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Deformations of geosynthetic-reinforced column-supported embankments

Huang, J. & Han, J.
Civil, Environmental, & Architectural Engineering (CEAE) Department, the University of Kansas, 2150 Learned Hall, 1530 W. 15th Street, Lawrence, Kansas 66045-7609 USA; PH (785) 864-3766; FAX (785) 864-5631; jhuang@ku.edu; jiehan@ku.edu.

Collin, J.G.
The Collin Group, Ltd., 7445 Arlington Road, Bethesda, MD 20814, USA; jim@thecollingroup.com

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ABSTRACT: Geosynthetics have been used in conjunction with columns to support embankments over soft soils. In this system, the geosynthetics enhance the transfer of the embankment load to the columns. As a result, total and differential settlements are reduced. Most analytical studies so far have focused on soil arching and the tension developed in the reinforcement. Very limited research has been conducted on the deformation behaviour of column-supported embankments over soft soils. However, deformations are the key to the serviceability of this system. In this study, a number of influence factors including column spacing, column size, properties of soft soil, and tensile stiffness of geosynthetics were chosen to investigate their effects on the deformations of column-supported embankments. Three-dimensional finite difference software-FLAC3D was used in this study. The equal-strain elastic theory was examined in terms of the accuracy for estimating the maximum settlement at the base of the embankment.

1 INTRODUCTION

While embankments are built over soft soil, geotechnical engineers face many challenges due to low bearing capacity and high compressibility of the soft soil. Columns together with geosynthetics as basal reinforcement have become an effective alternative to overcome these challenges. Since columns, such as vibro-concrete columns and deep mixed columns, have higher elastic modulus and strength, they can increase the overall bearing capacity of the foundation. In addition, a large portion of the load is transferred from soft soil to the columns by soil arching induced by the relative stiffness difference between columns and soft soil so that the total and differential settlements can be greatly reduced (Collin, 2003). Geosynthetic reinforcement can improve the load transfer efficiency. As a result, the geosynthetic-reinforced column-supported embankment is more effective than that without geosynthetics. As compared with other ground improvement techniques, such as preloading, column-supported embankments typically do not require waiting time needed for soil strength gain and pore water pressure dissipation so that the construction can progress continuously and faster (Collin et al, 2005).

So far, most theoretical studies on geosynthetic-reinforced column-supported embankments have been focused on the investigation of load transfer mechanisms including soil arching and tension developed along geosynthetics (e.g., Han and Gabr, 2002). However, limited researches have been conducted to investigate the deformation behaviour of geosynthetic-reinforced column-supported embankments especially based on three-dimensional numerical analysis (e.g., Huang et al, 2005). In practice, however, deformation is often the key factor controlling the serviceability of earth structures. In this study, a finite difference software-FLAC3D was used to evaluate the influence of several important factors (such as the modulus, spacing, and size of columns, the modulus of soft soil, and the tensile stiffness of geosynthetics) on the deformation of geosynthetic-reinforced column-supported embankments.

2 NUMERICAL MODELING

2.1 *Numerical model and baseline case*

A typical two-lane (in one direction) highway embankment was selected as a baseline case in this study. Due to its symmetry, only half of the embankment was modelled to save computing time. Figure 1 shows the numerical model of the baseline case, which has a 5 m high embankment with a 2:1 side slope built over 10 m thick soft soil bounded by

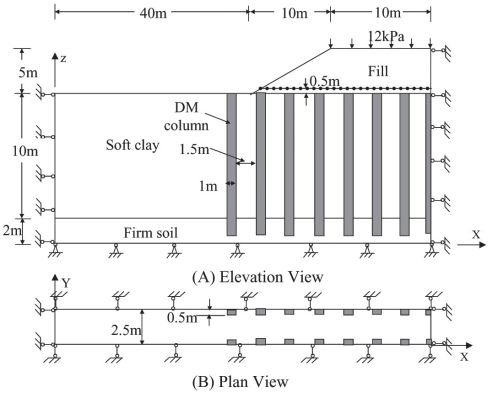

Figure 1. Numerical Model.

a firm soil layer. Columns were installed in a square pattern and spaced at 2.5 m.

Foundation soil, embankment fill, as well as columns were modelled as linearly elastic-perfectly plastic materials with Mohr-Coulomb failure criteria. The material properties of the baseline case are provided in Table 1. In the analysis, an undrained condition was assumed. The elastic moduli of foundation soil and DM columns were determined based on the relationship of $E = 200c_u$. The properties of the embankment fill were selected based on typical values of sandy soil provided by Budhu (2000). The properties of the firm soil were selected to ensure no failure and insignificant deformation of this layer. The DM columns had a tensile strength (c_t) equal to 20% of the undrained shear strength of the columns (c_u) as typical. For ease of modelling, columns were modelled in a square shape. Structural (geogrid) elements, which are plane stress elements not resisting bending loading (Itasca, 2002), were adopted to simulate the mechanical behaviour of geosynthetic reinforcement. To simplify the modelling, only one layer of geosynthetic was modelled and its properties used in the baseline case were also listed in Table 1.

Table 1. Parameters of numerical model baseline case.

Material	Properties
Columns	γ = 18 kN/m^3, c_u = 235 kPa, ϕ = 0°, E = 47 MPa, ν = 0.3, c_t = 20 kPa
Soft soil	γ = 18 kN/m^3, c_u = 10 kPa, ϕ = 0°, E = 2 MPa, ν = 0.3, c_t = 0 kPa
Firm soil	γ = 18 kN/m^3, c_u = 500 kPa, ϕ = 0°, E = 100 MPa, ν = 0.3, c_t = 0 kPa
Embankment fill	γ = 18 kN/m^3, c = 0 kPa, ϕ' = 30°, E = 30 MPa, ν = 0.3, c_t = 0 kPa
Geosynthetic	J = 1000 kN/m, c_a = 0 kPa, $\phi'_{s/GSY}$ = 25°, K_s = 20 MN/m/m^2,

Note: E = elastic modulus, ν = Poisson's ratio, γ = unit weight, c_u = effective cohesion, c_t = tensile strength, ϕ' = effective friction angle, J = tensile stiffness of geotextile, c_a = adhesion between geosynthetic and fill, and $\phi'_{s/GSY}$ = effective interface friction angle between geosynthetic and fill, and k_s = shear stiffness per unit area between geosynthetic and soil.

The construction of the embankment was modelled in ten lifts, i.e., each lift having a thickness of 0.5 m. After construction, the traffic load was simulated by applying a distributed load at a magnitude of 12 kPa on the crest of the embankment.

2.2 *Parametric study*

Once the analysis of the baseline case was accomplished, the parametric study was preceded to investigate the influence of various factors on the deformation of the geosynthetic-reinforced column-supported embankments. The investigated factors included the modulus, spacing, and size of the columns, the soft soil modulus, and the tensile stiffness of geosynthetics. One parameter was deviated once from the baseline case to evaluate the effect of that factor on the deformation. In all the cases, the columns were assumed to be installed in a square pattern. The parameters used in the parametric study are listed in Table 2. The geosynthetic tensile stiffness at 0 kN/m stands for the case without geosynthetic.

Table 2. Parameters used in the parametric study.

Factors	Parameters used
Column size (m)	0.5, 1*, 1.5
Column modulus (MPa)	22, 47*, 247, 497
Column spacing (m)	2.5*, 3, 3.5
Soft soil modulus (MPa)	1, 2*, 4
Geosynthetic tensile stiffness (kN/m)	0, 1000*, 5000, 10000

Note: * for the parameters used in baseline case.

3 RESULTS AND ANALYSIS

Numerous results can be obtained from the numerical analysis, however, only the results related to the deformation at the base of the embankment are presented below due to the page limit.

3.1 *Influence of column modulus*

Figure 2 shows the settlement profiles at the base of the embankment at different column moduli. It is clearly shown that differential settlements exist between the toe and the center of the embankment and between the columns. An increase of the column modulus not only reduces the total settlements but also minimizes the differential settlements. For easy comparisons, the maximum settlement can also be plotted with respect to the column modulus as shown in Figure 3. Due to the page limit, the settlement profiles with other influence factors are not presented. Instead, the influence of the factors on the maximum settlements is presented and discussed. Figure 3 shows that the degree of reduction in the maximum settlement

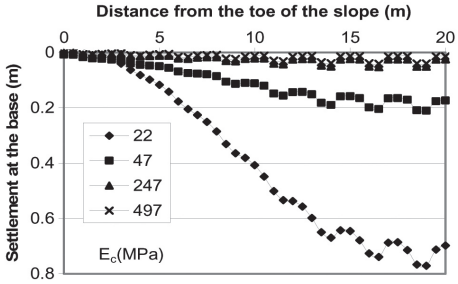

Figure 2. Settlement profile at the base of the embankment.

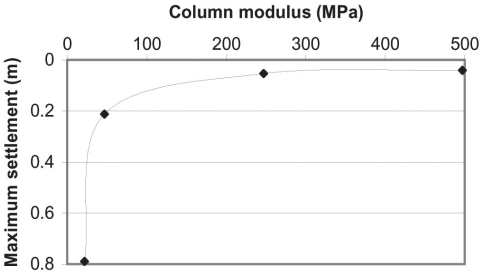

Figure 3. Maximum settlement vs. column modulus.

is significant when the column modulus increases up to 200 MPa. However, the effect of the column modulus becomes insignificant when the column modulus is greater than 200 MPa. When lower modulus columns are used, the soft soil must share a significant amount of load from the embankment. As a result, soft soil starts to yield and develop large deformation. An increase of the column modulus (also strength at the same time) enhances the load carrying capacity of the columns so that the soft soil shares less load and has less settlements. With a further increase of the column modulus, a stable soil arching forms above the soft soil, therefore, the stress applied onto the soft soil approaches constant and no further deformation develops.

3.2 *Influence of soft soil modulus*

The influence of soft soil modulus on the maximum settlement is presented in Figure 4, which clearly shows that the maximum settlement decreases with an increase of the soft soil modulus.

3.3 *Influence of area replacement ratio*

The area replacement ratio is defined as the ratio of the cross-sectional area of the column to its influence area, therefore, the area replacement ratio depends on the size of the columns and the spacing of the columns. The numerical results of the maximum settlement and the average settlement are plotted in Figure 5 by varying the column size and the column spacing. The maximum settlement, which is close to

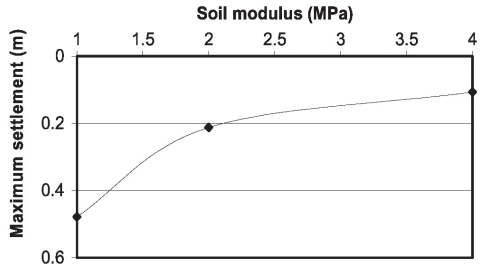

Figure 4. Maximum settlement vs. soft soil modulus.

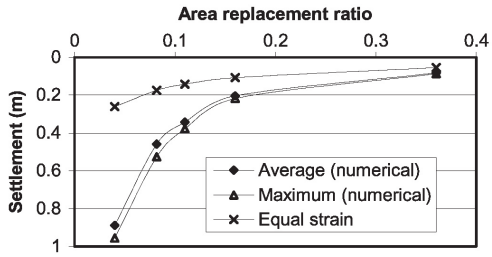

Figure 5. Settlement vs. area replacement ratio.

the centerline of the embankment, is determined at the base of the embankment across the whole profile. The average settlement is calculated based on the settlements between the soil and the last column close to the centerline of the embankment, which should be close to a unit-cell condition. It is shown that the difference between the maximum settlement and the average settlement close to the centerline is insignificant. The results in Figure 5 also show that an increase of the area replacement ratio reduces the maximum settlement, which is similar to the trends obtained by Priebe (1995) for stone columns.

In practice, however, the maximum settlement at the base of the embankment is commonly determined based on the equal strain concept as follows:

$$\delta = \Sigma \frac{\Delta\sigma_{zi}}{E_{com}} h_i \tag{1}$$

where δ = the settlement of the composite foundation under equal strain; $\Delta\sigma_{zi}$ = the additional stress at the mid-point of each sub-layer induced by the embankment fill and the traffic surcharge; h_i = the thickness of the sub-layer. The modulus of the composite foundation, $E_{com} = E_c a_s + E_s (1 - a_s)$, E_c = the elastic modulus of the DM walls or columns; E_s = the elastic modulus of the soft soil; a_s = the area replacement ratio of DM columns. The additional stress at the centerline of the embankment can be calculated as follows (Das, 2002):

$$\Delta\sigma_{zi} = \frac{2\gamma H}{\pi}\left[\left(\frac{a+b}{a}\right)(\alpha_1 + \alpha_2) - \frac{b}{a}\alpha_2\right] \tag{2}$$

where γ = the unit weight of the embankment fill; H

= the embankment height; a = the horizontal distance from the toe to the edge of the crest; b = the half width of the crest; $\alpha_2 = \text{atan}(b/z_i)$ and $\alpha_1 + \alpha_2 = \text{atan}((a + b)/z_i)$; z_i is the depth along the centerline where the stress is calculated.

The calculated settlements based on the equal strain concept are also plotted in Figure 5 with the numerical results for comparison. Apparently, there is a significant difference between the numerical results and those calculated based on the equal-strain elastic theory when the area replacement ratio is low. The difference becomes smaller when the area replacement ratio increases. There are three main reasons: (1) when the area replacement ratio is lower, more stresses concentrate on the columns and the yielding of the columns develops. As a result, the settlements computed by the numerical method include the plastic deformation, which is much higher than those calculated based on the elastic theory; (2) when the area replacement ratio is lower, more lateral movement develops under the embankment, which results in more vertical displacements (i.e., settlements); and (3) the differential settlement between the columns becomes larger when the area replacement ratio is lower, which is not considered in the equal strain concept. However, as the area replacement ratio increases, the difference in the settlement results from these two methods becomes smaller. In practice, however, the area replacement ratio typically ranges from 0.1 to 0.3 for geosynthetic-reinforced column-supported embankments (Han and Gabr, 2002). In this range, the equal-strain elastic theory underestimates the maximum settlement at least by half.

3.4 *Influence of geosynthetic tensile stiffness*

The influence of geosynthetic tensile stiffness on the maximum settlement is presented in Figure 6. As expected, an increase of geosynthetic tensile stiffness reduces the maximum settlement. However, the reduction of the maximum settlement is not that significant when one-layer reinforcement is used.

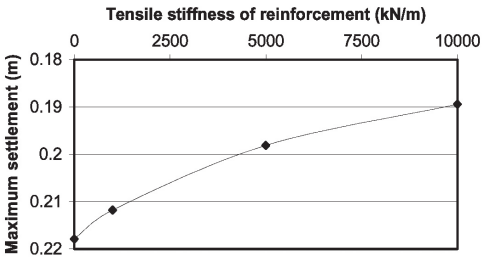

Figure 6. Maximum settlement vs. geosynthetic tensile stiffness.

4 CONCLUSIONS

The numerical study has shown that an increase of the column modulus, the soft soil modulus, the area replacement ratio, and the geosynthetic tensile stiffness can reduce the maximum settlement and the differential settlement at the base of geosynthetic-reinforced embankment. The efficiency of settlement reduction decreases with an increase of these influence factors. In practice, more than one parameter may be adjusted to achieve the optimum efficiency and design. The equal-strain elastic theory underestimates the maximum settlement of the geosynthetic-reinforced column-supported embankments currently used in the practice.

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