column from 40° to 50°, the modular ratio Ec/Es =20/28/40, the column and the soil behavior rule( linear-elastic and Mohr coulomb behavior rules )
- Geometric factors: L/B, L/dc, L/H (L: the length of the columns, H: soil layer thickness, B: square rigid footing width, dc: column diameter)
- For a finite group of columns, the area ratio is defined as the ratio of the footing area (A) to the area of the column beneath the footing:

$$\frac{A}{A_c} = \frac{B^2}{N\pi {R_c}^2}$$

With N: number of columns

- **The effects of columns position and properties**

This parametric study aims to show the effects of columns spacing, or more specifically, the relative position of the columns. Considering a group of four columns (rectangular mesh). The load is applied on the square rigid footing B = 4,5m and the spacing between the columns is varied: s = 1m /2 m/ 2,5m /3m. Keeping constant A/Ac =8,33 (η=12%), so Rc= 0,44m. The settlements of the group of 4 columns are compared with the settlement of the untreated soil.

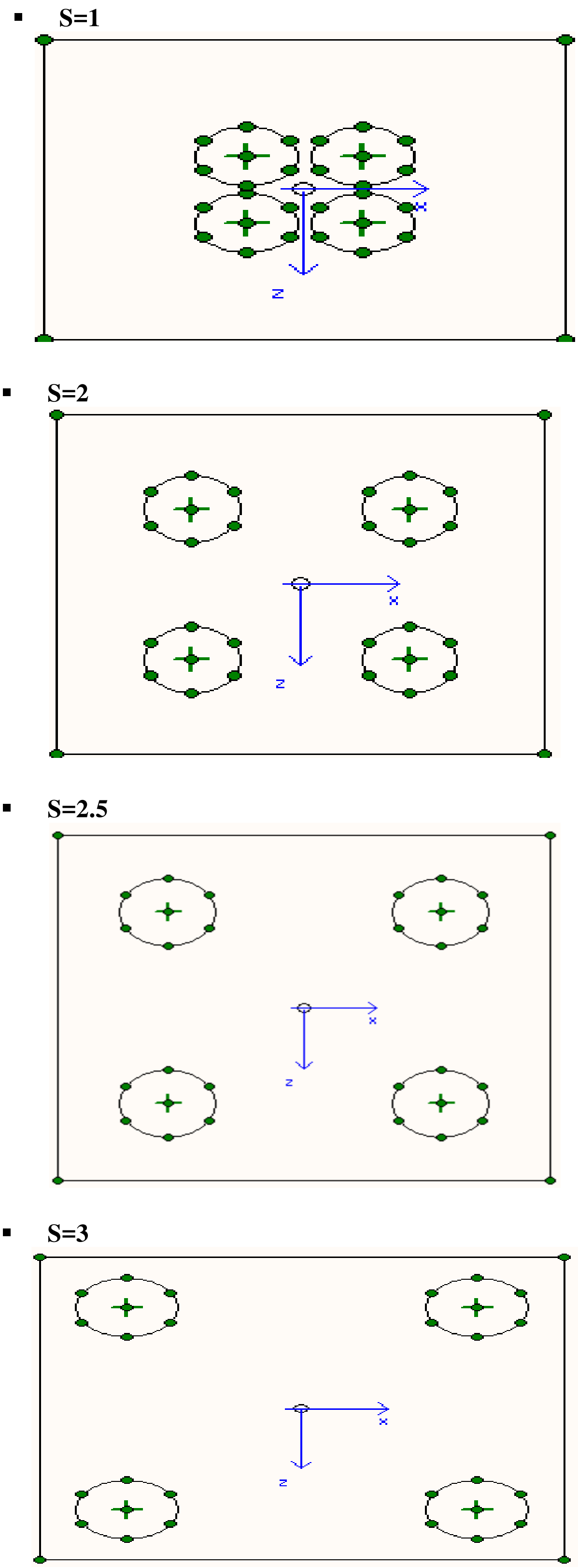


**Figure-5.** The variation of the columns spacing for a rectangular mesh.

- **Columns and the soil behavior rules**

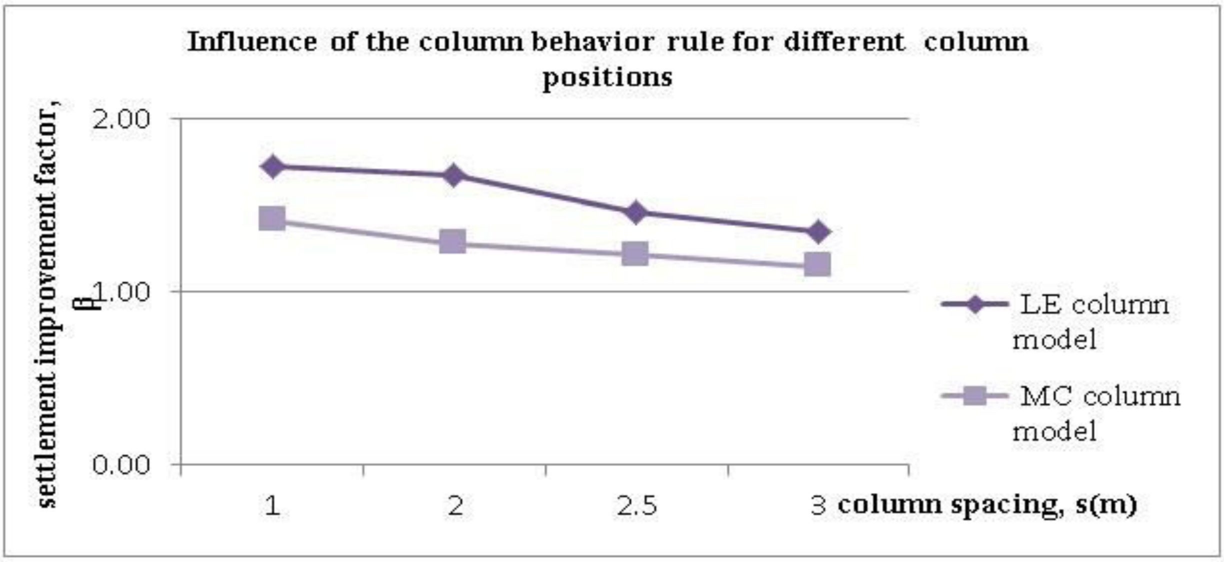


**Figure-6.** The effects of the columns behavior rule and their spacing.

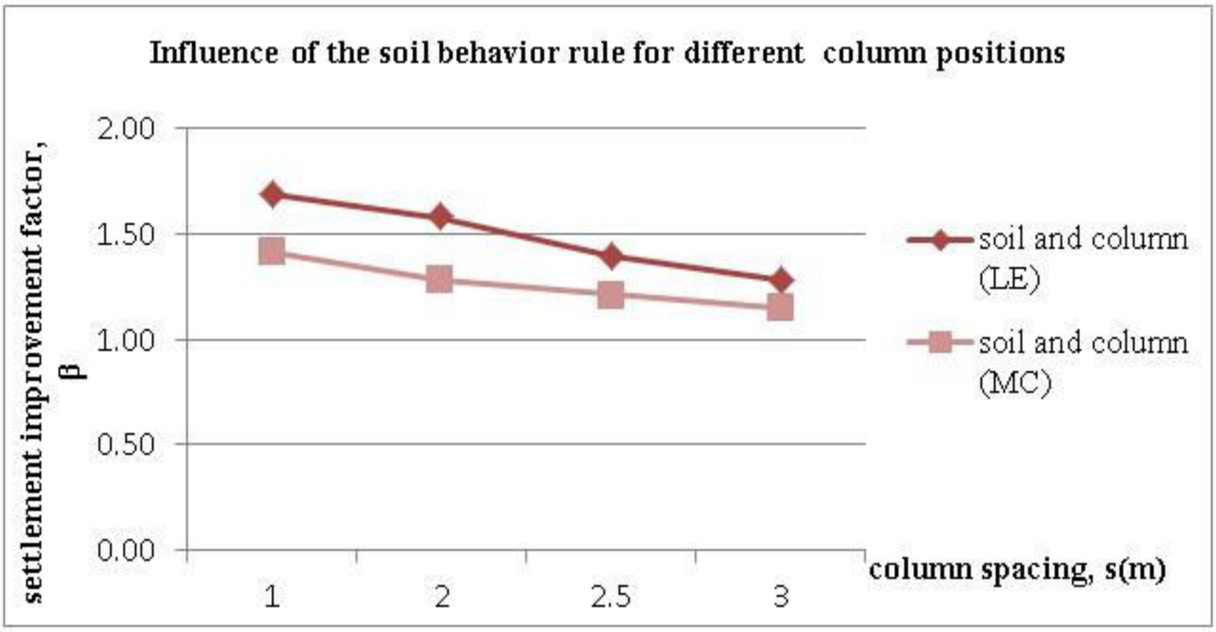


**Figure-7.** The effects of the soil behavior rule and the columns spacing.

- **Friction angle**

**Table-1.** The influence of the column friction and the columns spacing.

| s(m) : spacing | Settlement improvement factor β | | |
|---|---|---|---|
| | Φ=40° | Φ=45° | Φ=50° |
| 1 | 1,32 | 1,41 | 1,53 |
| 2 | 1,19 | 1,28 | 1,37 |
| 2,5 | 1,15 | 1,21 | 1,29 |
| 3 | 1,10 | 1,15 | 1,20 |

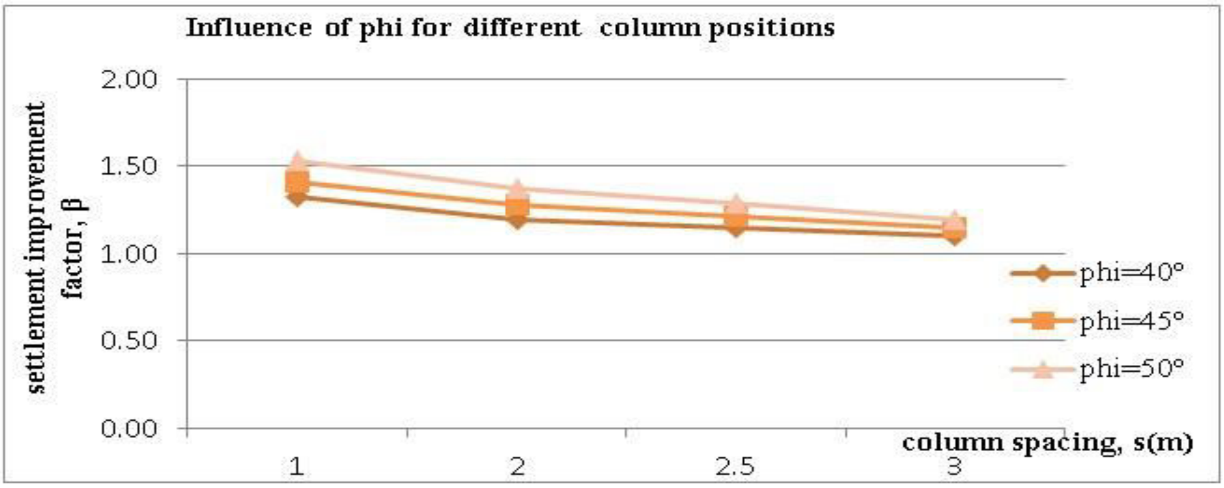


**Figure-8.** The effects of the Internal friction angle of columns and their spacing.

- **The modular ratio**

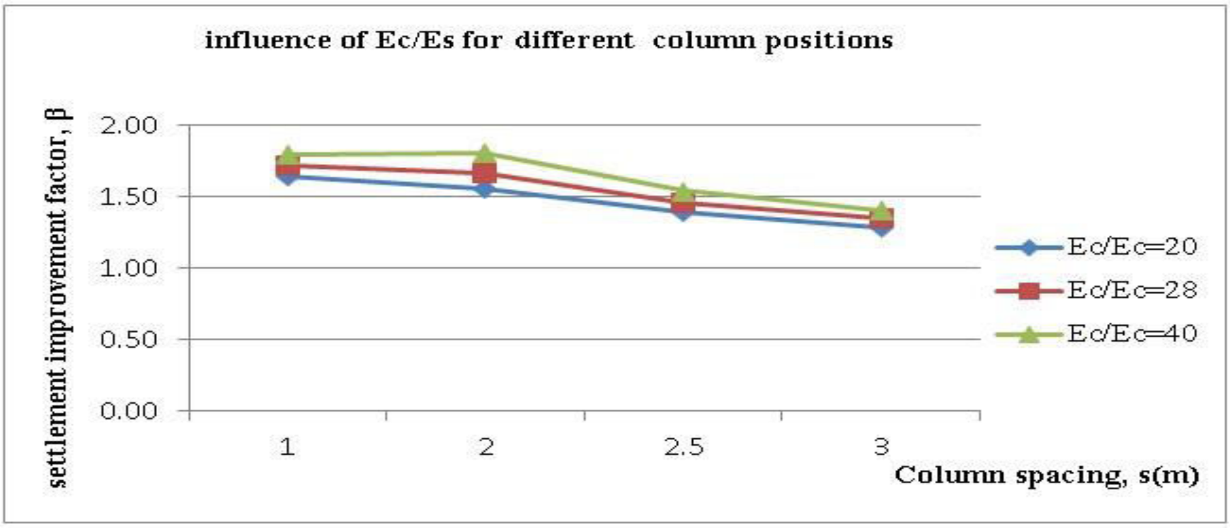


**Figure-9.** The effects of the columns modular ratio and their spacing.

- **The normalised column length (L/B)**

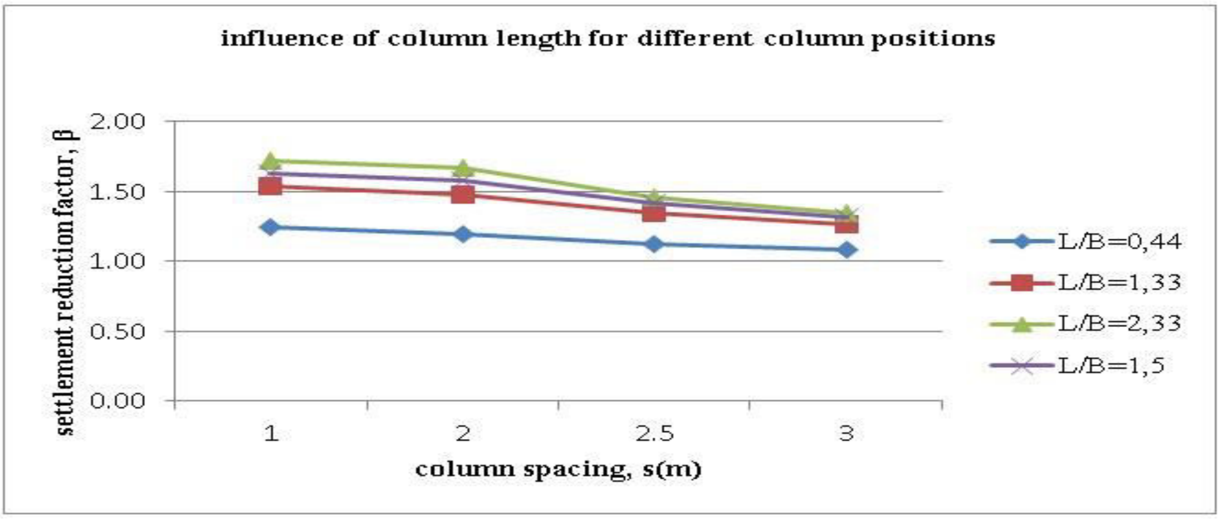


**Figure-10.** Influence of column length for different column positions.

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- **The L/dc ratio**

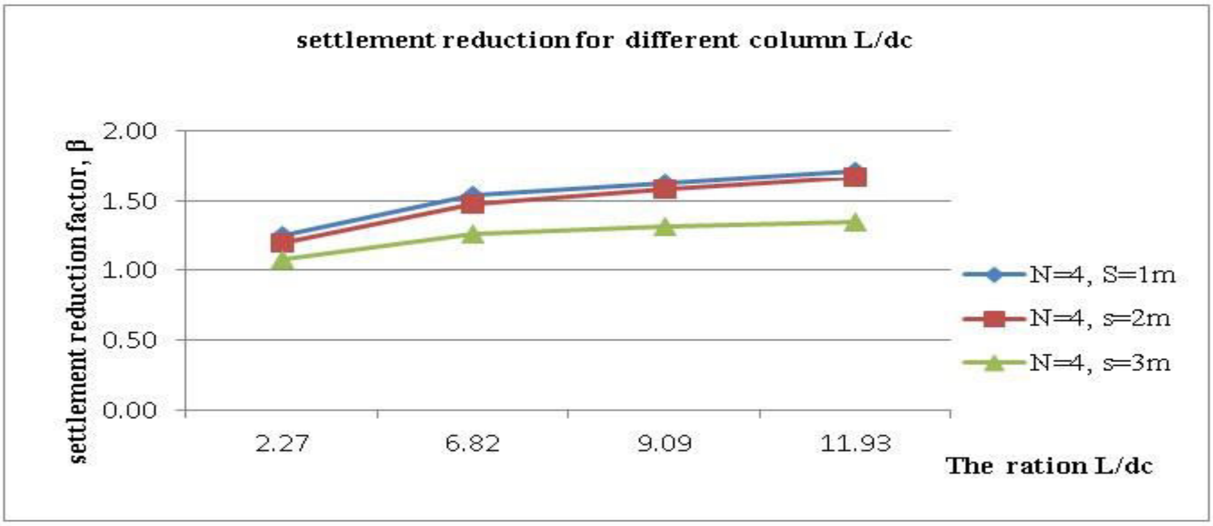


**Figure-11.** Settlement reduction for different column L/dc.

- **The effects of floating columns (L/H)**

**Table-2.**The influence of columns spacing and the L/H ratio.

| L/H | 0,19 | 0,57 | 0,76 | 1,00 |
|---|---|---|---|---|
| s=1m | 106,15 | 86,08 | 81,62 | 77,22 |
| s=2m | 110,74 | 89,54 | 83,78 | 79,57 |
| s=2,5m | 117,76 | 98,68 | 93,85 | 90,76 |
| s=3m | 122,27 | 104,74 | 100,95 | 98,46 |

## RESULTS AND DISCUSSIONS

- **The effects of columns position and properties**

**For columns and the soil behavior rules:**

The graphs (Figure-6 and Figure-7) illustrate for different values of column spacing, the settlement improvement factor, β for the two behavior rules (Mohr coulomb and linear elastic models).

For the first case (changing column behavior law):

- The linear elastic model of the column leads to values of β between 1,35 et 1,72 whereas β giving by the Mohr coulomb is between 1,15 and 1,41
- The settlement improvement factor decreases when the columns are more widely spaced for the Mohr Coulomb constitutive law. While for the law of linear elastic behavior) the settlement improvement factor still very close to the same value between S = 1 and S = 2, and then starts to decrease.
- It can be seen that for s=3m with the MC behavior law the settlement approaches 1 (contrary to the linear elastic model), so if the column spacing exceeds this value, the settlement increases excessively and the reinforcement is not beneficial.
- For the second case (changing soil behavior law):
- The settlement improvement factor decreases with increasing spacing for the two behavior laws.

The both graphs reach approximately the same value for high spacing values and away for small values.

**For the friction angle:** The table-1 and the graphs (Figure-8) illustrate for different values of column spacing, the settlement improvement factor, β for different values of Φ (40°/45°/50°)

- We observe that the increasing in the internal friction angle of the ballast, increases the settlement reduction.
- The settlement increases when the columns are widely spaced for all values of the internal friction angle of the ballast.
- The graphs reach the same values at high column spacing, so the increasing of ballast friction angle has no effects for high values of column spacing (near the edges of the footing).

**For the modular ratio:** The graphs (Figure-9) illustrate for different values of column spacing, the settlement improvement factor, β for different values of Ec/Es (20/28/ 40).

- Increasing the column stiffness and strength increases β values.
- The graphs reach the same values at high and low column spacing, so the increasing of column stiffness has no effects for low and high column spacing (in center and near the edges of footing). So uniformly distributed columns are slightly more beneficial.

- **The effects of column length**

Various column lengths were considered which allows studying the effect of floating columns using L/H term.

For floating columns, the column spacing is more relevant than for end bearing columns because the soil layer beneath columns is not improved, so it's able to deform due to the penetration of the columns into the underlying soil.

The graphs (Figure-10 and Figure-11) and the table-2 illustrate for different values of column spacing, the settlement improvement factor, β for different values of L/H,L/B and L/dc.

The examination of the results permits to note:

- It can be seen that Increasing the column length (L/B,L/dc, L/H) increases the settlement improvement factor (β) values.
- We observe that from a certain value of the ratio (L/B, L/dc), the settlement improvement factor (β) increases so negligently(still around a same value) that joined the notion of the critical length; as a result , when floating columns reach the critical length, their behavior is similar to end-bearing columns. This value is suggested as 4 to 6 times the pile diameter Hughes and Withers, 1974, Mckelvey *et al*,2004, Black *et al* 2007, and Najjaar *et al* 2010 [11-8-6-7].

## CONCLUSIONS

The finite element method is a powerful tool for analyzing complex engineering problems specialy the case of finite groups of columns beneath rigid footing. The settlement performance of various configurations of columns beneath rigid square footing is examined in this study.

The Comparison of Plaxis 3DF and analytical methods in the case of isolated column gives early confidence in the ability of Plaxis 3D foundation to capture stone column behavior.

For a group of four columns, the parametric study was carried out varying several properties: Column position, material properties: The friction angle, the modular ratio Ec/Es, the column and the soil behavior rule (linear-elastic and Mohr coulomb behavior rules) and the geometric factors: L/B, L/dc, L/H.

Increasing the column material properties (stiffness, friction angle) increases the settlement reduction factor, the influence of these parameters is related to the column arrangement (column position), and to the behavior law following by both columns and soils.

To study the effect of floating columns, various column lengths were considered. In this case the column spacing is more relevant and when floating columns reach the critical length, their behavior is similar to end-bearing columns. This value is suggested by literature as 4 to 6 times the pile diameter.

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