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Groups of encased stone columns: Influence of column length and arrangement

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ABSTRACT

This paper presents a set of systematic 2D and 3D finite element analyses that study the performance of groups of encased stone columns beneath a rigid footing. Those numerical analyses show that, if the area replacement ratio, i.e. area of the columns over area of the footing, and the ratio of encasement stiffness to column diameter are kept constant, the column arrangement (both number of columns and column position) has a small influence on the settlement reduction achieved with the treatment. For high encasement stiffnesses, placing the column near the footing edges may be slightly more beneficial reducing the settlement; on the contrary, the maximum hoop force at the encasement is notably higher. Based on the minor influence of column arrangement, this paper proposes a new simplified approach to study groups of encased stone columns, which involves converting all the columns of the group beneath the footing in just one central column with an equivalent area and encasement stiffness. This simplified model is used to conclude that, for settlement reduction and fully encased columns in a homogeneous soil, there is a column critical length of around two or three times the footing width. The critical length of the encasement for partially encased columns is slightly lower than that of the fully encased columns.

1. Introduction

Ground improvement using stone columns is a popular technique for foundation of embankments or structures on soft soils. Stone columns are vertical boreholes in the ground, filled upwards with gravel compacted by means of a vibrator. The inclusion of gravel, which has a higher strength, stiffness and permeability than the natural soft soil, improves the bearing capacity of the soft foundation thus enhancing stability of the embankments, reduces total and differential settlements, accelerates soil consolidation and reduces the liquefaction potential (e.g. Barksdale and Bachus, 1983).

Stone columns may not be appropriate in very soft soils that do not provide enough lateral confinement to the columns. In those cases, a proper shape of the column cannot be ensured during installation and excessive deformation is expected upon loading. An undrained shear strength of the soft soil of around 5–15 kPa (Wehr, 2006) is generally adopted as the limit value to define stone column feasibility. To increase the lateral confinement of the columns, and consequently, their vertical capacity, encasing the columns with geotextiles or other geosynthetics has been a successful solution in recent years (Alexiew and Raithel, 2015). Using horizontal geosynthetic disks placed in regular vertical intervals through the column length has also shown to be an efficient alternative (e.g. Ali et al., 2012, 2014; Hosseinpour et al., 2014; Sharma et al., 2004).

Stone columns and encased stone columns (ESC) are typically employed under embankments or large uniformly loaded areas (e.g. Almeida et al., 2015; Chen et al., 2015; Fattah et al., 2016; Yoo, 2016). In those cases, columns are distributed in a large regular mesh and the problem is usually simplified to a “unit cell”, i.e. only one granular column, its encasement, if present, and the corresponding surrounding soil. The large number of columns justifies symmetry boundary conditions. So, the lateral boundary of the “unit cell” is rigid, frictionless and shear free. The simplicity of the model allows for analytical solutions that provide the settlement reduction (e.g. Priebe, 1995; Raithel and Kempfert, 2000; Pulko et al., 2011; Castro and Sagaseta, 2013).

More recently, stone columns have also been deployed beneath small isolated pad or strip footings at low or moderate loading conditions (e.g. Watts et al., 2000). Several authors (e.g. Wood et al., 2000; Castro, 2014) have studied the bearing capacity and

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Notation

a_r	Area replacement ratio: $a_r = A_c/A_l$
c	Cohesion
c_u	Undrained shear strength
d_c	Column diameter
K_0	Coefficient of lateral earth pressure at rest
p_a	Uniform applied vertical pressure
p'_0	Initial mean effective stress
r	Radius
s	Centre-to-centre column spacing
s_x, s_y	Horizontal displacement
s_z	Settlement
s_{z0}	Settlement without columns
x,y,z	Cartesian coordinates
A	Cross-sectional area
B	Footing width
E	Young's modulus
E_{oed}	Oedometric (confined) modulus
F_g	Tensile hoop force at the encasement
H	Soft soil layer thickness
J_g	Encasement stiffness
L	Length
N	Number of columns in the group
β	Settlement reduction factor: $\beta = s_z/s_{z0}$
γ'	Effective unit weight
ε	Strain
ν	Poisson's ratio
σ	Stress
ϕ	Friction angle
ψ	Dilatancy angle

Subscripts

c,s,g,l	column, soil, encasement, loaded area
x,y,z	Cartesian coordinates

deformations of these groups of stone columns. The columns under pad or strip footings may also be encased, if necessary, forming groups of ESC. However, there is little information about the performance of these groups of ESC (Murugesan and Rajagopal, 2010; Raithel et al., 2011; Keykhosropur et al., 2012) as most studies focus on the behaviour of single ESC (e.g. Malarvizhi and Ilamparuthi, 2007) or very large groups, analysing only a "unit cell" (e.g. Lo et al., 2010). To the best of the author's knowledge, there is no published research on the influence of the arrangement of ESC, i.e. number of columns and column position, beneath a rigid footing. Besides, many papers use the column length to diameter ratio, for example, to give the critical column and encasements lengths (e.g. Malarvizhi and Ilamparuthi, 2007; Ali et al., 2012). This paper shows that the column length to diameter ratio has a minor effect and, for example, the critical column and encasement lengths should be given as a function of the footing diameter or width, which is the parameter that mainly controls the deformation mode.

To evaluate the performance of groups of ESC beneath rigid footings (circular or square), a set of systematic 2D and 3D finite element analyses have been carried out. These numerical simulations aim to show that, if the total column cross-sectional area and the ratio between encasement stiffness and column radius are kept constant, the column arrangement, i.e. column position and number of columns, has a minor influence on the settlement reduction. That allows for a simplified two-dimensional model in axial symmetry of groups of ESC beneath a rigid footing. Besides, the critical column and encasement lengths are analysed. So, the paper presents firstly a dimensional analysis in Section 2 to identify the main variables of the problem and the corresponding dimensionless parameters. Next, the numerical models are presented (Section 3). A common case is used as a reference, and using that case as a basis, parametric studies are performed. The results are discussed in Section 4, showing, for example, the small influence of column position within the group. That is confirmed by a reanalysis of previous experimental data in Section 5 and some summarizing comments on column arrangement are presented in Section 6. Using the presented numerical models, the critical column and encasement lengths are evaluated in Section 7. Finally, some conclusions are derived.

2. Dimensional analysis

Firstly, the variables of the problem are identified and a dimensional analysis is performed to get them in a dimensionless form. This dimensional analysis simplifies the parametric study and helps extrapolating the results of the numerical analyses presented in this paper. The variables of the problem may be classified as follows:

(a) Geometrical variables: Footing width, B; soft soil layer thickness, H; column length, L_c; encasement length, L_g; column radius, r_c; centre-to-centre column spacing, s; number of columns beneath the footing, N, and column position.
(b) Initial stress state (e.g., p'_0, K_0) and applied vertical pressure on the footing, p_a.
(c) Soil, column and encasement properties: stiffness and strength.
(d) Results, e.g., settlement, s_z.

As the encasement thickness is usually negligible, its radius corresponds to that of the column, r_c. The encasement length, L_g, may be normalised by that of the column, L_g/L_c, but this paper will show that, for groups of columns, L_g/B is more meaningful. The other geometrical variables are the same as those of groups of non-encased stone columns. They have been analysed in detail in Castro (2014) and only five of them are independent. The following dimensionless variables are used here: H/B, L_c/B, a_r, N and the column position. a_r is the area replacement ratio, which is a crucial dimensionless parameter that provides the percentage of soft soil replaced by gravel, i.e. a_r is the area of the columns, A_c, divided by the loaded area, A_l. Here, all the columns will be assumed to be beneath the footing because it is generally more efficient (Wehr, 2004). Additional columns beyond the footing increase the bearing capacity but do not noticeably reduce the footing settlement (e.g. Wood et al., 2000; Castro, 2014). It is worth noting that the footing width (B) or diameter plays an important role and some authors (e.g. Hong et al., 2016) seem to overlook its influence. On the contrary, L_c/d_c is commonly used (e.g. Dash and Bora, 2013) but it will be shown here that its influence is negligible.

The soil properties depend on the constitutive model but they are either dimensionless or have units of pressure. The latter ones are typically normalised using the initial stress state (e.g. c_u/p'_0). The applied vertical pressure may be normalised using either the initial stress state or a soil property (e.g. p_a/c_u). The column properties that have units are usually normalised by the soil