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Load-deformation behaviour of a stone column using the coupled DEM-FDM method

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Abstract

This paper presents a novel coupled model of discrete element method (DEM) and finite difference method (FDM) to investigate the load-deformation of stone columns reinforced soft clay. In the proposed model, the soft clay domain was modelled by the continuum method using FLAC and stone column was modelled by the discrete element method using PFC2D. Algorithms and mathematical framework to assist coupling between the two domains were introduced, in which the DEM transfers forces and moment to the FDM and then the FDM provides an update of displacements to the DEM. The predicted load-deformation responses obtained from the coupling model reasonably agreed well with data measured experimentally, indicating that the proposed coupling discrete-continuum model could capture the deformation behavior of stone column stabilized soft clay. Evolutions of contact force distributions developed in stone column at varying levels of settlement were presented. Shear stress-strain contours induced in the surrounding soft soils were also investigated.

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Load-deformation Behavior of a Stone Column using Coupled DEM-FDM Method

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ABSTRACT

This paper presents a novel coupled model of discrete element method (DEM) and finite difference method (FDM) to investigate the load-deformation of stone columns reinforced soft clay. In the proposed model, the soft clay domain was modelled by the continuum method using FLAC and stone column was modelled by the discrete element method using PFC2D. Algorithms and mathematical framework to assist coupling between the two domains were introduced, in which the DEM transfers forces and moment to the FDM and then the FDM provides an update of displacements to the DEM. The predicted load-deformation responses obtained from the coupling model reasonably agreed well with data measured experimentally, indicating that the proposed coupling discrete-continuum model could capture the deformation behavior of stone column stabilized soft clay. Evolutions of contact force distributions developed in stone column at varying levels of settlement were presented. Shear stress-strain contours induced in the surrounding soft soils were also investigated.

Keywords: discrete element method, finite different method, stone column, load-deformation

INTRODUCTION

Among various approaches that are currently used for low-rise buildings and embankments that can allow some settlements, stone columns provide a satisfactory method of support in soft soils, and thus are widely applied in practice (Black et al. 2011; Castro and Sagaseta 2011). Stone columns have been widely used to enhance the bearing capacity of soft soils and reduce long term settlements of structures built on them. The primary benefits of stone columns are: (i) to transfer foundation loads to greater depth by a combination of side resistance and end bearing; and (ii) to decrease the total and differential settlements; (iii) to decrease the liquefaction potentials of sand (Bouassida et al. 1995; Chai et al. 2010;

Deb 2010; Mohamedzein and H. 2011; Siahaan et al. 2011), among others. As presented by Guetif et al. (2007), the stone column is not only acting as a reinforcement, possessing greater strength and stiffness in comparison with the surrounding soils, but it is also accelerating the time-dependent dissipation of excess pore water pressure caused by surcharge load due to shortening the drainage path. Deformation behavior of stone columns has been a subject of experimental and numerical studies during last decades (Almgir et al. 1996; Lee et al. 2004; Chai et al. 2010; Castro and Sagaseta 2011; Sivakumar et al. 2011; Indraratna et al. 2015), among others. It is noted that, these studies assumed the unit cell concept to be valid, implying that the unit cell settlement is supposed to represent the settlement of an infinitely wide foundation.

Continuum-based numerical approaches have been increasingly applied to model insights into the settlements, lateral deformations, stress and strain-rate dependent behavior of soft soils at macroscopic scale (Indraratna et al. 2014). However, due to the discrete nature of stone columns, which commonly consist of granular materials (e.g., crushed rock, gravel or latile basalt), which could not be precisely captured by the continuum approach (Indraratna et al. 2011, Ngo et al. 2014). Stone column and surrounding soft soils often interact together during loading process and hence it poses a challenging task to couple them into a numerical model. The study of the interaction between a stone column and soft soils whereby applied loads are transmitted from the stone columns to the soils has limitedly presented in micromechanics perspectives. In this study, a coupling of discrete element method (DEM) and finite difference method (FDM) is presented to study the load-deformation behavior of soft soils stabilized by a single stone column. The ultimate purpose is to take advantage of each modelling scheme for minimizing the requirement of computational resources. Details of the coupled model were presented earlier by Indraratna et al. (2015). Basically, coupling between the DEM and FDM can be achieved at the stone column-soil interface by: (a) treating the finite difference nodal displacements as velocity boundary conditions for the discrete elements and vice versa, and (b) applying the forces acting on the discrete elements as force boundary conditions to the finite difference grids. Results of the load-deformation response obtained from the coupled model were compared with data published in literature for verifying the accuracy and reliability of the proposed model.

COUPLING DICRETE-CONTINUUM METHOD

The schematic diagram of coupling discrete-continuum method used to study load-deformation behavior of a stone column stabilized soft soils is illustrated in Figure 1. The model dimensions are followed the model test conducted by Sivakumar et al (2011). A domain of the stone column, which is consisting of discrete particles was modelled by the DEM, using PFC2D (Itasca 2013), whereas soft clay was simulated by the FDM, using FLAC (Itasca 2010). Basically, the DEM transfers forces and moment to FDM and then the FDM update wall displacements (i.e., velocity) back to the DEM model. Initially, a series of walls is generated in PFC2D, with each wall corresponding to a single surface segment of a FLAC zone. Upon external loading, the FLAC zones (continuum meshes) deform in large strain, grid-point displacements are transferred to PFC2D, so that the walls moves in exactly the same way as the boundary segments of the FLAC grid. The resulting wall forces, due to particles interacting with the walls, are transferred to FLAC as applied grid-point forces.

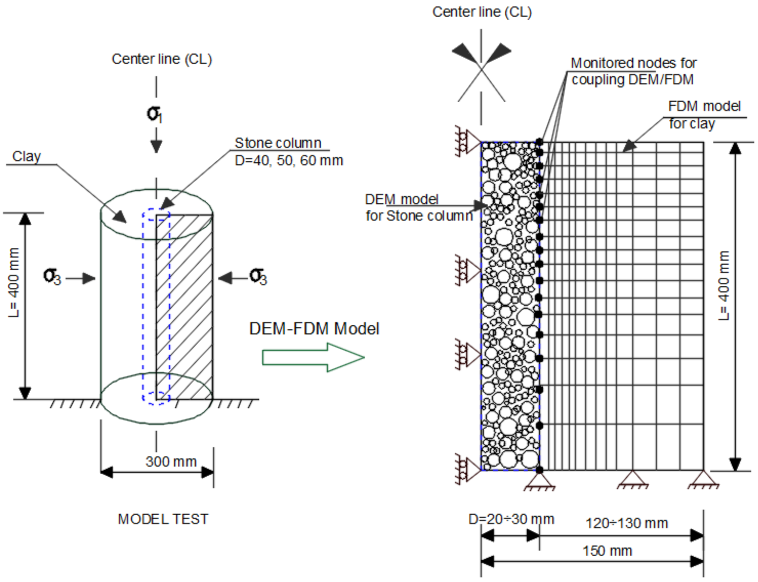

Figure 1. Schematic diagram of coupled DEM-FDM to model stone column (modified after Indraratna et al. 2015)

MICROMECHANICAL PARAMETERS USED

Basalt grains were used to simulate stone column, having relatively uniform grading (1.18-2.36 mm) and a particle size distribution is presented in Figure 2. The angularly-shaped grains of stone column were modelled by clustering of circular bonded particles together (Itasca 2013). The micromechanical parameters to model stone column were chosen based on calibration with experimental data reported by Sivakuma et al. (2011) and presented in Table 1. Since the salient aim of this paper is to study load-deformation response of a stone column stabilizes soft soils and to keep the paper size manageable, the details of aforementioned parametric study are not presented. Stone columns with diameters of D=40, 50, and 60 mm were simulated using the proposed coupling model under axisymmetric condition where the unit cell concept was adopted and analyses were carried out using Mohr-Coulomb's failure criterion considering elasto-plastic behavior for soft soils. Given the scope of the current coupled DEM-FDM analysis, the surrounding soil was presumed to be un-drained and a total stress analysis was considered. The input parameters used to model soft soil in the FDM model are presented in Table 2.

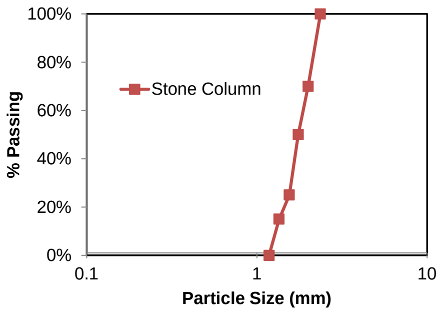

Figure 2. Particle size distributions of stone column modelled in DEM

Table 1. Micromechanical parameters used in DEM

Micro-mechanical parameters for stone column	Values
Contact normal stiffness k_n (N/m)	0.42 x 10^7
Contact shear stiffness k_s (N/m)	0.21 x 10^7
Inter-particle coefficient of friction μ	0.75
Contact normal stiffness of wall-particle, $k_{n\text{-wall}}$ (N/m)	1 x 10^7
Shear stiffness of wall of wall-particle, $k_{s\text{-wall}}$ (N/m)	1 x 10^7
Particle density (kg/m^3)	18.5
Particle sizes (mm)	1.5-3

Table 2. Model parameters used in FDM model

Materials parameters used for clay	Values
Modulus of elasticity E (kPa)	4000
Poison ratio μ	0.4
Undrained shear strength c_u (kPa)	20
Density, γ (kN/m^3)	15

NUMERICAL SIMULATION VALIDATION

The applied stress-settlement responses of stone column conducted by Sivakumar et al. (2011) were used to calibrate the current proposed DEM-FDM coupling model. Figure 3 shows the comparisons of applied vertical stress versus settlement obtained by the coupled model and data measured experimentally for three stone columns with diameters of 40 mm, 50 mm, and 60 mm. It is seen that the predicted stress-settlement responses seem to reasonably agree well with experimental data measured experimentally, although the coupling analysis showed some discrepancy particularly within the settlement of 4–10mm. Although the exact causes for the discrepancy were not clearly explained, they were possibly associated with the uncertainties in the model tests and limitations of numerical simulations where particle shape need to be modelled more accurately.

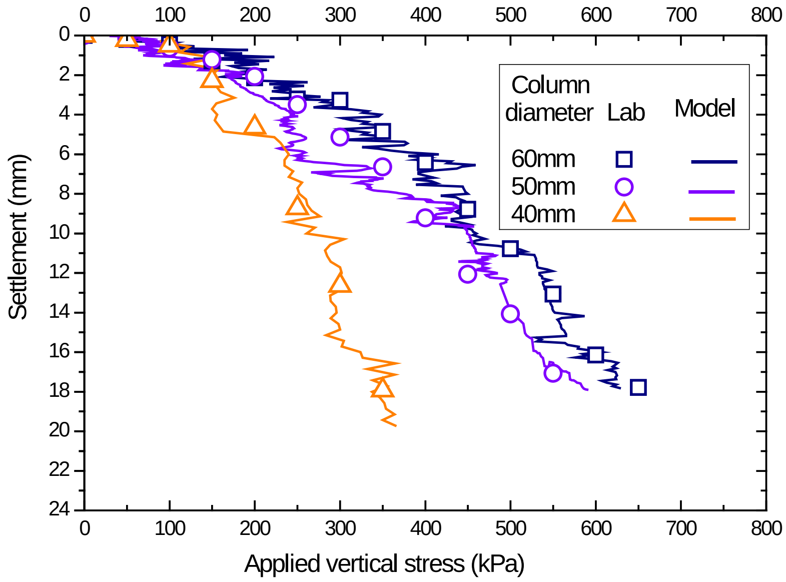

Figure 3. Comparisons of settlement responses between the model and laboratory data (modified after Indraratna et al. 2015)

It is widely believed that a stone column deforms and fails as a result of bulging that commonly occurs at the portion close to the top of column. Figure 4 shows the predicted lateral displacements with depth of stone columns. The lateral displacements obtained from the coupled model clearly confirm that stone columns bulge into the surrounding soils as a result of applied load. It is seen that the horizontal displacement of stone columns considerably increases with a decrease in diameter of the column. The bulging zone develops to about 100 mm from the top surface of the stone columns and then begins to decrease with depth. This finding could be related to bulging that leads to increased lateral confinement in the upper part of the column and induced variations in the orientation of contact forces within the stone column assembly.

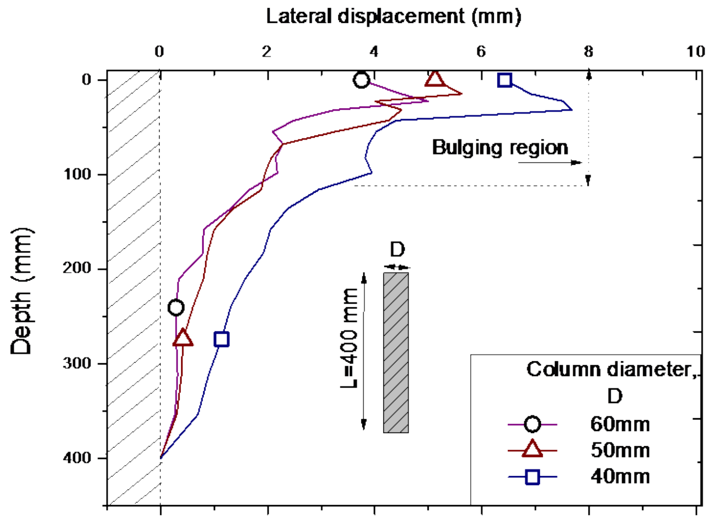

Figure 4. Predicted lateral displacement of stone column (modified after Indraratna et al. 2015)

MICROMECHANICAL ANALYSIS

The micromechanical analysis is shown herein focusing on the contact force distributions of the stone column. Figure 5 presents the inter-particle contact force distributions for the 40mm-diameter stone column at different settlement stages. Each contact force is represented by a segment with the same direction as the force and whose thickness is proportional to the force magnitude (Itasca 2013; Indraratna et al. 2013). For clarity, only those contact forces in the upper part of the stone column with a magnitude exceeding the average value are plotted. It is seen that the total number of contact forces and maximum contact forces increases with increased settlements, mainly because the column compresses to support the applied load and bulges into the surrounding soft soils. Moreover, when the loading process ceased (i.e. at the settlement of, S=15 mm) the number of contact forces and maximum contact force (Figure 5d) are both slightly lower than those measured at smaller settlements. These results could be associated with the extensive bulging of the stone column and the associated reduction in its bearing capacity.

SHEAR STRESS DEVELOPED IN THE SURROUNDING SOILS

Shear stresses that developed in the surrounding soils due to bulging of stone columns are often difficult to capture in the laboratory or in the fields, as instrumentations are easily being damaged by sharp edges of stone aggregates and associated compaction. However, the shear stress could be captured in the coupled DEM-FDM model. Figure 6 presents contours of shear stress induced in the surrounding soils reinforced by the 40mm-diameter stone column, at settlements of 5 mm and 15 mm. The shear stress develops non-uniformly in the soil media and its magnitude depends upon vertical or lateral deformation.

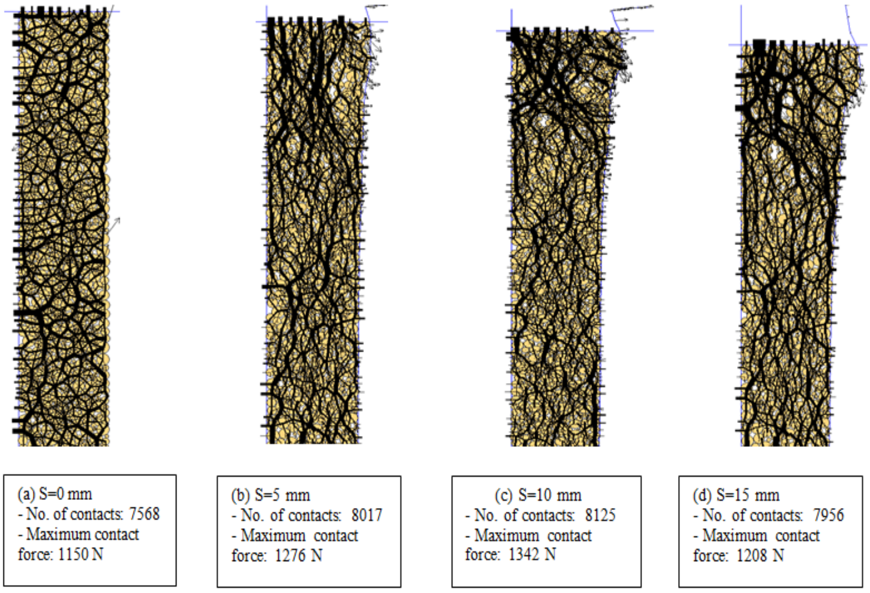

Figure 5. Contact force distribution at varied settlements: (a) S=0 mm; (b) S=5 mm; (c) S=10 mm; and (d) S=15 mm

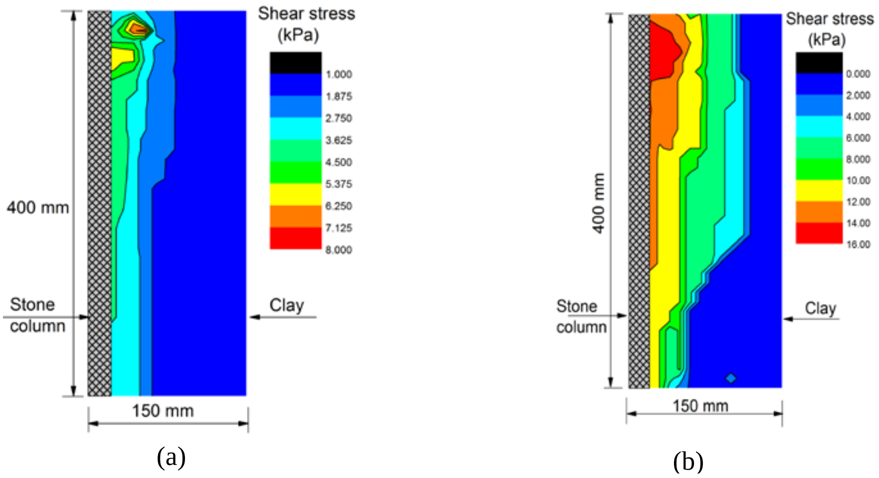

Figure 6. Shear stress contour at different settlements: (a) S=5 mm, and (b) S=15 mm (modified after Indraratna et al. 2015)

CONCLUSION

A coupling discrete and finite difference methods was presented to model a stone column stabilized soft soil. The stone column was modelled using discrete element method (DEM) while the soft clay is simulated using finite different method (FDM). Coupling between the DEM and FDM was achieved by using finite difference nodal displacements as velocity boundary conditions for discrete elements and, by applying the forces acting on discrete element as applied loads to the finite difference grids. The results of applied stress versus settlement were reasonably comparable with the experimental data, indicating that the coupling model introduced in this study could capture the load-displacement behavior of stone column reinforce soft clay. The contact force distribution and the shear stress contours developed in the stone column and surrounding clay were captured to better understand the bulging behavior of the column. The total number of contact forces and the maximum contact force increased with an increase in settlement, and this is attributed to the column compressing under the external load and the associated bulging of the upper part of column into the surrounding clay.

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