Foundations of embankments using encased stone columns

Fondations de remblais avec des colonnes ballastées entourées de géotextile

Castro J., Sagaseta C., Cañizal J., Da Costa A., Miranda M.
University of Cantabria, Santander, Spain

ABSTRACT: Stone columns are a common improvement technique for foundations of embankments in soft soils. When the soft soil does not provide enough lateral support, the columns are encased with a geosynthetic. This paper presents a closed-form solution to study soft soil improvement, both reduction of settlement and consolidation time, by means of encased stone columns. An end-bearing column and its surrounding soil, is modelled in axial symmetry under a rigid and constant load. Soil is assumed as elastic but plastic strains are considered in the column. An elasto-plastic behaviour is also considered for the encasement by means of a limit tensile strength. Parametric studies of the settlement reduction and stress concentration show the efficiency of encasing the columns, which is mainly ruled by the encasement stiffness compared to that of the soil. The analytical results are in good agreement with numerical analyses. Finally, the encasement length is analysed using the closed-form solution.

RÉSUMÉ: Les colonnes ballastées sont une technique d'amélioration de sol pour les remblais en sols mous. Lorsque le sol mou ne fournit pas assez de soutien latéral, les colonnes sont entourées avec un géosynthètique. Cet article présente une solution analytique pour étudier l'amélioration des sols mous, la réduction des tassements ainsi que le temps de consolidation, au moyen des colonnes entourées en géotextile. Une colonne ne reprenant les efforts que par la pointe et le sol environnant sont modélisés en axisymétrie sous une charge constant. Le comportement du sol est supposé élastique mais les déformations plastiques sont considérées dans la colonne. Un comportement élasto-plastique est également pris pour le géosynthètique au moyen d'une résistance à la traction limite. Des études paramétriques de la réduction du tassement et de concentration de contraintes montrent l'efficacité de l'enveloppe géosynthètique des colonnes, ce qui est principalement régie par la rigidité de l'enveloppe géosynthètique par rapport à celle du sol. Les résultats analytiques présentent une bonne concordance avec les analyses numériques. Finalement, la longueur de l'enveloppe géotextile est analysée en utilisant la solution basée sur une cellule élémentaire constituée d'une colonne et d'un volume élémentaire de sol.

KEYWORDS: soft soils, ground improvement, encased stone columns, analytical solution, numerical analyses.

1 INTRODUCTION

Stone columns, either by the vibro-replacement or vibro-displacement methods, are one of the most common improvement techniques for foundation of embankments or structures on soft soils. The inclusion of gravel, which has a higher strength, stiffness and permeability than the natural soft soil, improves the bearing capacity and the stability of embankments and natural slopes, reduces total and differential settlements, accelerates soil consolidation and reduces the liquefaction potential. Alteration of the natural soft soil caused by stone column installation (Guetif et al. 2008, Castro and Karstunen 2010) is not usually considered in their design.

Stone columns may not be appropriate in very soft soils that do not provide enough lateral confinement to the columns. It is generally accepted that those are soils with undrained shear strengths below 5-15 kPa (Wehr 2006). To increase the lateral confinement of the columns, and consequently their vertical capacity, encasing the columns with geotextiles has proved to be a successful solution in recent years.

A high tensile stiffness of the encasement is recommended as it will be shown in this paper; and therefore, other geosynthetics, such as geogrids, are also used to encase the column (Sharma et al. 2004, Gniel and Bouazza 2009). However, geogrids do not act as a filter and do not avoid contamination of the column with fines.

The development of encased stone columns as a ground improvement technique has come with an increasing number of studies in the last decade. However, most of the research is done using numerical methods (e.g. Murugesan and Rajagopal 2006, Malarvizhi and Ilamparuthi 2007, Smith and Filz 2007, Yoo 2010, Lo et al. 2010) and there are very few analytical solutions available in the literature (Raithel and Kempfert 2000, Pulko et al. 2011). That recently motivated the authors to develop a new closed-form solution to study the deformation and consolidation around encased stone columns (Castro and Sagaseta 2011). That solution is an extension of another previous analytical solution developed for non-encased stone columns (Castro and Sagaseta 2009).

This paper analyses the main features of that closed-form solution, showing its limitations and range of applicability, the influence of the key parameters for routine design and a comparison with numerical analyses.

2 CLOSED-FORM SOLUTION

2.1 *Model*

The vertical capacity of the columns is a fundamental issue when the applied load is concentrated on the columns. Therefore, column encasement is very useful in those cases (Murugesan and Rajagopal 2010, Khabbazian et al. 2010); but also under distributed loads, such as tanks or embankments, because the increase of lateral confinement reduces the settlement.

The authors' closed-form solution (Castro and Sagaseta 2011) is limited to distributed uniform loads because it is based on a "unit cell" model, i.e. only one column and its surrounding soil are studied in axial symmetry. Furthermore, the column is assumed to be fully penetrating in the soft soil and the applied load is considered as rigid, i.e. uniform settlement. The area of soft soil, A_l, that is improved by each column, A_c, is generally expressed by the area replacement ratio, a_r=A_c/A_l, but sometimes is also defined in terms of the relation between diameters or radii, N=r_l/r_c=1/$\sqrt{a_r}$.

The solution is developed for a horizontal slice at a depth z of the unit cell, and consequently, shear stresses between slices at different depths are not considered (Figure 1). The overall behaviour of the whole unit cell is obtained by means of integration of the solution at the different depths.

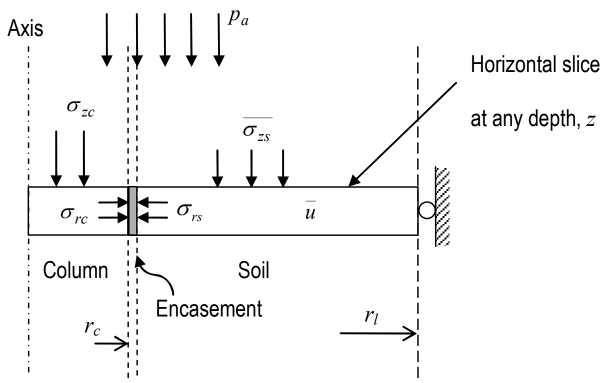

Figure 1. Analytical model.

2.2 *Consolidation*

The analysis of consolidation around encased stone columns as a fully coupled problem is difficult to deal with. As a simplifying assumption, the solution uses the average value of the excess pore pressure along the radius, $\bar{u}$, which is a simple way of getting a reasonably accurate solution. The details of this kind of approach can be found in Castro and Sagaseta (2009). Multiple instantaneous load steps may be considered. The column (drain) is considered to be fully permeable, which is doubtful for conventional stone columns but is reasonable if the columns are coated with a geotextile. In this way, consolidation around encased stone columns is studied using any conventional solution for radial consolidation (e.g. Barron 1948) and a modified coefficient of consolidation that accounts for the influence of column and encasement.

2.3 *Encasement*

The encasement is modelled as a cylindrical shell of negligible thickness around the column. Therefore, it is valid for different types of coating, such as geotextiles, geogrids... Encasement behaviour is supposed to be linear elastic-perfectly plastic and characterized by a tensile stiffness, J_g, and a maximum tensile strength, $T_{g,max}$. During column installation, the encasement is pre-stressed to an initial tensile stress, $T_{g,i}$. The encasement tensile stress obtained with the analytical solution is the increment from that value, ΔT_g.

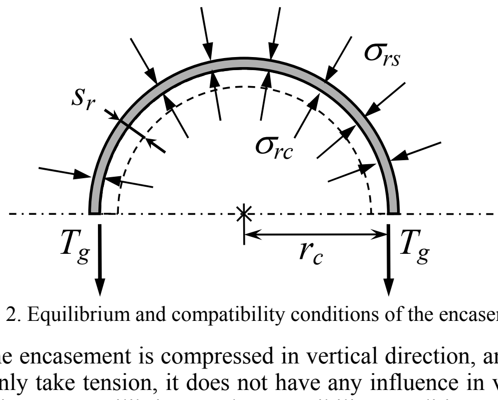

Figure 2. Equilibrium and compatibility conditions of the encasement.

The encasement is compressed in vertical direction, and as it can only take tension, it does not have any influence in vertical direction. Its equilibrium and compatibility conditions (Figure 2) are those of a thin tube under internal, σ_{rc}, and external pressure, σ_{rs}.

$$\sigma_{rc} = \frac{T_g}{r_c} + \sigma_{rs} \quad (1)$$

$$T_g = J_g \frac{s_r}{r_c} \quad (2)$$

where s_r is the radial displacement of the interface.

Combining these two equations, the radial equilibrium between soil and column at their interface depends on the encasement properties (stiffness and radius) and its radial expansion.

$$\sigma_{rc} = \frac{J_g s_r}{r_c^2} + \sigma_{rs} \quad (3)$$

Those simple equations (Eq. 2 and 3) show how the encasement influence depends on its stiffness and radius.

2.4 *Formulation*

The detailed formulation of the solution can be found in Castro and Sagaseta (2009, 2011). Three different possible phases are identified: (a) soil, column and encasement in the elastic range, (b) column yielding and (c) encasement yielding, which will occur after column yielding in a real situation.

A sensible design should cause yielding of the column but not of the encasement. Therefore, the last phase of the solution may not be considered and it is just necessary to check that the tensile stress of the encasement does not exceed its strength.

The solution considers just one instantaneous load step, but it is quite straightforward to generalize it for multiple loading steps (Castro and Sagaseta 2008), taking the initial stresses as the final ones of the previous load step. However, modelling the real loading steps is only necessary to study the consolidation process but not for the final values as it gives the same results.

2.5 *Drained solution*

The studied closed-form solution models the consolidation process. However, consolidation around stone columns, especially if the columns are coated with a geotextile, may be nearly as fast as the loading pace, which means that for these cases drained condition is a more reasonable assumption.

In any case, depending on the soil permeability and the loading pace, the real behaviour is between drained condition and an undrained loading followed by consolidation. Fortunately, both cases yield very similar final values as can be shown numerically.

Nonetheless, analytical solutions use simplifying assumptions that have different consequences in each situation. The most evident example is disregarding the elastic strains in the column once it has reached its active state. This assumption gives acceptable results for non-encased columns or when the consolidation process is modelled but not if drained conditions are considered for encased columns (Castro and Sagaseta 2011). Hence, in that last case it is necessary to account for those elastic strains in the column (Pulko et al. 2011).

3 PARAMETRIC STUDY AND NUMERICAL ANALYSES

3.1 *Numerical model*

Numerical simulations are included in the parametric study to evaluate the accuracy of the closed-form solution and the influence of its simplifying assumptions, such as neglecting the shear stresses and using an average pore water pressure along the radius. Coupled numerical analyses of the unit cell were performed using the finite element code Plaxis v8.6 (Brinkgreve 2007). For comparison purposes, the same boundary conditions and material properties of the analytical solution were chosen for the numerical models. Therefore, a rigid plate was set on top of the unit cell, the soil was modelled as elastic and the encasement and the column as elastic-perfectly plastic.

3.2 *Stress concentration*

The ratio between the vertical stress on the column and on the soil is usually called the stress concentration factor ($SCF=\sigma_{zc}/\sigma_{zc}$) and gives an idea of the part of the applied load that the soil transfers to the column. Figure 3 shows its variation with time. The vertical stresses on the soil and on the column may vary with the radius, and therefore, their averaged values are used to calculate the *SCF*.

A higher encasement stiffness provides a better lateral confinement to the column, and hence, the column supports a higher load. A good agreement is found between the analytical and the numerical results. However, as it happens for the stone column solution (Castro and Sagaseta 2009), the agreement for low degrees of consolidation (<30%) is not very good due to inherent assumptions of Barron's solution.

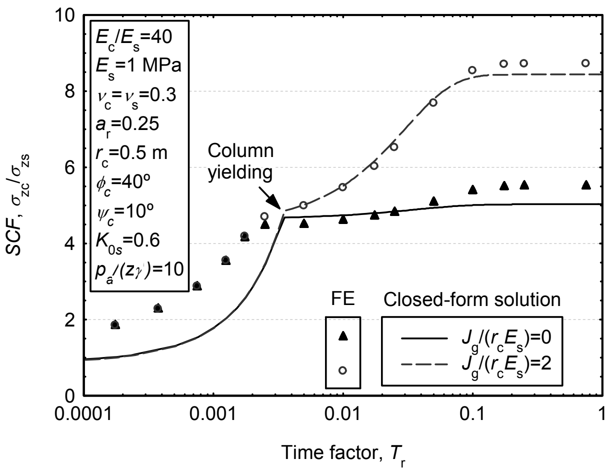

Figure 3. Stress concentration on the column with time.

3.3 *Settlement reduction*

The settlement reduction decreases with the applied load, p_a, from an elastic value, β^e, and approaches a plastic one, β^p, at the same rate as plastic strains develop in the column (Figure 4). The applied load is normalized by the initial vertical stress because column yielding depends on that factor, $p_a/(L\gamma'_s)$.

On the other hand, the settlement reduction introduced by the encasement is nearly the same for different area replacement ratios (Figure 5), which means that column encasement is equally useful for different area replacement ratios, yet columns of smaller diameters are better confined. In Figures 4, 5 and 6, the numerical results validate the accuracy of the analytical solution, but the agreement gets slightly worse as the tensile stiffness of the encasement increases. Hence, the only assumption that has a slightly noticeable effect in the results is neglecting the elastic strains in the column during its plastic deformation. A future improvement of the analytical solution including those elastic strains is currently being developed.

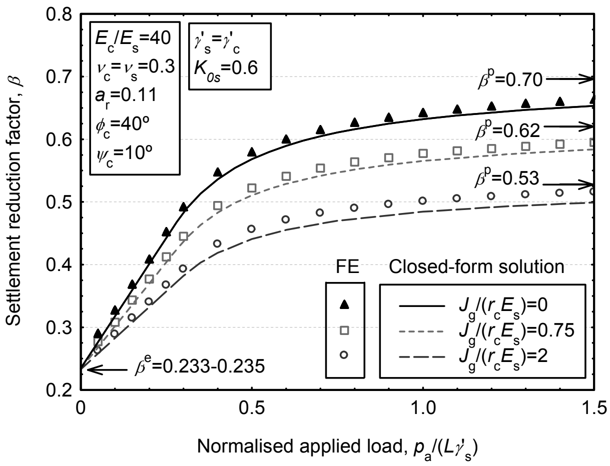

Figure 4. Settlement reduction. Influence of the applied load.

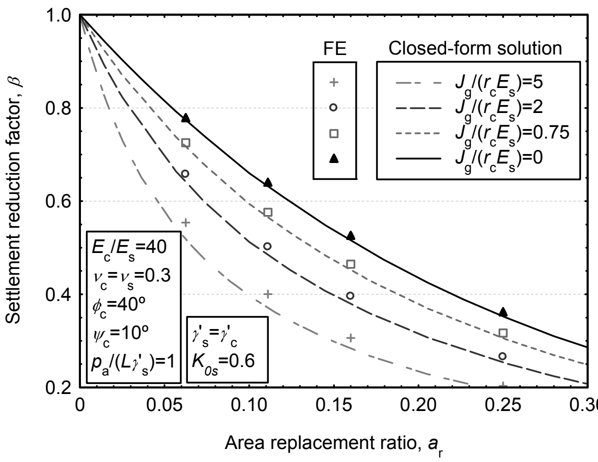

Figure 5. Settlement reduction. Influence of the encasement stiffness for different area replacement ratios.

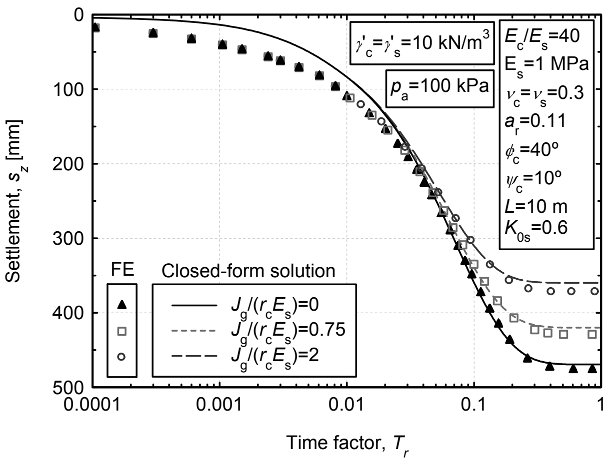

Figure 6. Time-settlement curve.

3.4 *Encasement length*

The effectiveness of encasing the columns in reducing the settlement is directly related to the tensile stress of the encasement, which provide lateral support to the column. Some authors (e.g. Khabbazian et al. 2010, Gniel and Bouazza 2009, Murugesan and Rajagopal 2006) have proposed a partial encasement of the columns, limiting it to the upper part where the initial lateral stresses are lower. Then, the analysis focuses on the length of the column that should be encased. Here, a preliminary study of the encasement length is presented using the authors' closed-form solution.

The closed-form solution provides the vertical strain of the column at different depths. Figure 7 shows that those strains are higher at shallow depths and linearly decrease with depth, as initial horizontal stresses increase. If the column is encased, those strains are lower but follow a similar pattern. Therefore, encasing the columns is more effective in their upper part but that varies linearly with depth and there is not a critical length of the encasement that should specifically be used.

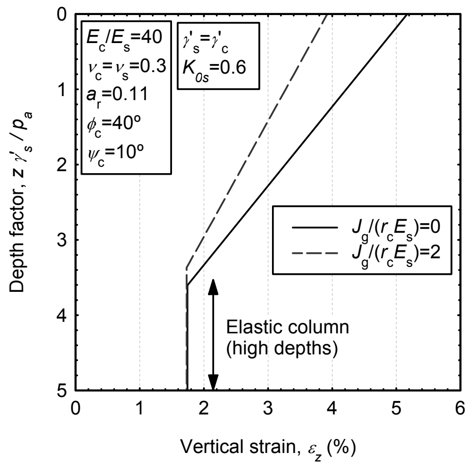

Figure 7. Vertical strain at different depths.

4 CONCLUSIONS

The main features of a closed-form solution, recently developed by the authors (Castro and Sagaseta 2011), to study soft soil improvement, both reduction of settlement and consolidation time, by means of encased stone columns are presented. The analytical solution pretends to be a simple and useful tool for design. Therefore, only a unit cell, i.e. an end-bearing column and its surrounding soil, is modelled in axial symmetry under a rigid and constant load.

Parametric studies of the settlement reduction and stress concentration show the efficiency of encasing the columns, which is mainly ruled by the encasement stiffness compared to that of the soil. Therefore, encasing stone columns is recommended in very soft soils and the encasement should be stiff enough. Besides, the settlement reduction decreases with the applied load. Column encasement is equally useful for common area replacement ratios but columns of smaller diameters are better confined.

The results of the closed-form solution agree well with numerical analyses. The only assumption of the solution that has a slightly noticeable effect in the results is neglecting the elastic strains in the column during its plastic deformation. Therefore, including those elastic strains is an improvement of the presented solution under development.

Finally, a preliminary analysis of the encasement length shows that is more efficient to encase the columns in the upper part, as expected, but there is not a critical length of the encasement that should specifically be used.

5 ACKNOWLEDGEMENTS

The work presented is part of a research project on "An integrated calculation procedure for stone columns, considering the influence of the method of installation", for the Spanish Ministry of Science and Innovation (Ref.: BIA2009-13602).

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