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Soft Clay Treatment with Two Types of Reinforced Stone Columns: A Numerical Study

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Abstract. Stone columns are usually preferred to enhance the engineering behavior of soft grounds especially in the case of flexible loaded structures such as embankments. When the clays are very soft with undrained shear strength $S_u \leq 15$ kPa, a lack in performance of stone columns is reported by researchers. In order to enhance the performance of stone columns, a geosynthetic encasement is provided in the form of vertical encapsulation. Alternatively, they can also be reinforced with horizontal disc type reinforcements. In the present study, numerical analysis using PLAXIS-2D was conducted to study and compare the performance of an embankment with ordinary and two types of reinforced stone columns. The comparison is made in terms of consolidation settlements, pore pressure dissipation, stress sharing between the stone column and surrounding soil and bulging of stone columns. The influence of parameters namely, friction angle of the stone column material, stiffness of geosynthetic on the consolidation settlements, and bulging behavior are also discussed in brief.

Keywords: Soft Clay; Embankment; Settlement; Geosynthetic; Stone Columns.

1 Introduction

Soft clays are problematic soil deposits of marine origin characterized by low shear strength and high compressibility. The natural moisture content of these deposits are usually close to liquid limit. These problematic deposits pose a variety of challenges to the civil engineers in constructing any infrastructure. Hence, in order to improve the engineering behavior of these deposits, various ground improvement methods are adopted. Especially for soft clays, preloading, sand drains, stone columns, deep mixed soil columns, and most recently vacuum preloading techniques are adopted. Among all the techniques listed above, the treatment with stone columns (also referred as granular columns, granular piles) are popular and widely adopted globally. The granular columns act as strong reinforcement inclusions helping to transfer the structural loads to deeper depths and in addition act as large drainage elements in dissipating the excess pore pressures developed during the construction process. These columnar elements are constructed by drilling the bore holes and subsequently filling them with aggregates like gravel having size in the range to 80 mm down for top-feed approach and 40 mm down for bottom-feed approach of construction of stone columns.

Nevertheless, a reduction in performance of these granular columns is observed when they are installed in very soft clays (S_u < 15 kPa) due to poor lateral support McKenna et al. (1976), and Gue and Tan (2005). In order to overcome this limitation, they are usually encapsulated with a geosynthetic Van Impe (1989). Additionally, due to encasement, the granular aggregates are prevented from intermixing with the soft clay, which eventually leads to increase in performance of the granular columns as both reinforcement and drainage elements. Several other researchers Raithel and Kempfert (2000), Malarvizhi and Ilamparuthi (2003), Murugesan and Rajagopal (2007), Yoo and Kim (2009), Almeida et al. (2013), Mohapatra and Rajagopal (2017), Jayapal and Rajagopal (2020) and Miranda et al. (2021) have worked on various analytical, numerical, laboratory and field studies on geosynthetic encased granular columns (EGC). Among the different type of studies discussed above, researchers have significantly focused on understanding the granular column-geosynthetic-soft clay foundation system through numerical modelling. Mostly the studies have focused on tubular geosynthetic encasement provided vertically, referred hereafter as (VE). Very few attempts have been made on reinforcing the granular columns with horizontal disc type reinforcements (HDR) such as Sharma (1998), Ayadat and Hanna (2008), Ali et al. (2014) and Hasan and Samadhiya (2016). However, to the best knowledge of the authors, a comparative study on these two types of reinforcements on a field case history is not reported in the literature pertaining to stone columns. Hence in the present numerical study an attempt has been made to investigate the performance of an embankment supported by EGC′s with two different types of reinforcement followed by parametric studies.

2 Problem Definition and Numerical Modelling

The present numerical investigations are performed for an embankment constructed for Penchala Toll Plaza project at New Pantai Expressway, Malaysia, in the year (2003). A brief description of the project is given by Tan et al. (2008). FE code PLAXIS 2D (2019) with 15 noded triangular elements were used for the simulations. The 20 m wide and 1.8 m high embankment was filled by sandy material. The embankment was supported by granular columns reinforcing the soft clay of thickness 6 m, followed by a stiff clay of thickness 4 m. A square type installation pattern was adopted for installation of granular columns. Granular layer of thickness 1 m was provided above the soft clay to improve the soft ground for stable construction activities and to serve as a drainage layer during consolidation. The ground water table was located at 1 m below the embankment base.

The 1.8 m high embankment was simulated on a stage wise construction technique for 9 days in three equal heights of 0.6 m. The initial phase consisted of activating the soil and the geosynthetic elements, followed by embankment construction. In order to simulate the long-term conditions, a consolidation phase was included just after constructing the last layer of the embankment to a minimum excess pore pressure less than 1 kPa. Granular columns without and with two types of reinforcement was considered in the simulations. The diameter of the unit cell for a 0.8 m diameter granular column installed in a triangular pattern at 2.4 m center to center spacing was 2.712 m. The secant modulus (J) of the geosynthetic encasement used for vertical encapsulation and horizontal reinforcements is 800 kN/m.

The soft clay, granular column and the embankment soils were modelled using the Mohr-Coulomb model. The soft clay soil was modelled as undrained and the rest of the granular soils was modelled to simulate the drained behavior. The inbuilt 5- noded geogrid element was chosen to model the geosynthetic reinforcements with axial stiffness (EA) as input parameter. An interface (R_{inter} =1) was used in the present analysis which implies a perfect adherence between geogrid and adjacent soil. As the interface behaviour between soft clay-geosynthetic and granular aggregate is difficult to estimate in laboratory and also in reality, R_{inter} value mentioned above has been adopted by many researchers Yoo and Kim (2009), Almeida et al. (2013) and Hosseinpour et al. (2018). A fine type of mesh was adopted in the present numerical study. In this study, the spacing between the individual disc type reinforcements was investigated for three cases namely 0.25D, 0.5D and 1D, where "D" is the diameter of the granular column. The ordinary granular column was also simulated in the numerical analysis by switching off the geosynthetic reinforcements in order to compare the performance with EGC's. Fig.1 depicts the FE model showing the OGC and the two types of geosynthetic reinforced stone columns. The material properties are listed in Table 1.

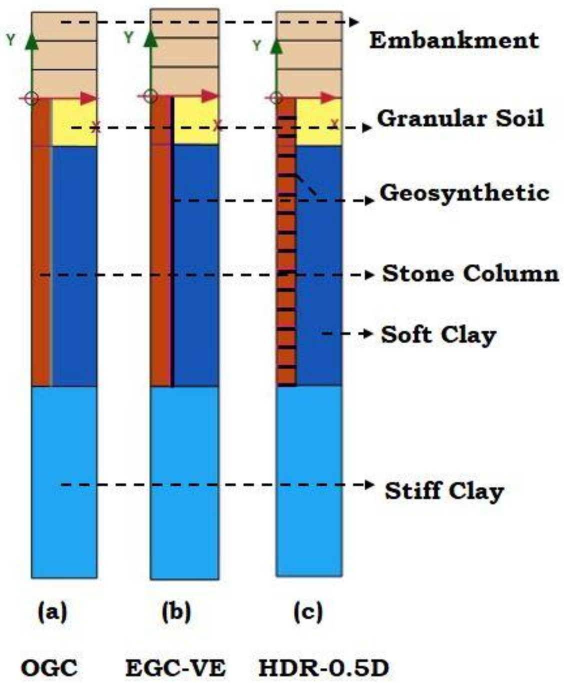

Fig. 1 Unit cell FE models of embankments supported by ordinary and encased stone columns; VE – *Vertical Encasement* and HDR –*Horizontal Disc Type Reinforcement*.

Table -1: Material Properties of the Foundation Soil and Embankment

S.No	**Properties**	**Embankment material**	**Granular layer**	**Soft Clay**	**Stone Column material**
1	Constitutive model	Mohr-Coulomb			
2	Unit Weight γ (kN/m^3)	18	17	15	19
3	Elastic Modulus E (kPa)	15000	15000	1100	30000
4	Effective cohesion c′ (kPa)	3	3	3	1
5	Effective friction angle ϕ′ (degrees)	33	28	22	40
6	Dilation angle ψ (degrees)	0	0	0	0
7	Horizontal permeability k_h (m/day)	1	0.029	3 x 10^{-5}	10
8	Vertical permeability k_v (m/day)	1	0.010	1 x 10^{-4}	10

3 Validation of the FE model

The present study is validated from the field test results of Almeida et al. (2015) for a trial embankment supported by geosynthetic encased granular columns located in Rio de Janiero, Brazil. The material properties and the method of construction of the embankment are not explained herein due to the lack of space. The time-settlement plot is shown in Fig. 2, which indicates a good agreement between the results obtained from the present analysis and that of the measured values from the field by Almeida et al. (2015).

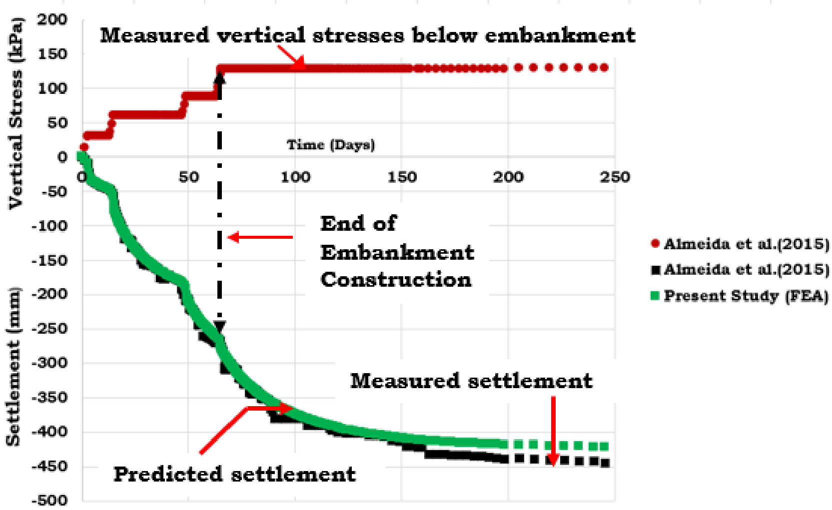

Fig. 2 Validation of the present study with Almeida et al. (2015)

4 Results and Discussion

The numerical analyses were performed using coupled analysis and hence the variation of consolidation settlement, excess water pore pressure and vertical stresses against time are discussed in this paper. Additionally a discussion on the bulging of the granular columns with and without reinforcement is also included followed by the parametric analysis. The diameter and c/c spacing between the granular columns was kept constant in the entire study.

4.1 Consolidation Settlements

The variation of consolidation settlement (in mm) with time is displayed in Fig. 3. The values are 87.1, 82, 76.7, 68.7, and 64.1 respectively for soft clay reinforced ordinary granular columns (OGC), vertically encased granular column and the granular columns reinforced with horizontal discs at different vertical spacings. It can be clearly seen that the magnitude of settlement decreases gradually when reinforcing the granular columns either by vertical encasement or through horizontal reinforcements. In the vertical encasement type the column is laterally confined as a whole thereby increasing the strength and stiffness of the granular column, on the other hand with horizontal reinforcements, the frictional interaction increases between the reinforcement and the granular aggregates through sliding and interlocking resulting in lesser and least settlements especially with closer reinforcement spacings HDR-0.25D. The percent reduction in settlement when compared to OGC are 5.82, 11.93, 21.04 and 26.43 respectively for the EGC-VE, HDR-1D,0.5D and 0.25D cases as listed in the legend in Fig.3. It is also interesting to observe that the settlements are almost same for all the cases until the construction of embankment (9 days) and start increasing with the increase in time of consolidation.

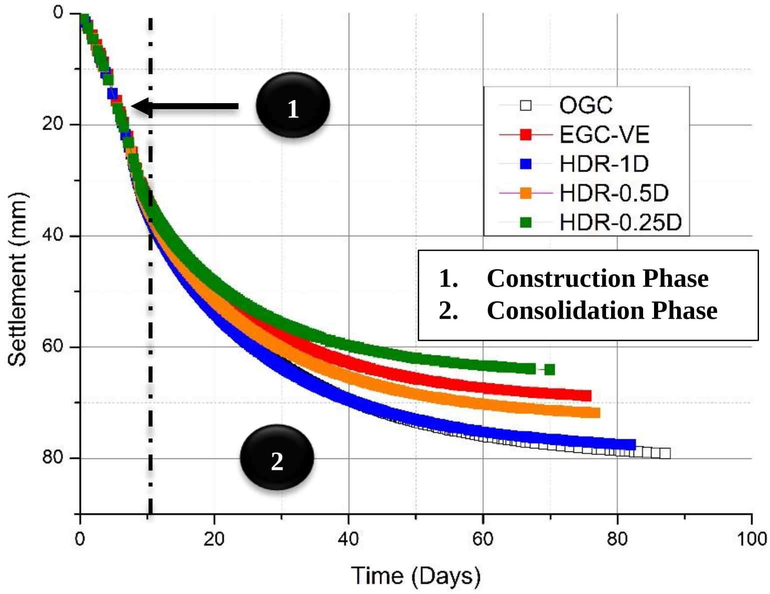

Fig. 3 Variation of settlement with time for granular columns

4.2 Excess pore pressure

During the construction of the embankment, the excess pore pressures are generated in the soft clay soil and are dissipated by the granular columns with time. The pore pressures were monitored at a depth of 3.5 m below the embankment layer for all the cases. The variation of excess pore pressure with time is shown in Fig. 4 below. The maximum excess pore pressures are 20.58 kPa, 19.93 kPa, 21.45 kPa, 20.24 kPa and 18.92 kPa for OGC, EGC-VE, HDR-1D, 0.5D and 0.25D respectively. With an effective all around confinement provided to the granular column, the vertical encasement type has displayed marginally lesser values when compared to ordinary granular columns. The least excess pore pressure value namely 18.92 kPa recorded for HDR-0.25D could be due to higher stiffness of the granular column, as only lesser load is transferred to the soft clay Rajesh (2017). Additionally, the time required to dissipate the excess pore pressure are 87 days, 75 days, 82 days, 77 days and 70 days respectively for the cases listed in Fig. 4.Though, the relative difference between all the maximum excess pore pressure values are observed to be less in particular to this case, the time taken to dissipate indicates the difference between the vertical and horizontal reinforcement types. The consolidation time is observed to decrease with decrease in vertical spacing between the individual horizontal reinforcements. However, it is felt that the vertical encasement type is likely to be beneficial when compared to horizontal reinforcements as the granular aggregates are protected from intermixing of the surrounding soft clay leading to reduced drainage capabilities. This aspect needs further investigation.

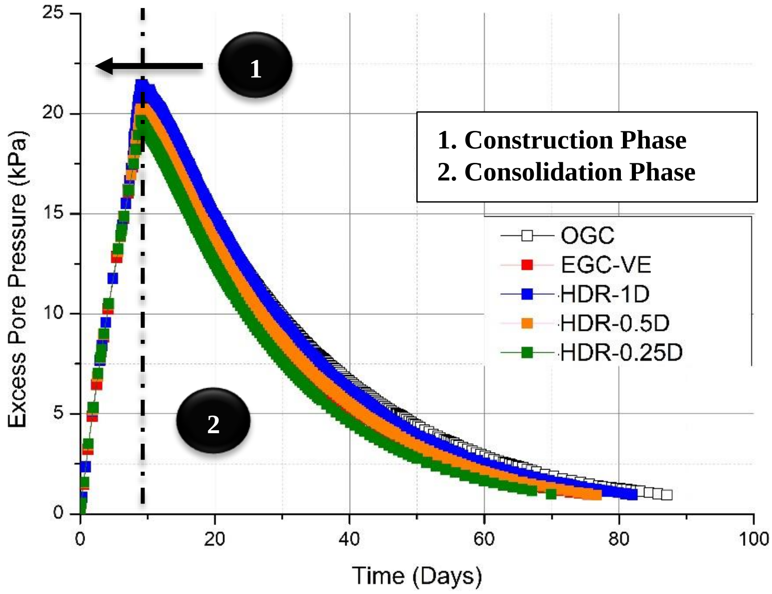

Fig. 4 Variation of excess pore pressure with time

4.3 Vertical stresses on the granular column and soft clay

The vertical stresses shared by the granular columns and the soft clay are shown in Fig. 5. The vertical stresses were obtained by choosing a point just below the granular layer for the soft clay soil and granular columns. The vertical stress values are 129.66, 157.3, 150.5, 158.1 and 173.2 kPa for OGC, EGC-VE, HDR-1D, 0.5D and 0.25D and 42.1, 39.2, 40.4, 39.4 and 37.4 kPa respectively for the corresponding soft clays. It can be seen that the load carrying capacity of the granular column increases irrespective of the type of reinforcements. And correspondingly, a reduction in stresses transferred to the soft clays can be observed which indicates the arching phenomenon that occurs with increase in the stiffness of the granular column. This can be quantified by a term called as the stress concentration factor (n) which is defined as the ratio of stresses shared by the granular column to that of the soft clay. The n values obtained from the present analysis are 3.1, 4, 3.7, 4. and 4.6. These "n" values obtained are in good agreement with the range of values specified by IS 15284 part 1 (2003) for the OGC's and Hosseinpour et al. (2018) for EGC's.

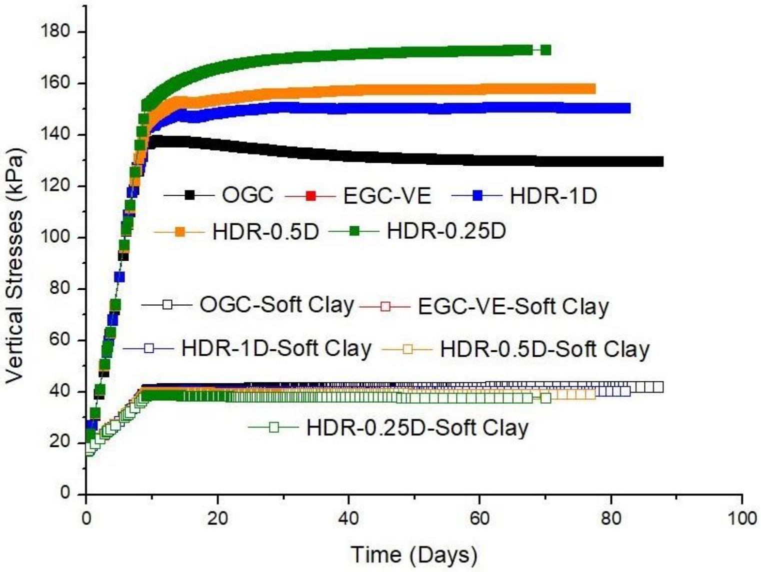

Fig. 5 Variation of vertical stresses on the granular columns and soft clay with time

4.4 Bulging of the granular columns

A larger part of load transfer from the embankment occurs through the resistance to bulging of the granular columns. Fig. 6 shows the bulging profile of the ordinary and reinforced granular columns. Due to lack of lateral support, the granular column without reinforcement (OGC) has suffered the largest bulging ≈ 4 mm. Further, for the case of EGC-HDR-1D the width of bulging is 3.8 mm which is very close to OGC. Hence it can be concluded that the horizontal disc type geosynthetic reinforcement is ineffective, when vertical spacing between the individual reinforcements is ≥ 1D. This fact is in line with the results reported by Hosseinpour et al. (2013) and Ali et al. (2014).

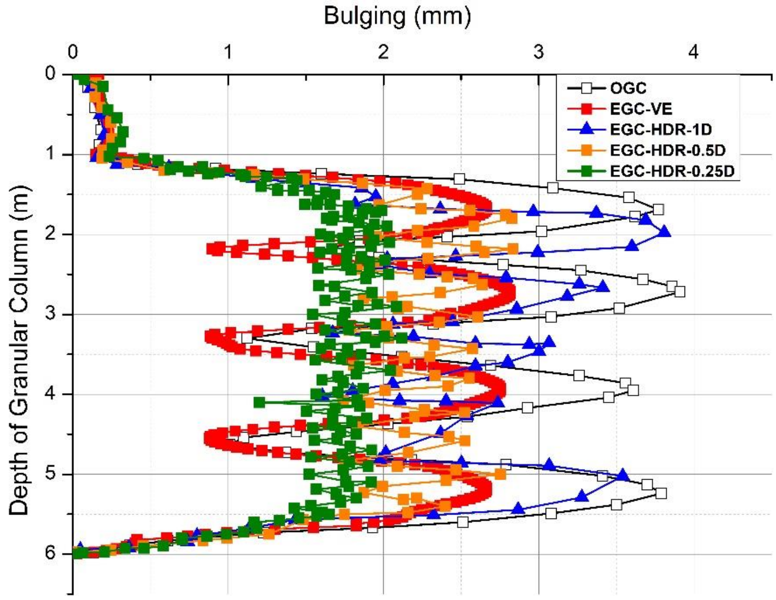

Fig. 6 Variation of bulging of the granular columns with depth

5 Parametric analysis

In order to further investigate the behavior of the vertically encased and horizontally reinforced stone columns, parametric analysis was conducted in brief by varying the friction angle of the infill material and the secant modulus (J). The analyses were performed for the case of consolidation settlements and bulging of the granular columns.

The bar charts illustrated in Figs. 7- 8 indicate the effect of friction angle of the granular column material on the consolidation settlements of the composite ground and the bulging behavior of the granular columns. With better quality stone charge in a granular column a prominent reduction in settlement and bulging is observed for both OGC and EGC invariably. However, the maximum reduction in consolidation settlements and bulging is observed for EGC-HDR-0.25D ≈ 28% and 39% due to higher frictional mobilization with the disc type reinforcement when compared to other cases. It is also, interesting to note that the percentage reduction in settlements for EGC-VE & HDR-0.25D are equal for the range of lower and upper bound "ϕ" values 30° and 45°.
Similarly, with increase in secant modulus (J) i.e. with better confinement, a prominent reduction in consolidation settlements and bulging is noticed from Tables 2 and 3. At (J = 5000 kN/m) the settlement and bulging values were almost the same for VE type and HDR-0.25D. Further investigations are required in these lines as a future scope.

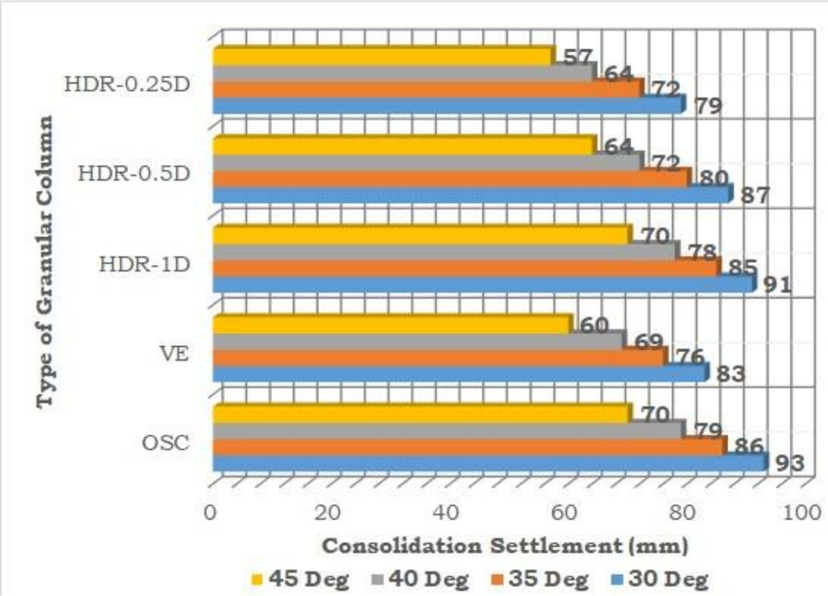

Fig.7 Effect of the friction angle of the infill soil on consolidation settlements.

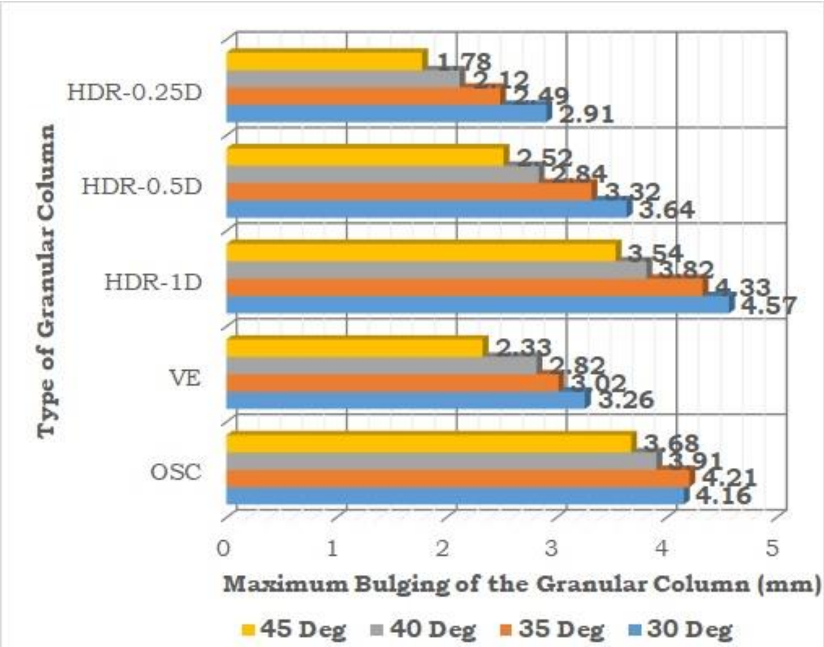

Fig. 8 Effect of the friction angle of the infill soil on bulging of granular columns.

Table 2: Effect of Secant Modulus of the geosynthetic on consolidation settlements in (mm).

S.No	Secant Modulus (J) kN/m	EGC-VE	HDR-1D	HDR-0.5D	HDR-0.25D
1	800	69	78	72	64
2	1500	63	76	68	58
3	3000	55	74	63	52
4	5000	49	73	59	48

Table 3: Effect of Secant Modulus of the geosynthetic on maximum bulging of EGC in (mm)

S.No	Secant Modulus (J) kN/m	EGC-VE	HDR-1D	HDR-0.5D	HDR-0.25D
1	800	2.82	3.82	2.84	2.12
2	1500	2.27	3.76	2.54	1.72
3	3000	1.55	3.66	2.28	1.27
4	5000	1.04	3.53	2.09	1.02

6 Limitations of the present study

In the field, the installation of horizontal disc type reinforcements for granular columns, may cause construction difficulties and delay. There are no instrumented field projects reported till date in the literature on disc type reinforcements to stone columns which requires further research.

7 Summary and Conclusions

In the present numerical analysis, granular columns without and with two different types of reinforcement supporting the embankments on soft clays was investigated. Parametric studies was also conducted to understand the effect of column material and the geosynthetic reinforcement on the settlements and bulging of the granular columns. The following conclusions are drawn based on this study.

- Geosynthetic encased and horizontally reinforced granular columns are better alternatives when compared to OGC′s especially for treating very soft clays.
- With higher secant modulus (J) values and friction angles of the infill material lesser settlements and column bulging is observed.
- The vertical spacing of the horizontal disc type reinforcements should be less than the diameter of the granular column to harness the benefits of reinforcement.
- The VE type and HDR-0.25D yield almost the same values of settlements and column bulging at higher (J) values.
- Further studies are required in optimizing the length of reinforcements in both the type of reinforcement attempted in this study.

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