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The performance of a sand column internally reinforced with horizontal reinforcement layers

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A R T I C L E I N F O

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A B S T R A C T

The responses of sand columns internally reinforced with horizontal geotextile layers are studied using a numerical method. The sand in the column is modeled using a non-associated plasticity flow rule. The numerical results are validated through laboratory triaxial compression tests carried out on sand columns 70 mm in diameter and reinforced with 4, 6 and 8 layers of geotextile. Numerical and experimental results are compared for deviatoric stresses and volumetric strains. The numerical analysis also provides an insight into the reinforcement mechanism. The factors affecting the reinforced column response and the advantage of horizontal reinforcement are outlined. Parametric studies on the influences of reinforcement properties, reinforcing layer spacing and specimen diameter as to the response of reinforced sand columns are examined. The numerical results show reinforcement has a significant influence from the edge toward the center of the column. The boundary makes a constant inclination angle with the reinforcement. For the reinforced column with low spacing/diameter ratio, the stresses in the influenced areas developed from the two consecutive reinforcements overlapping and the effects compounded. The lower the spacing/diameter ratio the greater the column reinforcement strength improved. An advantage of horizontal reinforcement is reinforcement rupture or soil-reinforcement interfacial slippage will not cause dramatic collapse of the entire column.

1. Introduction

Granular columns are effective in improving the bearing capacity of soft soil. The bearing capacity improvement via granular columns is achieved through including stronger granular material. In the last two decades column enhancement, especially the top portion of the column, has been proposed and studied to improve bearing capability and reduce the bulging of columns embedded in soft soil. Column enhancement is established either by enveloping a granular column within a flexible fabric or applying horizontal reinforcement sheets to the column (Cai and Li, 1994; Madhav et al., 1994; Broms et al., 1995; Nods, 2002; Sharma et al., 2004; Wu and Hong, 2008; Araujo et al., 2009; Gniel and Bouazza, 2009; Wu et al., 2009; Lo et al., 2010; Murugesan and Rajagopal, 2010; Ali et al., 2012; Hong, 2012; Yoo and Lee, 2012).

The reinforcing effects have been verified through laboratory triaxial tests carried out on cylindrical sand specimens reinforced with horizontal discs or external sleeves (Al-Joulani, 1995; Ashmawy and Bourdeau, 1998; Haeri et al., 2000; Ayadat and Hanna, 2005; Madhavi and Murthy, 2007; Wu and Hong, 2009; Nguyen et al., 2013). The test results demonstrated reinforcement increases the peak strength and axial strain at failure and reduces the post-peak strength loss. Although the reinforcement strength and stiffness effects, as well as the effect of reinforcement spacing/column diameter ratio on the reinforced column behavior, have been qualitatively validated through laboratory experimental tests, the experimental results have been limited to direct field applications. Since the experimental tests report results for specific test conditions (i.e. soil and reinforcement materials, reinforcement spacing, column size, and confining pressure), numerical and analytical methods have their advantages in providing the means to deal with general in-situ conditions properly.

The reinforcing effect of a column internally reinforced with horizontal reinforcement layers comes from the development of shear stress at the soil-reinforcement interface. This depends on the frictional characteristics between the two adjacent constituents, mechanical properties of the two constituents, and the environment (e.g. spacing of the reinforcements and the stress conditions acting on the column). Soil or reinforcement yielding and slippage between these two materials may occur locally inside the soil-reinforcement composite or at the soil-reinforcement

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interface. Hence, the reinforcing mechanism of an internally reinforced column is more complicated than that for an encased column. The number of detailed studies that have investigated this subject is limited.

In an encased column, hoop stress generated by the extended reinforcement acts on the column perimeter and induces uniform confining pressure to the entire soil mass. In contrast, column bulging mobilizes shear stresses at the soil-reinforcement interface due to the difference in their moduli of deformation. The mobilized shear stress distributes along the radial direction from the perimeter to the center of the column and provides additional confining stress to the neighboring granular material. Since the shear stress induces additional confining pressure originating at the soil-reinforcement interface, the influence of this confinement propagates from the interface toward the adjacent soil area. Hence, the additional confining pressure may distribute non-uniformly in the soil mass between two consecutive reinforcements.

To simplify the analytical analysis due to complicated mechanisms in the soil mass and soil-reinforcement interface, additional confining pressure along the axial direction between two reinforcing discs is assumed to be uniformly distributed and the principal stress directions cohere (Wu and Hong, 2008). However, numerical methods are expedient in examining complicated soil-reinforcement interfacial behavior and reinforcement yielding in a column internally reinforced with horizontal layers. The numerical method is released from many hypotheses and assumptions in analyzing local behavior. For that purpose, this study employs a numerical method to analyze the behavior of a column internally reinforced with horizontal layers. The proposed method is validated through laboratory experimental triaxial testing and the factors affecting the reinforced column behavior are examined.

2. Numerical modeling

The present model is proposed based on prediction accuracy and parameter availability concerns (Huang et al., 2009), and the model acquisitions are reported in this section.

2.1. Soil elastic-plastic model

Because axial compression causes lateral expansion in a reinforced column, shear stress is induced at the soil-reinforcement interface due to the difference in their moduli of deformation. The mobilized shear stress provides additional confining stress to the neighboring granular material. This causes a reinforced column to become subject to increasing axial stress when the confining pressure is coincidently increased. Confining pressure acts on the soil accumulated along the radial direction from the perimeter to the center of the column. It also varies along the axial direction due to upward and downward propagations of additional confining pressure from the soil-reinforcement interface toward the soil mass.

The magnitude of column expansion is determined by the soil volumetric strain and column axial strain. Therefore, a model capable of modeling volumetric strain is needed to capture the relative displacement at the soil-reinforcement interface and accordingly the developed shear stress along the reinforcement. Soil mechanical properties represented as a function of the confining stress are also needed to conform to reinforced column behavior. According to these concerns, this study adopts a model based on the plasticity theory with non-associated flow rule to delineate the constitutive behavior of the sand filled in the column. A strain hardening constitutive model following the non-associated flow rule could characterize the prominent expansive behavior of medium to dense sands.

The mechanical constants and functions employed in the current analysis include the elastic modulus, bulk modulus, yield and the plastic potential functions. The mobilized friction angle and mobilized dilatancy angle concepts are employed in this analysis. Detailed derivatives and acquisition procedures in determining the material parameters for the numerical formulations were presented in Hong (2012).

2.2. The sand properties and parameters for numerical modeling

This study develops numerical expressions specifying the mobilized friction and dilatancy angles of the test sand as a function of monotonically increased confining pressure to conform to the experimental data. The mechanical properties for numerical analysis are all extracted based on the experimental results obtained from cylindrical sand specimens subjected to triaxial compression conditions. The regression functions are formulated using test results conducted over the confining pressure range of 20 kPa–200 kPa.

Sub-angular shaped quartz sand is used in all unreinforced and reinforced sand columns in this study. The sand has a specific gravity of $G_s = 2.63$, maximum dry unit weight of $\gamma_{dmax} = 16.48$ kN/m^3, and minimum dry unit weight of $\gamma_{dmin} = 13.73$ kN/m^3. Triaxial compression tests are conducted on dry sand compacted to 70% relative density.

2.2.1. Tested sand modulus of elasticity

Fig. 1 displays the deviatoric stress-axial strain-volumetric strain relation for cylindrical sand specimens subjected to various chamber pressures. The initial tangential modulus of the deviatoric stress-strain curve is taken as the elastic modulus of the sand because sand behaves elastically only in the minimal axial strain range. Regression for parameter E is developed from test results and expressed as

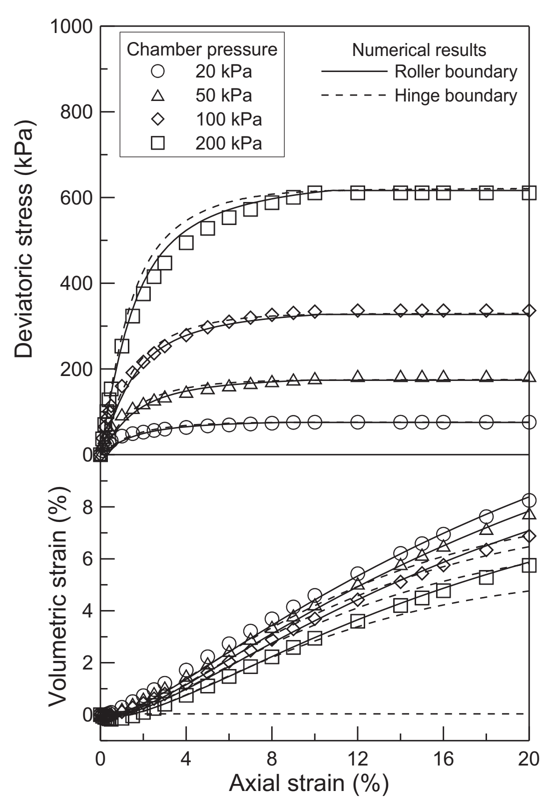

Fig. 1. Numerical predictions of the soil behavior under triaxial compression.