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A hybrid DEM-FDM approach for load-deformation analysis of stone columns

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Abstract

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A hybrid DEM-FDM approach for load-deformation analysis of stone columns

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Abstract. Stone columns are being increasingly used as a cost-effective and environmentally friendly method for improvement of weak soils. Deformation behavior of stone columns reinforced soft clay has been the subject of an extensive number of experimental and modelling studies during last decades. Continuum-based numerical models provide valuable insights into the settlement, lateral deformation, stress and strain-rate dependent behavior of stone column at macroscopic scale. However, owing to the discrete nature of stone columns, which are comprised of granular material, cannot be properly modelled by the continuum methods. This paper presents a coupled micro-macro method for numerically simulating a single stone column stabilized soft soils. A novel coupling model of discrete element method (DEM) and finite difference method (FDM) was introduced to investigate the load-deformation behavior of stone columns considering micromechanical analysis. In the coupled discrete-continuum model, the soft soil domain was modelled by the continuum method using FLAC and stone column was modelled by the discrete element method using PFC2D. A force-displacement transmission mechanism was introduced to achieve the interaction of both domains in which the DEM transfers forces and moment to the FDM and then the FDM updates displacements back to the DEM. The predicted load-deformation results were in good agreement with the data measured experimentally indicating that the proposed coupling discrete-continuum model could capture the deformation behavior of stone column reinforced soft soils.

Keywords. discrete element method, stone column, deformation behavior

1. Introduction

The increasing infrastructure growth in urban and metropolitan areas has resulted in a dramatic rise in land prices and lack of suitable sites for construction. As a result,

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infrastructure is now built on sites which, due to poor ground conditions, would not previously have been considered economic to develop [1, 2]. The use of stone columns is preferable as it increases the bearing capacity of soft soils, decrease the long term settlement and accelerate consolidation, apart from the simplicity of its construction method [3, 4, 5]. Unlike other improvement techniques, stone columns are considered not to affect significantly the properties of the surrounding ground. They act mainly as inclusions with a higher stiffness and greater permeability than the natural soil [6, 7]. As reported by Guetif et al. [8], the stone columns not only act as reinforcement, possessing greater strength and stiffness in comparison with the surrounding soil, but they also speed up the time-dependent dissipation of excess pore water pressure caused by surcharge loading due to shortening the drainage path.

Deformation behavior of stone columns reinforces clay has been the subject of an extensive number of experimental and numerical studies during last decades [9, 10, 11, 12, 13], among others. Upon external loading, stone column deforms laterally and distributes stresses at the upper portion of the surrounding soft clay profile rather than transferring the stresses into deeper layers, and failure often occurs associated with bulging on top of the stone column [5, 6,12,14].

Continuum-based numerical method has been widely adopted to study the load-deformation behavior of soft soils reinforced by stone columns at macroscopic scale. Due to the discrete nature of stone columns, comprising of discrete granular materials (e.g., crushed rock, gravel or latile basalt), the continuum approach cannot model properly the inter-particle interaction. The computational resource required to model soft clay in the discrete element method (DEM) is enormous, especially when the particle size has to be sufficiently small to produce reasonable solutions. Furthermore, as stone column and clay media interact together during loading process, it remains a challenging to incorporate them into a coupled numerical model. In addition to this, a mechanism whereby load is transmitted from stone columns through surrounding clays has limitedly reported in terms of micromechanical perspective. The motive of this study is to apply the coupled discrete-finite different method (DEM-FDM) approach, taking advantage of each modelling scheme for minimizing the requirement of computational resources while considering micromechanical properties of the stone column. Principally, coupling between the DEM and FDM is 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.

2. Couple simulation model for stone column

A conceptual model of a single stone column reinforced soft clay using coupled discrete-continuum method is presented in Figure 1, where the model geometry adopts the model test conducted by Sivakumar et al [12]. Given the scope of the current analysis, an equivalent plane strain unit cell was used to simulate an axisymmetric stone column reinforced soft soil. The coupled model is divided into two domains: the DEM region to model stone column and the FDM region to model surrounding soft clay, and they are coupling together via interface elements. A series of interface elements were generated between the stone column and clay assisting the coupled model in exchanging boundary conditions, i.e., transferring forces from DEM to FDM and then updating the displacement back to the DEM region. Within every time step, the contact forces and displacements of the interface elements are determined using the motion equations given by Itasca [15] and then applied back to the two domains. Time steps in the coupled DEM-FDM are implemented based on an explicit "time-marching" finite difference solution scheme. The time step of DEM and FDM was identical which was achieved by running the FDM in static mode and DEM with differential density scaling so that the time step is in unity for both processes.

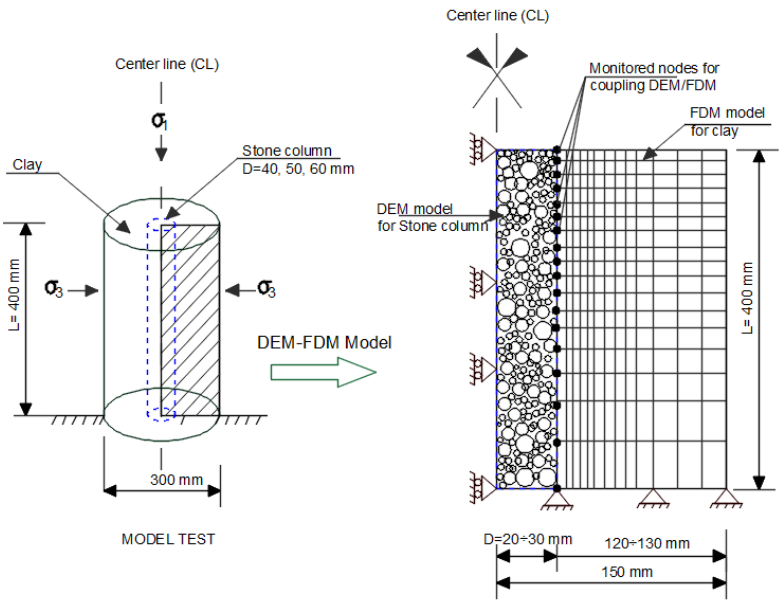

Figure 1. Schematic view of the coupled approach to model a single stone column.

3. Determination of micromechanical parameters

In the discrete model, particles with sizes ranging between 1.5 and 3 mm were simulated to model stone column. The angularly-shaped grains of stone column were simulated using clusters of circular bonded particles. The micromechanical parameters adopted to simulate stone column are given in Table 1, determined based on the calibration with experimental data reported by Sivakumar et al [12]. The simulated test was implemented based on a large triaxial cell capable of testing samples 300 mm in diameter by 400 mm high. Three stone columns with diameters of D=40, 50, and 60 mm were simulated using the proposed coupling model. A linear contact model was adopted to model stone column. To model elasto-plastic behaviour of surrounding clay, Mohr-Coulomb's failure criterion was adopted. Given the scope of the current coupled DEM-FDM analysis, the surrounding clay was assumed to be undrained and a total stress analysis was conducted. The following undrained shear strength parameters are used: undrained cohesion of 22 kPa are given in Table 2

Table 1. Micromechanical parameters used in DEM

Micro-mechanical parameters	**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
Parallel bond normal and shear stiffness (N/m)	6.25 x 10^8
Parallel bond normal and shear strength (N/m^2)	5.78 x 10^6
Parallel bond radius multiplier	0.5
Particle density (kN/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

4. Numerical simulation validation

Experimental results conducted by Sivakumar et al. [12] were used to validate the proposed coupling model. Vertical settlements at varying applied stresses were captured during the loading process. Figure 2 shows the comparisons of applied vertical stress versus settlement obtained by the coupled DEM-FDM 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 curves appear to reasonably match data measured in the laboratory, 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.

The evolution of stress distribution at three locations, PC1, PC2, and PC4 obtained from the coupling simulation and those reported by Sivakumar et al. [12] is presented in Figure 3. The vertical stresses at three different locations predicted by the coupling model reasonably match with those measured experimentally, and increase with an increase in settlement. As expected, the vertical stress decreases with depth, primarily as a result of the load transfer mechanism between stone column and surrounding clay. The load in the column is transferred to the surrounding clay as the lateral stresses increase, causing bulging and mobilizing friction at the interface. Not surprisingly, there is some disparity in the vertical stresses between the numerical predictions and the laboratory data. This can be attributed to the difference in particle shape between the coupled model and the experiment, as well as particle breakage, an aspect which was not examined in the current analysis. Based on results obtained from numerical analysis, it is possible to conclude that the proposed coupled DEM-FDM model can capture load-deformation behavior of stone column stabilized soft clay. The model was then adopted to investigate changes of micromechanical properties of the stone column with the increase of settlement and column bulging.

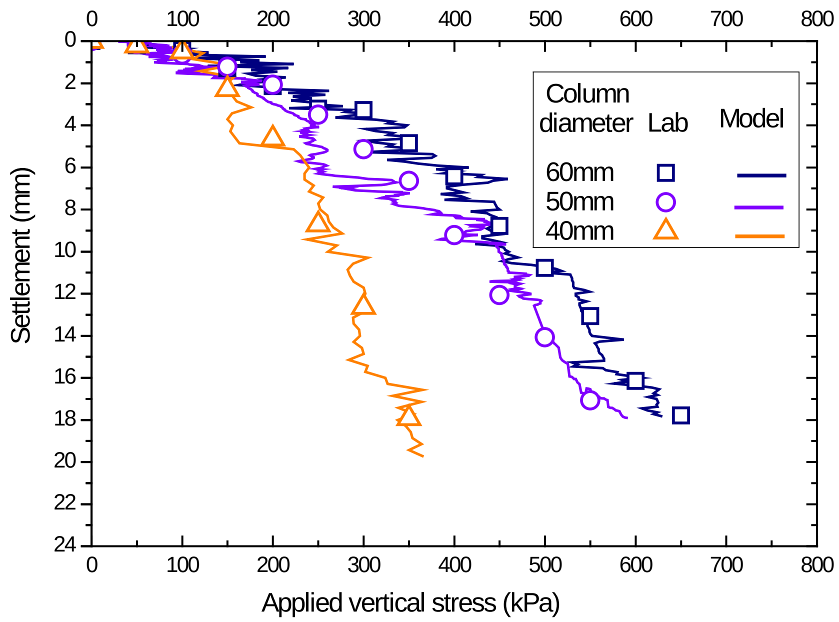

Figure 2. Comparisons of settlement versus vertical stress between the coupled DEM-FDM model and experimental data.

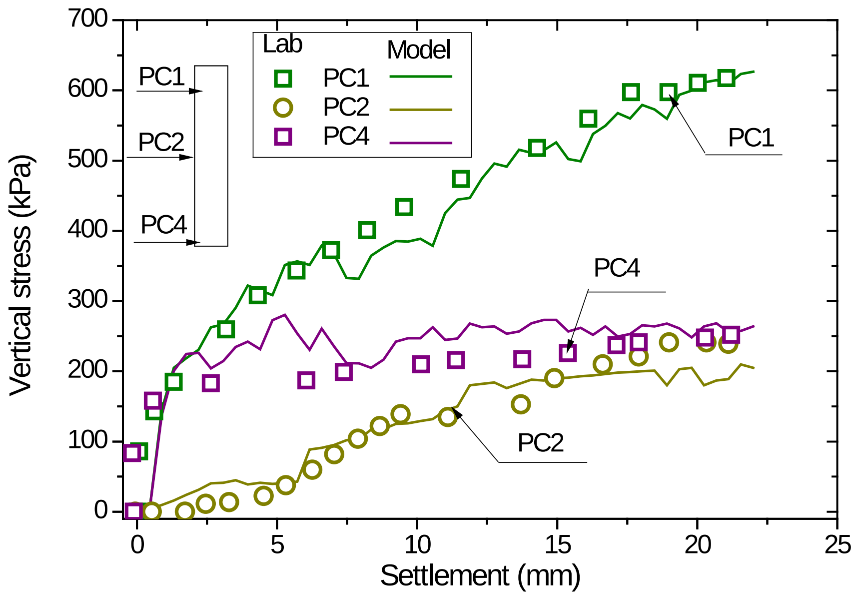

Figure 3. Comparisons of vertical stress distribution at different depths of stone column with diameter of 50mm.

5. Micromechanical response of stone column

The micromechanical analysis presented herein focusing on the contact force distribution within the stone column assembly, at varying settlement levels. Figure 4 illustrates the inter-particle contact force distributions for the 40mm-diameter stone column at different settlements (i.e., development of column bulging). Each contact force is represented by a segment with the same direction as the force and whose thickness is proportional to the force magnitude. For clarity, only those contact forces in the upper part of the stone column with a magnitude exceeding the average value were plotted. The total number of contact forces and maximum contact forces increases with increasing settlement, mainly because the column compresses to sustain the applied load and bulges into the surrounding clay. 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 4d) 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.

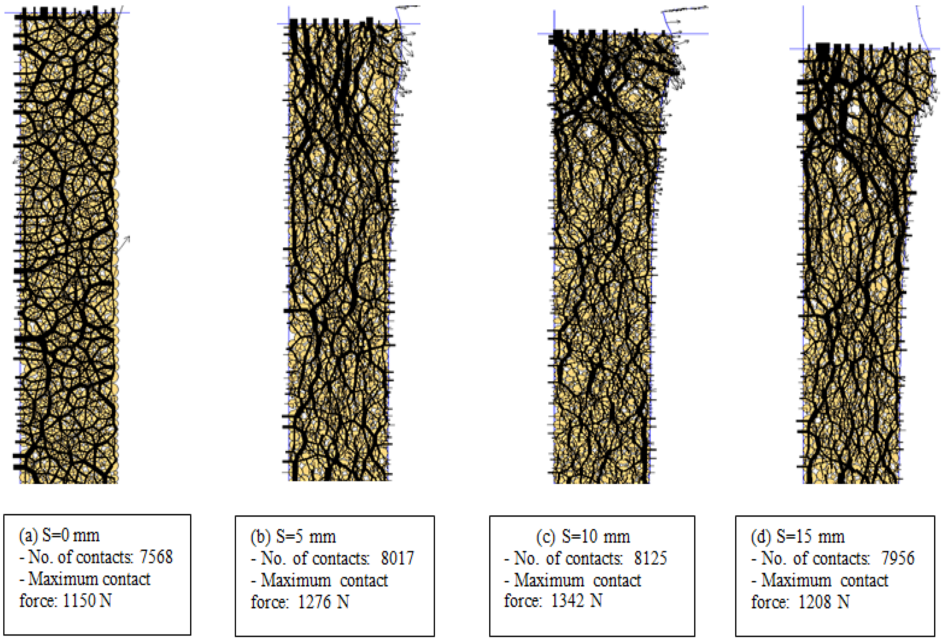

Figure 4. Contact force distribution of 40 mm diameter stone column at varying settlements, S: (a) S=0 mm; (b) S=5 mm; (c) S=10 mm; and (d) S=15 mm

6. Shear stress developed in the surrounding clay

The shear stresses developed in the surrounding clay by the bulging of stone column are generally difficult to measure in the laboratory or on sites, as in-situ pressure cells tend to be damaged by the sharp edges of the aggregates at the interface. However, these shear stresses can readily be obtained via numerical simulation and are presented herein. Figure 5 shows the contours of shear stress developed in the surrounding clay stabilized by the 40mm-diameter stone column, at settlements of 5 mm and 15 mm. As expected, the shear stress is non-uniform in the clay, and its magnitude varies with settlements and lateral displacements, i.e. the level of bulging. Indeed, the shear stress contours are concentrated close to the upper part of the stone column where bulging occurred. It is noted that the maximum shear stress has occurred within the bulging region and its magnitude increases as the column settlement increases. The maximum shear stresses developed in the clay at a settlement of 15 mm are greater than those at a settlement of 5 mm (i.e. 16 kPa compared to 8 kPa, respectively). This may be caused by the increased lateral bulging effect of the stone column which is resisted by the frictional stresses mobilized at the interface with the surrounding clay.

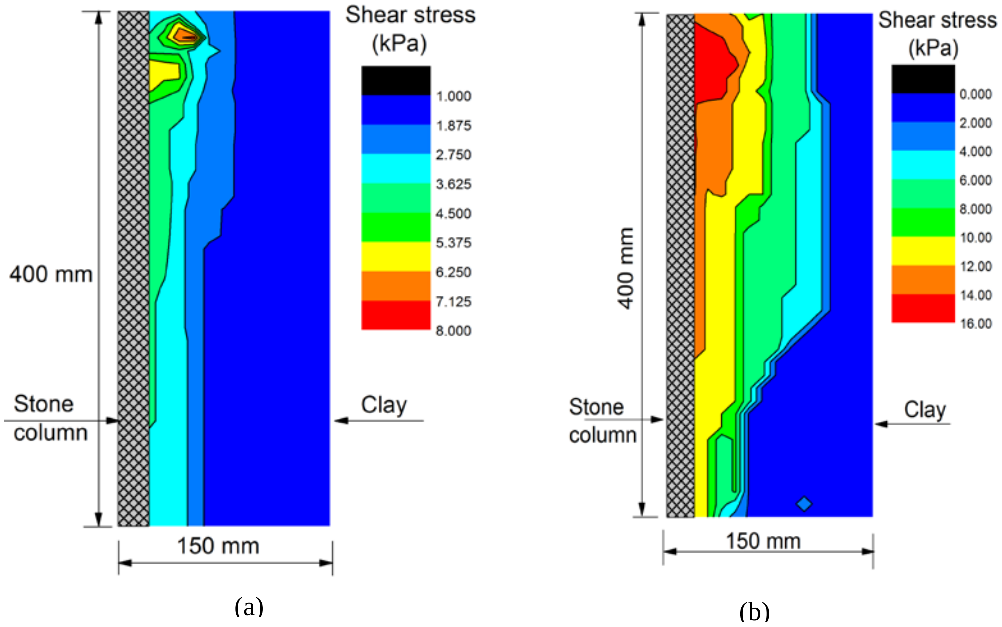

Figure 5. Shear stress contour developed in clay stabilized by 40 mm diameter stone column at different settlements : (a) S=5 mm, and (b) S=15 mm

7. Conclusion

A coupling discrete and finite difference methods was presented to model a stone column stabilised 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 behaviour 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 behaviour 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.

8. Acknowledgement

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