First step to model the installation effect of geosynthetic encased sand columns on existing columns

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ABSTRACT: Installation effect of encased sand columns on virgin soil and surrounding columns is an important field in geotechnical research domain. Numerical simulations of a step of the installation process of geosynthetic encased sand columns (GEC) in soft soils in the Coupled Eulerian Lagrangian (CEL) framework is performed. Installation of 400 mm diameter geosynthetic encased stone columns is simulated. A 400 mm internal diameter steel probe filled with granular material and surrounded by geosynthetic is modelled to execute the installation process. The soft soil and granular material in the column was modelled by the visco hypoplastic model and hypoplastic model respectively. The geosynthetic is modelled as an elastic material with an out of plane tensile strength. The real life installation of encased sand columns is performed in steps over the entire depth of column however in the work, a single installation step was modelled due to computational constraints. An already wished in place full depth column was modelled at the start of the simulation followed by the installation of an adjacent encased sand column. The installation effect of encased sand column on the adjacent column in terms of the developed stress state and deformations in and around the already existing column is studied. The effect of nature of soft soil and spacing between columns is analyzed. The simulation of the installation process shows that deformations in the already existing sand column was a function of the column spacing and soft soil strength.

Keywords: geosynthetic, encased sand column, hypoplastic, visco-hypoplastic, CEL

1 INTRODUCTION

The installation of the geosynthetic encased sand column is a ground improvement which can be used to improve the bearing capacity of soft cohesive soil. Vibrators displace the soil and introduce coarse material along with a geosynthetic encasement into the cavity. The resulting encased sand columns improve the material properties of the soft soil. The installation of the encased sand columns leads to substantial changes in the stress state of the soft soil. In real life construction sites large number of such columns need to be installed. In such cases the effect of installation of an already existing column is of importance. Therefore the effect of column installation on the adjacent column in terms of variation of stress state and deformations in the existing column is studied. Increase in horizontal stress state improves the system whereas deformations in the adjacent column are highly undesirable. Parametric studies are performed and the effect of soft soil strength and spacing of columns on the aforementioned variables is studied. The CEL approach capable of handling large scale deformations is used in order to simulate the installation process.

2 ENCASED SAND COLUMN INSTALLATION METHOD

The installation of the sand columns is executed with a vibrator pin jointed to a stay tube (Kirsch, 2004). The vibrator is a closed end steel probe filled with granular material and encased with geosynthetic material. The probe is driven to the required depth with the geosynthetic and the cavity created by the probe is filled in with the granular material. The installation is performed in steps over the entire depth of the column. The steel probe is vibrated out in steps ensuring a compacted column of sand encased by geosynthetic layer (Figure 1). This method leads to a vertical zone of improved soil properties. The installation of the columns leads to substantial stress changes around the sand column which can eventually affect the already installed adjacent sand column (Figure 1).

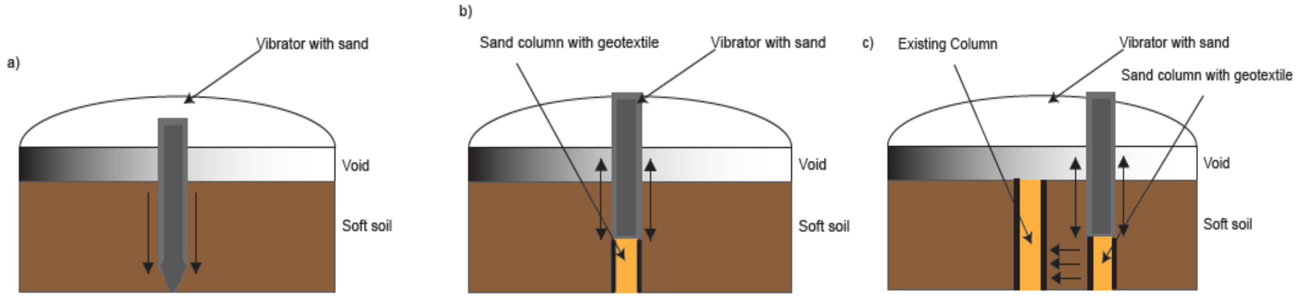

Figure 1. Schematic explain the GEC installation process and effect of it on existing column (not to scale)

3 NUMERICAL MODELLING

In order to study the effect of installation process, numerical simulation is conducted. First approaches towards modelling of stone and sand columns used the homogenization approach where equivalent improved material parameters due to the addition of columns in soft soil was used (Schweiger 1989, Lee & Pandey 1998, Wehr 1999). But these methods were not sufficient and could not capture the effect of addition of such columns in soft soils. Realistic 3D modelling of the column's various stages of construction is important in understanding the various physical processes involved (Kirsch, 2004). Hence in this a 3D modelling technique based on the CEL approach is used to simulate the encased sand column installation technique.

3.1 *CEL method*

The installation of the encased sand columns involves large scale deformations and hence the CEL approach was adopted which is suited for problems involving large scaler deformations. This method combines the advantages of the Lagrangian analysis with those of an Eulerian formulation. A characteristic of the Lagrangian formulation is the deformable mesh which moves with the material meaning that the movement of a continuum is described as a function of time and material coordinates. In an Eulerian analysis on the other hand the movement of a continuum is formulated by a function of time and spatial coordinates. The mesh of an Eulerian formulation remains undeformed and the material can move freely through the mesh. Both techniques are depicted in Figure 2.

During a coupled Eulerian-Lagrangian analysis a Lagrangian object can move into and inside an Eulerian region. The material distribution inside the Eulerian region is defined by the Eulerian Volume Fraction (EVF). An element can take all states between completely filled with material (EVF = 1) or being void (EVF = 0). The Lagrangian object can move though the region without resistance until it touches Eulerian material. Then the contact algorithm starts to act. The algorithm is implemented as a general contact formulation based on the penalty method and therefore, assumes a hard pressure-overclosure behavior, is less strict than a kinematic method and allows small penetrations of the Eulerian material into the Lagrangian object (Figure 2).

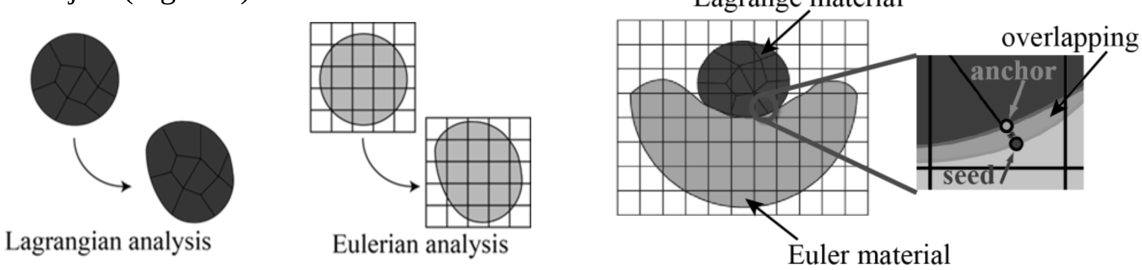

Figure 2. (a) Deformation of a continuum in a Lagrangian (left) and an Eulerian analysis (right) (Qiu, 2012) (b) illustration of the penalty method (Qui, 2012)

3.2 *Numerical model*

A 3D model based on the CEL method was created as shown in Figure 3. The Eulerian region which models the soft soil around the column, was modelled as a cylinder of 12 m radius and a height of 2.2 m (shorter height was chosen to reduce the computational effort). A void region of height of 0.5 m was created on top of the model in order to allow the material flow into the region. The soil body was modelled using the eight noded Eulerian elements with reduced integration. The already existing encased sand column and the sand in the vibrator is modelled as part of the Eulerian mesh. The vibrator is modelled as a cylindrical pipe of internal diameter of 0.4 m and height of 2.2 m. The vibrator is modelled as already wished in place at a depth of 2 m. The vibrator is modelled as with eight noded hexadron Lagrangian elements. Sand and the geosynthetic layer are modelled within the vibrator pipe and this sand flows into the cavity created in the soft soil due to movement of the vibrator. The geosynthetic encasement is modelled as cylinder of diameter of 0.4 m composed of membrane elements with an out of plane tensile strength. The bottom of the model is assumed to be a hard strata and hence bottom boundary is completely fixed and lateral boundaries are fixed against any lateral movement.

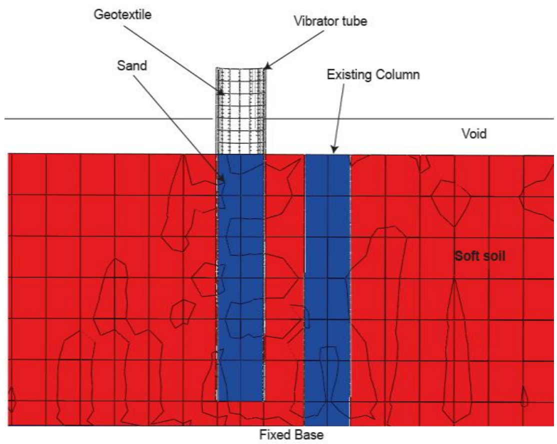

Figure 3. FEM model details (section near the columns)

3.3 *Constitutive Models*

In order to model such complex processes a high class constitutive model is necessary in order to capture the realistic behavior of the soil. The soft soil is modelled using the visco hypoplastic model of Niemunis (2003). The model is able to capture viscous effects such as creep relaxation and rate dependence. The hypoplastic model according to von Wolffersdorff (1996) with the extension for intergranular strains by Niemunis and Herle (1997) was used to model the sand. This model is able to capture various complex behavior such as contractancy, dilatancy and pressure and void ratio depended stiffness. This model considers different stiffnesses for loading, unloading and reloading and hence can effectively capture various physical processes in soils during installation. The material parameters for visco hypoplastic and hypoplastic model are tabulated in Table 1 respectively.Vibrator is assumed to be composed of steel and is modeled with a linear elastic constitutive model. The geosynthetic is modelled as an elastic material with an out of plane tensile strength with secant stiffness of 1000 kN/m and Poisson’s ratio of 0.3.

Table 1. Material properties of soft soil (right) and filling sand (left)

Parameter	Value	Description
e_{por0} [-]	1.09	Void ratio at 100 kPa
v [-]	0.2	Poisson's Ratio
C_c [-]	0.1	Butterfield lamda
C_s [-]	0.026	Butterfield kappa
β_x [-]	0.05	Shape of Rendulic surface
I_v [-]	0.05	Viscosity index
D_r [-]	$1\text{x}10^{-6}$	Reference creep rate
φ_c [°]	18.5	Critical state friction angle
m_T [-]	2	Stiffness ratio at 90˚ change of direction
m_R [-]	5	Stiffness ratio at 180˚ change of direction
R [-]	0.0001	Maximum value of intergranular strain
β_R [-]	0.95	Exponent
χ [-]	1	Exponent
OCR [-]	Value varied	Over Consolidation Ratio

Parameter	Value	Description
φ_c [°]	36	Critical state friction angle [°]
h_s [MPa]	32	Granular hardness [MPa]
N [-]	0.324	Exponent
e_{d0} [-]	0.57	Minimum void ratio
e_{c0} [-]	1.04	Critical void ratio
e_{i0} [-]	1.20	Maximum void ratio
α [-]	0.4	Exponent
β [-]	1.0	Exponent
m_T [-]	2.0	Stiffness ratio at 90˚ change of direction
m_R [-]	5.0	Stiffness ratio at 180˚ change of direction
R [-]	0.0001	Maximum value of intergranular strain
β_R [-]	0.5	Exponent
X [-]	6.0	Exponent

3.4 *Contact formulation*

The contact between the soil as an Eulerian region and the steel tube as Lagrangian element is implemented in the model with a general contact formulation based on the penalty method. The penalty method is chosen because it is less strict than a kinematic contact method used for Lagrangian approaches in numerical modeling. A hard pressure overclosure behavior is approximated. Furthermore, the tangential contact is defined according to Coulomb's friction law with a friction coefficient of $\mu = \tan(\delta)$, where δ is the wall friction angle between steel tube and soft soil. φ_c is the friction angle of the soft soil and the wall friction angle is defined as $\delta = 2/3\varphi_c$. The occurring stresses of the filling material while inside the tube are not important for the simulation. Therefore, the contact between the steel tube and the filling material is approximated as frictionless contact.

3.5 *Validation*

In order to validate the accuracy of the CEL framework to model complex process such as the installation of GEC, a preliminary validation was carried out. The process of installation of a step of the 0.8 m diameter sand column without geosynthetic was modelled at a depth of 9 m and the results of the excess pore water pressure generated due to construction of the base of the column was compared to field test results as reported by Castro and Sagaseta (2007). The index parameters of the clay as described by Castro and Sagaseta (2007) have been used and other parameters were chosen as per a clay of similar nature whose visco hypoplastic parameters are already known. The numerical results and field results were seen to be in good agreement (Figure 4).

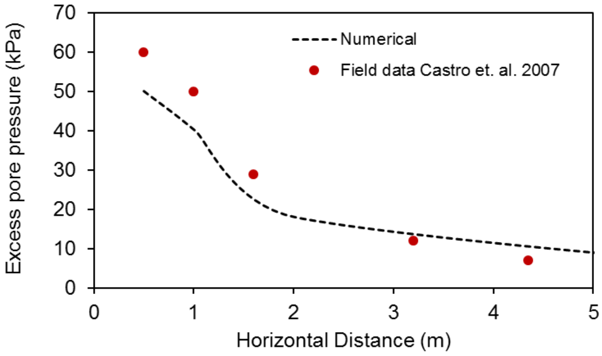

Figure 4. Validation of CEL model with field test results

3.6 *Process simulation*

The steel tube vibrator along with geosynthetic layer and sand is modelled as wished in place at a depth of 2 m at the start of the simulation. Entire penetration of the vibrator tube in the soft soil was not modelled due to computational restraints. After the initial step of where K_0 stress state is initialized, the tube along with the sand and geosynthetic layer is then pushed 0.2 m into the soft soil coupled with a vibratory force of 100 kN. In the following step the tube is lifted by 0.2 m followed by the next step where the tube is pushed down again by 0.1 m. This is to ensure that the sand is plugged against the surrounding soft soil along with the geosynthetic.

3.7 *analysis cases*

In order to study the installation effect on adjacent columns various cases were considered. The shear strength of the soft soil was varied and the effect of the installation process was studied. The spacing between adjacent columns was also considered as a parameter. In all of the cases the columns were assumed to be resting on a hard base, one set of simulations are also performed in order to study the installation effect on floating columns which do not rest on a hard strata.

4 SIMULATION RESULTS

The results of the various cases as described in the previous section are discussed in the following section.

4.1 *Shear strength of soft soil*

Figure 5 shows the horizontal movement of the existing column due to installation of the second column. The figure shows the volume of Eulerian elements filled with sand and it can be seen that the column has undergone lateral movement from its original position before the start of the installation. It can be seen that the top part of the column remains intact and the movement is predominant at the bottom of the column, depth at which the installation process was simulated. In order to visualize the entire deformation in the column due to installation, the entire depth of column installation needs to be simulated which is currently not under scope due to computational constraints. It can also be observed that the distribution of sand inside the column has also changed. Shear strength of soft soil plays critical role in the behavior of sand columns (Ambily & Gandhi, 2007). The shear strength of the soft soil determines the stress state that develops in the soil after the installation process. These stresses affect the deformations in the adjacent column. Simulations were performed with properties of Kaolin clay at different shear strengths (20, 10 and 5 kPa). The shear strength is not a direct parameter in the visco hypoplastic model and hence a correlation was developed by means of unconfined compression tests to relate OCR value to the shear strength. The horizontal deformation in the adjacent column at the tip of the column due to the installation of the new column was found to increase with increasing shear strength (Figure 6). The probable explanation could be the high magnitude of horizontal stress that develops between the columns. It can be seen in Figure 7 that the magnitude of horizontal stress between columns increases with shear strength.

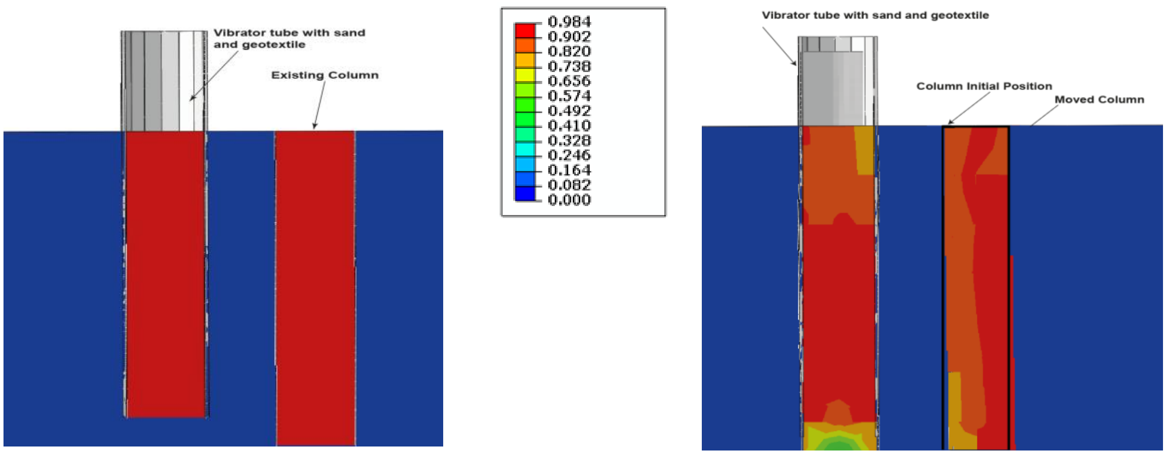

Figure 5. Columns before installation (right) and horizontal shift of column due to installation shown by the shift of Eulerian elements filled with sand (left)

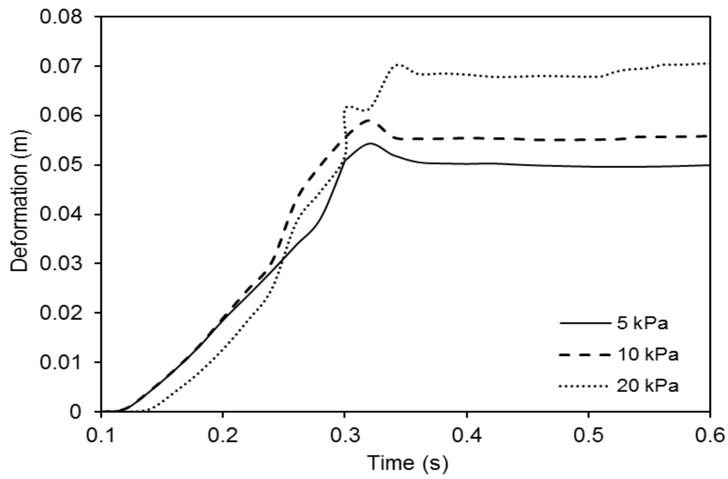

Figure 6. Horizontal deformation of adjacent column at tip with varying shear strength of soft soil

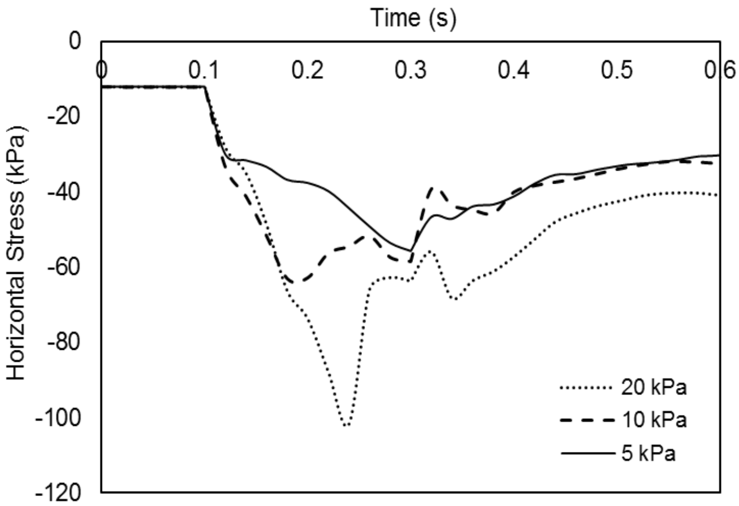

Figure 7. Horizontal stress in between columns at tip with varying shear strength of soft soil

4.2 *Spacing of Columns*

The effect of installation is limited to a radial distance of 2 m from the center of the column (Castro & Karstunen, 2010). The effect reduces substantially as the distance from the center of the column increases. Hence the spacing between columns would play a key role in determining the installation effect on already existing column. Simulations are carried out at variable spacing of 0.75, 1 and 1.5 m for the 0.4 m diameter column in soft soil of 5 kPa shear strength. It is observed in Figure 8, as the spacing increases the horizontal deformation in the adjacent column reduces. This is easily justifiable from the fact that as the distance increases the column moves away from the zone where the installation effects are predominant and hence the deformations reduce.

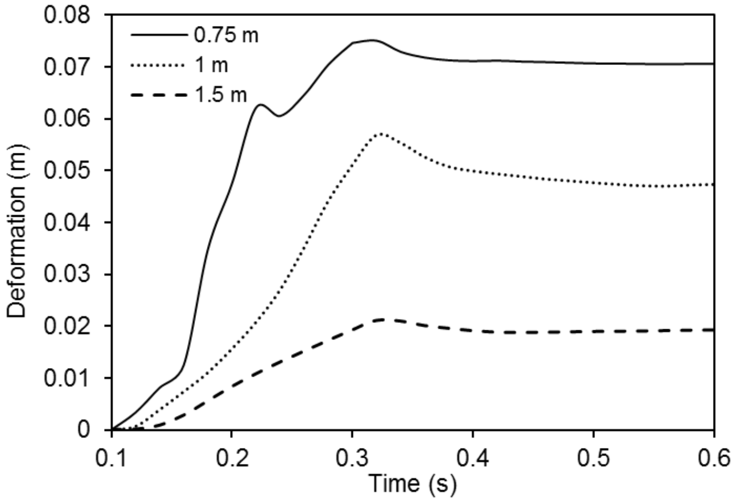

Figure 8. Horizontal deformation of adjacent column at tip with varying spacing between columns

4.3 *Type of Column*

Two kinds of encased sand columns are encountered, one resting on a hard strata and the other floating in the soft soil. Floating encased columns are generally installed in vertically extensive soft clay deposits found near coastal areas (Dash & Bora 2013). Floating columns are terminated in the soft clay layer and exhibit different behavior in comparison to columns resting on hard strata. Simulation are carried out for encased sand columns terminated mid depth of the soft clay layer of shear strength of 5 kPa. It is observed in Figure 9 that installation of floating column lead to an increased horizontal deformation in the adjacent existing floating column. Lack of support at base, makes the column more vulnerable to horizontal shift as the soft clay is unable to provide the required confining stresses and support at the base.

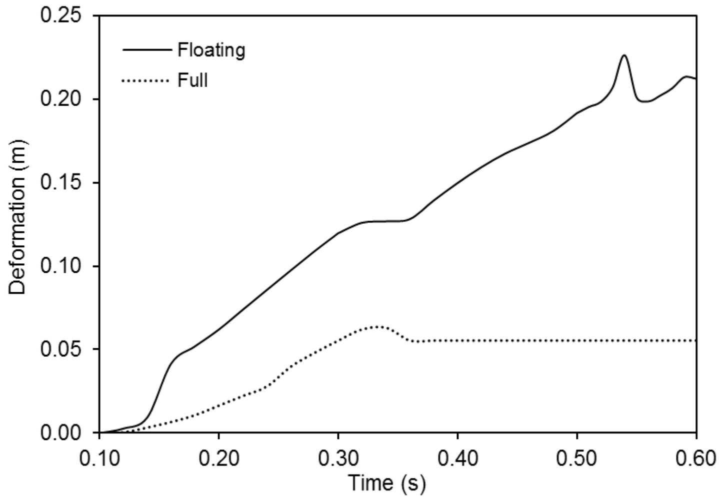

Figure 9. Horizontal deformation of adjacent column at tip with varying column type

5 CONCLUSIONS

CEL computational framework can serve as an effective medium to model such complex processes. The effect of installation of GEC on already existing column is studied by the simulation of a step of the installation process. Horizontal deformation was observed near the base of the existing column. The magnitude of deformation increased with increasing shear strength. The horizontal deformations in columns reduced with spacing as expected. Preliminary simulations showed that floating columns not resting on a fixed base would undergo increased deformations. It is worthy to mention that these simulations are first step towards studying the feasibility of the CEL method to model installation process of the GECs. In order to study the realistic deformations in adjacent columns, the entire column installation process needs to be simulated. This would help the industry optimize the spacing between columns with respect to damage instilled in adjacent columns which has been of serious concern in GEC based projects.

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