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Technical note

Numerical study on ground improvement for liquefaction mitigation using stone columns encased with geosynthetics

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ABSTRACT

The geosynthetic-encased stone column (ESC) strategy has been extensively used for improving soft soils. However, no studies have been conducted to assess the use of ESCs to mitigate sand strata. In this study, three-dimensional finite element (FE) analyses were conducted to explore the mitigation of mildly sloped saturated sand strata using ESC approaches. We investigated the encasement effect in ESC remediation and the effect of the following important design parameters in reducing lateral ground deformation: the thickness, the tensile stiffness, and the permeability of the geosynthetic; the ESC diameter; and the distributed load at the stone column (SC) surface. The results showed that the ESC remediation reduced more lateral deformation, compared to the SC approach. The ground stiffening was also dramatically enhanced as the stiffness and thickness of the geosynthetic and the ESC diameter were increased, but the encased efficiency gradually decreased. The lateral ground displacement began to decrease significantly when the permeability of the geosynthetic exceeded 0.1 m/s. The larger surface load did not prevent soil liquefaction, but it produced significantly less displacements and virtually no permanent deformation.

1. Introduction

The liquefaction-induced lateral spreading of mildly sloping ground during earthquakes can cause major destruction to foundations and associated buildings (Fiegel and Kutter, 1994; Kishida, 1966). Several methods, such as gravel drains/stone columns (SCs), densification, and solidification, are available to reduce the liquefaction risk and the associated ground deformation (Adalier et al., 2003; Baez, 1995; Gniel and Bouazza, 2009; Lo et al., 2010; Shen et al., 2005). Among these methods, the SC technique is preferred for mitigating liquefaction hazards because of its effectiveness and the simple construction involved (Adalier et al., 2003). A novel SC technique has recently been developed in which an individual SC is encased by a geosynthetic layer and does not involve an encasement, unlike the traditional SC approach (Sharma et al., 2004).

The ESC technology has proven to be an economical ground improvement technique for soft soils and has been effectively used to reduce the deformation of soft foundations (Sharma et al., 2004). Many researchers have conducted numerical analyses and experimental studies on the behavior of soft ground that has been improved using ESCs (Katti et al., 1993; Murugesan and Rajagopal, 2009).

Extensive research has been carried out on various applications of ordinary SCs without encasement and to assess the effectiveness of these methods for liquefaction mitigation using field case histories (Miwa et al., 2006; Saxena and Hussin, 1997), field tests (Ashford et al., 2006), physical experiments (Adalier et al., 2003; Ali et al., 2014; Dash and Bora, 2013; Haldar and Babu, 2010; Murugesan and Rajagopal, 2009; Najjar et al., 2010; Wilson et al., 2000), and numerical simulation (Almeida et al., 2013; Castro and Karstunen, 2010; Elgamal et al., 2009; Khabbazian et al., 2010; Lu et al., 2011; Murugesan and Rajagopal, 2006; Yoo, 2010).

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Recently, Elgamal et al. (2009) conducted three-dimensional (3D) FE simulations using the open-source computational platform OpenSees (http://opensees.berkeley.edu, Mazzoni et al., 2006) with the aid of OpenSeesPL as a pre- and post-processing tool (Lu, 2006) and evaluated the liquefaction mitigation of sand strata via then SC approach. Later, Asgari et al. (2013) assessed the effectiveness of the SC method for a liquefiable stratum based on several important factors using OpenSeesPL. Rayamajhi et al. (2014) systematically studied the shear stress distribution for discrete columns in liquefiable soils using OpenSeesPL. However, no studies have been conducted on the liquefaction mitigation of sand strata that have been improved by ESCs.

In this study, we use FE simulations to investigate the effectiveness of remediation using the ESC technique for sand strata. The results of this parametric study are used to highlight the effect of important parameters on the lateral extent of remediation. Finally, insights and conclusions are drawn based on the reported results.

2. Numerical modeling

2.1. Computational formulation

The open-source computational platform OpenSees (Mazzoni et al., 2006) was used to perform all of the FE simulations, which are efficiently executed using OpenSeesPL (Lu, 2006).

The 3D FE modeling of the soil and the SC was carried out using the 20-8 noded, effective-stress solid–fluid fully coupled brick element (Lu, 2006). This element is based on the solid–fluid formulation for saturated soil. A total of 20 nodes are used to describe the solid translational degrees of freedom, and 8-corner nodes are used to represent the fluid pressure (Chan, 1988; Yang, 2000). The SC and the soil were modeled using a multi-surface-plasticity constitutive model (Yang, 2000; Yang et al., 2003).

The geosynthetic encasement around the SC was modeled as a linear elastic material for simplicity (Ghazavi and Nazari, 2013; Han and Gabr, 2002; Keykhosropur et al., 2012; Lo et al., 2010; Murugesan and Rajagopal, 2006; Pulko et al., 2011; Wu and Hong, 2014; Yoo, 2010). The value of E for the geosynthetic was derived from the relationship $J = E \times t$, where t is the thickness of the element representing the geosynthetic, and J is the tensile stiffness of the geosynthetic, which is defined as the ratio of the tensile force per unit width to the average strain. The geosynthetic was discretized into 20-node brick solid elements. The mass density of the geosynthetic was 1500 kg/m^3 (Giroud, 1994) and its Poisson ratio was 0.3 (Murugesan and Rajagopal, 2006), respectively.

2.2. Model cases for SC and ESC

Typical SCs [Fig. 1(a)] were constructed in a grid pattern to improve the sand stratum covering the entire building footprint. A "unit cell" (i.e., a representative area of improved soil) with a Periodic boundary was used to model the remediated area with a large spatial extent. Using this approach, a half-mesh for a representative cell was explored using the following boundary conditions: (1) the penalty method was used to set equal displacement degrees of freedom for the corresponding left and right boundary nodes at any spatial location in the horizontal and vertical directions (Periodic boundary); (2) the inner (symmetric) and outer boundaries were fixed against out-of-plane displacement but are free to move longitudinally and vertically; (3) the soil surface was stress-free; (4) the seismic excitation was imposed on the base along the x-axis, and a scaled El Centro (1940) north–south acceleration record (Chopra, 2001) with a peak value of 0.2 g was applied (Fig. 2).

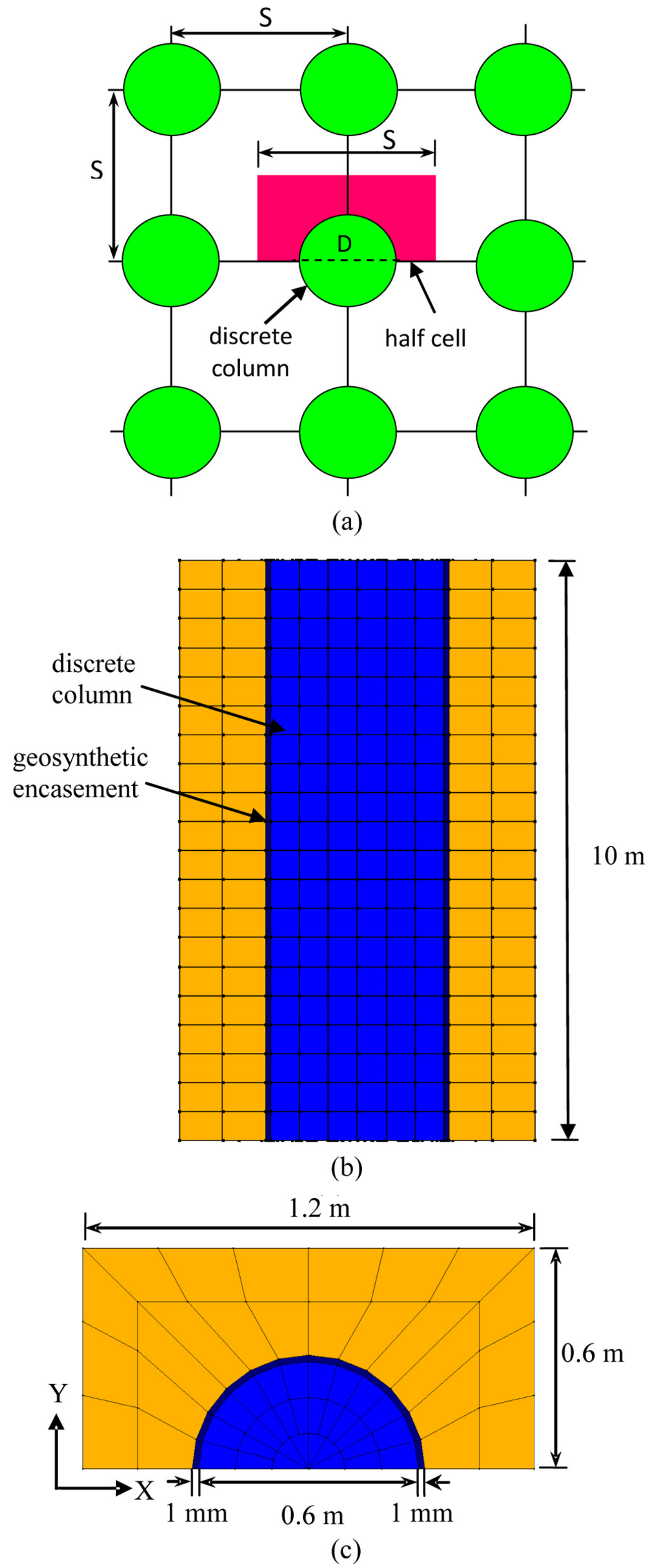

Fig. 1. FE mesh for ground modification by geosynthetic-reinforced SC (dark zone represents remediated domain; replacement ratio $A_r = 20\%$; SC diameter $D = 0.6$ m): (a) Schematic plan view of discrete column layout; (b) FE model elevation (1/2 mesh used because of symmetry); and (c) plan view (3D mesh).