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Numerical analyses of the optimum length of stone columns and their encasements

Analyses numériques de la longueur optimale des colonnes ballastées et de leurs enveloppes géotextiles

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ABSTRACT: Stone columns are vertical inclusions in soft soils formed by gravel. In very soft soils, they may be wrapped typically with a geotextile to increase its lateral capacity. In the latter case, they are usually named encased stone columns. Their critical or optimum length may be defined as the one where further lengthening of the column provides a negligible improvement and it is therefore not cost-effective to build columns longer than it. Besides, for encased stone columns, the optimum length of the encasement is also relevant. In previous finite element analyses, the authors have studied the column and encasement critical length considering a uniform soft soil layer with a linear elastic perfectly plastic behaviour for simplicity. For those cases, the optimum column length is around 1.5-2.0 times the footing diameter for encased stone columns, and slightly lower for ordinary stone columns, namely around 1.5. These critical lengths should be related to the loaded area and not to the column diameter. Here, the authors extend those previous analyses using a constitutive model that considers a stress-dependent soil stiffness, namely the Hardening Soil model. The results are very similar, but columns are slightly more effective when considering stress-dependent stiffness and the optimum column length is slightly lower. Finally, the critical length of the encasement is found to be slightly lower than the critical column length.

RÉSUMÉ: Les colonnes ballastées sont des inclusions verticales dans les sols mous, composées de gravier. Dans les sols très mous, elles peuvent être enveloppées dans un géotextile pour augmenter leur capacité latérale. Dans ce dernier cas, elles sont généralement appelées colonnes ballastées enveloppées. Leur longueur critique ou optimale peut être définie comme celle où un allongement supplémentaire de la colonne apporte une amélioration négligeable, donc il n'est pas rentable de les construire plus longues. En plus, pour les colonnes ballastées enveloppées, la longueur optimale du géotextile est également importante. Dans les analyses précédentes, les auteurs, pour simplifier, ont étudié la longueur critique de la colonne et du géotextile en considérant, une couche de sol uniforme avec un comportement élastique parfaitement plastique. Dans ces cas, la longueur optimale de la colonne est d'environ 1.5-2.0 fois le diamètre de la semelle pour les colonnes ballastées enveloppées, et légèrement inférieure pour les colonnes ballastées classiques, à savoir environ 1,5. Ces longueurs critiques devraient être liées à la surface chargée et non au diamètre de la colonne. Ici, les auteurs étendent ces analyses précédentes en utilisant un modèle de comportement du sol qui prend en compte leur rigidité en fonction des contraintes, le modèle Hardening Soil. Les résultats sont très similaires, mais les colonnes sont légèrement plus efficaces lorsque l'on considère une rigidité dépendante de la contrainte, et la longueur optimale est légèrement inférieure. Enfin, la longueur critique du géotextile est légèrement inférieure à la longueur critique de la colonne.

Keywords: Finite element analyses, encased stone columns, critical length, settlement.

1 INTRODUCTION

Ground improvement using stone columns, also known as granular piles or aggregate piers, is a widely spread technique to improve soft soils for foundation of embankments or structures (e.g. Barkdale and Bachus 1983; Kirsch and Kirsch 2010). In very soft soils, stone columns may suffer of lack of lateral confinement ($c_u \leq 5 - 15\ kPa$) (e.g., Wehr, 2006). In those cases, stone columns are usually encased with geotextiles or other geosynthetics (e.g., Alexiew and Raithel, 2015; Almeida et al., 2019)

Ordinary or encased stone columns (OSC or ESC) may reach a rigid substratum (end-bearing columns) or may be embeded just on a soft soil layer (floating columns). For the latter case, the length of the columns is an important design parameter to be chosen. In some cases, it may be more cost-effective to add additional columns than increase the length of the columns. In this way, the concept of the optimum or critical length of stone columns appear. For columns longer than the optimum length, the improvement achieved with stone columns does not notably change or increase. Although the load transfer mechanisms are different from piles, the concept of optmimum or critical length is equivalent (e.g., Fleming et al., 2009). The authors have also applied this concept to dynamic problems (Fernández-Ruiz et al., 2021).

Some existing proposals for the column critical length include those by Hughes and Withers (1974), McKelvey (2002) and Black et al. (2011), amongst others. The authors (Castro et al., 2019; Miranda et al., 2021) have analysed them and have shown that the column critical length should be expressed in terms of the footing width or diameter (B, D) because the column length to diameter ratio, L/d_c (slenderness of the column), has a minor influence (second order effect) on the ground improvement achieved with stone columns.

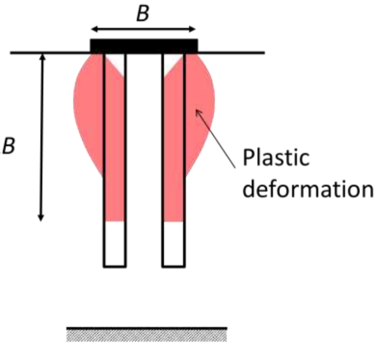

Figure 1. Justification of critical column length in a homogeneous soil layer.

Muir Wood et al. (2000) pointed out the importance of the deformation mechanism beneath the footing. Castro (2017) conceptually showed that the critical column length for bearing capacity depends on the failure mechanism and the critical column length for settlement reduction is related to the extension of the pressure bulb beneath the footing. Since the critical length is larger for settlement reduction, this is the one that is normally used. The pressure bulb is a useful concept, but it is strictly only valid for an elastic behaviour, which is not usually the case for an efficient design of OSC or ESC. The authors (Castro et al., 2019; Miranda et al., 2021) have shown that the critical column length is related to the extension of plastic deformation in the soil and column (Figure 1).

The concept of optimum column length is useful only for footings or small groups of columns because for large loaded areas (e.g., embankments), the critical length is larger than the soft soil layer thickness and then, there is no critical length in practise (e.g., Yoo, 2010).

Here, the authors extend their previous work on column critical length (Castro et al., 2019; Miranda et al., 2021), which considered a simple linear elastic perfectly plastic model ("Mohr-Coulomb", M-C) to reproduce the soil and column behaviour, to cases where a more advanced constitutive model is used to reproduce the soil behaviour, namely the Hardening Soil Model (HSM) (Schanz et al., 1999).

2 NUMERICAL MODEL

The finite element code Plaxis 2D 2023 (Brinkgreve et al., 2023) was used to represent a simplified 2D axisymmetric model of only one centred column beneath a rigid circular footing (Figure 2). This is the same 2D simplified model used in previous analyses by the authors (Castro et al., 2019; Miranda et al., 2021) and provides similar values of the footing settlement than those of a full 3D model of a group of columns with the same area replacement ratio and the same encasement stiffness to column diameter ratio (J_g/d_c). The area replacement ratio (a_r) is the ratio between the area of the columns and the loaded area.

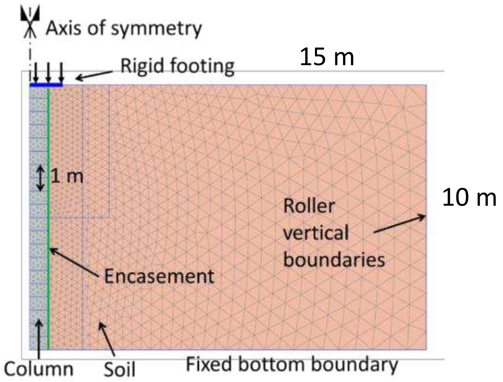

Figure 2. Numerical model and finite element mesh.

As a starting point, the same reference case as in previous analyses was used. The footing diameter, D, was 2.5 m and the column diameter (d_c=1.37 m) was chosen to give an area replacement ratio of a_r=30%. The soil profile was simplified to only one homogeneous soil layer, with a thickness of H=10 m (Fig. 2). The rigid footing was assumed as perfectly rough and modelled as a very stiff plate (EA = 10^{10} kN/m and EI = 10^{12} kN m^2/m) that produces uniform settlements. Drained conditions were assumed for all the process, i.e. no excess pore pressures were generated. Geostatic initial stresses were generated using the effective soil unit weight (γ') and the coefficient of lateral earth pressure at rest, K_0=0.6. For simplicity, the ground water level was assumed to be at the ground surface and an effective unit weight of γ'=10 kN/m^3 for soil and column was directly considered without modelling pore water pressures. The applied pressure on the footing, p_{app}, was 100 kPa.

The column length was varied from L =10 m (end-bearing column, L/H=1) to L=0 m (no column) in steps of 0.5 m (Figure 2). The critical column length was identified from the variation of the settlement reduction factor with the column length. The settlement reduction factor (β) is the ratio between the settlement with columns and the settlement without columns (s_z/s_{z0}). Some mesh sensitivity (of around 3%) was observed between different cases, but the same mesh was used to identify each critical column length, i.e. for each case with different column lengths.

Table 1. Column and soil parameters using M-C.

Material	***E*** (MPa)	***ν*** (-)	***c*** (kPa)	***ϕ*** (º)	***ψ*** (º)
Soil	2	0.33	5	25	0
Column	30	0.33	0.1	45	10

In previous analyses (Castro et al., 2019; Miranda et al., 2021), the soil and column were modelled using the M-C model (Table 1). Here, the column constitutive model and parameters were kept, but the soil is modelled using the HSM to be able to reproduce, for example, its stress-dependant stiffness. A reasonable common set of parameters that gives a similar settlement as in previous calculations was adjusted (Table 2). The reference pressure for the stiffnesses values is p_{ref}=100 kPa. Since stone columns are commonly employed in clays, the stress-dependant stiffness parameter was chosen equal to m=1 (oedometric behaviour).

Table 2. Soil parameters using HSM.

E_{50}^{ref} (MPa)	E_{oed}^{ref} (MPa)	E_{ur}^{ref} (MPa)	ν_{ur} (-)	***c*** (kPa)	***ϕ*** (º)	***ψ*** (º)
8.7	8.7	26.1	0.2	5	25	0

3 NUMERICAL RESULTS

3.1 Influence of soil constitutive model

The results of the non-encased case for different a_r values are summarized in Figure 3. The value of a_r was varied by varying the column diameter. The settlements without column for the MC and HSM are the same and equal to 121 mm because the HSM stiffness parameters (Table 2) were calibrated to provide the same settlement. With column, the settlement reduction factor is slightly lower for the HSM than for the MC model because columns are more effective in a soil which stiffness increases with depth, than for a uniform stiffness, even more for short columns and large area replacement ratios.

The column optimum length is approximately indicated around 1.5D because the settlement reduction beyond that depth is negligible. A detailed analysis indicates that the column optimum length slightly decreases for larger values of a_r and for the HSM.

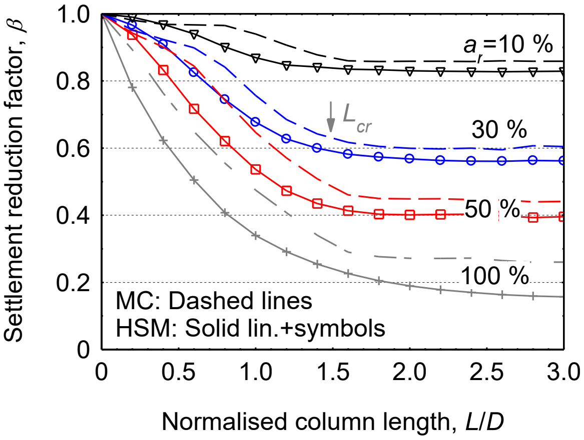

Figure 3. Settlement reduction factor for different column lengths, area replacement ratios and soil constitutive models.

3.2 Encasement critical length

Here, the numerical results considering an encasement with a circumferential stiffness of 0.5, 2 or 5 MN/ml are presented. A null Poisson's ratio is assumed for the geosynthetic encasement (ν_g=0) because it is assumed to have two major directions (radial and longitudinal), which behave independently.

Just as there may exist a column optimum length, there may exist an encasement optimum length. To systematically analyze them, both the column and the encasement lengths were varied (please, refer to Miranda et al., 2021 for details).

Table 3. Values of optimum column and encasement length for different area replacement ratios and geotextile encasement stiffnesses.

J **(MN/ml)**	***a_r*=10%**	***a_r*=30%**	***a_r*=50%**
0.5	1.7D / 1.4D	1.6D / 1.3D	1.5D / 1.1D
2	1.8D / 1.5D	1.7D / 1.3D	1.6D / 1.1D
5	2.0D / 1.7D	1.8D / 1.3D	1.6D / 1.2D

The optimum column and encasement lengths for different a_r and J values are summarized in Table 3. It may be observed that the optimum encasement length slightly increases with higher geotextile stiffnesses, as the applied load is transmitted deeper. On the other hand, the critical encasement length reduces with the increment of a_r. Both trends are similar to the ones of the optimum column length (Table 3), but the values of the optimum encasement length are slightly lower. Therefore, from these numerical analyses, the optimum encasement length is slightly lower than the critical column length. Leaving the column tip without encasement could also contribute to create an enlarge column tip (Dash and Bora, 2013), whose effect has not been considered in the presented numerical simulations. On the other hand, leaving the column tip without encasement has disadvantages for the column construction process and consequently, it is not generally cost-effective. Thus, encasing the full column length is usually the best option. When partial encasement could be calculated as beneficial (e.g. Murugesan and Rajagopal, 2006), it will be more economical in most cases to reduce the whole column length and keep the full encasement of the column.

4 CONCLUSIONS

Previous analyses by the authors of the optimum column length are here extended using a constitutive model that considers a stress-dependent soil stiffness, namely the Hardening Soil model. The results show that the optimum column length for the analyzed cases (without encasement) is around 1.5 times the footing diameter (loaded area). Besides, the column optimum length slightly decreases for larger values of a_r and for the HSM when compared with the cases using the MC model. Finally, the critical length of the encasement is found to be slightly lower than the critical column length.

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