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Technical note

3-Dimensional numerical modeling of geosynthetic-encased granular columns

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ABSTRACT

In this paper, series of three-dimensional (3-d) numerical modeling of geosynthetic-encased granular columns were performed both in model and prototype scale using FLAC^{3D} software to understand the lateral load carrying capacity of ordinary and geosynthetic encased granular columns (OGC and EGC). In the first part of the study, numerical modeling of direct shear tests were carried out. The soil in the direct shear box was reinforced with two different diameters of granular columns (50 mm and 100 mm) and three different patterns of arrangement (single, triangular and square) to study the effect of group confinement. The numerical simulations were carried out at four different confining pressures namely 15, 30, 45 and 75 kPa. From the numerical simulations it was observed that higher shear stresses are mobilized inside the granular column due to geosynthetic encasement and the magnitude of shear stress increases with increase in the normal pressure. It was found that the tensile forces in the geosynthetic encasement were mobilized both in circumferential and vertical directions, which helps in mobilizing additional confinement in the granular column. In the second part, the influence of the geosynthetic encasement of granular column treated soft ground was demonstrated through 3-dimensional slope stability analyses.

1. Introduction

The granular columns are primarily used to improve the bearing capacity of marginal soils by replacing a part of it with sand or aggregate columns. Typical area replacement ratio (A_r) for this type of granular column treatment varies from 10 to 30% (Barksdale and Bachus, 1983). The area replacement ratio is defined as the plan area of the granular columns to the total plan area within the treated zone of soil. Choice of optimum value of A_r depends on the load intensity, properties of the foundation soil and the time available for pre-treatment of the soil. The granular columns are primarily used to support flexible and rigid structures like embankments, oil storage tanks, buildings etc. (Deb and Mohapatra, 2013; Gniel and Bouazza, 2009, 2010; Murugesan and Rajagopal, 2006, 2007, 2008). Apart from improving the bearing capacity, the granular columns also act as vertical drains by virtue of their high coefficient of permeability compared to the surrounding soil. This helps in accelerating the rate of pre-consolidation of foundation soil and reduces the post-construction settlements (Murugesan and Rajagopal, 2008; Ali et al., 2012; Dash and Bora, 2013; Rajesh, 2016). The granular columns derive their strength from the confinement offered by the surrounding soil, which in turn depends on the undrained shear strength (c_u) of clay soil (Hughes and Withers, 1974; Hughes et al., 1975). In the case of very soft clay soils ($c_u \leq 15$ kPa) with high ground water table, installation of granular columns becomes difficult (Raithel et al., 2002). In such conditions, they are likely to get clogged with fine soil particles, which may reduce their load carrying capacity and water discharge capacity (Weber et al., 2010; Indraratna et al., 2012). To improve the performance of ordinary granular column (OGC) in very soft clay, geosynthetic encasement can be used. This provides additional confinement leading to mobilization of higher shear resistance of the foundation soil. The encasement doubles up as a filter and prevents the clogging of granular columns (Murugesan and Rajagopal, 2008; Castro and Sagaseta, 2011).

The granular columns located below the centerline of an embankment are primarily subjected to vertical loading. Literature is available in plenty towards understanding their mechanism

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under vertical loads (e.g. di Prisco et al., 2006; Murugesan and Rajagopal, 2006, 2007, 2010; Yoo and Kim, 2009; Gniel and Bouazza, 2009, 2010; Lo et al., 2010; Khabbazian et al., 2010; Pulko et al., 2011; Elsawy, 2013; Ali et al., 2012, 2014; Keykhosropur et al., 2012; Dash and Bora, 2013; Ghazavi and Afshar, 2013 Almeida et al., 2015). However below the toe of the embankment, granular columns are primarily subjected to lateral loads and studies are rarely available in the literature to understand the mechanism of OGC and EGC subjected to lateral loading.

Murugesan and Rajagopal (2008) carried out laboratory tests using plane-strain tank and found that encased granular column (EGC) performed better compared to OGC when subjected to shear loading. However, the effect of column diameter was not considered in their study. Abusharar and Han (2011) carried out two dimensional slope stability analysis of stone column supported embankment using FLAC^{2D}. From their study it was concluded that, shear failure is the most common mode of failure in the case of stone columns. Chen et al. (2015) carried out laboratory tests and three dimensional (3-d) numerical modeling to understand the mechanism of embankment loading on soft soils reinforced with geosynthetic-encased stone column and concluded that encased columns undergo bending instead of shear failure. From the 3-d numerical modeling, it was observed that stone columns below the toe of the embankment undergo large lateral displacements compared to the columns closer to the center line of the embankment. However, the effect of column diameter and stiffness of encasement were neglected in their study. Mohapatra et al. (2016) carried out large direct shear (LDS) tests with granular columns and reported that OGC undergo rupture failure along the shear plane and their shear resistance can be significantly improved due to geosynthetic encasement. They also compared the load carrying capacity of group granular columns with single granular column having the same A_r and found that group columns perform better compared to single column. However, the mechanism of load transfer from soil to the granular column and the magnitude of tensile force mobilization in the geosynthetic encasement were not addressed by them.

From the above discussion it is quite clear that encasing the granular column improves the lateral load carrying capacity to a great extent. However, the load transfer mechanism, magnitude of confinement generated in the intervening soil in case of group arrangement, magnitude tensile forces mobilized in the geosynthetic encasement and its direction needs to be investigated in detail. This data is required to design the geosynthetic encasement material.

This paper presents the results of a series of 3-d numerical simulations performed on geosynthetic-encased granular columns, both in model and prototype scale using finite difference software FLAC^{3D} to understand the lateral load carrying capacity of OGC and EGC. In the first part of the study, numerical modeling of LDS tests were carried out using FLAC^{3D} software (version 3.1) to identify the load transfer mechanisms involved in the interaction behaviour of granular column(s), surrounding soil and geosynthetic encasement. In the second part of the study, 3-d slope stability analyses of granular column supported embankment were carried out using FLAC^{3D} software (version 5.0). Higher factor of safety (FS) was found to be mobilized in case of EGC compared to OGC supported embankment.

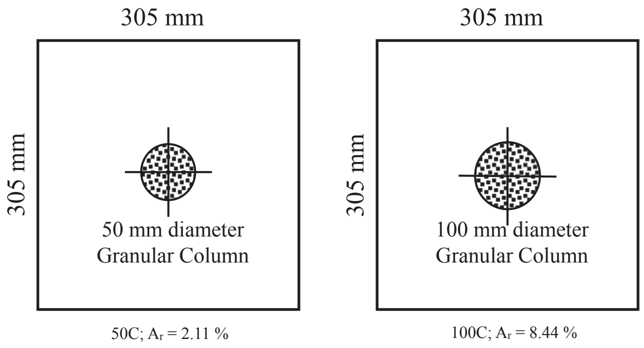
1.1. Large Direct Shear (LDS) tests

This paper focuses on the numerical modeling of LDS tests carried out by Mohapatra et al. (2016) on OGC and EGC, the details of which are briefly presented here for completeness. Plan area of the shear box used was 305 mm × 305 mm and sample height inside the shear box was 140 mm. The tests were carried out at different normal pressures varying from 15 kPa to 75 kPa which corresponds to 1 m–5 m height of fill material on top of the soil. The normal pressure was applied through an inflatable air bladder. The input air pressure was controlled manually to maintain constant normal pressure during the progress of the tests.

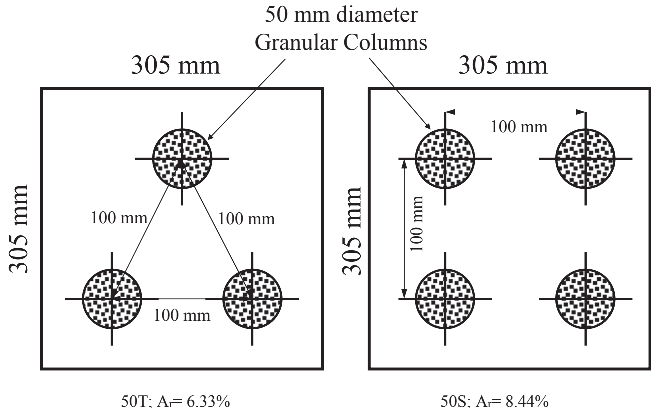
Two different diameters of granular columns, 50 mm and 100 mm were used in the study. The tests were carried out on both single and group (triangular 50T and square 50S) granular columns (Fig. 1). For group arrangement, 50 mm diameter granular columns were installed at a center-to-center spacing of 100 mm. The granular columns were installed in a sand bed prepared at 1.66 g/cm^3 dry density which corresponds to a relative density of 72%. The aggregates were compacted to a dry density of 1.75 g/cm^3 and 1.65 g/cm^3 for 100 mm and 50 mm diameter granular columns respectively. A woven geotextile having ultimate tensile strength (ASTM D4595-05, 1986) of 34 kN/m at 37% strain was used to fabricate the encasement using quick setting epoxy adhesive. The ultimate tensile strength of the seam was 2.2 kN/m and secant modulus at 5% strain was found to be 29 kN/m. All the tests were carried out at a strain rate of 1 mm/min. Details of the LDS testing program are presented in Table 1. Detailed explanations about the sample preparation procedure for OGC and EGC are given by Mohapatra et al. (2016).

2. Numerical modeling

3-d numerical modeling of the above described laboratory tests were carried out using FLAC^{3D} software to capture the failure mechanism. The FLAC^{3D} is a 3-d finite difference program that uses explicit Lagrangian calculation scheme. The Lagrangian formulations are capable of modeling plastic collapse and flow due to large



(a) Schematic of single granular column



(b) Schematic of group granular column

Fig. 1. Different arrangements of granular column inside the shear box.

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