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A numerical analysis of a fully penetrated encased granular column

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A B S T R A C T

This paper studies the performance of an individual encased granular column that is embedded in soft soil using a numerical analysis. The numerical analysis is verified by experimental tests that are performed in the laboratory, using a model encased sand column that is embedded in a soft clay deposit. In addition to bearing stress-settlement response, detailed characterizations of the encased column, in terms of the distribution of lateral earth and sleeve-induced pressure along the column length, are determined. The numerically analyzed results are compared with those for the model tests and analytical results. Parametric studies over the encasement stiffness, the diameter of the granular column and the loading area are conducted to determine the influence of encasement on the column. The sleeve-induced confining pressure and the bearing stress of the encased sand columns, calculated using the cavity expansion theory and the simplified approach that assumes a constant volume for the granular column, are compared with the numerical results to justify the use of these two methods. The numerical results show that the stiffness of the encasement significantly affects the bulging length of an encased granular column. An increase in the column diameter or the loading area produces a significant reduction in the sleeve-induced confining pressure, which leads to a reduction in the bearing stress improvement of an encased granular column, but the total load supported by the loading plate has an almost linear relationship with the loading plate diameter/column diameter ratio.

1. Introduction

Encasing a cylindrical granular column in a flexible sleeve improves the bearing performance of the column, especially for a site of very soft clays having low undrained shear strength (Raithel et al., 2002, 2005; de Mello et al., 2008; Araujo et al., 2009; Almeida et al., 2015). A number of laboratory tests and numerical analyses have been performed over the years for encasement applications (Murugesan and Rajagopal, 2006, 2007, 2010; Gniel and Bouazza, 2009; Wu and Hong, 2009; Wu et al., 2009; Yoo and Kim, 2009; Khabbazian et al., 2010; Lo et al., 2010; Ali et al., 2012, 2014; Hong, 2012; Yoo and Lee, 2012; Dash and Bora, 2013; Ghazavi and Afshar, 2013; Gu et al., 2016; Hong et al., 2016; Ou Yang et al., 2017). Numerical methods have been used in many studies to determine the performance of encased granular columns (Murugesan and Rajagopal, 2006; Malarvizhi and Ilamparuthi, 2007; Yoo and Kim, 2009; Khabbazian et al., 2010; Lo et al., 2010; Yoo, 2010; Hong, 2012; Elsawy, 2013; Rajesh, 2017). Different types of constitutive laws have been proposed for overall performance studies.

Axial deformation of the encased granular column induces a radial strain on the column and a circumferential strain on the encasement, which in turn induces additional confining pressure on the column and increases the bearing capability of the column. Stiff encasement provides greater confining pressure so the encased granular material may not reach the yield state. Therefore, the constitutive law for the granular material under all stress states (pre- and post-yield) is important in determining the sleeve-induced confining pressure and the bearing stress for an encased granular column. Although it is easier to acquire the parameters for a simple constitutive model and the calculation process is simpler, it is only suitable for equilibrium problems, where yield or failure criteria govern the results. Deformation problems that involve load-response for a structure require the constitutive models to represent the involved constituents. Hong (2012) reported that

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predictions using an elastic-perfectly plastic model for filled material deviate strongly from the measured values owing to improper volumetric predictions. The simple model underestimates the deviatoric stress owing to its inability to elucidate the expansive behavior of a granular material in the early strained stage. A method incorporates the elastic-plastic constitutive law with the non-associated flow rule for filled material and the elastic-perfectly plastic relationship for encasement has been proven to model the behavior of a granular column that is unreinforced or encased, under a triaxial condition (Hong, 2012). However, using a comprehensive constitutive model to describe material behavior or interfacial interaction requires elaborate formulation and the acquisition of parameters is laborious.

This study determines the performance of an encased granular column that is embedded in soft clay and determines the parameters that significantly influence the effectiveness of any reinforcement using a thoroughly verified numerical model. The overall performance of an encased granular column is verified. Constitutive models for three constituents and two boundaries, namely granular soil, soft clay, encasement, and interfacial boundaries between granular material and loading plate and between soft soil and loading plate, are detailed. Prior to a parametric study, the proposed method is verified in laboratory experimental tests that use a model encased sand column that is embedded in soft clay (Hong et al., 2016).

2. The numerical method

An encased granular column that is embedded in soft soil is composed of four constituent materials and two interfaces: the loading plate, the soft soil that surrounds the column, the granular material that fills the column, the reinforcement that encases the cylindrical granular column and the loading plate-granule and loading plate-soft soil interfaces.

The performance analyses for the encased granular column were carried out using the numerical finite difference commercial code FLAC; Fig. 1 shows the grid used for the numerical analysis. The actual sizes of test tank and loading plate were used in modeling the model test, whereas clay boundary equal to 40 folds of column radius was adopted in parametric study. The encased sand column under axisymmetric condition was analyzed in accordance with an encased column embedded in clay deposit.

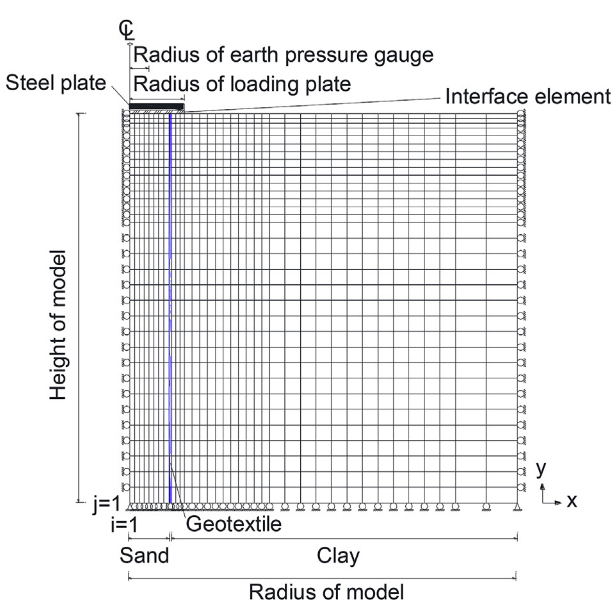

Fig. 1. Finite difference mesh for an encased granular column embedded in clay deposit.

The proposed method incorporated the elastic-plastic constitutive law with the non-associated flow rule for filled material. Modified Cam-clay model was used to characterize the mechanical behavior of the soft clay. Because the encasement and the soil deform simultaneously in the axial direction, perfect bonding between geotextile and soil and column was assumed for the interface of these materials (Murugesan and Rajagopal, 2006; Lo et al., 2010). The sand-loading plate interface at the top of the column was modeled using Mohr-Coulomb yield criteria and a shearing stiffness that is dependent on the normal stress. The clay-loading plate interface was modeled as a rigid plastic element, using the undrained strength of the soft clay to represent the yield strength of the interface. The loading plate was compressed in the axial direction by applying a 10^{-9} m/step rate on the upper boundary. The models for the mechanical characteristics of these constituent materials and interfaces are briefly presented in this section. Detailed derivations and acquisition procedures for determining the material parameters for the numerical formulations are given in Hong (2012).

2.1. The mechanical properties of the granular material

Axial compression causes lateral expansion in an encased granular column, which induces extension of the encasing sleeve and generates additional confining stress on the granular material. Therefore, the encased column is subject to increasing axial stress when the confining pressure is increased. The magnitude of the expansion of the column depends on the volumetric strain of the soil and the axial strain of the column. Therefore, a model that models the volumetric strain of the sand that fills the column was developed to determine the circumferential strain on the encasement and the sleeve-induced confining pressure along the length of the column (Hong, 2012). The model is based on the plasticity theory, using a non-associated flow rule to delineate the constitutive behavior of the sand that fills the column. A strain hardening constitutive model that follows the non-associated flow rule characterizes the prominent expansive behavior of medium to dense sands.

The mechanical constants and the functions used in this analysis include the elastic modulus, the bulk modulus, the yield and the plastic potential functions. The mobilized friction angle and the mobilized dilatancy angle are also used. The equations for the relevant properties used in the numerical analyses are tabulated in Table 1.

2.2. The mechanical properties of the soft clay

Modified Cam-clay model is used to characterize the mechanical behavior of the test soft clay. Usually, the parameters for soil modeling using Modified Cam-clay model (i.e. M, λ, κ, and Γ) are determined using an isotropic consolidation test, which is performed on a cylindrical specimen, where M = the critical state frictional constant, λ = the gradient of the compression line, κ = the gradient of the swelling line and Γ = the specific volume that corresponds to the critical state. However, the clay in the experimental model tests (Hong et al., 2016) was so soft that preparing a cylindrical specimen for isotropic consolidation test was impracticable. Therefore, all of the parameters were obtained using one-dimensional consolidation and undrained shear tests.

The two constants, λ and κ, are calculated using one-dimensional consolidation test results using the correlations: