A Study on the Behavior of a Geosynthetic Encased Stone Column Group Using 3D Numerical Analyses

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ABSTRACT

This paper introduces the assumptions, procedure and results of a number of three dimensional numerical analyses for simulating the behavior of an encased, versus un-encased, stone column group installed in a very soft soil layer; the finite element technique is employed for this purpose. Settlements and lateral deformations (so called bulging) of stone columns are selected as criteria for judgment and comparison of the behavior of the ordinary and geosynthetic encased stone columns (GEC's). Also, parametric studies and analyses are carried out to investigate the effects of parameters such as stiffness and length of the geosynthetics as well as modulus of elasticity and friction angle of the column's material on the mechanical behavior of the group of GEC's. The results indicate that increasing the stiffness of the encasement clearly enhances the behavior of the group of GEC's. The results also showed that the performance of the GEC's is comparatively less sensitive to values of internal friction and modulus of elasticity of the column's materials. Moreover, complementary analyses suggested that encasing only the outer columns of a group is very efficient in providing an optimal design, both economically and technically.

RÉSUMÉ

Cette article présente les hypothèses, la procédure et les résultats d'un certain nombre de trois dimensions des analyses numériques pour simuler le comportement d'un enrobé, par rapport non encastrés, groupe des colonnes installées dans une couche de sol très mou, la méthode des éléments finis est utilisée à cette fin. Les établissements et les déformations latérales (dite bombée) de colonnes de pierre sont sélectionnés comme critères pour le jugement et la comparaison du comportement des colonnes ordinaires et géosynthétiques pierre encastrée (GECs) . Aussi étude paramétrique et les analyses sont effectuées pour étudier les effets des paramètres, tels que la rigidité et la longueur des géosynthétiques ainsi que le module d'élasticité et l'angle de frottement du matériau de la colonne sur le comportement mécanique du groupe des (GECs). Les résultats indiquent que l'augmentation de la rigidité d' encaissement améliore nettement le comportement du groupe des (GECs). Les résultats ont également montré que la performance du s (GECs) est relativement moins sensible aux valeurs de frottement interne et le module d'élasticité des matériaux de la colonne. En outre, des analyses complémentaires ont suggéré que enrobage suelment les colonnes extérieures d'un groupe est très efficace dans la fourniture et la conception optimale, à la fois économiquement et techniquement.

1 INTRODUCTION

The Stone Columns have been frequently used as a cost-effective and environmentally friendly method for improvement of weak soils such as clays, silts and silty sands over the past few years,

The main functions of this technique are the increase in the bearing capacity, reduction in total settlement, and also mitigation of the liquefaction potential of saturated loose deposits. The main principle in this method is replacing the soft soil with vertical columns of compacted aggregates which turn the in-situ soil into a compound material with higher shear strength and lower compressibility. Stone columns derive their strength and stiffness primarily from the confinement stress provided by the surrounding soil. In very soft soils (c_u<15kPa), this confinement is not enough and although some additional confinement is mobilized through applying the load of the structure, in these soils the generation of this confinement needs high radial deformation of the stone column, and this can leads to it's failure.

An alternative method to enhance the bearing capacity and also to provide the required lateral confinement in these soils, is to encase them with high stiffness and creep resistant geosynthetics, resulting in "Geosynthetic Encased Columns (GECs)". The main advantage of GECs in comparison with ordinary stone columns is that the confinement stress in the soft soil can be much less due to the radial confinement effect of the encasement. The geosynthetic encasement also prevents the lateral squeezing of aggregates when the stone columns are installed in very soft soils, leading to minimal loss of aggregates and quicker installation (Murugesan and Rajagopal, 2006).

The concept of encasing the stone columns was proposed for the first time by Van Impe in 1985. Bauer and Al-joulani (1994) have investigated the behavior of sleeved stone columns through uni-axial and tri-axial compression tests. Ayadat and Hanna (2005) studied the advantages of encasing stone columns in collapsible soils. Murugesan and Rajagopal (2006) analyzed the performance of ordinary stone columns and encased stone columns through numerical studies, they also performed some laboratory tests on stone columns installed in unit-cell tank in 2007 and reported that the tensile modulus of the encasement has the most important role in the strength of GECs. Gniel and Bouzza (2008) evaluated the effect of encasement's length on the behavior of GECs through experimental tests and also numerical analyses which were based on the Unit-Cell concept. Wu and Hong (2008) investigated the axial stress-strain relations of embedded granular column encapsulated with flexible reinforcement using an analytical procedure based on the cavity expansion method which was verified through experimental tri-axial tests on a reinforced sand specimen. Murugesan and Rajagopal (2009) have done some laboratory tests to compare the shear load capacity of stone columns with and without encasement by inducing lateral soil movements in a stone column treated soft soil. Researchers such as Lo et al. (2010) and Khabazian (2010) also analyzed the performance of GECs through numerical studies.

In this paper, we use the 3D finite element method to study the performance of GECs in comparison with ordinary stone columns (OSCs). Parametric analysis is also done to evaluate the influence of different parameters such as stiffness of the encasement, frictional angle and elastic modulus of stone column's material on the behavior of the group of GECs. Moreover, a 3D numerical approach is used to study the effect of varying the encasement length of different columns of a group of GECs on it's mechanical performance.

2 NUMERICAL ANALYSES

All of the numerical analyses in this section were carried out in three-dimensional space using the finite element program (ABAQUS). A group of 25 encased stone columns in which 80cm diameter stone columns were located in a 2m center to center spacing(s) with a square pattern was analyzed. Thickness of the soft soil surrounding the columns and also length of stone columns were assumed to be 10m. A 500kPa pressure was applied on the group through a rigid foundation and in 100kPa increments (figure 1). The soft soil and stone column's material were simulated using the Modified Cam Clay and Drucker-Prager Cap constitutive models, respectively. Finite element mesh was developed using 8-node linear brick elements for stone columns, rigid foundation and the soft soil. The geosynthetic encasement was also modeled as a linear elastic material using 3-node triangular membrane elements. The material properties selected in the analyses were based on the material properties that Gniel and Bouzza (2009) had used in their tests and are presented in table (1). According to Alexiev (2005), the most common range of tensile stiffness (J) of the encasement is between 2000kN/m and 4000kN/m, therefore a tensile stiffness of 3000kN/m was used in the analyses. Assuming the thickness of the encasement to be equal to 5mm in all models, the elastic modulus was calculated from the equation (J=E×t). It should be noted that both the stone column-geosynthetic and geosynthetic-clay interfaces were assumed to be full strength. This is because 1) the installation of a stone column will automatically lead to an undulating interface, and 2) these interfaces are internal drainage nodes (Lo et al., 2010).

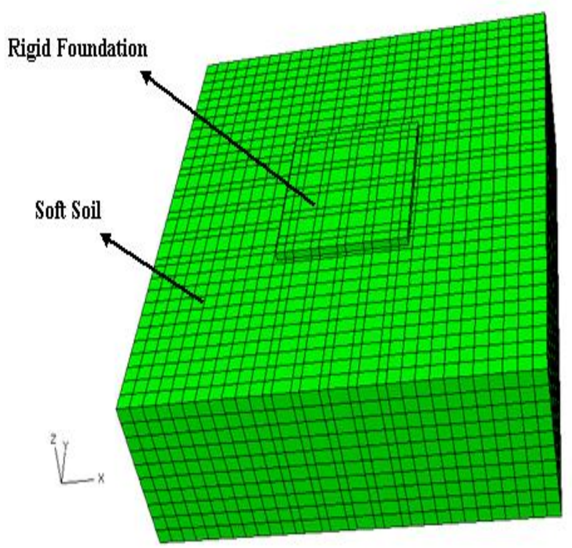

Figure 1. Typical finite element mesh used in the analyses

Table 1. Material Properties used in numerical models

Characteristics	Soil	Stone column
Friction angle, $\beta(\circ)$	-	54.81
Saturated Density, (kN/m^3)	-	20.2
(λ)	0.3478	0.0047
(κ)	0.0391	0.0013
Elastic Modulus, (MPa)	-	60
Poisson ratio, (υ)	0.35	0.3
(M)	0.7	-
P'_c, (kPa)	50	-
(e_0)	2	0.595
(R)	-	0.4
(α)	-	0.05

In table (1), (λ) and (κ) are the slopes of the normal consolidation line and unloading-reloading line in the e-ln(p′) plane, respectively. M is the slope of critical state line in Shear stress-Mean effective normal stress plane, P'_c and e_0 are pre-consolidation stress and initial void ratio, respectively. (R) is the eccentricity of the cap yield surface in the Drucker-Prager cap model and (α) is a small number used to define a smooth transition surface between the Drucker-Prager shear failure surface and the cap. The parameters (d) and (β) are the cohesion and internal frictional angle used in the Drucker-prager cap model. More details on these parameters and the elasto-plastic constitutive models can be found in Helwany (2007).

In order to better describe the model, stone columns were numbered as shown in Figure 2.

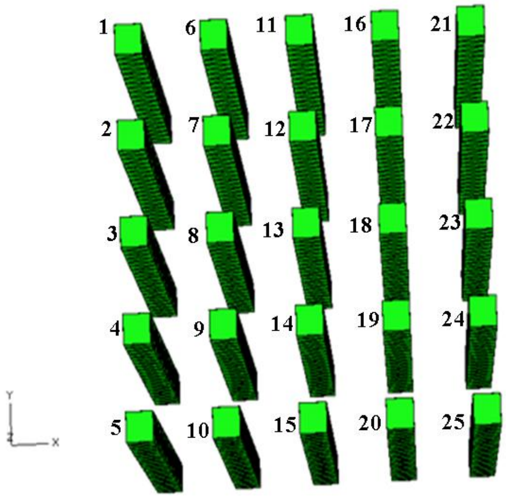

Figure 2. Stone column numbers in numerical models

3 NUMERICAL RESULTS

In order to evaluate the effect of encasement of the stone columns, settlement of column number 13 and lateral deformation of column number 25 obtained from the analyzed models are presented in Figures 3 and 4, respectively. As it can be seen from the results, encasing the columns results in stiffer columns due to the confinement provided by the encasement; and, the settlement and lateral deformation of the aforementioned columns decrease by up to (42%) and (57%), respectively.

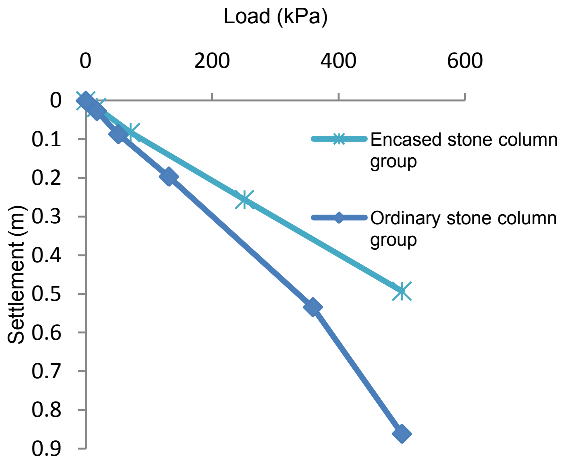

Figure 3. Comparison of settlements of stone column number 13 obtained from analyzed models with and without encasement

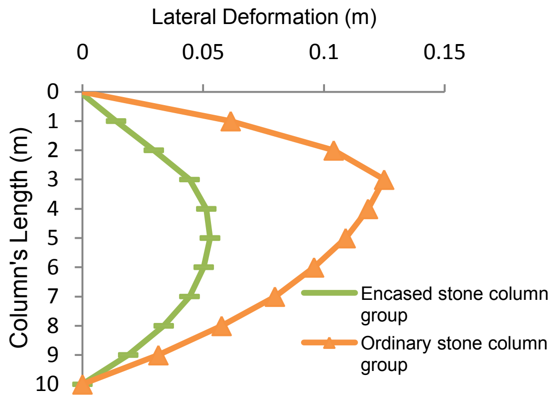

Figure 4. Comparison of lateral deformations of stone column number (25) obtained from analyzed models with and without encasement

4 PARAMETRIC ANALYSES

In this section the influence of different parameters on the performance of the group of encased stone columns is studied through 3D numerical analyses. The settlement and lateral deformation of stone columns are used as a criteria for the judgment. The geometric properties, material properties, load conditions and the finite element types developed are the same as mentioned in previous section.

4.1 Influence of Encasement Stiffness

Tensile stiffness (J) of geosynthetic encasement was varied between (300-10000)kN/m and assuming the thickness of the encasement equal to 5mm in all models, the elastic modulus was calculated from the equation (J=E×t). Settlement of the column number 13 and lateral deformation of column number 25 obtained from the analyzed models are presented in Figures 5 and 6, respectively.

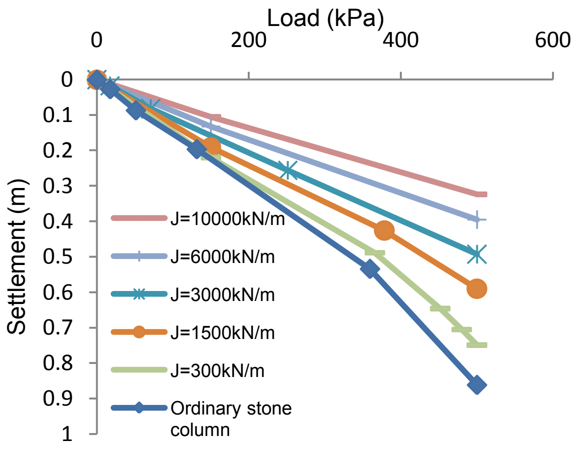

Figure 5. . Comparison of settlements of stone column number 13 obtained from analyzed models with various encasement stiffness

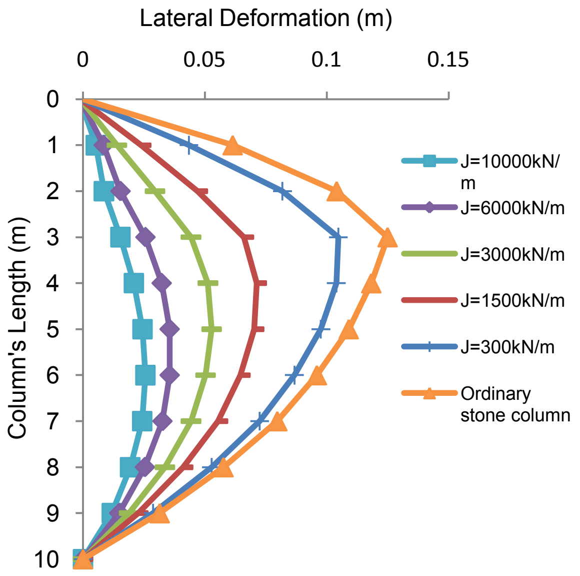

Figure 6. Comparison of lateral deformations of stone column number 25 obtained from analyzed models with various encasement stiffness

Increasing the stiffness of the geosynthetic makes stone columns stiffer and consequently under a constant load the hoop tension force mobilized in the encasement and the lateral confinement provided by it, increase significantly. Therefore the lateral deformation and the resultant settlement of the GEC group decrease so that with increasing the encasement tensile stiffness (J) to 10000kN/m, amounts of settlement and lateral deformation of the aforementioned columns of the GEC group decreased by up to 62.38% and 79.47% proportional to the model in which stone columns were un-encased, respectively.

4.2 Influence of internal friction angle of the stone column's material

The internal friction angle of the stone column's material (φ_s) was varied between 30° to 45° to evaluate it's effect on the performance of the GEC group. It should be noted that since the stone column's material was modeled with the Drucker-Prager Cap model, (φ_s) was converted to the parameter (β) through the equation ($\tan\beta = \frac{6\sin\phi'}{3-\sin\phi'}$). Settlement of column number 13 and lateral deformation of column number 25 obtained from the analyzed models are presented in Figures 7 and 8, respectively.

By increasing the (φ_s) from 30° to 45°, the amounts of settlement and lateral deformation of the aforementioned columns of the modeled GEC group decreased by up to 20.35% and 20.45%, respectively. It is obvious from the results that increasing the internal friction angle makes the stone column's material harder and consequently under a constant load, the lateral deformation and settlement of the GEC group decrease and the behavior of the GEC group improves slightly.

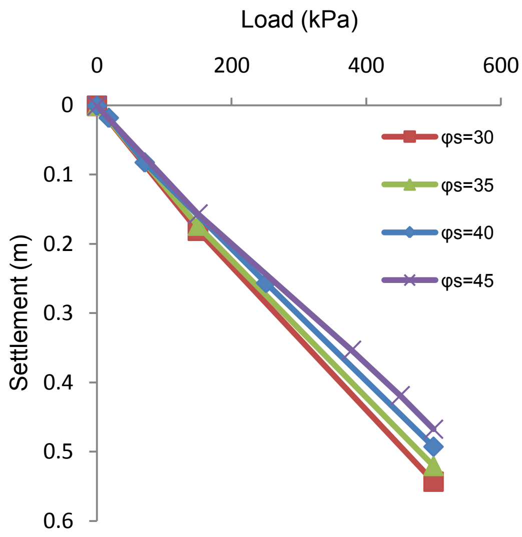

Figure 7. Comparison of settlements of stone column number 13 obtained from analyzed models with various (φs)

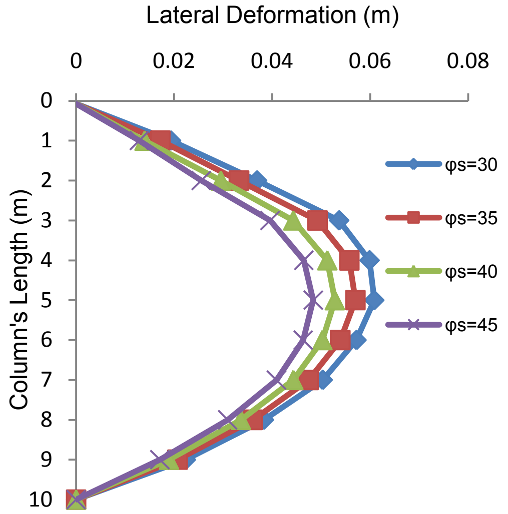

Figure 8. Comparison of lateral deformations of stone column number 25 obtained from analyzed models with various (φs)

4.3 Influence of elastic modulus of the stone column's material

The elastic modulus of the stone column's material (E_s) was varied between 30MPa to 100MPa and the effect of it on the performance of the GEC group was investigated. Settlement of column number 13 and lateral deformation of column numbers 13 and 25 obtained from the analyzed models are presented in Figures 9 to 11.

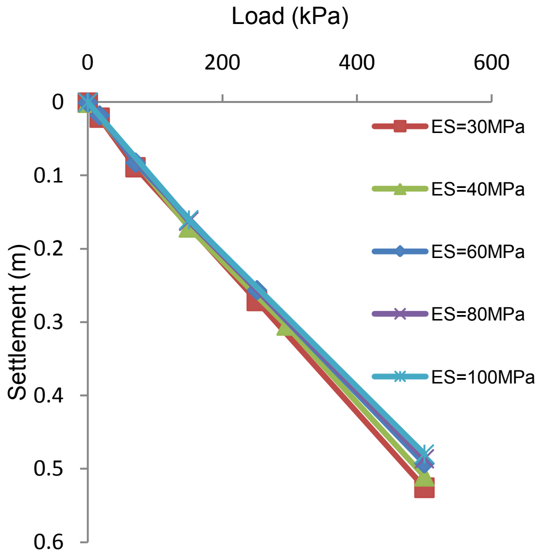

Figure 9. Comparison of settlements of stone column number 13 obtained from analyzed models with various (E_s)

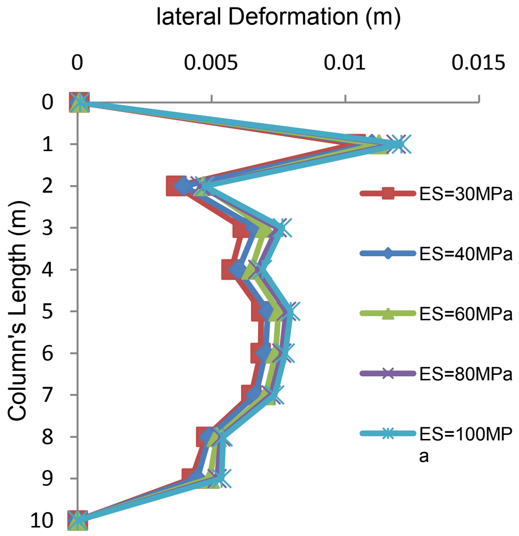

Figure 10. Comparison of lateral deformations of stone column number 13 obtained from analyzed models with various (E_s)

The total settlement of the stone column is made up of three components: elastic settlement due to the axial loading, settlement caused by the downdrag force due to the consolidation of the surrounding soil and the settlement due to the lateral deformation of the stone column (Ayadat and Hanna, 2005). Reduction of the (E_s), results in the increase of all these settlement components but the decrease of the load portion carried by the GEC in relation to it's surrounding soil makes this settlement increase negligible (Figure 9).

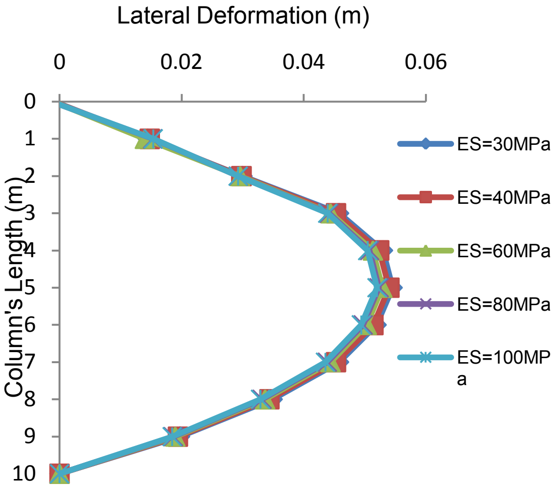

Figure 11. Comparison of lateral deformations of stone column number 25 obtained from analyzed models with various (E_s)

Reduction of (E_s) proportional to the encasement stiffness, increases the hoop tension force induced in column's encasement and consequently the radial strain and lateral deformation of the GEC increase. But the horizontal stress difference ($\Delta\sigma_{h,diff}$) between the horizontal stress in the stone column ($\Delta\sigma_{h,c}$) and sum of horizontal stresses provided by the encasement ($\Delta\sigma_{h,geo}$) and the soft soil ($\Delta\sigma_{h,s}$) is another parameter which has an effect the soft soil and leads to horizontal deformation until a corresponding additional earth pressure is mobilized in the soft soil layer to bring the horizontal stresses in equilibrium directly (Kempfert, 2006). By reduction of (E_s) which leads to increase of both ($\Delta\sigma_{h,geo}$) and ($\Delta\sigma_{h,s}$), ($\Delta\sigma_{h,diff}$) and the resultant bulging of the (GEC) decrease. As it can be figured out, in the middle columns of the group such as column number 13, decrease of the ($\Delta\sigma_{h,diff}$) has more effect on bulging than the increase of the hoop tension force of the encasement and reduction of (E_s) results in a very slight decrease of bulging of the columns, whilst in circumferential columns of the group such as column number 25, because of less confinement stresses provided by the soft soil, the situation is inverse and reduction of (E_s) slightly increases bulging of stone columns.

4.4 Influence of encasement length arrangement

20 numerical models with different encasement length arrangements that are shown in Table 2 were analyzed to study the effect of encasement length arrangement on the behavior of the modeled GEC group. In Table 2, column number 13 is introduced as (central column). Similarly, columns (7, 8, 9, 12, 13, 14, 17, 18, 19) and (1, 2, 3, 4, 5, 6, 10, 11, 15, 16, 20, 21, 22, 23, 24, 25) are defined as (central ring columns) and (circumferential ring columns), respectively. Final settlement of column number 13 and final lateral deformation of column number 25 for the

analyzed models are presented in Figures 12 and 13, respectively.

Table 2. Encasement length formations of the analyzed models

Model No.	Characteristics
1	All columns encased 100%
2	Central column length 75% encased
3	Central column length 75% encased- Central ring columns lengths 75% encased
4	Central column length 50% encased
5	Central column length 50% encased- Central ring columns lengths 75% encased
6	Central column length 25% encased
7	Central column without encasement
8	Central column length 25% encased- Central ring columns lengths 75% encased
9	Central column without encasement- Central ring columns lengths 75% encased
10	Central column length 50% encased- Central ring columns lengths 50% encased
11	Central column length 25% encased- Central ring columns lengths 50% encased
12	Central column length 75% encased- Central ring columns lengths 50% encased
13	Central column without encasement- Central ring columns lengths 50% encased
14	Central column length 25% encased- Central ring columns lengths 25% encased
15	Central column and Central ring columns without encasement
16	Central column and Central ring columns without encasement- circumferential ring columns lengths 90% encased
17	Central column and Central ring columns without encasement- circumferential ring columns lengths 75% encased
18	Central column and Central ring columns without encasement- circumferential ring columns lengths 50% encased
19	Central column and Central ring columns without encasement- circumferential ring columns lengths 25% encased.
20	All columns without encasement

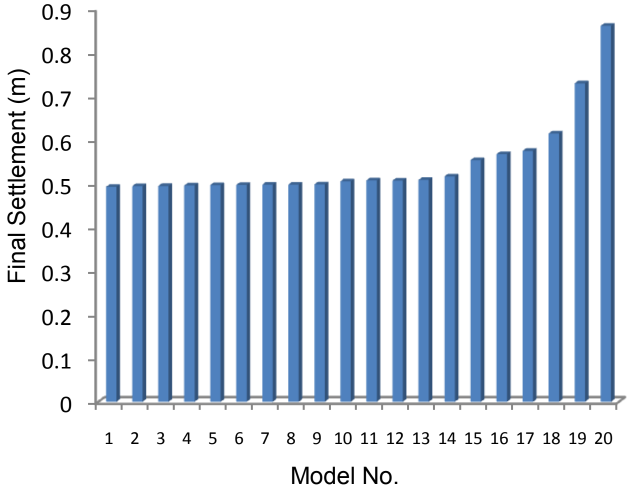

Figure 12. Comparison of final settlements of stone column number 13 obtained from analyzed models

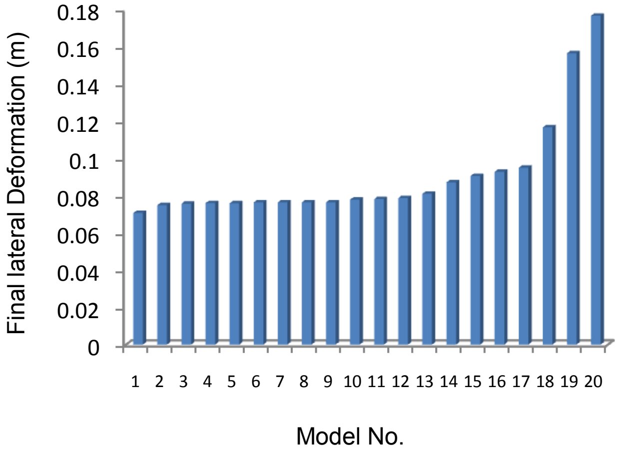

Figure 13. Comparison of final lateral deformations of stone column number 25 obtained from analyzed models

It can be figured out that encasement of the central column and also central ring columns have little effect on the behavior of the group and the increase of settlement and bulging of the selected columns induced by removing the encasement of these columns from model No. 1 to 15 is negligible, However encasement of circumferential ring columns is so important in improving the performance of the group and removing the encasement of these columns results in increase of the settlement and bulging of the selected columns up to 74.8% and 150% in relation to the initial model that all of the columns are encased, respectively.

According to the analyzed models in this section, it can be concluded that in different practical projects using GECs, considering the allowable settlement and also the amount of applied load, we can encase only the outer columns without losing a considerable percent of bearing capacity of the system.

5 CONCLUSIONS

In this paper, we have studied the influence of different parameters on the performance of geosynthetic-encased stone columns through 3D numerical models. Based on the results obtained from this study, the following conclusions are made:

1) Increasing the stiffness of the geosynthetic (J) encasement of stone columns makes the stone columns stiffer and under a constant load, the hoop tension force mobilized in the encasement and the lateral confinement provided by it, increase significantly. Therefore increasing of (J), results in a substantial enhancement of the performance of the GEC group.

2) Results obtained from analyses showed that increasing the internal friction angle of stone column's material makes it harder and consequently the lateral deformation and settlement of the columns decrease. However, performance of GECs is less sensitive to values of internal friction angle of column's material.

3) The load carrying capacity of the GECs is almost insensitive to the variation of elastic modulus of stone column's material.

4) Evaluation of the influence of the encasement length arrangement on the performance of GEC groups indicated that in different practical projects using GECs, depending on the allowable settlement and amount of the applied load, it may be sufficient to encase only the outer columns without losing a considerable percent of the overall bearing capacity of the system.

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