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Numerical evaluation of a granular column reinforced by geosynthetics using encasement and laminated disks

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ABSTRACT

Structures built on soft strata may experience substantial settlement, large lateral deformation of the soft layer and global or local instability. Granular columns reinforced by geosynthetic materials reduce settlement and increase the bearing capacity of the composite ground. Reinforcement is more common in the form of geosynthetic encasement, but laminated disks can also be used. This paper compares these two forms of reinforcement by means of unit cell finite element analyses. Numerical results were initially validated using field and experimental data, and parametric studies were subsequently performed. The parametric studies varied the geosynthetic interval and the geosynthetic tensile stiffness of the laminated disks as well as the length of the reinforced column. The analyses showed that in both modes; encasement and laminated disks; the geosynthetic increases the vertical stress mobilized on the reinforced column and reduces settlement on soft soil. It was also observed that in order to achieve the same performance as with encased column, the optimum interval between laminated disks is dependent on the stiffness of the geosynthetics and the column reinforced length.

1. Introduction

Granular columns are often considered versatile and cost-effective ground improvement solutions (Bergado et al., 1991; Almeida and Marques, 2013). Using granular columns results in stiffer composite ground, where vertical and lateral deformations are reduced compared with untreated soft foundations (Almeida et al., 1985, 1986). In addition, the consolidation will speed up due to the reduction in flow path length. A single granular pile under compressive load may fail in different modes, such as bulging (Hughes and Withers, 1974), general shear failure (Greenwood, 1970; Madhav and Vitkar, 1978), and sliding (Aboshi et al., 1979). Madhav et al. (1994) stated that a short granular column bearing on a firm layer will undergo a general shear failure or a local shear failure at the surface. A granular column greater than three diameters in length fails by bulging and less than two to three diameters in length fails by end bearing. In the case of a wide flexible loading, such as an embankment constructed over a granular pile to improve weak ground, sliding failure can occur due to lateral movement of soil and granular piles.

The granular columns derive their load-bearing capacity by mobilizing the passive earth pressure from the surrounding soft soil against bulging. When granular columns are installed in extremely soft clay, insufficient lateral confinement especially in the upper portion of the columns may significantly reduce their capacity (Greenwood, 1970; Murugesan and Rajagopal, 2007). In these cases, reinforcing the columns with geosynthetic materials with appropriate axial stiffness is one of the best ways to improve the performance of columns in very soft foundations (Raithel and Kempfert, 2000). The granular column can be reinforced either by encasement i.e., wrapping the column with a geosynthetic (encased column) or by placing horizontal disks of a geosynthetic through the column length at regular intervals (laminated column). In both reinforcing modes the geosynthetics restrict column bulging by providing additional confinement to the column.

The main advantage of the geosynthetic encased granular column over a traditional granular column is that there is higher resistance against bulging resulting from the hoop stresses in the geosynthetic. This confinement leads to an increase in load capacity of the encased column over a traditional granular column. In addition, geosynthetic encasement prevents the lateral squeezing of the granular material into the surrounding soil, and vice versa (Gniel and Bouazza, 2009). The idea of encasing granular columns was first proposed by Van Impe and Silence (1986). Afterward, several studies have been carried out using numerical analyses,

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experimental and model tests to evaluate the effectiveness of geosynthetic encasement on settlement improvement and load-bearing of treated soft soils (Alexiew et al., 2005; Murugesan and Rajagopal, 2006, 2007, 2010; Gniel and Bouazza, 2009; Khabbazian et al., 2010; Yoo, 2010; Keykhosropur et al., 2012; Zhang et al., 2012; Almeida et al., 2013; Castro and Sagaseta, 2013; Elsawy, 2013; Ghazavi and Afshar, 2013). When a geosynthetic is used as a laminated disk, column bulging is locally restricted by friction mobilization on the geosynthetic surface. The degree of decrease in bulging and increase in load-carrying capacity depends on the number of reinforcement layers, the spacing between the reinforcement layers and the angle of shearing resistance of the granular medium (Madhav, 1982; Wood et al., 2000; Sharma et al., 2004; Shahu and Reddy, 2011; Ali et al., 2012, 2014). Based on numerical analysis, Madhav et al. (1994) suggested that greater numbers of reinforcement layers and closer spacing lead to less bulging.

This paper presents the results of finite element analyses to assess the influence of the reinforcing mode on the performance of geosynthetic-reinforced granular columns in soft clay. The finite element method using *PLAXIS* program (Brinkgreve and Vermeer, 2010) was adopted to model the unit cell of the unreinforced and reinforced granular column. Long term analyses (drained calculation) were performed to achieve the maximum values of settlements and stresses. Firstly, the numerical model was verified by field measurements and experimental data and by changing the geosynthetic axial stiffness (J), the vertical interval between geosynthetic disks (S_v), the embankment height (H_{em}), and the column diameter (d_c) parametric analyses were subsequently performed.

2. Finite element simulation

2.1. Model description and boundary conditions

In order to model the embankment supported by geosynthetic-reinforced granular column in soft ground, the *PLAXIS 2D* finite element code was used, thus allowing calculation of the tensile strains and hoop tensile forces acting on the geosynthetic at any depth, as well as settlements in the column and surrounding soil. An axisymmetric unit cell was employed including three materials: soft clay, granular column and embankment fill. Fig. 1a and b shows the unit cell adopted for a geosynthetic encased and laminated granular column, respectively. During the generation of the mesh, material clusters are divided into triangular elements. The 15-node element provides an accurate calculation of stresses and deformation; therefore, these were employed for the modeling of soil materials. When 15-node soil elements are used, each geogrid element is modeled by 5-node line elements. A geogrid element is a slender structure with normal stiffness that can only sustain tensile force by producing axial stiffness. The tensile forces are evaluated at stress points that coincide with the nodes.

Values of the interface ratio R_i were assigned to simulate the interaction between the geosynthetic and the surrounding soils (granular soil internally and soft soil externally). This factor relates the geosynthetic interface strength to the soil strength. The vertical or horizontal displacements were restrained at the bottom boundaries of the unit cell, but vertical displacements were allowed at the lateral borders. In all analyses, the adopted unit cell consisted of soft clay (8 m thick) and a fully penetrated column (diameter of 0.8 m). The columns were arranged in 2 m center-to-center distance (S) square pattern. Using columns in a square pattern produces a unit cell with a diameter of 2.26 m ($d_I = 1.13 \times S = 2.26$ m) and the area ratio of 12.5% ($a_E = d_c^2/d_I^2$), which is kept constant for parametric analyses. The unit cell was loaded by embankment fill on the top surface to simulate vertical stress ($\gamma_{em} \times H_{em}$) and the embankment construction was simulated in one stage. Loading the composite unit cell by an embankment simulates an arching effect, which is not considered in the case when uniform loading is applied (Almeida et al., 2013). The Hardening Soil (HS) model was used to simulate soft clay; therefore, the oedometeric modulus of the soft soil (E_{oed}) is stress dependent. An elasto-plastic Mohr–Coulomb (*MC*) model was adopted for both the granular

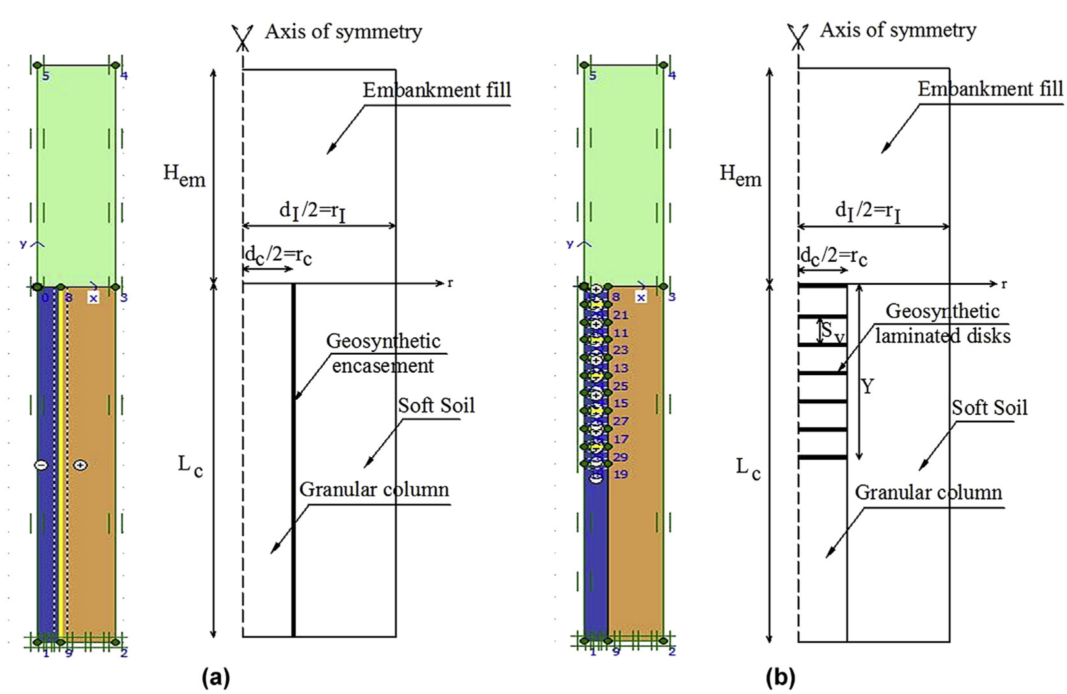

Fig. 1. Different modes of geosynthetic-reinforced granular columns used in FEM. (a) Granular column reinforced by geosynthetic encasement and (b) granular column reinforced by geosynthetic laminated disks.