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Coupled discrete element–finite difference method for analysing the load-deformation behaviour of a single stone column in soft soil

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ABSTRACT

Experimental studies and numerical modelling of the deformation of soft clay stabilised by stone columns have been conducted over the past few decades. Continuum-based numerical models have provided valuable insight into the prediction of settlement, lateral deformation, and stress and strain-rate dependent behaviour of stone columns at a macroscopic scale, but because they consist of granular material such as crushed rock, gravel, and waste rock aggregates, their behaviour is influenced by inter-particle micromechanics and cannot be modelled properly using these models. In this paper a novel coupled model of the discrete element method (DEM) and finite difference method (FDM) is presented to study the deformation of a single stone column installed in soft ground. In this coupled discrete–continuum method, PFC2D and FLAC were used to model the interaction between the stone column and surrounding clay, respectively. The contact forces at the interface between the two zones were determined through a socket connection that allows the DEM to transfer forces and moments to the FDM and vice versa. The predicted results were comparable to the data measured experimentally, showing that the coupled discrete–continuum model proposed in this study could simulate the load-deformation behaviour of a stone column installed in clay. The contact force distribution and shear stress contour developed in the stone column and surrounding clay were captured to provide a better understanding of the load-deformation behaviour of the stone column.

1. Introduction

The increasing value of land and the limited availability of suitable sites for construction are driving engineers to apply appropriate ground improvement techniques to weak soil deposits. The use of stone columns is one of the most commonly adopted methods, and they have been employed worldwide to increase the bearing capacity of soft soils and decrease the long term settlement of superstructures. The main purpose of a stone column system are: (i) to transmit foundation loads to a greater depth by a combination of side resistance and end bearing, (ii) to decrease the total and differential settlements, (iii) to decrease the liquefaction potential of fine grained soils, and (iv) to decrease the drainage path for soft soil through radial consolidation under foundation loading [5,25,2,27,12,1,4]. The deformation of stone columns installed in clay has been the subject of an extensive number of experimental and numerical modelling studies [24,3,10,7,8,11,14,26,9,17,16], among others). Stone columns reduce the drainage paths in soft clay, which accelerates consolidation and increases the load carrying capacity due to the subsequent reduction in settlement [15,10,13,20,26,1,23,28]. Upon external loading, stone columns distribute the applied stress and deform laterally, especially in their upper zones, rather than transfer the stresses into the deeper layers. When stone columns are installed in soft clay, however, they may not increase the load bearing capacity due to the low confining pressure at shallow depths which leads to extensive bulging. Indeed, failure often occurs due to this bulging within the top part of the column.

Continuum-based numerical models have been used extensively to provide valuable insight into the behaviour of soft soils at the macroscopic scale such as settlements, lateral deformations, and stress and strain-rate dependency. However, owing to the discrete nature of stone columns, which typically consist of granular material such as crushed rock, gravel or waste rock aggregates, the discrete inter-particle micro-mechanical aspects cannot be properly modelled by a continuum approach.

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Nomenclature

a_s	area replacement ratio
A_c	cross section area of the stone column
A_s	cross section area of the surrounding soil
B	half width of plane strain unit cell d distance between the centre of the particle and the wall
e_{ijk}	permutation symbol
E_p	modulus of elasticity
F_w	water discharge flow
$F_i^{[C]}$	contact force vector at the interface
$F_i^{[B]}$	superposition of the contact forces
$F_{ni}^{[C]}$	normal force at the interface
$F_{si}^{[C]}$	shear force at the interface
F_X	force on horizontal direction
F_{XA}, F_{XB}	forces on horizontal direction at nodes A, B
F_Y	force on vertical direction
F_{YA}, F_{YB}	forces on vertical direction at nodes A, B
$\Delta F_{ni}^{[C]}$	contact normal force increment
$\Delta F_{si}^{[C]}$	contact shear force increment
Δt	time step
k	horizontal permeability of the undisturbed soil
k_{sm}	horizontal permeability of the smear soil
k_{pl}	permeability soil in equivalent plane strain
k_{ax}	permeability soil in axisymmetric unit cell k_n contact normal stiffness
k_s	contact shear stiffness
$k_{n\text{-}wall}$	contact normal stiffness of wall–particle
$k_{s\text{-}wall}$	contact shear stiffness of wall–particle
m	mass of the particle M moment at the centre of a wall
$M_i^{[B]}$	superposition of the moments of the contact forces
n_i	unit vector
N_j	type function
r_c	radius of the column
r_s	radius of the smear zone
R	radius of axisymmetric unit cell
$R_i^{[B]}$	radius of particle B
S	vertical settlement
t_{crit}	critical time step V_i shear velocity of the wall relative to the particle at the interface
v_i	velocity of a node
x_i	node location of finite difference element $x_i^{[C]}$ location of the contact point
$x_i^{[B]}$	centre of the particle
$x_j^{[C]}$	contact point coordinates
$x_j^{[B]}$	centre coordinates of the contacted particle
$\Delta x_{ni}^{[C]}$	normal vectors of the contact displacement increment
$\Delta x_{si}^{[C]}$	tangential vectors of the contact displacement increment
Δt	time step
$\dot{x}_{i,E}^{[C]}$	velocity of the element (wall) at the interface
$\dot{x}_{i,B}^{[C]}$	velocity of the ball at the interface
u	pore water pressure in the undisturbed soil
u'	pore water pressure in the smear soil
$\dot{u}$	average pore water pressure
U^n	overlapping distance
v_x	rate of pore water flow
α, β, θ	dimensionless parameters
$\omega_3^{[B]}$	rotational velocity of the particle
$\partial\, \varepsilon_y$	change in volumn
γ_c	density of clay
γ_w	unit weight of water
μ	coefficient of friction
v	poison's ratio
φ_u	undrained friction angle
Θ	parameter

Furthermore, stone columns and soil media interact strongly during loading and, simulating this interaction using a coupled numerical model is a challenging task. Studies of this behaviour from a micro-mechanical perspective have been limited mainly to the load transmitted from a stone column through to the surrounding clay, with previous attempts to analyse the behaviour of the stone column itself using discrete particle-based techniques being constrained by available computational technology. A coupled DEM–FDM approach is applied here to take advantage of the strengths of each modelling scheme, as well as to minimise the computing resources required. For a unit cell analysis, the finite difference (continuum) method is used to model the surrounding clay, while the discrete element model is used to represent the stone column. Principally, coupling between the DEM and FDM can be achieved at the soil-column interface by: (a) treating the finite difference nodal displacements as velocity boundary conditions for the discrete elements and vice versa, and (b) by applying the forces acting on the discrete elements as force boundary conditions to the finite difference grids.

The key objective of this paper is to propose a mathematical framework to couple the discrete element method and finite difference method to numerically simulate the unit cell of a stone column. The results of the load-deformation behaviour of a stone column are studied using the proposed coupled model and then compared with data published in the literature to verify the accuracy and reliability of the model.

2. Implementation of the coupling discrete–continuum method

The concept of coupling the discrete–continuum method to study the deformation of a unit cell stone column is illustrated in Fig. 1, where the model geometry follows the test setup described by Sivakumar et al. [26]. The load-deformation behaviour of stone column is axisymmetric in nature. Given the scope of the current 2D coupled DEM–FDM analysis, an equivalent plane strain model is adopted, and Fig. 1 shows a diagrammatic illustration of the conversion of axisymmetric stone column (REV) into an equivalent plane strain unit cell. The transformed deformation behaviour of an axisymmetric single stone column to its equivalent counterpart is formulated on the basis of geometric and soil permeability adjustment (Appendix A) as proposed by Hird et al. [18] and Indraratna and Redana [19]. Although there is no radial flow is considered during the undrained analysis, the plane strain conversion is still necessary to include the overall effect of the column-soil composite stiffness during compression. In other words, the plane-strain material stiffness still needs to be adjusted to capture the geometrical changes as described in the Appendix A. It is also noted that the coupled DEM–FDM analysis does not include smear zone because for non-displacement type ground intrusions, there is no significant smear zone created, as also reported by Sivakumar et al. [26] for a pre-bored stone column. The domain of the stone column, which is governed by discrete particle interaction, was modelled by the Discrete Element Method, using PFC2D [21], whereas the soft clay was simulated using the finite difference