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Coupled discrete-continuum method for studying load-deformation of a stone column reinforces rail track embankments

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Abstract

Stone columns are being increasingly used as a cost-effective and environmentally friendly method for reinforcing soft soils of rail track embankments. Deformation behavior of stone columns reinforced soft clay has been the subject of an extensive number of experimental and modelling studies during last decades. A continuum-based numerical method provides valuable insights into the settlement, lateral deformation, stress and strain-rate dependent behavior of stone column at macroscopic scale. However, due to the discrete nature of stone columns, which are comprised of granular aggregates, they cannot be properly modelled by the continuum methods. This paper presents a novel coupling model of discrete element method (DEM) and finite difference method (FDM) to investigate the load-deformation behavior of stone columns considering micromechanical analysis. In the coupled discrete-continuum model, the soft soil domain under track embankment is modelled by the continuum method using FLAC and stone column is modelled by the discrete element method using PFC2D. A force-displacement transmission mechanism is 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 are 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; finite element method; stone column, track embakment*

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1. Introduction

Among various approaches that are currently used for rail track embankments that can allow some settlements, stone columns provide a satisfactory method of support in soft soils, and thus are widely applied in practice [1-2]. Stone columns have been widely used to enhance the bearing capacity of track embankments and to decrease long term settlements of rail tracks 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 reduce the liquefaction potentials of sand [3-7] among others. Guetif et al. [8] presented that a stone column is not only acting as reinforcement, possessing greater strength and stiffness in comparison with the surrounding soils, but it is also increasing the time-dependent dissipation of excess pore water pressure due to shortening the drainage path. Deformation behaviour of stone columns has been a subject of experimental and numerical studies during last decades [2, 4, 9-12], 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 methods (i.e. finite element or finite different methods) have been increasingly used to model insights into the settlements, lateral deformations, stress and strain-rate dependent behaviour of soft soils at macroscopic scale [13]. 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 [14-15]. Stone column and surrounding soft soils often interact together during loading process and hence it poses a challenging task to couple them into a comprehensive 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 behaviour of soft soils stabilized by a single stone column. The main aim is to take advantage of each modelling approach for minimizing the requirement of computational resources. Details of the coupled model were presented earlier by Indraratna et al. [12]. 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.

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2. Coupled discrete-continuum approach

The diagram of coupled discrete-continuum method used to study load-deformation behaviour of a stone column stabilized soft soils in rail track embankments is presented in Figure 1. The model dimensions are followed the model test conducted by Sivakumar et al. [11]. A domain of the stone column, which is consisting of discrete particles was modelled by the DEM, using PFC2D [16], whereas soft clay was simulated by the FDM, using FLAC [17]. Basically, the DEM transfers forces and moment to FDM and then the FDM update wall displacements (i.e., velocity) back to the DEM model, as illustrated in Figure 2. 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.

2.1. Micro-mechanics parameter used

Basalt aggregates were used to simulate stone column, having relatively uniform grading (1.18-2.36 mm). 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 selected based on calibration with experimental results reported by Sivakuma et al. [11] as presented in Table 1. Since the salient aim of this paper is to study load-deformation response of a stone column stabilising 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 behaviour for soft soils. Given the scope of the current coupled DEM-FDM analysis, the surrounding soil was presumed to be undrained and a total stress analysis was considered. The input parameters used to model soft soil in the FDM model are presented in Table 2.

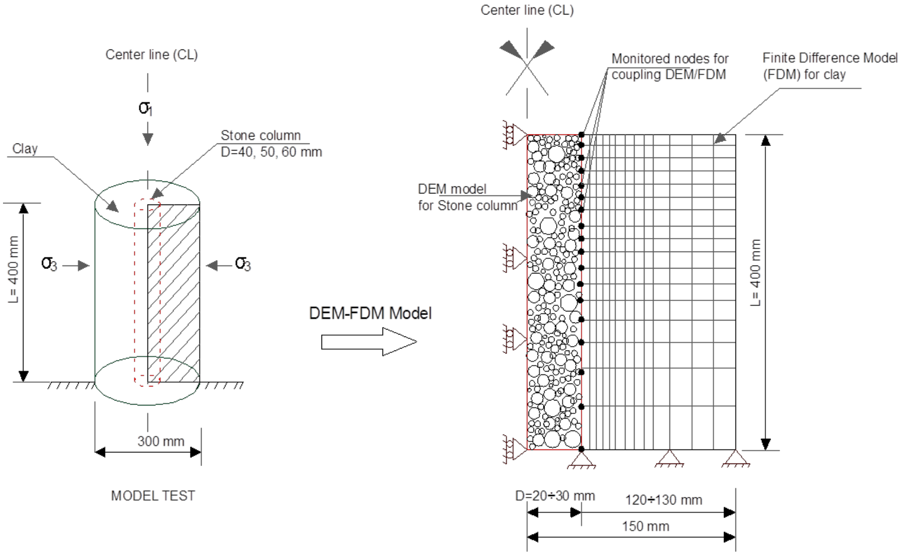


Fig. 1. Schematic diagram of coupled DEM-FDM to model stone column (*modified after Indraratna et al. [12]*)

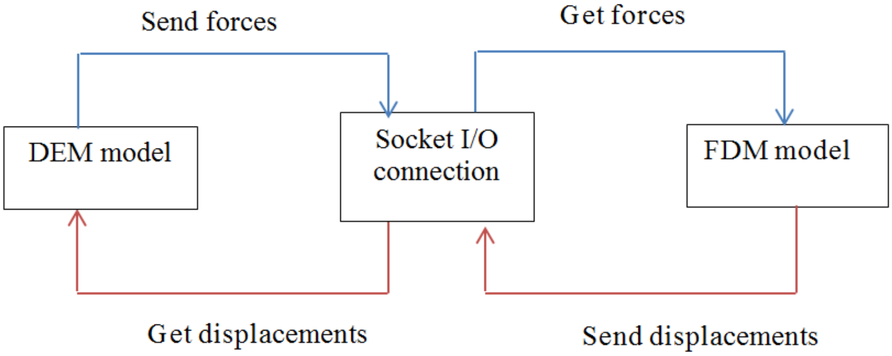


Fig. 2. Data transfer between DEM and FDM via a socket connection

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

3. **Numerical simulation validation**

The applied stress-settlement responses of a single stone column carried out by Sivakumar et al. [11] were used to calibrate the current proposed DEM-FDM coupling model. Figure 3 presents comparisons of applied vertical stress versus settlement obtained by the coupled model and data measured in the laboratory 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.

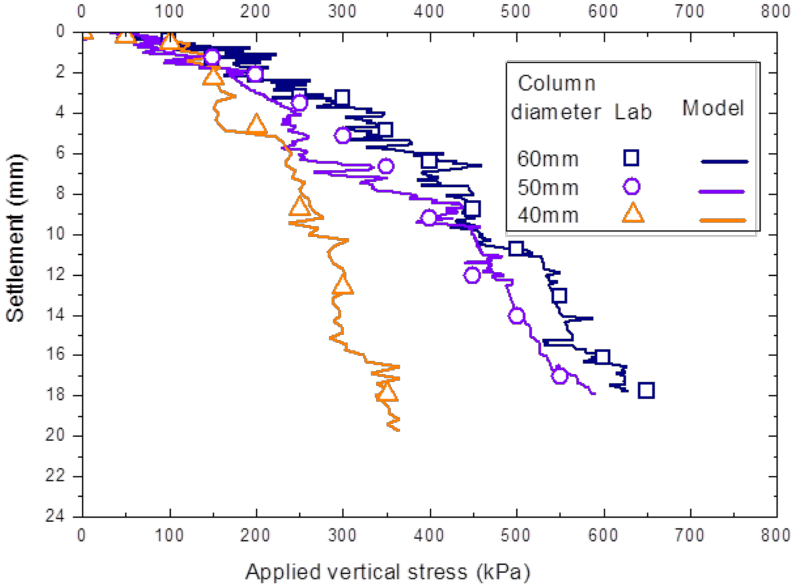
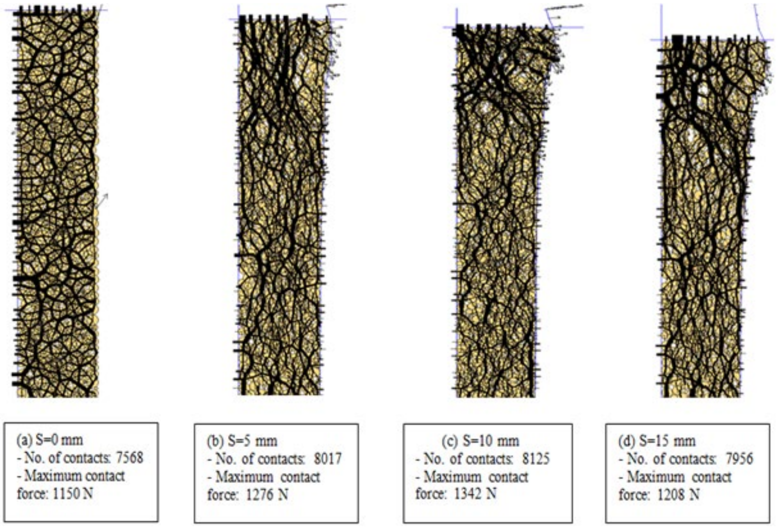


Fig. 3. Comparisons of settlement responses between the model and laboratory data (*modified after Indraratna et al. [12])*

4. 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.



(a) S=0 mm
- No. of contacts: 7568
- Maximum contact force: 1150 N

(b) S=5 mm
- No. of contacts: 8017
- Maximum contact force: 1276 N

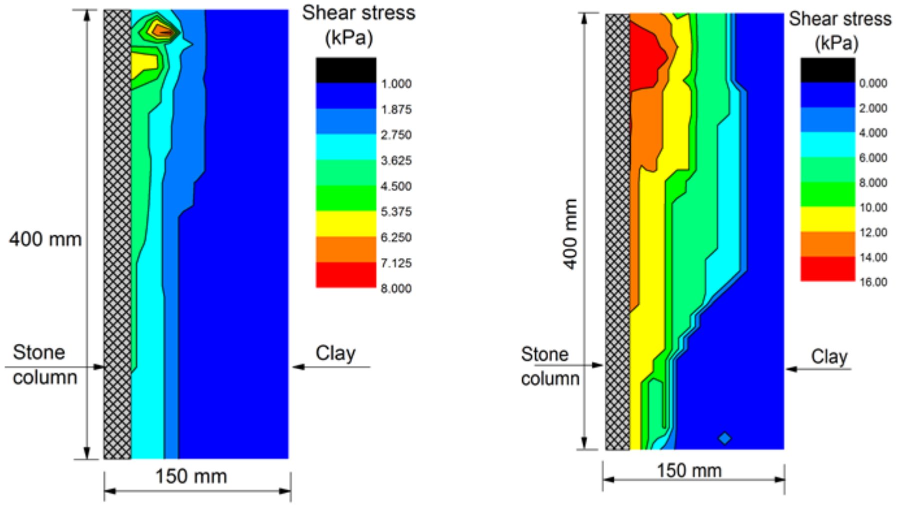
(c) S=10 mm
- No. of contacts: 8125
- Maximum contact force: 1342 N

(d) S=15 mm
- No. of contacts: 7956
- Maximum contact force: 1208 N

Fig. 4. Contact force distribution at varied settlements: (a) S=0 mm; (b) S=5 mm; (c) S=10 mm; and (d) S=15 mm

5. 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.



(a) (b)

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

6. Conclusion

A coupling discrete and finite difference method was presented to model a stone column stabilising soft soil under rail track embankments. A stone column was modelled using discrete element method (DEM) while the soft clay was 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.

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