Numerical Analysis of Geosynthetic encased granular columns in soft clays based on 2D and 3D FE models

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Abstract. Geosynthetic encased granular columns are used to effectively stabilize marine soft clay deposits with low undrained shear strength. Present study focuses on assessing the behaviour of geosynthetic encased granular columns in very soft clays using two FE approaches namely 2D axisymmetric and 3D unit cell. The study compares the results obtained for three cases namely virgin soft clay without any granular column, ordinary granular column and geosynthetic encased granular column. The effectiveness of geosynthetic encasement is examined by assessing the length of the geosynthetic encasement and the tensile secant modulus of the geosynthetic on the dissipation of excess pore pressures and settlement. Additionally the settlement reduction ratio parameter is also investigated for both the approaches and the results are compared.

Keywords: Geosynthetic, Soft clay, 2D Axisymmetric, 3D Unit cell, Granular column.

1 Introduction

Granular columns (or stone columns) are one among the various ground improvement techniques used for effectively addressing the problems due to soft clays. This technique is adopted due to the twin function offered on par with other ground improvement techniques. Firstly they function as strong reinforcements in effectively bearing the structural loads and secondly they act as drainage elements in effectively dissipating the excess pore water pressures. These granular columns when employed in very soft marine clay deposits with low undrained shear strength say (Su ≤ 15 kPa) depict a lack in performance due to insufficient lateral confinement as reported by McKenna et al. (1976) and Chummar (2000).

Studies on geosynthetic encased granular columns in very soft clays have started gearing up after the pioneering idea of encasing the granular column with geosynthetics by Van Impe (1989). Several other researchers Malarvizhi and Ilamparuthi (2003), Murugesan and Rajagopal (2007), Yoo and Kim (2009), Castro and Sagaseta (2013), Almeida et al (2013), Mohapatra and Rajagopal (2017) have worked on various laboratory, analytical, field and numerical aspects of encased granular columns related to load settlement behaviour. Particularly, the numerical modelling of geosynthetic encased granular columns has gained interest among the researchers worldwide to understand the response of geosynthetic encased granular columns for effectively treating very soft clays. Very few studies Elsawy (2013), Rajesh (2017) Pandey et al (2018) have focused on the time dependent behaviour of embankment loaded encased granular columns out of which the importance of length of geosynthetic encasement and the tensile modulus have scarcely been attempted. Hence in the present study, the behaviour of geosynthetic encased granular columns in soft deposits are numerically studied by both 2D axisymmetric unit cell and 3D unit cell FE approaches with due importance to length and tensile modulus of the geosynthetics and the results are discussed.

2 Problem Definition and Numerical Modelling

The present numerical study is performed for a hypothetical case of embankment resting on granular columns. FE code PLAXIS 2D (2017) with 15 noded triangular elements and 3D Version (2017) with 10 noded tetrahedron elements was used to perform all the numerical simulations. The foundation bed comprises of 9.5 meters of soft clay deposit below which competent ground exists. A coarse sand layer above the soft clay of 0.5m thickness was provided to serve as a loading platform just below the embankment. The ground water table was present just above the loading platform. The embankment with a total height of 6m was constructed using staged construction technique in three equal stages for about 120 days. After construction of the last stage of the embankment, the foundation bed was allowed to consolidate to a minimum excess pore pressure say (< 1 kPa). End bearing ordinary and encased granular columns of 0.8m diameter and length 10 m with a spacing of 2.5 m were installed in square arrangements for 2D axisymmetric analysis. The radius of the 2D unit cell was worked out to be 1.13 m. Due to the limitations of the software an equivalent square area of 2m X 2m as that of 2D analysis was adopted to simulate the 3D unit cell FE model. The 2D axisymmetric unit cell and 3D unit cell models of embankment loaded granular columns are shown in Fig.1.The geosynthetic encasement was varied between 0.5L to 1L, where L is the length of the column. The geosynthetic tensile modulus (J) was varied from 500 kN/m to 7500 kN/m as suggested by previous researchers Yoo (2010) and Khabbazian et al (2010).

The soft clay soil was modelled using soft soil model which is an advanced non-linear constitutive model of cam clay type. The Embankment material, granular column and the loading platform were simulated using linear elastic perfectly plastic Mohr-Coulomb model. The soft clay deposit was simulated with undrained behaviour, and the other soils were modelled using drained behaviour. The geosynthetic encasement was modelled as a linear elastic element which can take only tensile forces. The granular columns and the surrounding soft clay deposit were assumed to be intact and hence no interface parameters were used in the present analysis. A medium fine type of mesh was used in the study after conducting sufficient trials on various degree of fineness of the meshes. The settlement with time plot for ordinary granular column (OGC) as shown in Fig.2 depicts the mesh sensitivity for fine and medium grade meshes. The material properties are listed below in Table 1.

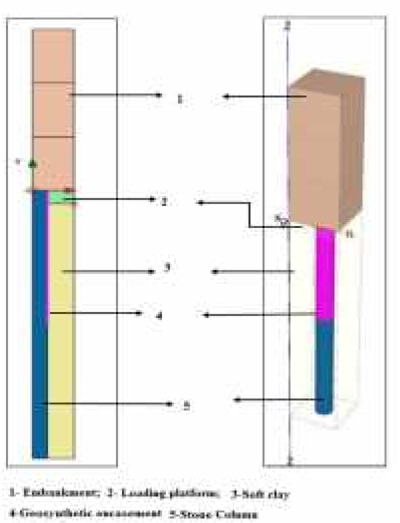

Fig.1. 2D and 3D Unit cell FE models of embankment loaded partially encased granular column.

Table 1. Material properties of the foundation bed and Embankment

S.No	Properties	Embankment	Loading Platform	Soft Clay	Stone Column
1	Constitutive model	Mohr-Coulomb	Mohr-Coulomb	Soft Soil	Mohr-Coulomb
2	Unit weight γ' (kN/m^3)	20	20	15	22
3	Elastic Modulus E (kPa)	20000	20000	--	40000
4	Effective Cohesion C (kPa)	5	3	5	2
5	Effective Friction Angle ϕ' (degrees)	30	32	20	38
6	Dilation Angle ψ (degrees)	0	0	0	10
7	Compressibility Index C_c	--	--	0.526	--
8	Swelling Index C_s	--	--	0.097	--
9	Horizontal Permeability k_h (m/day)	1	1	0.0002	10

10	Vertical Permeability k_v (m/day)	1	1	0.0001	5

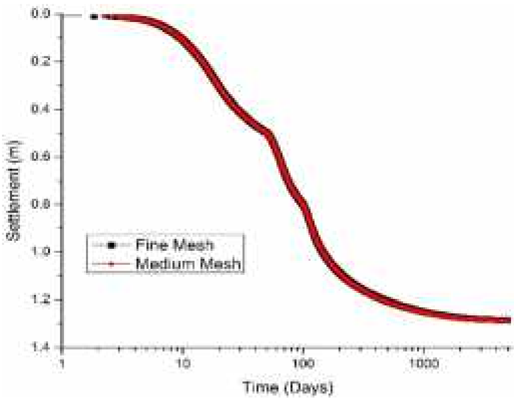

Fig.2. Mesh sensitivity for Medium and Fine type meshes

3 Validation of the numerical model

The present study is validated from the numerical investigations conducted by Elsawy (2018) on embankment loaded granular columns for 2D axisymmetric and 3D analysis. The material properties were nearly the same as that of the present study except for the fact that soft clay was also modelled using linear elastic perfectly plastic Mohr Coulomb model. The settlement with time plot obtained is shown in Fig.3 which indicates a good agreement between the results obtained and the referred study for 2D axisymmetric analysis. The validation results for 3D Analysis are not reported here in due to lack of space.

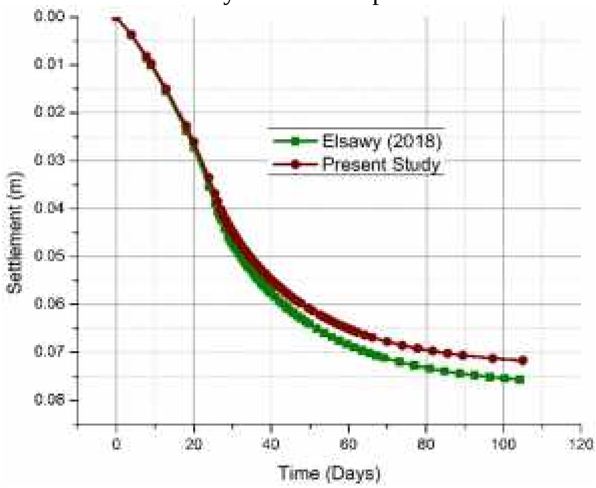

Fig.3. Validation of present study with Elsawy (2018)

4 Assessment of Results

The plots discussed below correspond to the 2D axisymmetric unit cell approach and the values corresponding to the 3D unit cell model are listed in Table 2. The investigations were numerically performed for evaluating the excess pore pressure dissipation and settlement with time for all the cases described below.

4.1 Effect of geosynthetic encasement

The undrained shear strength of soft clay (Cu = 5 kPa) necessitates the use of geosynthetic encapsulation to granular columns for adequate lateral support. When the soft clay soil is loaded by the embankment, excess pore water pressures are generated which are in turn dissipated through drainage elements (granular columns) due to relatively higher permeability. Fig.4 indicates clearly the excess pore pressure generated for embankment loaded virgin soft clay, clay stabilized with ordinary granular column (OGC) and geosynthetic encased granular columns (EGC). All the pore pressures were monitored at mid depth of soft clay at 5m depth. The peak values observed are correspondingly 76.46 kPa, 38.25 kPa and 3.05 kPa respectively for soft clay, OCG and EGC. With an effective confinement offered to the granular column by the geosynthetic encasement, the EGC's (J = 7500 kN/m) quickly dissipated the pore water pressures at about 12.5 times as that of ordinary granular columns and ≈ 29 times as that of soft clay. The superior performance of EGC when compared to OGC in terms of pore water pressure dissipation is due to two reasons. Firstly, EGC being relatively stiffer only lesser excess pore pressures are generated in the soft clay due to load transfer. Secondly, the generated pore pressures are quickly dissipated as the drainage quality of the aggregates being preserved by encasement as reported by Yoo (2010), Elsawy (2013) and Rajesh (2017). When compared with 3D unit cell analysis, the 2D axisymmetric analysis underestimated the pore pressures by 1.41% and 10.50% for soft clay and OGC, whereas for EGC, the pore pressures were overestimated by 13.50%.

Settlement at the end of the consolidation time period for the embankment supported by Soft clay, OGC and EGC is shown in Fig.5. Settlements for all the cases reported in the present study were observed from a point on top of the granular column. With geosynthetic encasement (J = 7500 kN/m), the settlements were drastically reduced when compared to OGC and soft clay deposit. The values observed are 2.02 m, 1.30m and 0.264 m. This shows that softer the clay, proper lateral confinement is necessary for encasing the column to reduce the settlements. Further, the settlement values obtained by 3D unit cell analysis were 16.35 %, 4.66 % and 1.93% lesser than that of the 2D analysis.

The possible reasons for the discrepancies of the values in both pore pressure dissipation and settlements may be due to the conversion of 2D axisymmetric unit cell to equivalent 3D unit cell. Further the magnitude of discrepancies between these approaches obtained from the present study are less than 20 % and are in line with the studies conducted by Khabbazian et al (2015) and Yoo and Kim (2010) and are of little practical importance.

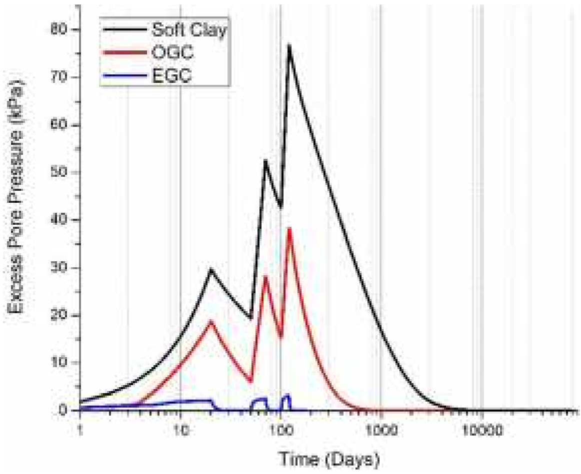

Fig.4. Variation of Excess pore pressure with time for Soft clay, Ordinary Granular Column (OGC) and Encased Granular Column (ECG).

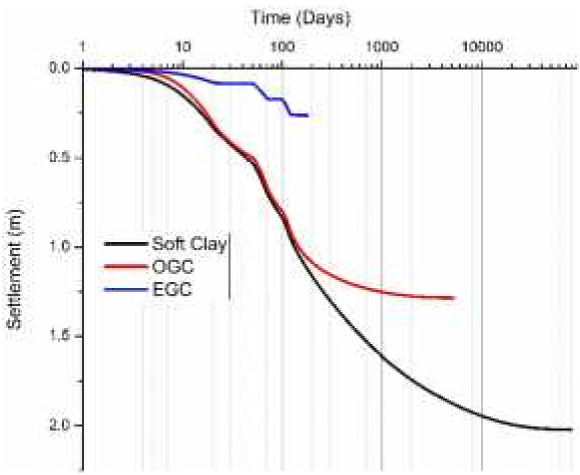

Fig.5. Variation of Settlement with time for Soft clay, OGC and ECG.

4.2 Effect of Secant Modulus of the geosynthetic

The effect of secant modulus of the geosynthetic on the dissipation of excess pore pressure and settlement with time is shown in Figs 6 and 7. For the cases analyzed in the present study, the excess pore pressures varied from 38.25 kPa (OGC) and 3.14 kPa (EGC; J = 7500 kN/m). It is observed that with steady increase in secant modulus of the geosynthetic, the excess pore water pressures are quickly dissipated due to increase in degree of confinement. Correspondingly, the stress transfer to the surrounding soft clay is considerably less and due to which the settlements reduce with increase in secant modulus of the geosynthetic as depicted from Fig.7. With increase in secant modulus of the geosynthetic, the settlements obtained from both the FE approaches were nearly equal with a variation of (< 2%). However in the case of pore pressure dissipation, considerable variations upto 16.72% (for J = 7500 kN/m) existed between the two approaches.

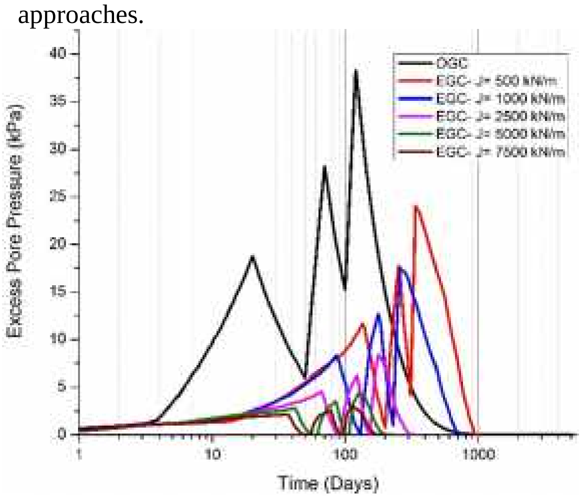

Fig.6. Variation of Excess pore pressure with time for OGC and EGC with increasing secant modulus.

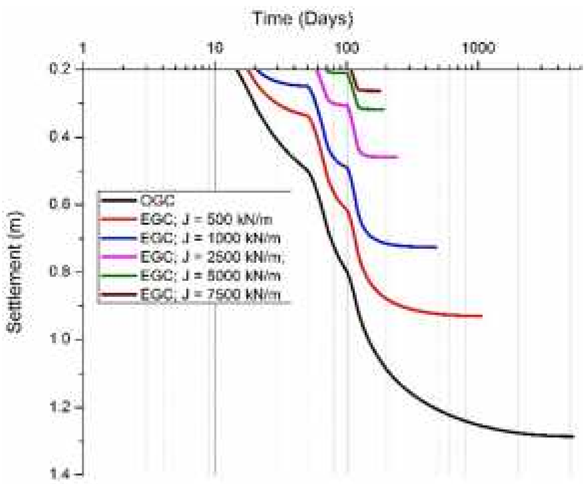

Fig.7. Variation of settlement with time for OGC and EGC with increasing secant modulus.

4.2 Effect of Length of the geosynthetic encasement

Effect of length of geosynthetic encasement (partially encasement) on the behaviour of geosynthetic encased granular columns were investigated for both the FE models along with ordinary granular columns without encasement as shown in Figs.8 and 9. Fig.8 clearly portrays the effectiveness of dissipation of pore pressures when the granular columns are encased, however a fully encased granular column and a granular column encased to about 75% of its length nearly yielded the same values say 9.48 kPa and 8.42 kPa. Further, in the case of settlement reduction aspect, fully encased granular columns (for J = 2500 kN/m) displayed reduced settlement when compared to partially encased and ordinary granular columns as observed from Fig.9 and Table 2. The effect of length of reinforcement on settlements observed from both the methods were nearly the same with a variation of (< 3.5%) in the case of settlements, however for pore pressures, the 2D axisymmetric approach underestimated the values by 16.76% for 50% encasement length (5m) and overestimated the values by 7.11% and 10.49 % for 75% length of encasement (7.5 m) and Full encasement (10 m).

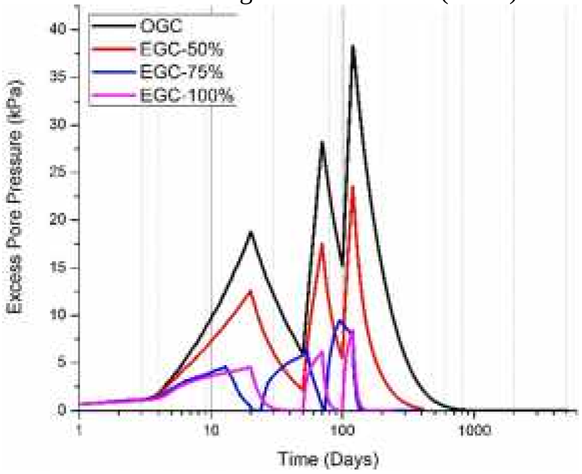

Fig.8. Variation of Excess pore pressure with time for OGC and Partially Encased Granular Column.

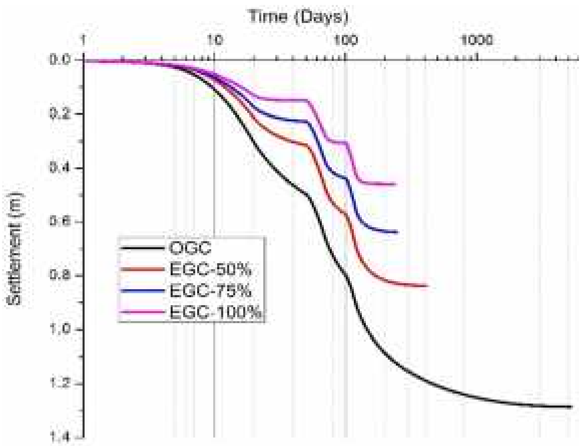

Fig.9. Variation of settlement with time for OGC and Partially Encased Granular Column.

4.3 Settlement reduction ratio (β)

Settlement reduction ratio (β) can be defined as the ratio of the settlement of stone column treated ground to that of settlement of virgin clay without granular columns. The variation of (β) with secant modulus of the geosynthetic and length of encasement is shown in Figs.10 and 11. It can be observed that fully encased granular columns with high secant modulus resulted in lesser settlements. Further, both 2D Axisymmetric and 3D unit cell models nearly yield the same settlement ratios for the cases discussed in the present study.

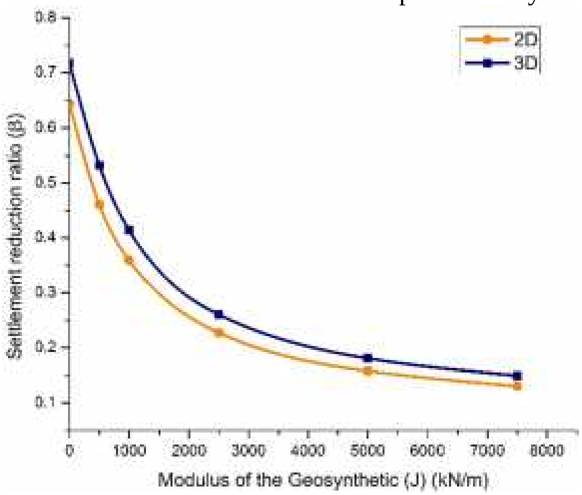

Fig.10. Variation of settlement reduction ratio with Secant modulus of geosynthetic encasement.

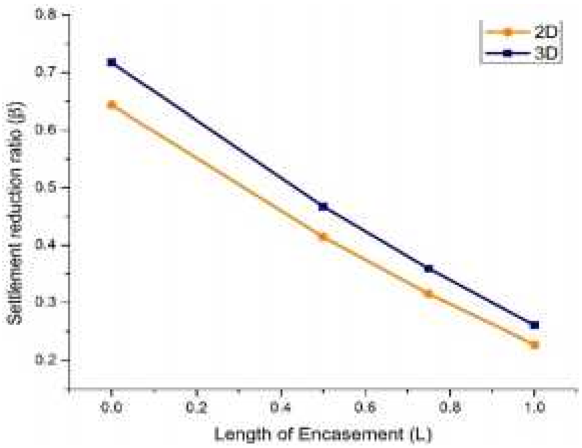

Fig.11. Variation of settlement reduction ratio with length of geosynthetic encasement.

Table 2. Settlement and Excess pore pressure values from 3D unit cell analysis

S.No	Column Material	Settlement (m)	Peak Excess Pore Pressure (kPa)
1	Soft Clay without granular columns	1.736	77.54
2	OGC	1.242	42.27
3	EGC; J = 500 kN/m	0.922	25.49
4	EGC ; J = 1000 kN/m	0.717	17.66
5	EGC; J = 2500 kN/m	0.451	7.62
6	EGC; J = 5000 kN/m	0.313	3.78
7	EGC; J = 7500 kN/m	0.259	2.69
8	EGC; 50 % Encasement	0.810	27.44
9	EGC; 75 % Encasement	0.622	8.85
10	EGC; 100 % Encasement; J = 2500 kN/m	0.451	7.62

Conclusions

Based on the limited numerical investigations on the behaviour of geosynthetic encased granular columns in soft clay deposits using 2D Axisymmetric and 3D unit cell studies, the following conclusions are arrived.

- Encased Granular Column technique is an effective foundation alternative for stabilizing very soft clays when compared to ordinary granular columns.
- Fully encased granular columns with a high secant modulus yielded reduced settlements and quickly dissipated the pore pressures due to the high degree of confinement.
- The settlements obtained by both 2D and 3D FE approaches were in good agreement with a very less variation.
- The pore water pressure dissipation values computed based on the two numerical approaches had acceptable discrepancies possibly due to the equivalent conversion from circular area to square area unit cell in the case of 3D approach.
- Comparison of additional parameters like vertical stresses, lateral deformation and stress sharing between the granular column and soft soil with full scale field results may likely reveal the similarity and differences between these two FE Approaches.

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