International Journal of New Technology and Research (IJNTR)
ISSN:2454-4116, Volume-3, Issue-4, April 2017 Pages 22-25

Settlement Behavior of Reinforced Embankments Supported by Encased Columns

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***Abstract*- Stone column supported embankments on soft clay deposits have some construction problems due to low bearing capacity, high compressibility and lack of lateral resistance. To overcome these difficulties, geosynthetics have been widely preferred by geotechnical engineers in recent years. This paper presents a two dimensional (2D) finite element model study, simulating a geosynthetic-reinforced (GR) and geosynthetic-encased stone column (GEC) supported embankment on soft soil. Numerical analyses are performed to investigate the effect of reinforcement and encasement on the vertical displacement of stone columns and soft soil. The results reveal a significant decrease in settlement with encasement, which is thought to be a direct consequence of the additional confining pressure produced by the geosynthetic encasement. With the help of base reinforcement, the surface settlement values of the soft soil reduced significantly.**

***Index Terms*— column-supported embankment, encasement, geosynthetics, reinforcement, settlement.**

I. INTRODUCTION

Construction of embankments over soft soils has several difficulties related to the weak strength properties of the soil. In recent years with an increasing demand, stone column technique has been used for improving the load carrying capacity which depends on the surrounding soil [1-6]. But it is impossible to construct the stone columns in very soft clays, due to the insufficient lateral confinement. In such soils, the required lateral confinement can be induced by encasing the individual stone column with a suitable geosynthetic over the full or partial height of the column [7-12].

The general idea of encasing the columns with geotextile was firstly recognized by Van Impe and Silence (1986) [13]. They presented analytical design technique assessing the required tensile strength of geotextile. The project, where a seamless geotextile sock used as a column encasement, was fulfilled successfully in Germany in 1995. Development of the construction and geosynthetics production technology throughout the 1990ies, new design procedures were developed. Later, Kempfert et al. (1997) [7], Raithel and Kempfert (2000) [8] and Raithel et al. (2002) [9] studied the performance of geosynthetic-encased stone columns (GECs) through numerical and analytical models and produced an analytical design technique for the assessment of column settlement based on geotextile stiffness. Ayadat and Hanna (2005) [14] performed an experimental investigation and reported the benefit of encasing stone columns. Murugesan and Rajagopal (2006a, 2006b) [15, 16] evaluated the concept of encasing individual stone columns with geosynthetics through numerical analyses, and found that the encased stone columns are stiffer than conventional stone columns. Malarvizhi and Ilamparuthi (2007) [17] investigated the settlement of fully encased and isolated stone columns by small-scale laboratory testing and numerical modelling and presented significant reduction with increasing geosynthetics stiffness. Yoo and Kim (2009) [18] presented the results of the full 3D model of GECs and applicability of continuum elements instead of membrane elements in 3D modeling. Murugesan and Rajagopal (2010) [19] performed load tests on individual and group of stone columns with and without encasement in a large scale testing tank, and developed design guidelines for the given load and settlement. Lo et al. (2010) [20] presented fully coupled analyses results on the contribution of geosynthetic encasement in enhancing the settlement reduction in the embankment reinforced with stone columns. Khabbazian et al (2011) [21] performed three-dimensional finite element analyses of GECs utilizing three different forms of hyperbolic model for the encased granular material in order to investigate the lateral response of GECs more realistically during loading and found that modeling the behavior of soil near failure is essential for properly simulating the behavior of GECs. Yoo and Lee (2012) [22] performed field-scale load tests to investigate the enhancement improvement in load-carrying capacity and settlement reduction of a GECs focusing on the effect of the encasement length and column strain.

It has been observed in the available studies that mainly unreinforced embankments built on soft soil with GECs have been studied and the effect of basal reinforcement in the embankment has not been considered. The work presented in this paper intends to improve the axisymmetric unit cell model of reinforced embankments built on soft soil reinforced with GECs. To compare the performance of the basal reinforcement, parallel analyses were also performed on unreinforced embankment. Furthermore, the effectiveness of geosynthetic stiffness on the settlement behavior is investigated through parametric analyses.

II. NUMERICAL ANALYSES

PLAXIS 2012 [23] is the finite element code used in the numerical analyses of this paper. In all of the performed numerical analyses, the height of geosynthetic-reinforced embankment built on soft soil is assumed to be 3m. The soft soil is 10m thick lying on a rigid and firm layer. The water level locates at the ground surface (Fig. 1). Stone columns having a diameter of 0.8m (D) are arranged in a square grid pattern with 2.4m center-to-center spacing, giving an area

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replacement ratio of 9%. All stone columns are encased with geosynthetics. At the base of the embankment, there is one layer of geosynthetic for basal reinforcement.

Fig. 2 shows an axisymmetric finite element unit cell model where the overall radius of the cylinder was selected to be 1.2m. The finite element mesh used in the numerical simulations was developed using fifteen-nodded triangular elements. The clusters between soil and the columns were refined twice due to the expectation of high deformation.

No horizontal displacement was allowed on the vertical boundaries while the bottom boundary is completely fixed in both vertical and horizontal directions. The ground surface is a drainage boundary (zero value of excess pore pressure), while the vertical and bottom boundaries of the mesh are assumed to be impermeable.

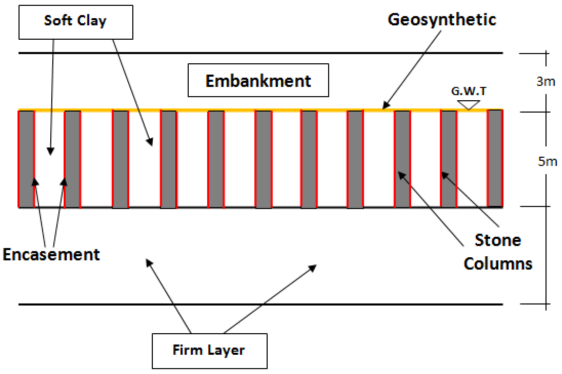


Figure 1. Cross-section of reinforced embankment built on soft soil reinforced with GECs

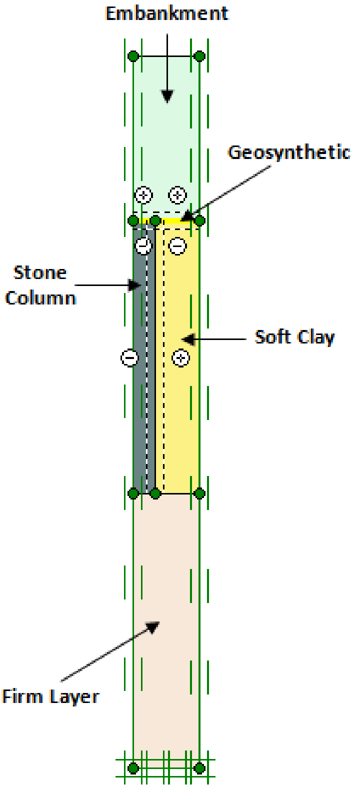


Figure 2. Axisymmetric cylindrical unit cell used in the analyses

The stone column and the embankment fill were modelled using a linear elastic perfectly plastic model with Mohr–Coulomb failure criterion. The Mohr–Coulomb model is defined by five parameters: effective friction angle (ϕ'), effective cohesion (c'), dilation angle (φ'), elastic modulus (E) and Poisson's ratio (υ). The soft soil was modelled as a modified Cam Clay material. Five material parameters are associated with this model, namely the slope of the swelling line (κ), the slope of the virgin consolidation line (λ), the void ratio at unit pressure (e), the slope of the critical state line (M) and Poisson's ratio (υ). The Mohr–Coulomb and the modified Cam Clay parameters used in the numerical analyses were similar to the typical values used by other researchers e.g. [24-26].

The geosynthetics used for both basal reinforcement and encasement were modelled as linear elastic material with axial stiffness in elastic or elastoplastic forms, with an assumed Poisson's ratio of 0.3 e.g. [27]. The secant stiffness of the geosynthetic (J) was defined as the ratio of the tensile force per unit width to the average strain in the geosynthetic. To determine the geosynthetic elastic module, the initial tensile modulus was computed at 3 % axial strain. Alexiew et al. (2005) [10] documented that design values of tensile modulus (J) between 1000 and 4000 kN/m were required for the geosynthetic used to encase granular columns on a number of different projects (the tensile modulus of the encasement, J, is also commonly referred to as the geosynthetic stiffness. Consequently, a value of J=1000 kN/m was used in the numerical analyses for both encasement and reinforcement. Interface elements that can be characterized by two sets of parameters were used to model interaction behavior between the geosynthetic and the granular column, and between the geosynthetic and the surrounding soft soil. The coefficient of sliding friction (μ) between the geosynthetic and the granular column was selected to be 0.5 ($\mu = 2/3 \tan\phi$) [28], where ϕ is the friction angle of the column material. For interaction between the geosynthetic and the soft soil, μ was assumed to be 0.3 ($\mu = 0.7 \tan\phi$) [29], where ϕ is the friction angle of the soft soil. The parameters used in the numerical analyses are summarized in Table 1.

Table 1. Model parameters

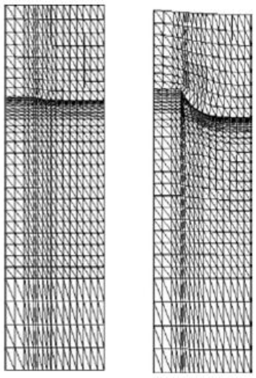
Property	Stone Column	Soft Clay	Embankment
	Model Type		
	Mohr-Coulomb	Modified Cam-Clay	Mohr-Coulomb
ϕ' (°)	40	-	32
c' (kPa)	1	-	1
φ' (°)	10	-	2
E (kPa)	40000	-	15000
υ	0.3	0.3	0.3
K	-	0.02	-
λ	-	0.4	-
e	-	1.0	-
M	-	1.0	-
Permeability (m/s)	1x10^{-2}	1x10^{-6}	1x10^{-2}

After establishing the initial stress and pore pressure with appropriate boundary conditions, the stone column, the geosynthetic encasement and geosynthetic reinforcement were activated as wished-in-place. The embankment construction was then simulated in equal stages with 0.5m fill placement. Each embankment fill placement was assumed to be completed in 10 days, followed by a 20 day consolidation period. In order to compare the performance of the reinforced and encased column supported embankment, parallel analyses were also performed on both stone column without reinforcement.

In the numerical analyses, four different stiffness of basal reinforcement (1000, 2000, 3500, 5000kN/m) are used in order to investigate the influence of basal reinforcement stiffness on the deformation behavior of stone columns.

III. RESULTS AND DISCUSSION

Fig. 3 and Fig. 4 show the deformed mesh and settlements at the embankment base, respectively after the construction period and at the end of consolidation. These results show that, at the end of construction, the maximum settlement of the soft soil is about 15% of the maximum long term settlement occurred at the end of consolidation. As expected, settlements are higher in the soft soil than in the column. Fig. 4 shows the evolution in time of the settlements, at the embankment base, on the center of column top (x=0) and on the soft soil at the periphery of the unit cell (x=1.2m) where maximum value occurs; the differential settlement is also depicted. Long term settlement on the soft soil at the periphery of the unit cell is 13.6cm whereas on the column center is 1.5cm, the differential settlement is 12.1cm.



a) b)

Figure 3. Deformed mesh of the model
a) at the end of construction b) at the end of consolidation

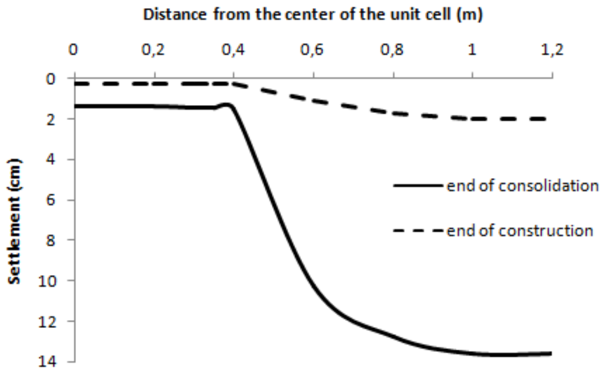


Figure 4. Settlement at the embankment base

Fig. 5 compares the maximum settlement at the embankment base, for both reinforced and unreinforced cases the end of consolidation period. The results show that with reinforcement there is a decrease of the long term maximum settlement from 13.6cm to 4.1cm, i.e. the settlement reduction ratio (ratio between settlements of the reinforced and unreinforced cases) is 0.3.

Fig. 6 shows the settlement behavior of soft soil for the reinforced embankment cases with different stiffness values. The results show that there is a decrease of the settlement of soft soil with base reinforcement from 13.6cm to 3.2cm. When the stiffness value of reinforcement increases (encasement stiffness is constant, J=1000kN/m), settlement value decreases as it is expected. For small stiffness values of reinforcement, settlements decrease much more significantly; for higher values, settlements become less noticeable and remain approximately constant. The settlement value on the soil is decreasing from 4.1cm to 3.2cm.

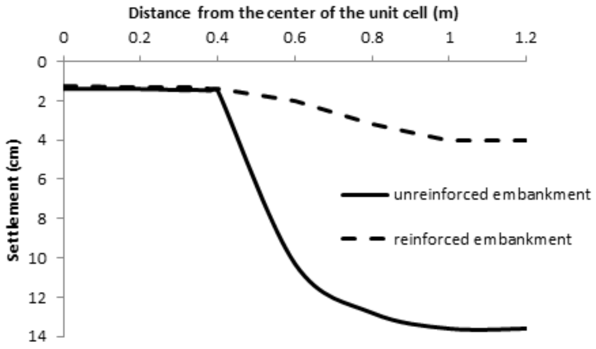


Figure 5. Settlement at the embankment base for the reinforced and unreinforced cases

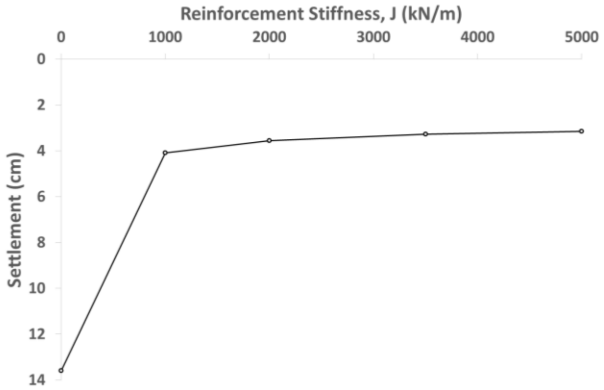


Figure 6. Settlement of soft soil under embankment reinforced with geosynthetics having different stiffness values

IV. CONCLUSION

This paper presents numerical analyses of the reinforced and encased stone column supported embankments built on soft soil. The effectiveness of basal reinforcement in embankment is investigated. The following consequences can be pointed out:

1) Using one layer of geosynthetic at the base of the embankment as basal reinforcement decreases the settlement. The ratio between settlements of the

reinforced and unreinforced embankment cases is determined as 0.3.

2) The stiffness of the reinforcement does not have a considerable effect on the settlement behavior of GEC.
3) The stress–settlement response of stone columns can be significantly improved by encasing them.

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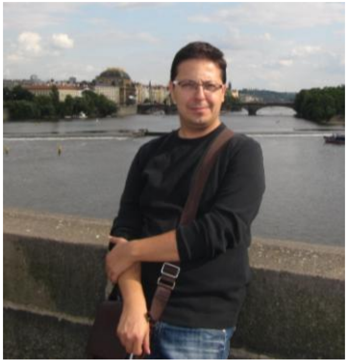

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