THEORETICAL ANALYSIS OF A LAMINATED REINFORCED GRANULAR COLUMN

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Abstract: The axial stress-strain response of reinforced granular columns was studied and the results presented in this paper. The reinforcement is provided by applying horizontally laminated reinforcing sheets to a granular column. An analytical procedure based on using a normalized relation between the volumetric and axial soil strains was adopted to analyze the response of the reinforced columns. The proposed analytical method was verified through laboratory triaxial tests carried out on sand columns reinforced with four layers of horizontal geotextile sheets. It is found from the analyses that the reinforced granular column embedded in clay exhibited an increase in axial resistance significantly greater than that loaded under constant chamber pressure.

Keywords: analysis, geotextile sheet, reinforced, reinforcing effect, stone column, strength.

INTRODUCTION

Granular columns have been used in engineering practice to improve the bearing capacity of a weak or soft soil and reduce settlement for foundations resting on weak soil (Bergado et al. 1991, 1992; Raithel et al. 2002; Kempfert 2003). The soil improvements via granular columns are achieved from consolidation acceleration of the weak soil due to a shortened drainage path, increased load carrying capacity and/or settlement reduction due to the inclusion of stronger granular material. When vertical and corresponding lateral deformations of the granular column occur under a vertical load, the surrounding soil stratum generates additional confining pressure to the column. Because lateral confining pressure of in situ soil generally increases with an increase in depth, and the mechanical behaviour of the granular material is usually controlled by the lateral confining pressure, most granular columns fail from bulging near the top due to insufficient lateral support (Hughes and Withers 1974; Madhav and Miura 1994). The bulging failure consequently results in a lower load carrying capacity irrespective of the stiffness and strength of constituent materials (Madhav and Miura 1994). Therefore, granular column reinforcement, especially for the top section, is proposed to enhance lateral confinement to the column. The reinforcement is established through enveloping the granular column in a flexible fabric or applying horizontally laminated reinforcing sheets to the granular column (Rao and Bhandari 1977; Alamgir 1989; Cai and Li 1994; Madhav et al. 1994; Broms 1995; Raithel and Kempfert 2000; Nods 2002; Sharma et al. 2004; Ayadat and Hanna 2005; Murugesan and Rajagopal 2006; Wu et al. 2008). The improvement in load carrying capability is mobilized from lateral or confining stress exerted by the surrounding soil and the encapsulation or lamination of reinforcing material.

In response to column expansion, the shear stress mobilized between the horizontal reinforcing sheet and the granular material provides additional confinement to the column. Therefore, the granular material is subjected to monotonically increasing confining pressure during axial loading. The proposed method is able to analyze the stress-strain response of a granular column subjected to confining pressure in this feature. This paper aims at investigating the granular column reinforcing effect from flexible sheet lamination.

METHODS OF ANALYSIS

The granular column reinforced with flexible sheet lamination is composed of three constituent materials, the native soil that surrounds the column, the granular material that fills the column and the reinforcing sheets in layer form. Wu et al. (2008) adopted models from Duncan and Chang (1970) and Wong (1990) to formulate the mechanical characteristics of granular materials and establish analytical procedures to investigate the axial stress-strain response of an encapsulated granular column. In this method, the increasing confining pressure induced by the surrounding soil is analyzed from an analogy to cylindrical cavity expansion. The procedures are extended to analyze columns with laminated reinforcement. The column is assumed to fail from bulging due to insufficient lateral support.

Confining stress provided by the horizontal reinforcing sheets

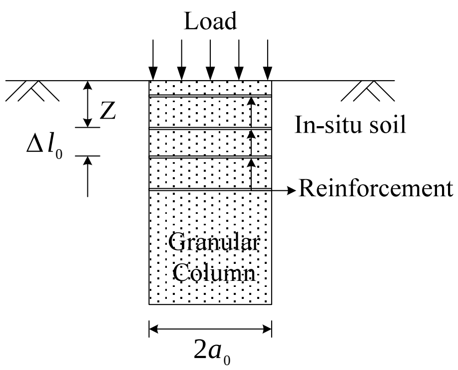
Column bulging mobilizes shear stresses at the soil-inclusion interface due to the difference in their modulus of deformation. The mobilized shear stresses along the radial direction thus provide additional confining stress to the granular material. These stresses accumulate along the radial direction from the perimeter to the centre of the column. Therefore, the additional confining stress varies along the radial direction. Because the confining stress acting on the column is a conjunction of surrounding soil and shear mobilization at the soil-inclusion interface, the confining stresses along the radial direction are not uniform. The shear stress development at the soil-inclusion interface depends on the frictional characteristics between the two adjacent constituents, mechanical properties of the two constituents, and the stresses condition acting on the column.

The increase in confining stress $d\sigma_h$ provided by the reinforcing sheet is evaluated by dividing the reinforcing sheet into numerous concentric rings, as shown in Figure 1. In the axial direction, the effect of the mobilized shear stress is assumed to distribute uniformly to the entire soil layer between the two reinforcing sheets. Thus, the increase in the confining stress mobilized by the shear stress is expressed as

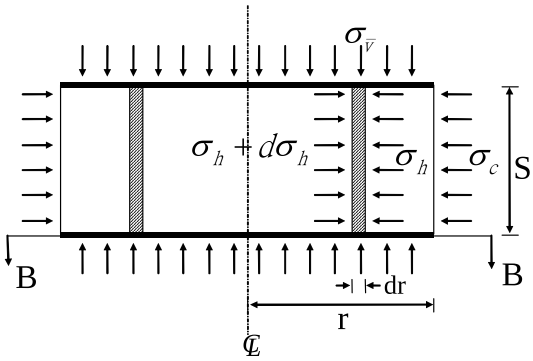
$$d\sigma_h = \frac{2\tau}{S} dr \tag{1}$$

where $d\sigma_h$ is the additional confining stress due to shear mobilization at the soil-inclusion interface, S is the vertical spacing between two reinforcing sheets, τ is the shear stress mobilized at the soil-inclusion interface, and r is the distance from the center of the column.

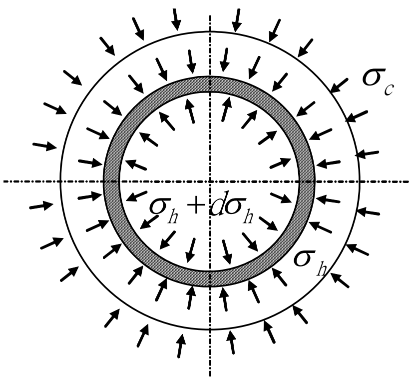
Because the deformation modulus of the two adjacent constituents are different, the initially bonded interface may slip due to relative displacement between the two materials. Thus, different concentric ring interactive mechanisms result in varied mobilized shear stresses along the radial direction. The distribution of additional confining stress produced by the shear stress for fully bonded and slippage mechanisms is discussed in the next subsections.



(a) Laminated reinforced granular column



(b) Stress acting on granular column between two reinforcing sheets



(c) Cross section B-B

Figure 1. Schematic of a reinforced granular column

Firmly bonded mechanism

The shear stress at the interface of two firmly bonded materials is

$$\tau = \frac{T}{2a_1} \tag{2}$$

where T is the radial tensile force per unit width of the reinforcing sheet and a_1 is the deformed column radius.

By modelling the reinforcing sheet as an elastic-perfectly plastic material, the relation between the additional confining stress and the column radius for a reinforcing sheet in elastic and plastic states are expressed as

$$\frac{d\sigma_h}{dr} = \frac{E_f\left(a_1 - a_0\right)}{S a_1 a_0} \tag{3}$$

and

$$\frac{d\sigma_h}{dr} = \frac{T_{fp}}{a_1 S} \tag{4}$$

where E_f and T_{fp} are elastic modulus and tensile yield strength of the reinforcing sheet, a_0 is the initial column radius.

Slippage mechanism

For the frictional interaction between a sandy soil and reinforcing inclusion the shear strength at the interface can be written as

$$\tau = \sigma_1 \tan \phi_a \tag{5}$$

where ϕ_a is the frictional angle at the soil-inclusion interface.

Using the widely used function formalized by Duncan and Chang (1970), the relation between the confining pressure σ_3, axial stress σ_1 and axial strain ε_1 for a granular material can be obtained by dividing the axial strain ε_1 into numerous increments and summing the axial stress values corresponding to each strain increment as

$$\sigma_1 = \sum_{i=0}^{m-1} \frac{\varepsilon_1}{m} \left[1 - R_f \frac{(\sigma_{1,i} - \sigma_3)(1 - \sin \phi)}{2c \cos \phi + 2\sigma_3 \sin \phi} \right]^2 K P_a \left(\frac{\sigma_3}{P_a} \right)^n \tag{6}$$

in which c and ϕ are the cohesion and frictional angle of the granular soil, σ_3 and σ_1 are the principal stresses and P_a is the reference atmosphere pressure, R_f, K and n are constants of the granular soil to be determined experimentally, i represents the i^{th} strain increment and m is the total number of strain increments.

The relation between the additional confining stress and the radius for a granular material subjected to pre-yield stresses can be obtained by substituting vertical stress (Equation (6)) into Equations (1) and (5) and written as

$$\frac{d\sigma_h}{dr} = \frac{2 \tan \phi_a}{S} \left\{ \sum_{i=0}^{m-1} \frac{\varepsilon_1}{m} \left[1 - R_f \frac{(\sigma_{1,i} - \sigma_h)(1 - \sin \phi)}{2c \cos \phi + 2\sigma_h \sin \phi} \right]^2 K P_a \left(\frac{\sigma_h}{P_a} \right)^n \right\} \tag{7}$$

The shear stress at the interface for granular soil at the yield state can be obtained by substituting the vertical normal stress from Mohr-Column criteria into Equation (5), expressed as

$$\tau = \left(\sigma_h + \frac{2c \cos \phi + 2\sigma_h \sin \phi}{1 - \sin \phi} \right) \tan \phi_a \tag{8}$$

Thus, the relation between the additional confining stress $d\sigma_h$ and the radius is

$$\frac{d\sigma_h}{dr} = \frac{2 \tan \phi_a}{S} \left(\sigma_h + \frac{2c \cos \phi + 2\sigma_h \sin \phi}{1 - \sin \phi} \right) \tag{9}$$

Evaluation the additional confining stress

The additional confining stress provided by each ring can be evaluated from one of the (3), (4), (7) and (9) equations depending on the frictional resistance between the two constituents and thus the bonding mechanism. Each ring of the reinforcement may firmly bond to the granular soil or slip along the interface. If a concentric ring in the reinforcement is firmly bonded to the granular soil, the additional confining stress can be evaluated using Equation (3) or (4) for a pre- or post- yield reinforcing sheet, respectively. The additional confining stress is controlled by the tensile force of the reinforcing sheet. If slippage occurs on a concentric ring Equation (7) or (9) is used to evaluate the additional confining stress for the soil subjected to pre- or post- yield stress, respectively. The additional confining stress is controlled by the vertical stress of the granular material. By comparing the additional confining stresses obtained using the two interactive mechanisms at the interface (perfectly bonded and slippage), the mechanism provides the smaller value is adopted as the prior occurrence mechanism.

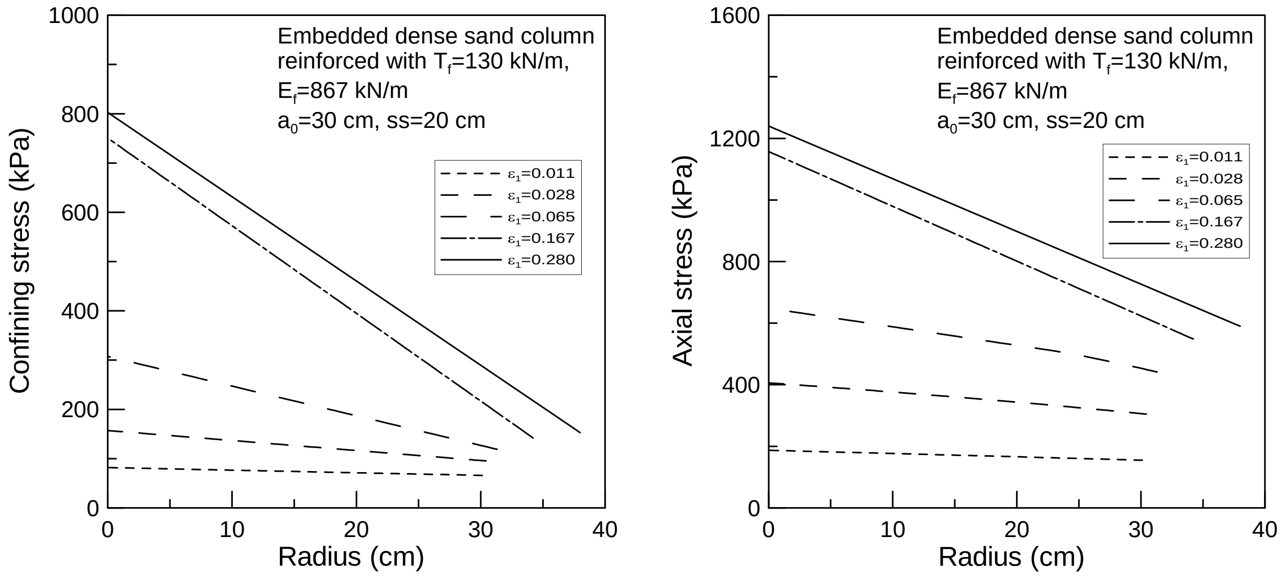
The diminishing additional confining stress at the outmost ring is the boundary condition of the confining stress increment, which implies that confining stress acting on the perimeter of the column is provided only by the surrounding soil. Iteration is needed in evaluating the additional confining stresses provided by each ring. Figure 2 illustrates the non-uniformly distributed confining stresses along the radial direction and the distribution of the corresponding normal stresses for a reinforced granular column. A 60-cm diameter column embedded in soft clay expands to 76 cm at 28% axial strain. The confining stress on the perimeter of the column increases from 44 kPa to 153 kPa. This behaviour corroborates earlier analytical results reported by Madhav et al. (1994). The non-uniformed distributions of confining stress being more pronounced the greater the axial strains.

ANALYTICAL RESULTS

Verification of the proposed method

The proposed analytical method was verified against experimental laboratory test results. Triaxial compression tests were carried out on 14 cm high 7 cm diameter cylindrical specimens of dry sand reinforced with four layers of geotextile (thermally bonded non-woven geotextile). The spacing between consecutive layers was kept equal and double the distance from the end, as shown in Figure 3. The tensile force-strain relation of the geotextile is presented in Figure 4, which was obtained from tensile test of a 200 mm wide 100 mm long specimen at 10 mm/min tensile velocity. The sand used has a specific gravity of G_s = 2.65, maximum dry unit weight of $\gamma_{d(max)}$ = 16.5 kN/m^3, and minimum dry unit weight of $\gamma_{d(min)}$ = 13.7 kN/m^3. The sand was filled into a cylindrical column with 70% relative density. The frictional angle between the geotextile and sand was 33°, which was determined using a modified direct shear box. The upper half of the shear box containing the sand sample slid on a layer of geotextile that was inserted in the shear box at the shearing plane.

The deviatoric stress-axial strain and volumetric strain-axial strain relations for the unreinforced granular sand are shown in Figure 5. The relation between the corrected stress ratio $\kappa(\varepsilon_1)$ and axial strain for the test sand is presented in Figure 6. The analytical results for a non-reinforced sand specimen using the proposed method are in good agreement with the experimental results (Figure 5). Figure 7 presents the experimental and predicted results for reinforced specimens subjected to various confining pressures. The test results for reinforced specimens show that the deviatoric stress increases with increasing strain. Note that the reinforced specimens do not reach their peak compressive stresses at high vertical strain (30%). Test results demonstrated that reinforcement increased peak strength and axial strain at failure. Furthermore, the agreement between experimental and computed results was satisfactory.



(a) Distributed confining stresses (b) Distributed axial stresses

Figure 2. Confining stress and axial stress distribution of a reinforced column at various axial strains

(a) Initial shape of the reinforced triaxial specimen (b) Deformed shape of the reinforced triaxial specimen

Figure 3. Initial and deformed triaxial specimen with four-layer reinforcement

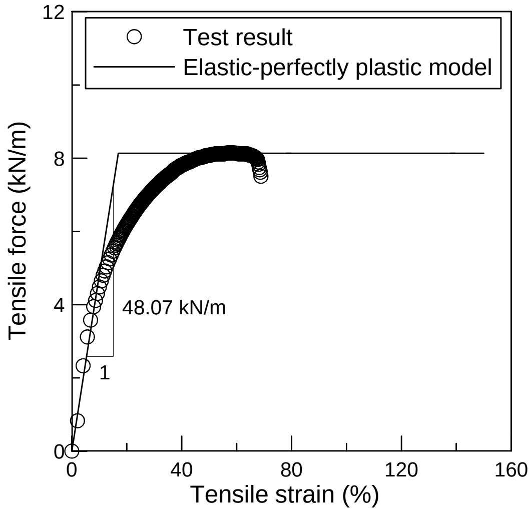


Figure 4. Tensile force-strain relation of reinforcing sheet

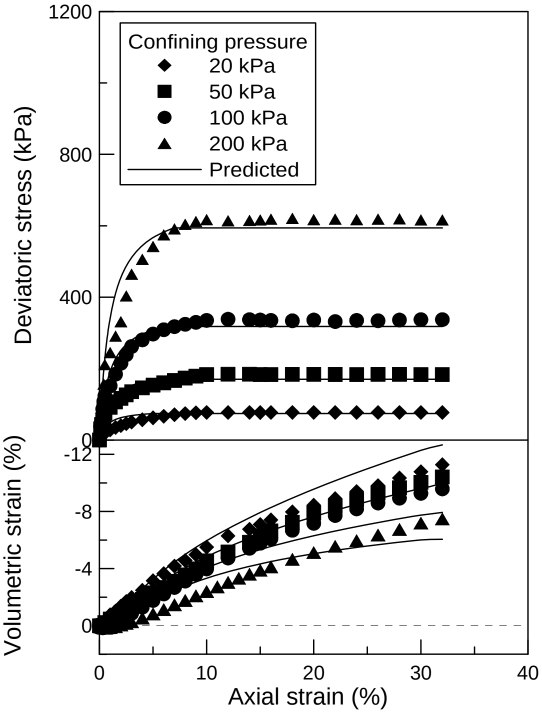


Figure 5. Triaxial test results for unreinforced sand specimen

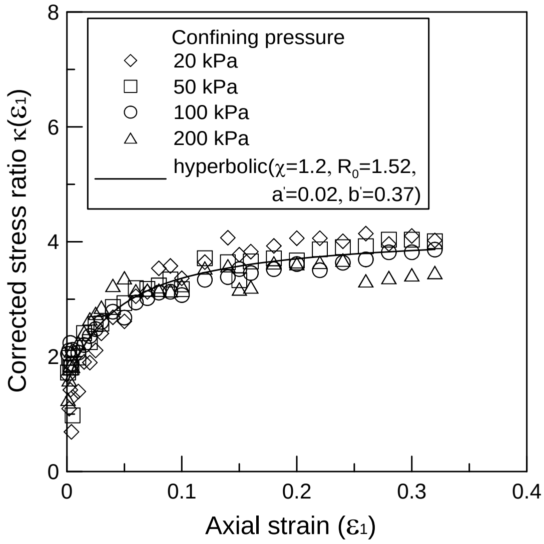


Figure 6. $\kappa(\varepsilon_1)$ vs. ε_1 for test sand

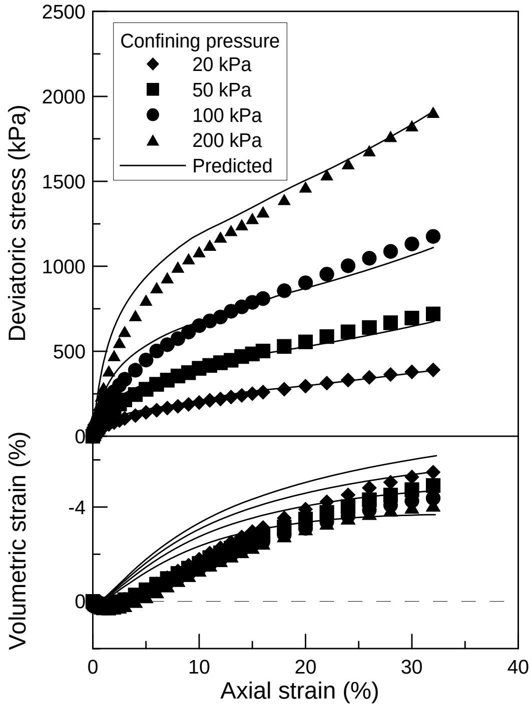


Figure 7. Experimental and analytical results for reinforced sand specimen

Axial stress-axial strain relation of a reinforced granular column under increased confining pressure

In the field, granular column expansion upon axial stress induces incremental confining pressure from the surrounding soil. The gradually increased axial load is resisted by stronger material due to the continuous increase in confining pressure. To demonstrate this effect on granular column behaviour, a reinforced granular column 60 cm in diameter embedded in saturated clay was studied. The column was constructed of dense sand and reinforced with tensile resistant sheets in the form of layers at a given spacing. The reinforcing sheets had modulus of elasticity E_f = 867 kN/m and tensile strength T_f = 130 kN/m. The properties of the dense sand were D_{50} = 0.84 mm, C_u = 1.29, C_c = 0.84, G_s = 2.65, $\gamma_{d(max)}$ = 16.5 kN/m^3, $\gamma_{d(min)}$ = 13.7 kN/m^3, D_r = 70%. Sand normalization was conducted using experimental data from triaxial tests. The variation in confining pressure with the radius expansion for two initially different confining pressures is depicted in Figure 8. The initial lateral pressure acting on the column is assumed to be twice the un-drained clay cohesion as that measured by Hughes et al. (1975). Axial stress-strain relation of reinforced columns with 30 cm and 60 cm spacings are presented in Figure 9. Embedding a reinforced granular column dramatically increases the strength of the granular column compared to a reinforced column subjected to constant confining pressure. While the reinforced columns are embedded in the clay and subjected to 44 kPa initial confining pressure (Figure 9(a)), the axial stresses corresponding to 10% axial strain increased by 15% and 24% respectively for 30 cm and 60 cm spacing with reference to constant confining pressure. The increases for reinforced columns subjected to 74.2 kPa initial confining pressure were 20% and 30% respectively for 30 cm and 60 cm spacing (Figure 9(b)). We observed that the larger the axial strain, the greater the axial stress discrepancy between the constant and various pressures.

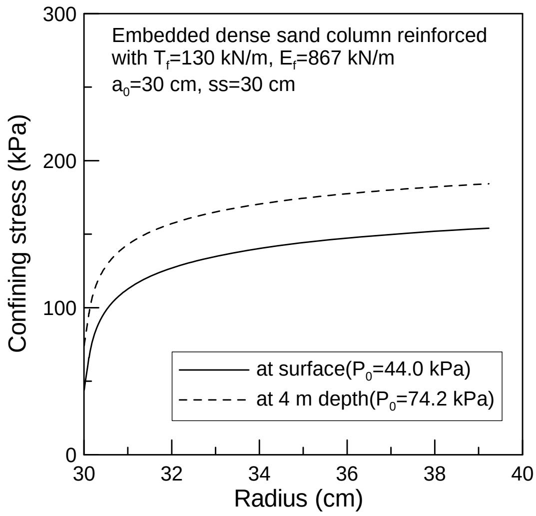
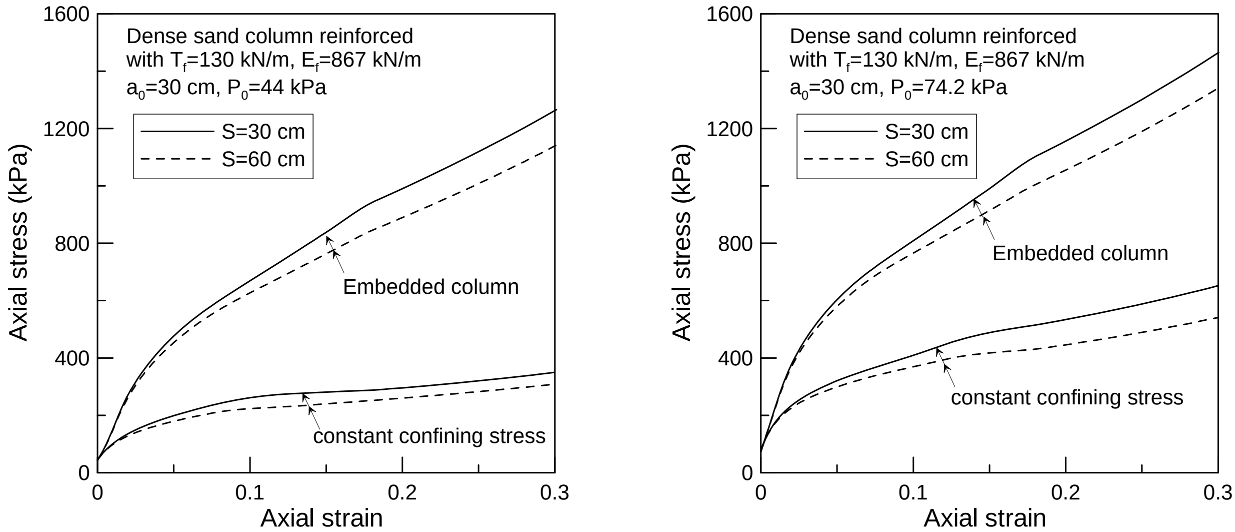


Figure 8. Variation in confining pressure with radius expansion



(a) Initial confining pressure = 44 kPa (b) Initial confining pressure = 74.2 kPa

Figure 9. Axial stress-strain relations for embedded and constant-confined reinforced sand columns

CONCLUSIONS

The axial stress-strain relation for granular columns reinforced with laminated flexible sheets was analyzed numerically. The relation was affected by monotonically increased lateral pressure compounded by interfacial shearing and lateral restraint. The shearing stress between the reinforcing sheets and granular material produces a non-uniformed distributed confining pressure while the counteraction of the surrounding in-situ soil upon column expansion raises lateral restraint to the whole column. The results reveal that the proposed method attains good agreement with the experimental results for a column reinforced using four-layer reinforcement. The continuous increase in lateral pressure resulted in increases in the stiffness and strength of granular columns compared to columns subjected to constant lateral pressure. Thus, the stress-strain relations for reinforced granular columns embedded in clay and loaded under a constant confining pressure are different.

Acknowledgements: The authors would like to thank the National Science Council of the Republic of China for financially supporting this research under Contract no. NSC96-2628-E-032-038-MY3.

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