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Modified unit cell approach for modelling geosynthetic-reinforced column-supported embankments

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ABSTRACT

Geosynthetic-reinforced and column-supported (GRCS) embankments have proven to be an effective construction technique for fills on soft foundations. The paper introduces a modified unit cell approach to model GRCS embankments supported by deep mixed column walls. The modified unit cells include linear elastic springs at one or both vertical boundaries to simulate lateral displacements of the embankment fill and foundation soil. The finite difference program FLAC is used to compare numerical outcomes using the modified unit cells with those using the typical unit cell arrangement with lateral rigid side boundaries. Numerical results demonstrate good agreement between simulations using small-strain and large-strain modes in some cases and large differences in other cases. Lateral displacements of the embankment fill and foundation soil using the modified unit cells are shown to have large influence on reinforcement loads. Finally the paper demonstrates that calculated reinforcement loads are sensitive to choice of small-strain or large-strain mode when using program FLAC.

1. Introduction

Embankments over soft foundations must be designed to avoid bearing capacity failure of the foundation, unacceptable lateral spreading of the embankment fill, and damage to adjacent structures due to large differential settlements. An effective technique to overcome these challenges is to use geosynthetic-reinforced and column-supported (GRCS) embankments (Fig. 1). The addition of geosynthetic reinforcement improves the performance of column-supported embankments that predate the use of GRCS embankments. Common support types for GRCS embankments are cement–soil deep mixing (DM) columns (e.g., Bergado et al., 1999; Borges and Marques, 2011; Bruce et al., 2013; Chai et al., 2015; Forsman et al., 1999; Han et al., 2007; Huang and Han, 2009, 2010; Huang et al., 2009; Lai et al., 2006; Liu and Rowe, 2015, 2016; Yapage and Liyanapathirana, 2014) and geosynthetic-encased stone columns (e.g., Hosseinpour et al., 2015; Khabbazian et al., 2015; Yoo, 2010; Ali et al., 2014; Gu et al., 2016). Concrete and timber piles with and without pile caps and basal reinforcement have also been used to increase the construction rate and to improve load transfer from the soft soil to the stiffer piles (e.g., Briançon and Simon, 2012; Liu et al., 2007; Nunez et al., 2013; Rowe and Liu, 2015; Zhang et al., 2013; Blanc et al., 2014; Xing et al., 2014; Bhasi and Rajagopal, 2015a, 2015b). The basic working mechanisms for DM column/pile-supported embankments with geosynthetic reinforcement are soil arching and tensioned membrane effects resulting in load transfer from the embankment fill self-weight (plus any surcharge) to the DM columns/piles. The load on the DM columns/piles is then transferred to the deeper and stiffer soil stratum (Fig. 1).

GRCS embankments can be designed using closed-form solutions that take advantage of soil arching and tensioned membrane load transfer mechanisms within the GRCS embankment system (e.g., Hewlett and Randolph, 1988; Low et al., 1994; Love and Milligan, 2003; Kempfert et al., 2004; BS8006, 2010; EBGEO, 2011; Van Eekelen et al., 2011, 2013, 2015). Advanced numerical models for complex soil–structure interaction problems using the finite element method (FEM) and finite difference method (FDM) are becoming more common as a research tool to improve understanding of the behaviour of GRCS embankments (e.g., Liu and Rowe, 2015; Han et al., 2007). The advantage of using a full-width numerical model of a GRCS embankment is that lateral

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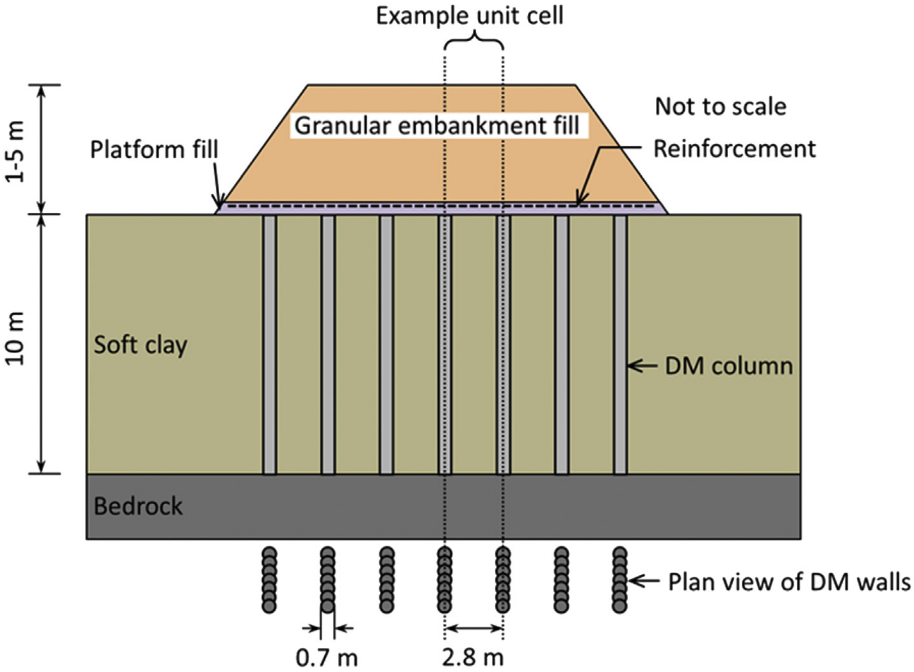

Fig. 1. Schematic showing a full-width model of a GRCS embankment with DM column walls.

deformations that vary across the width and depth of the embankment fill and foundation are predicted. Of course, the accuracy of numerical predictions will depend on mesh refinement and the complexity of the constitutive models used for the component materials and their interfaces. However, parametric analyses at the design stage using a full-width model can be very time consuming and may not adequately capture local load transfer mechanisms particularly if a coarse numerical mesh is used in the simulations. A strategy to overcome this shortcoming is the unit cell approach (e.g., Han and Gabr, 2002; Smith and Filz, 2007; Zhuang et al., 2010; Khabbazian et al., 2015). The location of an example unit cell in a GRCS embankment is shown in Fig. 1. However, there are also limitations associated with typical unit cells including the use of fixed lateral boundaries (Fig. 2a). Khabbazian et al. (2015) showed that the tensile loads in the geosynthetic reinforcement using a full-width GRCS embankment model were much greater than those using the unit cell approach for the same structure. They attributed this discrepancy to lateral spreading of the embankment fill and foundation soil in the full-width model that was not captured by the unit cell. Regardless of which approach is used to model GRCS embankment performance, numerical results can also depend on how geometric nonlinearity of the soil and reinforcement is modelled using the small-strain and large-strain options in the FDM program FLAC (Itasca, 2011) or with and without mesh updating in FEM software programs.

The objectives of this paper are to demonstrate a new modelling technique using a modified unit cell approach to simulate the lateral spreading of the embankment fill and foundation soil, and to examine the influence of large-strain and small-strain model options in program FLAC on numerical outcomes (i.e., with and without mesh updating during calculation steps). Numerical results using (conventional) unit cells with lateral rigid boundaries and units cells with one or both vertical boundaries supported by horizontal linear elastic springs are presented and compared. The effect of lateral spring stiffness values on lateral spreading of the embankment fill and foundation soil, and reinforcement loads are demonstrated.

2. Small- and large-strain mode in FLAC

Numerical analyses using FLAC models (Itasca, 2011) can be executed in either large-strain mode (based on the Lagrangian formulation) or small-strain mode (based on the Eulerian formulation). For the Lagrangian formulation, the numerical grid coordinates at the end of each calculation step (or specified steps) are updated by adding the grid incremental displacements to grid coordinates before the next step. Hence, stresses and displacements at the current calculation step are calculated based on the updated grid representing the deformed material zones. However for the Eulerian formulation, the grid is fixed to the original geometry and material zones. The calculation of stresses and displacements is based on the fixed grid even though the material zones move and deform during subsequent calculation steps. The reader is directed to the FLAC manual (Itasca, 2011) for details regarding small- and large-strain options in the program.

3. Problem definition and parameter values

Fig. 1 shows a GRCS embankment where the soft foundation soil is improved by the cement–soil DM column walls. The numerical simulations carried out in this paper are for two-dimensional cases because of the plane-strain condition associated with Fig. 1. However, the general approach presented in this paper can be extended to model three-dimensional GRCS embankment cases. This paper uses the example of GRCS embankments with 10-m thick soft foundation soil and 1–5-m thick embankment fills. Above the soft foundation soil is a working platform fill with a geosynthetic layer placed 0.3 m above the foundation soil surface. The spacing of 0.7-m thick column walls was 2.8 m (e.g., Forsman et al., 1999; Han et al., 2007; Huang and Han, 2010). The area replacement ratio in the numerical examples in this paper is 25%. The column walls are founded on bedrock.

The location of an example unit cell in this study is shown in Fig. 1. Fig. 2a shows a unit cell (Case 1) with typical boundary conditions (e.g., fixed *y*-direction at bottom of the cell, and fixed *x*-