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Numerical modelling and validation of geosynthetic encased columns in soft soils with installation effect

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ABSTRACT

If the bearing capacity of the soil is not sufficient an improvement method has to be considered. In case of soft and cohesive soils the vibroreplacement technique can be used. This paper describes the numerical simulation of a group of encased granular columns under an embankment based on a real life project situated to the north of Hamburg, Germany. The soft soil creep model and the hardening soil model were used to model the behaviour of the soft clay and granular material respectively. The material parameters were determined based on laboratory tests conducted on test samples from the field. The installation effect of columns in numerically modelled based on the cavity expansion method in a 2D axis symmetric model. The results of the installation effect in terms of stress state changes in the soft soil after complete consolidation are then imported to the 3D model involving group of columns. The results of the numerical simulations are validated against field measurement data in form of vertical settlement of the ground at various locations with respect to time and horizontal deformations in the encased columns with depth.

1. Introduction

The vibroreplacement method is a ground improvement which can be used to improve the bearing capacity of soft and cohesive soil. Vibrators displace the soil and introduce granular material into the cavity. The resulting granular columns improve the material properties of the soil. The columns provide rapid dissipation of excess pore pressure and reduce the magnitude of vertical stress to be borne by the soft soil. The granular columns when installed in very soft clay, experience low confinement in the upper part of the column and hence exhibit reduced capacity (McKenna et al., 1975; Wehr, 2006; Murugesan and Rajagopal, 2007; Ghazavi et al., 2018). Hence in order to increase their efficiency the concept of encasement of the columns with geosynthetic was introduced (Van Impe, 1989). The increase in capacity of the granular columns due to encasement has been acknowledged by numerous researchers (Raithel and Kempfert, 2000; Raithel et al., 2002; Kempfert et al., 2002; Murugesan and Rajagopal, 2006; Lee et al., 2007; Yoo et al., 2007; Almeida et al., 2013; Hong et al., 2016; Gu et al., 2016; Fattah et al., 2016; Miranda et al., 2017; Ou Yang et al., 2017; Miranda et al., 2017, 2017; Mehrannia et al., 2017; Debnath and Dey, 2017; Cengiz and Guler, 2018).

All the previous research has provided valuable insight into the behaviour of encased granular columns, both in terms of experimental findings and numerical simulations but majority of them have been based on the unit cell concept and involve 2D simulation (Murugesan and Rajagopal, 2006; Gniel and Bouazza, 2009, 2010; Wu et al., 2009; Murugesan and Rajagopal, 2010; Khabbazian et al., 2010; Lo et al., 2010; Ali et al., 2012, 2014; Elsawy, 2013; Almeida et al., 2013; Ghazavi and Nazari Afshar, 2013; Choobbasti and Pichka, 2014; Hosseinpour et al., 2014; Yoo et al., 2015; Miranda and Da Costa, 2016; Hong et al., 2016; Gu et al., 2016; Fattah et al., 2016; Ou Yang et al., 2017; Mehrannia et al., 2017; Debnath and Dey, 2017; Rajesh, 2017; Cengiz and Guler, 2018). Granular columns and encased granular columns are extensively used for construction of embankments in soft soils (Almeida et al., 2015; Chen et al., 2015; Detert et al., 2017; Schnaid et al., 2017). Numerical modelling of single or group of encased granular columns in 3D can provide effective insight into the various relevant processes the column soft soil system undergoes (Yoo and Kim, 2009; Khabbazian et al., 2010; Keykhosropur et al., 2012; Geng et al., 2016; Gu et al., 2017a, 2017b; Debnath and Dey, 2017). Extensive studies have been carried out on the load carrying capacity of single encased granular column and the same has been then extended to the behaviour of the group of columns (Yoo, 2010). Numerical simulations to understand the behaviour of group of encased granular columns without accounting for the installation effect have been attempted by few researchers (Yoo and Kim, 2009; Yoo, 2010, 2015; Keykhosropur

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et al., 2012; Hosseinpour et al., 2015, 2017). These numerical frameworks have been validated against results of load test on unit cell concept columns or full-scale test setups. The efficiency of numerical framework validated on the basis of load test in unit cell or full scale load tests under controlled environments, to model the behaviour of group of encased granular columns under embankment in real life scale can hence be questionable.

Installation effective plays a major role in the behaviour of encased granular columns (Castro and Karstunen, 2010). The installation effect may be negative, positive or negligible but it in turns effects the performance of the columns and hence needs to be considered. Various attempts in terms of field measurements have been made in order to study the effect of installation in soft soils in terms of horizontal stresses and increase of pore water pressure (Castro, 2008; Kirsch, 2004; Watts et al., 2000). Nevertheless numerical modelling has been proved to be a useful tool to model the installation effect of columns in soft soils. The installation effect has been modelled based on the cavity expansion method coupled with advanced soil models in order to quantitatively capture the effect of installation in soft soils (Castro and Karstunen, 2010).

Conventional design based on unit cell method does not include the installation effect. The design code suggests that appropriate changes need to be included in the design in order to account for the installation effect (Raithel et al., 2002). Field measurements have shown increase in undrained strength of surrounding soil after installation but, the same has not been accounted for in the design (Raithel et al., 2005). The conventional design also assumes a perfectly rigid base for the columns which may not be the case in real field conditions where columns are made to rest on sand layers. Column group is designed based on the unit cell concept and hence the positive group effect is not accounted for. Numerical simulations can hence serve as an effective tool for design and optimisation of the GECs and can help minimise the assumptions made for the design of the GECs. In this paper numerical simulation of group of encased granular columns under embankment, adopted from a real life project, has been carried out. The installation effect of columns has been numerically modelled based on the cavity expansion method in a 2D model. The corresponding stress state changes in the soft soil due to the installation effect was then imported to the model consisting of the group of encased granular columns. The numerical simulations results were then compared to field measurements. Once the numerical framework was verified, a procedure based on the numerical framework was identified to reach an optimised design.

2. Description of the Nordstrand project

In relation to the new coastal protection measures (LKN-SH, 2002), a dyke reinforcement was planned in the Nordstrand Alter Koog, north of Hamburg, Germany. The new norms led to the increase of the existing dyke height which eventually led to the expansion of the base of the dyke in order to counter the increasing sea levels. One section of planned extension of the dyke was characterized by thick layers of soft soil and hence geosynthetic encased columns (GECs) were planned as an effective ground improvement measure in order to increase the loading bearing capacity and reduce substantial settlements (Fig. 1).

Borehole data was collected and the soil profile of the area consisting of thick layers of soft clay was developed (Fig. 2). The virgin ground is composed of six different kinds of soils. The top clay layer followed by the middle soft clay, followed by the bottom clay layer (Fig. 2). These clay layers rest on a loadable sand layer. The GECs rest on this sand layer. The layers below the sand layer are not of high importance with respect to the GECs but have been considered in order to maintain close similarity to actual field condition.

The GEC reinforced ground consists of around 1950 columns of 0.8 m diameter and 12.5 m length (Fig. 1). The columns rest on a load bearing sand layer, reinforcing the top three layers of soft clay. The columns are encased by the Ringtrac 100/300 geotextile with a tensile strength of 125 kN/m. In order to ensure that the load from the dyke is uniformly distributed over the GEC reinforced ground, a sand layer with geotextile is constructed over the GEC reinforced ground.

Soil settlement gauge (SSG) and inclinometers are installed at various locations in order to measure the settlement of the improved ground and horizontal deformation in the GEC system with the construction of the dyke.

3. Field measurement

The field measurement data was recorded at a particular section of the dyke where the construction of the new dyke was executed between April and August 2015. Data in the form of settlement of ground surface and horizontal deformation of the GEC with time was recorded successfully. Pore water pressure were also installed but no proper data could be recorded as they were damaged during the construction of the dyke. The section as shown in Fig. 3 was chosen to install the settlement gauges and inclinometers. The settlement gauges were installed between three locations, first location being at the crown of the old dyke, other at middle of the GEC section and the last one at toe of the dyke as shown in Fig. 3. The settlement gauge recorded data between 07.07.2015 and 10.05.2016. The inclinometers were positioned at the outer edge, near the toe of the dyke till a depth of 22 m as shown in Fig. 3. They recorded data between 24.09.2015 and 10.05.2016. The settlement measurement gauges and the inclinometers were set to zero after the construction of the GECs. Hence the data recorded by the devices considers the deformation in the system due to construction of the new dyke. Fig. 4 shows the settlement of ground surface in the middle of the GEC section (31 mDA) and toe of the dyke (55mDA) for a period of 31 days in comparison to the increase of the dyke height. It can observed that the ground undergoes more settlement at section 31 mDA due to load from the increasing height of the dyke whereas the toe undergoes less settlement as the height of the dyke above the measurement point remains constant. Fig. 5 depicts the overall settlement of the ground and horizontal deformation of the toe of the GEC section with time. It can be seen that the settlements form a trough and the settlements are maximum in the middle of the section where substantial increase in the height of the dyke occurs.

4. Material model and parameters

Soil layers were modelled by different material models depending on the nature and importance of the soil layer. Undisturbed samples were collected in the form of cores from boreholes. The granular layers as in described in Fig. 2 are modelled using the Hardening Soil Model (HSM) and the clay layers are modelled using the Soft soil creep model (SSCM) developed by Vermeer and Neher (1998). The old and new dyke, sand layer on top of the GEC supported ground and the sand filling inside the GEC are modelled using the Mohr-Coulomb Model (MCM). The sand filling of the GEC is modelled with a Poisson's Ratio of 0.49 as the GEC is assumed to fully plasticised and hence undergoes only volumetric deformations (Table 1). This assumption leads to accurate modelling of the stiffening behaviour of the GECs upon loading due to the activation of the tensile strength of the geosynthetic upon lateral bulging. The geosynthetic encasement of the GEC and geotextile layer on top of the GECs to distribute the load uniformly over the GECs are modelled with an elastoplastic model and linear elastic model respectively (Table 1).

The elasto-viscoplastic Soft Soil Creep Model can effectively model the time dependent relaxation and viscous behaviour of soft soils in the form of creep and hence was chosen to model the behaviour of the clayey soils in the numerical model. Laboratory tests were performed on the three different clay layers in order to determine the SCCM parameters as tabulated in Table 1. The Hardening Soil Model effectively models the behaviour of granular materials by considering pressure dependent stiffness and different stiffness under loading and