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Three-dimensional numerical analysis of individual geotextile-encased sand columns with surrounding loose sand

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ABSTRACT

Use of geotextile-encased sand columns (GESC) to improve weak soils is an emerging technology that has great promise for field applications. This paper contains the results of a numerical study with the goal of quantifying the benefits of geotextile encasement under different conditions. A three-dimensional finite difference method implemented in FLAC3D 5.01 was used to evaluate the performance of a vertically loaded individual GESC installed in loose sand. The numerical model was first verified using the results of experimental tests performed on 150-mm diameter GESC installed in loose sand. The influence of various parameters was investigated in this study, including GESC diameter and length, soil thickness, geotextile encasement length, geotextile stiffness, and friction angle and dilation angle of the infill material. The results of the numerical model showed that vertically loaded GESC of smaller diameter experienced less settlement and lateral expansion than those of larger diameter. The geotextile material with higher stiffness had a substantial influence on the performance of GESC. The maximum effective geotextile encasement length depended on the load on the column head or the compressibility of the column.

1. Introduction

Large areas of the world are covered with soft clay and loose sand deposits, especially coastal regions. As a result of economic growth, many infrastructure projects, such as roadway embankments, have been constructed in areas with weak soil deposits. Many challenging problems have been encountered with regard to construction on weak soil deposits, including bearing capacity issues, excessive deformation, and slope instability. Several ground improvement techniques have been widely implemented to mitigate these issues in weak soils, including sand compaction columns, stone columns, and deep mixed columns (Han, 2015a, 2015b). The stone column, or granular pile technique, has been widely adopted to improve soft soils through the installation of granular columns, which have a much higher stiffness and drainage capability than the surrounding weak soil. In addition to the above benefits, installation of granular columns is a straightforward construction process. Ordinary stone columns (OSC) have been demonstrated to increase the bearing capacity, reduce the settlement, and accelerate the rate of consolidation of soft ground when compared with the weak native soil (Han and Ye, 2001, 2002; Ambily and Gandhi, 2007; Malarvizhi and Ilamparuthi, 2007; Murugesan and Rajagopal, 2009; Castro and Sagaseta, 2009).

Han and Ye (1991) summarized the potential modes of failure for an individual column subjected to an axial compressive load: punching failure, crushing failure, shear failure, and bulging failure. However, bulging failure is considered to be the most common mode of failure for stone columns when they are embedded in soft soil deposits.

The load capacity of ordinary stone columns relies primarily on passive resistance provided by the surrounding soil against the lateral bulging of the stone columns as a result of the axial load application. Soft soils have low strength and may not be able to provide sufficient passive resistance. Therefore, when stone columns are embedded in soft soil, they may bulge due to lack of confinement provided by the surrounding soft soil. Furthermore, the soft clays may enter the voids between granular particles that cause clogging and reduce the permeability of stone columns for drainage. In order to avoid these consequences, geosynthetic encasement can be used around stone columns to provide additional confinement and separation. It helps to isolate the granular particles inside the column from the surrounding soil and increase the stiffness of the column (Malarvizhi and

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Ilamparuthi, 2007; Murugesan and Rajagopal, 2006, 2009). A stone column encased by geosynthetic reinforcement is called a geosynthetic-encased stone column. Sometimes, sand is used instead of stone; these columns are referred to as geosynthetic-encased sand columns. The main difference between geosynthetic-encased stone columns and geosynthetic-encased sand columns is the strength and stiffness of the columns. Geosynthetic-encased stone columns typically have higher strength and stiffness than geosynthetic-encased sand columns. In this paper, the term "GEStC" is used for geosynthetic-encased stone columns and "GESC" for geosynthetic-encased sand columns. The most commonly used geosynthetic for this application is woven geotextile, although sometimes geogrid is used as well.

The installation of geosynthetic-encased stone columns involves driving a steel casing with a closed-end tip into the ground to create a hole. A geosynthetic tube is then inserted inside the steel casing and the granular material is then backfilled. The tip of the casing is opened as the steel casing is withdrawn from the soil with vibration to densify the infill material (Han, 2015a).

OSC may suffer larger lateral expansion close to the surface due to low confinement (Ambily and Gandhi, 2007). GEStCs have less lateral expansion close to the surface, but may have considerably larger lateral expansion at greater depths without encasement under a higher load since the superimposed load is transferred to greater depths because of the presence of the encasement (Murugesan and Rajagopal, 2006).

Researchers have investigated the partial encasement of stone columns in place of full length confinement (Murugesan and Rajagopal, 2006; Gniel and Bouazza, 2009; Yoo and Kim, 2009; Khabbazian et al., 2010; Gu et al., 2016). They reported that the radial expansion failure happened just beneath the level of the encasement.

Hong et al. (2016) addressed the effect of the mechanical properties of geotextile encasement (i.e. strength and stiffness) on the behavior of GEStCs constructed in a soft clay deposit. They reported that the weak geotextiles bulged within a depth of 2.5 times the diameter of the column, whereas for the geotextiles of higher stiffness, the lateral displacements distributed uniformly along the entire length of the column.

Due to the complexity of the problem, a great deal of research has been conducted to model the column-supported embankment system constructed on soft soil using numerical methods, such as the finite difference method (FDM), finite element method (FEM), and discrete element method (DEM). Several researchers have published their work on column-supported embankments with geosynthetic reinforcement placed at the base of the embankment fill (Han and Gabr, 2002; Smith and Filz, 2007; Plaut and Filz, 2010; Rowe and Liu, 2015; Xu et al., 2016). Yoo and Kim (2009) examined the behavior of geosynthetic-encased stone column-supported embankments using a three-dimensional (3D) full model, a 3D unit cell model, and an axisymmetric model. Their results showed the behavior of the full model was in good agreement with that of the unit cell model for rapid construction of embankments. Pulko et al. (2011) introduced a new analytical model to simulate the behavior of GEStCs. Khabbazian et al. (2012) investigated the effect of constitutive models to capture the behavior of the soft soil around GESC constructed under an embankment. The contribution of geosynthetic encasement to the performance of geosynthetic-encased columns to support roadway embankments has been quantified in the previous studies using a finite element approach (Yoo and Kim, 2009; Lo et al., 2010; Khabbazian et al., 2010, 2015; Kaliakin et al., 2012; Almeida et al., 2013; Chen et al., 2015; Hosseinpour et al., 2015; Yoo, 2015; Rajesh, 2016) and a discrete element method (Gu et al., 2017a, 2017b). A finite difference method was also used for the same purpose in the literature, for example (Basack et al., 2016, 2017; Hong et al., 2017).

Most of the previous studies used assumed parameters for numerical analyses, which might not be well calibrated. Most researchers investigated end-bearing encased columns in soft clay that had an undrained shear strength. However, these columns may be used to improve loose sand. The behavior of encased soil columns in loose sand has not been well understood including the effects of column length and encasement length. In reality, encased columns may partially penetrate loose sand (i.e., floating in the sand). Such a condition has not been well investigated. In most past studies, geosynthetic encasement was modeled as an isotropic structural membrane or geogrid sheet that had the same elastic modulus in all directions. In practice, when geosynthetic-encased columns are subjected to vertical loads, the geosynthetic encasement under compression in the vertical direction should have much lower modulus than that in the circumferential direction. In addition, when a seam is used for geosynthetic encasement, the effect of its reduced stiffness has not been investigated in the past. Therefore, further research is needed to improve the understanding of the behavior of geotextile-encased sand columns in loose sand.

This study describes the use of the finite difference method (FDM) incorporated in FLAC3D 5.01 program to evaluate the behavior of a vertically-loaded individual GESC in loose sand. The numerical model was verified using the experimental data and then a parametric study was conducted to investigate the parameters that may have an important influence on the performance of GESC, including GESC diameter, soil thickness, GESC length, encasement length, geotextile stiffness, and friction angle and dilation angle of infill material. The objective of this study was to understand the behavior of geotextile-encased sand columns in loose sand under different conditions using a numerical method. Development or use of simpler methods, such as analytical solutions, to design encased columns in soft soil is beyond the scope of this study.

2. Numerical modeling

A finite difference program, FLAC3D Version 5.01, was employed to perform three-dimensional numerical analyses of a vertically-loaded individual GESC in loose sand. The experimental test results obtained by Kadhim (2016) were adopted to verify the numerical model of the GESC in loose sand. Since geotextile encasement around a soil column under vertical loading is subjected to tensile stresses in the circumferential direction and compressive stresses in the vertical direction, the geotextile has an anisotropic behavior. In addition, the FLAC2D software could not model the geotextile encasement using structural elements if an axisymmetric model was selected. Therefore, the FLAC3D software was adopted in this study instead of the FLAC2D software.

Kansas River sand was used for both the infill material of the column and the weak soil in the experimental tests. The Kansas River sand for the column was compacted to 70% relative density while the Kansas River sand for the weak surrounding sand was placed to 30% relative density. Both sands were modeled as a linearly-elastic perfectly-plastic material with the Mohr-Coulomb criterion. The parameters of the Mohr-Coulomb model are: friction angle (ϕ), cohesion (c), dilation angle (ψ), elastic modulus (E), and Poisson's ratio (ν).

Geotextile encasement was modeled as an orthotropic linearly-elastic material using the embedded liner structural element. The decision to model the geotextile as an orthotropic material was based on the results of tensile tests conducted on geotextile sheets according to ISO 10319, which showed that the circumferential stiffness in the cross-machine direction of the geotextile was higher than that in the vertical direction (i.e., the machine direction of the geotetxile). This assumption was confirmed by Khabbazian et al. (2009), who proved that modeling the geosynthetic encasement as an isotropic linearly-elastic material increased the bearing capacity of GEStC by 10% and unfavorably influenced the profile of their lateral deformations. By default, liner elements can resist both bending and membrane forces. However, the membrane loading was only activated in the written code for the embedded liner since geotextiles can only resist membrane forces. In addition, a Constant Strain Triangle (CST) element, which is a three-node plane-stress triangular element, was utilized to simulate the geotextile material because it can only tolerate membrane loading.

Liner elements interact with the grid through two components: the