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Geosynthetic Encased Granular Columns: Design and Analysis under Vertical and Lateral Loads

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Abstract. Granular columns are commonly used to support flexible structures over soft clay soils. The installation of such columns increases both the strength and stiffness of the ground. However, constructing these columns in clay soils having low cohesive strength of about 15 kPa is a challenge due to inadequate confinement. The columns may be encapsulated in geosynthetic tubes to enhance their constructability and strength. The geosynthetic encasement is also known to improve their performance under shear loading. This paper reviews the application of geosynthetic encased granular columns for treatment of soft grounds. The design of these systems under vertical loads is described in this paper. The performance of geosynthetic encased granular columns under lateral loads and the influence of geosynthetic encasement on the factor of safety of embankments supported on soft clay soils is discussed. The use of geosynthetic encasement of granular columns is seen to change the deep-seated foundation failure mechanism to toe failure mechanism.

Keywords: geosynthetic, granular columns, encased granular columns, soft clays

1 Introduction

India has a long coast line of almost 6000 km. Most of the coastal regions are covered with soft and weak clay deposits. The depth of these deposits varies between 10 to 30m IRC 113 [1]. The need for utilization of these weak soil deposits along the coastal regions for construction activities poses various geotechnical challenges due to their low bearing strength coupled with high compressibility. Various ground improvement techniques such as preloading, PVD's, granular columns, Lime and Cement columns, grouting, vacuum preloading, etc. can be used to improve the engineering behaviour of these soft deposits. Among all these ground improvement techniques, granular column technique is a simple and economical method that has been adopted for several decades along the coastal regions of India and other countries. The granular column technique in infrastructure projects has become popular as majority of these are time sensitive. Hence, a technique which accounts for considerable savings in the cost and the time required for installation over other ground improvement solutions is a target for design engineers. Apart from all the other techniques mentioned above, granular columns are chosen as they offer two important functions unlike other methods. They act as strong and stiff load bearing members and also help in dissipating the excess pore pressures generated.

1.1 Need for geosynthetic encased granular columns

Ordinary Granular columns (OGC) have been used in weak deposits mainly to improve the bearing capacity, to reduce the total and differential settlements, to increase the stability of embankments and to improve the resistance to liquefaction in loose sands. Nevertheless, the granular columns do have some limitations. The formation of granular columns is a difficult task due to inadequate confinement when these are installed in clay soils having undrained cohesive strength less than about 15 kPa. Besides this, the granular aggregates may get contaminated as the soft clay can squeeze into the aggregates hindering the drainage function of granular columns. The frictional strength of the aggregates may also reduce leading to the poor performance of the granular columns in soft clays. The limitations listed above were reported from the field studies conducted by McKenna et al. [2], Chummar [3] and can be generally avoided by encapsulating the granular column with appropriate geosynthetics. A typical geosynthetic encased granular column (EGC) is shown below in Fig.1.

The surface load on the ground generates bulging in the granular column. This bulging provokes a counter pressure from the surrounding soft clay. The soft clay passively resists the bulging of granular column if it has sufficient shear strength. If the soil does not have adequate strength, the support can be offered by encapsulating the granular column with a geosynthetic tube. This is the key difference between ordinary and geosynthetic encased granular columns.

Studies on EGC’s were initiated by Van Impe and Silence [4]. Subsequently, other researchers Raithel and Kempfert [5], Malarvizhi and Ilamparuthi [6], Murugesan and Rajagopal [7] and several other researchers [8-16] have worked on the analytical, numerical, experimental and field studies on encased granular columns. A detailed literature review on the mechanism and the factors influencing the behaviour of encased granular columns in soft clays is reported in the author’s previous work Jayapal and Rajagopal [17]. Nevertheless, research work on the practical design methodologies for geosynthetic encased granular columns in soft clays are limited. This manuscript discusses the design of encased granular columns in two parts, by Raithel and Kempfert [5] method which is popular and accepted by the German design guidelines EBGEO [18] for earth structures using geosynthetic reinforcement and Modified IS code method based on finds from Murugesan and Rajagopal [7].

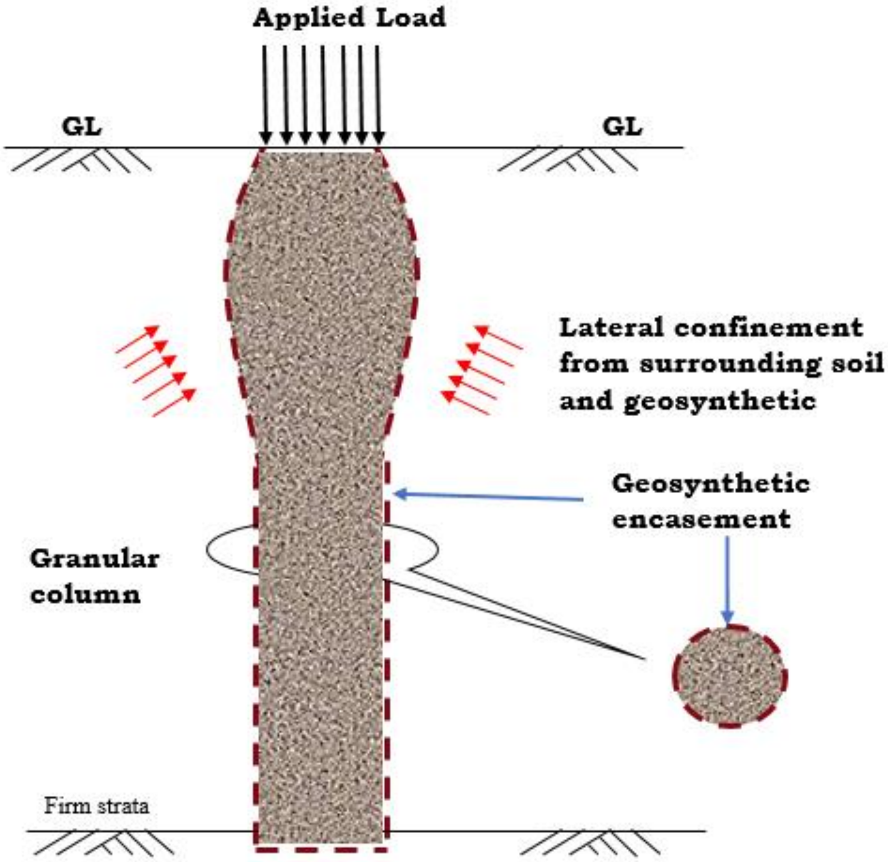


Fig.1. Geosynthetic encased granular column- Schematic (Murugesan and Rajagopal [7]).

2 Part A: Design Procedure By [5]

The recently published German design guidelines are based on the work of [5]. The design procedure is based on unit cell approach with the contribution of the geosynthetic encasement. The fundamental assumptions involved are listed below followed by a brief description of the method in simple steps. Detailed description of the procedure and the method of arriving at the settlement improvement factor can be found in Jayapal and Rajagopal [15, 18].

Assumptions in Raithel and Kempfert [5]

- The soft clay is at rest earth pressure condition before the application of loads.
- The granular column rests on a competent stratum.
- The settlements on the top of the granular column and the soft soil are same.
- The granular column is incompressible.

- The granular column is at an active earth pressure state.
- The applied additional stress does not decrease with depth as the plan of loading size is greater than the depth of soft deposit.
- The design procedure is based on drained condition (long term behaviour).

Unit cell representation of granular column encased with geosynthetic by [5] is shown in Fig.2.

Step 1: The radial stresses generated in the EGC and the soft soil are calculated as,

$$\sigma_{r,c} = \Delta\sigma_c K_{a,c} + \sigma_{z0,c} K_{a,c} = \left(\frac{1}{a_s}\Delta\sigma_z - \frac{1-a_s}{a_s}\Delta\sigma_s\right) K_{a,c} + \sigma_{z0,c} K_{a,c} \tag{1}$$

$$\sigma_{r,s} = \Delta\sigma_s K_{0,s} + \sigma_{z0,s} K_{0,s} \tag{2}$$

Step 2: Computation of the radial stress difference between the EGC and soft clay soil,

$$\Delta\sigma_r = \sigma_{r,c} - \sigma_{r,s} - \sigma_{r,g} \tag{3}$$

$$T_g = J \times \frac{\Delta r_g}{r_g} \tag{4}$$

$$\Delta r_c = \Delta r_g + \left(r_g - r_c\right) \tag{5}$$

$$\sigma r_g = \frac{T_g}{r_g} = J\frac{\Delta r_g}{r_g^2} = J\frac{\Delta r_c - (r_g - r_c)}{r_g^2} \tag{6}$$

Step 3: Calculation of the radial displacement of the EGC and settlement of the soft soil,

$$\Delta r_c = \frac{\sigma_{r,c} - \sigma_{r,s} + \frac{(r_g - r_c)J}{r_g^2}}{\frac{a_s E^*}{(1-a_s) r_c} + \frac{J}{r_g^2}} \tag{7}$$

$$E^* = \left(\frac{1}{1-\vartheta_s} + \frac{1}{1+\vartheta_s}\frac{1}{a_s}\right) E_S \tag{8}$$

$$E_s = \frac{(1+\vartheta_s)(1-2\vartheta_s)}{1-\vartheta_s} D_s \tag{9}$$

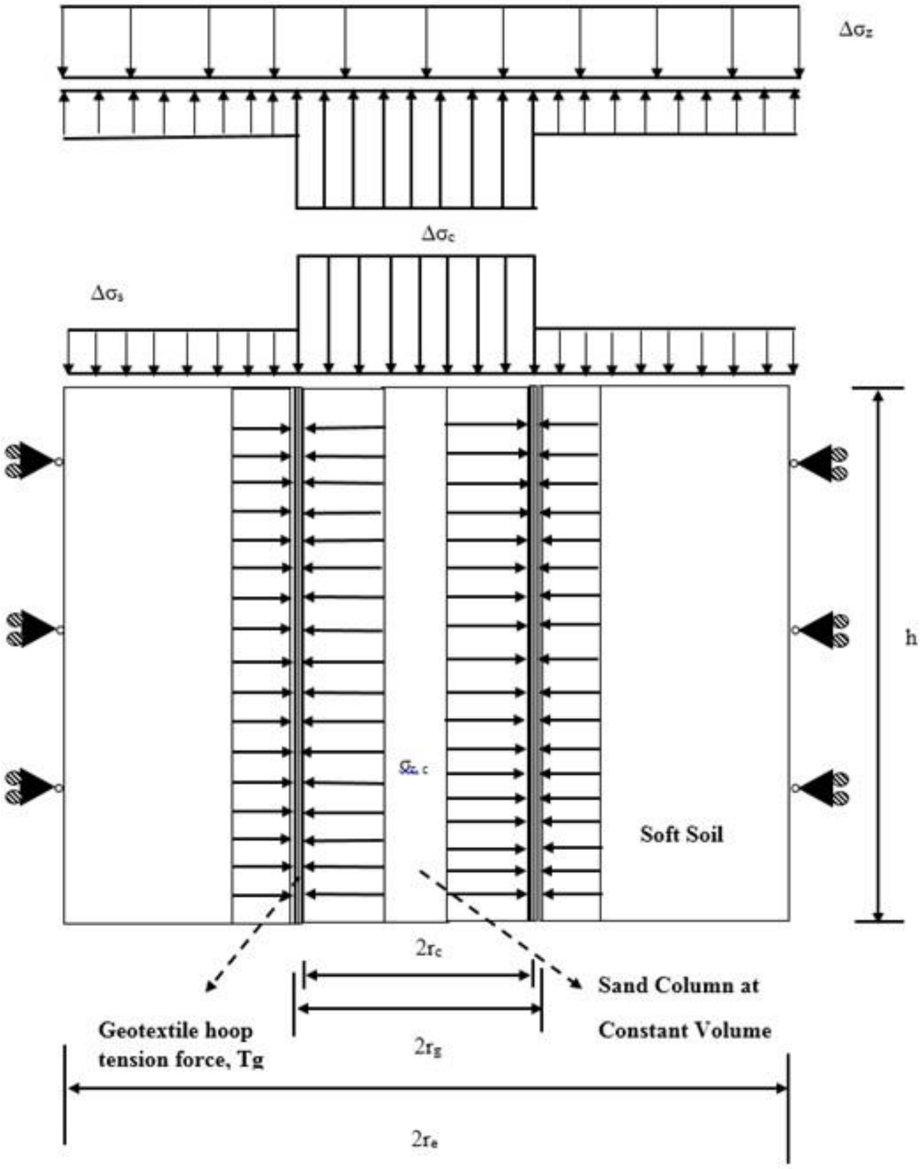


Fig.2. Unit cell model of granular column encased with geosynthetics [5]

Step 4: Calculation of the settlement of the EGC and the soft soil.

$$S_{cl} = \left[1 - \frac{r_c^2}{(r_c + \Delta r_c)^2}\right] h \tag{10}$$

$$S_{sl} = \left[\frac{\Delta\sigma_s}{D_s} - \frac{2}{E^*}\left(\frac{\vartheta_s}{1-\vartheta_s}\right)\Delta\sigma_r\right] h \tag{11}$$

Step 5: Equate the settlement of the EGC and the soft clay soil to obtain the additional vertical stress on the soil.

$$\frac{\Delta\sigma_s}{D_s} - \frac{2}{E^*}\left(\frac{\vartheta_s}{1-\vartheta_s}\right)\Delta\sigma_r = 1 - \frac{r_c^2}{(r_c + \Delta r_c)^2} \tag{12}$$

Step 6: Evaluate the Settlement Improvement Factor (SIF)

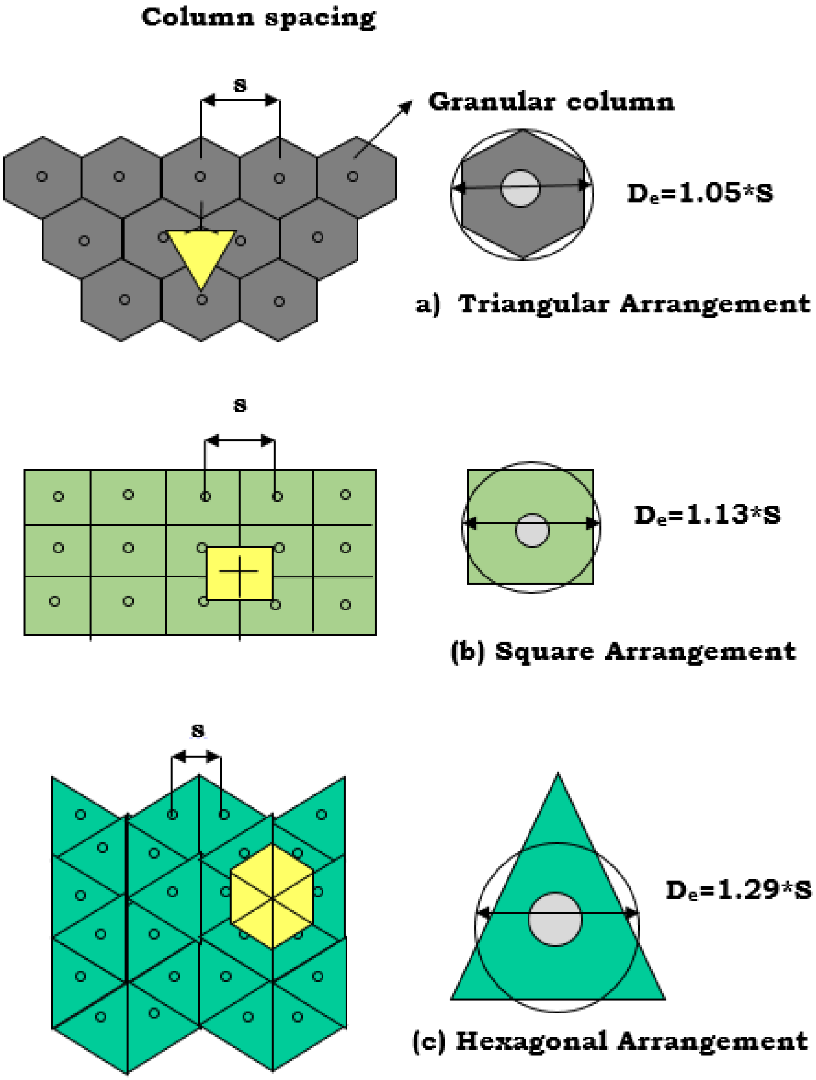
$$\text{SIF} = \frac{\Delta\sigma_z\, h}{D_s\, S_r} \tag{13}$$

The design of EGC by [5] described in the above steps are used to arrive at the settlement improvement factor (SIF). The symbols used in the above equations are described in the last part of the manuscript.

The area replacement ratio (a_s) indicates the amount of granular material used to replace the soft soil within a single unit cell. It can be computed using the equation suggested by Balaam and Booker [19] for different installation patterns namely Triangle, Square and Hexagon.

$$a_s = C\left(\frac{D}{S}\right)^2 \tag{14}$$

Where D and S are the diameter and c/c spacing of the granular columns. The Constant C can be computed as 0.907, 0.785 and 0.592 to account for the shape of the three-unit cell patterns. The three different plan arrangements are shown in Fig.3.



a) Triangular Arrangement

(b) Square Arrangement

(c) Hexagonal Arrangement

Fig.3.Different Plan arrangements of granular column – Balaam and Booker [19]

2.1 Methodology and evaluation of settlement improvement factor (SIF)

A real time field problem on soft clay improvement with ordinary and geosynthetic encased granular columns is worked out based on the input values suggested by [18]. The equations mentioned above (1-13) were coded in an EXCEL spread sheet program. The settlement Improvement Factor (SIF) which is defined as the ratio of the settlement of soft ground with and without granular columns was computed for various ranges of influencing parameters based on a trial and error procedure. The granular columns are generally formed in groups of large number for treatment of the site. The problems due to bearing failure granular columns is rarely accounted. Hence this procedure focuses on the settlement behaviour which is often encountered in field practice. The final aim of this study is to develop a comprehensive design chart for encased granular columns arranged in various patterns as indicated above in Fig.3. In order to achieve the aim, comprehensive parametric studies were conducted based on a real time problem described below to understand the influence of various parameters on SIF.

Problem statement and input data. A submerged normally consolidated soft clay deposit 10 m deep with ground water level close to the ground surface is proposed to be improved. The properties of the soil are assumed based on [18]. The hand calculations of the problem statement discussed above can be read from [15]. The data corresponding to the soft clay, granular column, embankment and geosynthetic encased is shown in the table below. The granular columns are proposed to be arranged in triangular pattern.

Table 1. Input data for the problem statement

S.No	Parameter	Soft Clay	Granular Column	Embankment	Geosynthetic Encasement
1	Unit weight (kN/m^3)	15	18	18	NA
2	Friction angle $(\phi)^o$	18	34	NA	
3	Constrained Modulus (kPa)	1300	NA		
4	Poisson's Ratio	0.47			
5	Diameter (m)	NA	0.6		
6	c/c spacing (m)		1.25		
7	Tensile Modulus (kN/m)	NA			2500 kN/m

2.2 Parametric evaluation

The parameters varied are, diameter, spacing and friction angle of the granular column followed by constrained modulus, at-rest earth pressure and thickness of the soft clay deposit. The height of embankment and the tensile modulus of the geosynthetic encasement are also varied in the present analysis. The input values listed in Table-1 correspond to the baseline case and the individual parameters are varied on one factor at a time basis. The performance of OGC in the soft clay deposit is also investigated by taking the tensile secant modulus of the geosynthetic (J) to be zero. The pattern of arrangement of granular columns are indicated by the markers in all the figures for granular columns with and without encasement. Dotted lines and continuous lines are used to indicate the response of OGC's and EGC's as indicated in the Legends.

Diameter of the granular column. The variation of SIF with 0.6m, 0.75m and 1m diameter granular columns is shown in Fig. 4. A decrease in SIF is observed with increase in the diameter of the granular columns irrespective of the plan arrangements. The plausible reason for the decrease in SIF is because of the lesser hoop tension forces in the geosynthetic encasement for larger diameter of granular columns at the same axial strains. Because of the increased area replacement ratio (a_s) along with higher degree of packing the triangular plan arrangement of EGC delivers higher SIF when compared to the rest of the arrangements namely square and hexagon. With constant spacing to diameter ratios (S/D), the SIF values obtained for ordinary granular columns are constant. This depicts the improved performance of granular columns with geosynthetic encasement when compared to OGC.

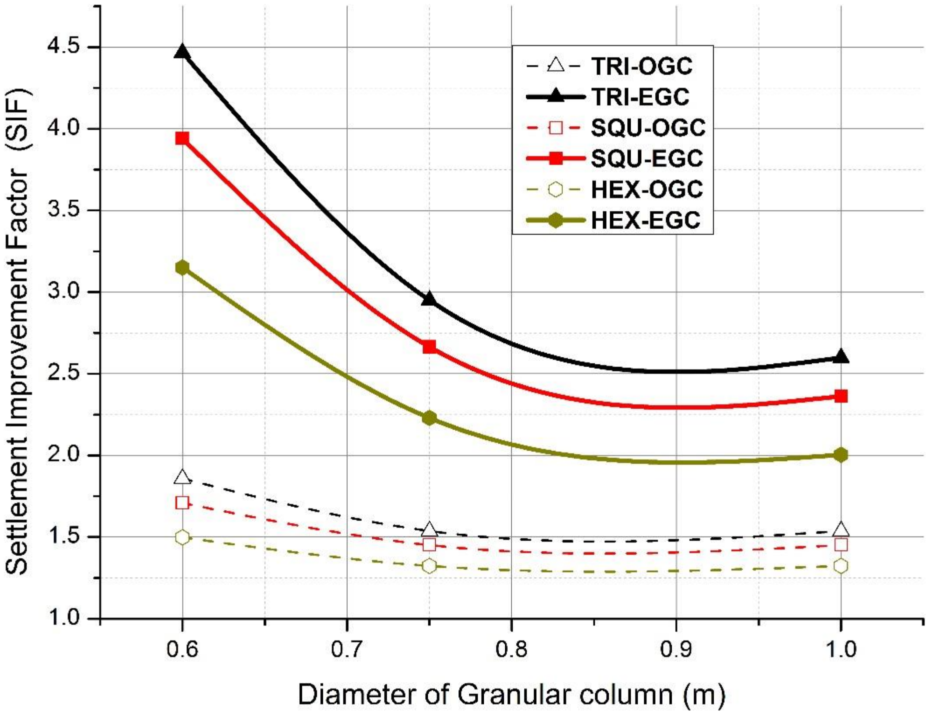


Fig.4. Effect of increasing the diameter of the granular columns

Friction angle of granular column (ϕ'_c). The settlement behaviour of granular columns is also influenced by the properties of the infill materials used to form the granular column. In the case of EGC's, friction angles greater than 30° are used based on guidelines [18] for the granular fill materials. As presented in Fig.5 the friction angle of the granular material was varied from 34° till 42° with an increment of 2˚ to investigate its influence on the SIF. With increase in friction angle of the granular column, larger settlement improvement factors are observed for granular columns with and without geosynthetic encasement. Further, the triangular pattern showed the highest performance with increasing SIF values when compared to other plan arrangements. The effect of the pattern of arrangements did not have a notable influence in the case of OGC's unlike EGC's. On an average, the improvement in SIF is 2.4 times higher for EGC's when compared to OGC's.

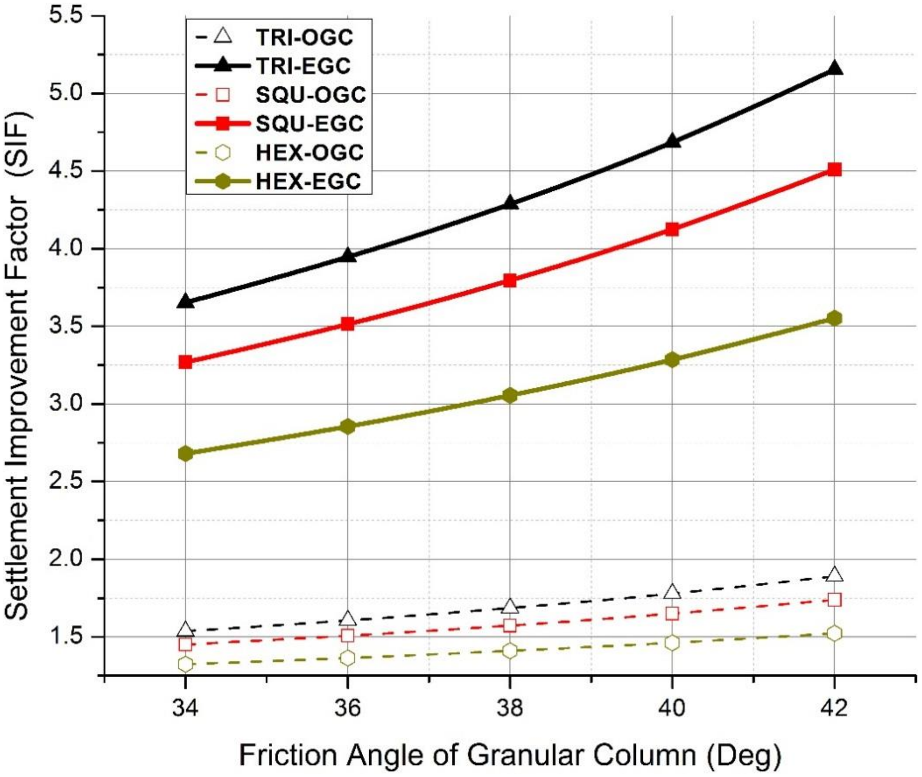


Fig.5. Effect of increasing the friction angle of the granular columns

Spacing to diameter ratio (S/D). The variation of SIF with S/D ratio is shown in Fig.6. Beyond 3D spacing the group effect of granular columns is found to be less and they tend to behave as single columns due to lack of additional confinement. The studies conducted by [20] revealed that the optimum spacing for OGC's ranges between 2 to 3 times the diameter. In the present analysis, the variation is extended up to (S/D = 4) to assess the performance of EGC's over OGC's. The study reveals that beyond S/D ratio of 2.5, the SIF for OGC's is nearly the same irrespective of the plan of arrangements. However, for EGC considerable variation in SIF is seen amongst the patterns until a spacing to diameter ratio of 3.5. This shows that the EGC's can function as better alternatives even at higher spacings which leads to a lesser (a_s). For a given diameter and installation patter, the (a_s) value reduces by 50% upon increasing the S/D ratio from 2.5 to 3.5. The results from Fig.6 also reveal that the influence of plan arrangement is significant only with closer spacings and sufficient lateral support from the soft clay soil. The geosynthetic encapsulation can be used for substantially improving the performance of the foundation system with limited use of aggregates.

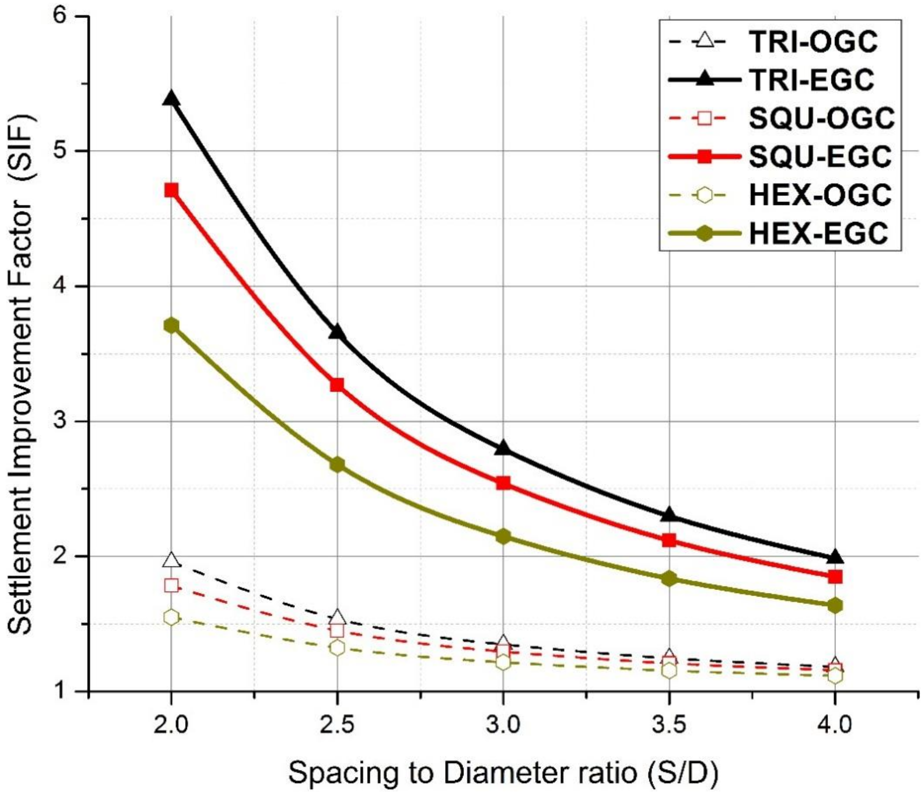


Fig.6. Effect of Spacing to Diameter ratio on the settlement improvement factor

Depth of soft deposit. Deep deposits of soft clays of about 30 m are observed in the coastal areas of Cochin [1]. Fig.7 presents the variation of SIF with depth of soft clays ranging between 10 to 30 m. Irrespective of the plan arrangement of the granular columns, a gradual increase in settlement improvement factor is observed for EGC and OGC. However, the level of increase in the case of OGC is found to be minimal. It should also be remembered that the design of EGC based on [5] is for end bearing conditions only and not applicable for floating type columns. The design considerations by [5] did not take into account the length to diameter (L/D) ratio which is one of the important factor which influences the behaviour of granular columns.

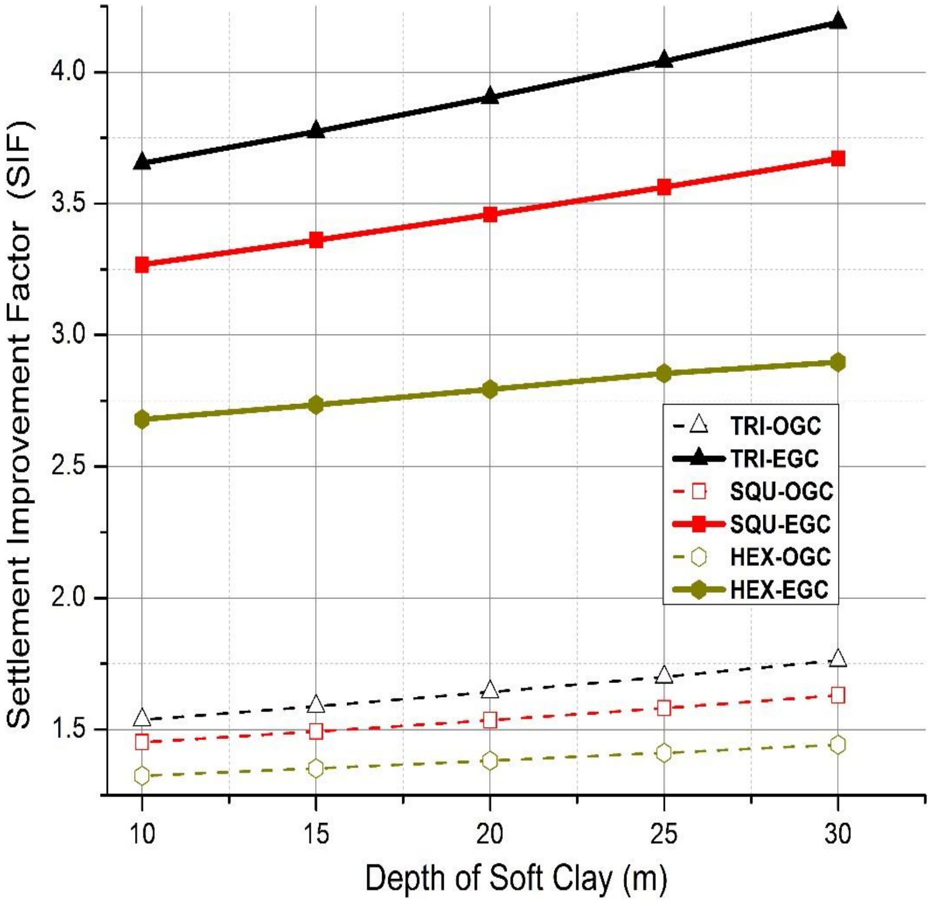


Fig.7. Effect of depth of soft deposit on the settlement of granular columns

Constrained modulus (D_s) of the soft clay. According to [18], for the soft clays which require treatment by EGC's the constrained modulus ranges between 500 to 3000 kPa. Fig.8 depicts the variation of SIF values with the constrained or (Oedometric) modulus. The constrained modulus is inverse of the coefficient of volume compressibility (m_v). As shown in Fig.8 irrespective of the plan arrangement of the granular column, the SIF decreases with increase in D_s values of the soft clay soil. In general, for stiff clays having constrained modulus values greater than 7500 kPa, the ground improvement by geosynthetic encased granular columns is not necessary.

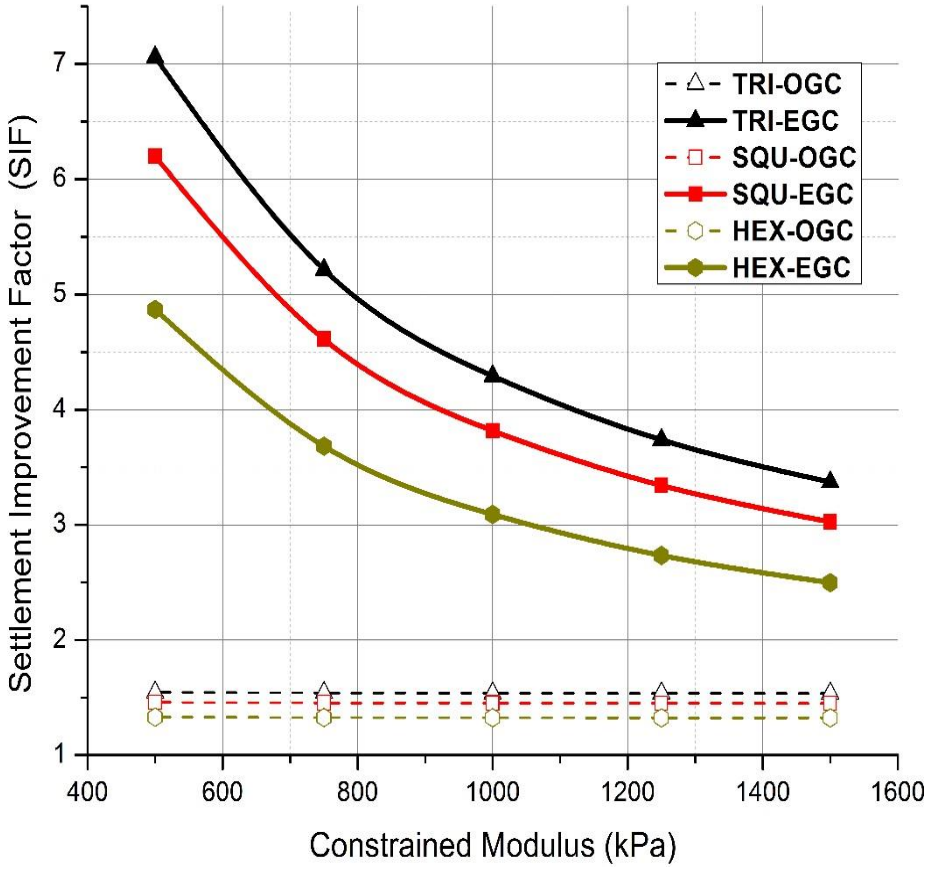


Fig.8. Effect of constrained modulus of the in-situ soft deposit.

At-rest earth pressure coefficient (K_o). The variation of SIF with at-rest earth pressure coefficient K_o of the foundation soil for granular columns with and without geosynthetic encasement for three different plan arrangements is shown in Fig. 9. These K_o values pertain to those of typical NC soft clays [21]. With increase in K_o, the SIF value increases for both OGC's and EGC's. The increase is more noticeable for EGC's compared to the OGC's. This could be due to two reasons, viz. higher confining pressures exerted on the granular columns with lower friction angle and poor load carrying capacity of the soft clay deposit. Due to these two reasons, the influence of the granular columns on the settlements increases with increase in K_o values.

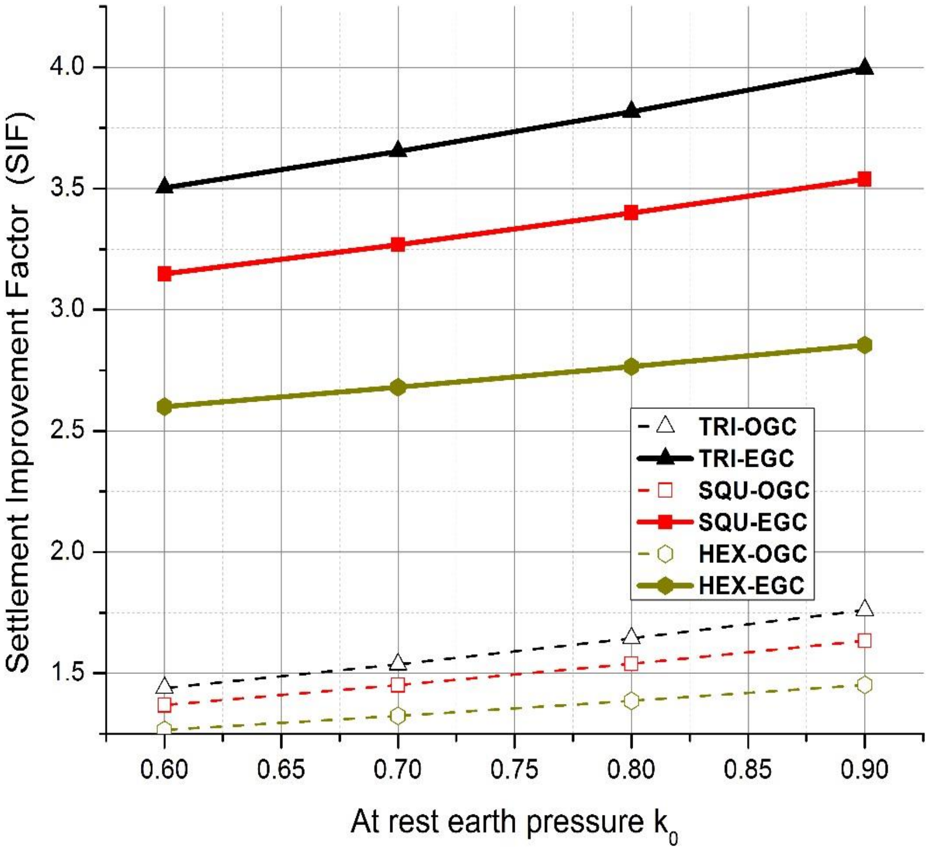


Fig.9. Effect of at rest earth pressure co-efficient on settlement of OGC& EGC

Height of embankment (H). The height of the embankment is varied between 2 and 6 m in the present parametric analyses. The variation of the SIF with the height of the embankment fill for different plan arrangements for both OGC’s and EGC’s is displayed in Fig.10. It can be seen that the SIF’s remain nearly the same for both the types of granular columns at all the heights. Further, the influence of plan arrangement is clearly seen only in the case of EGC unlike OGC where there is not much of influence. The high SIF values for EGC’s indicate the efficacy of improvement offered by them in soft deposits when compared to OGC’s.

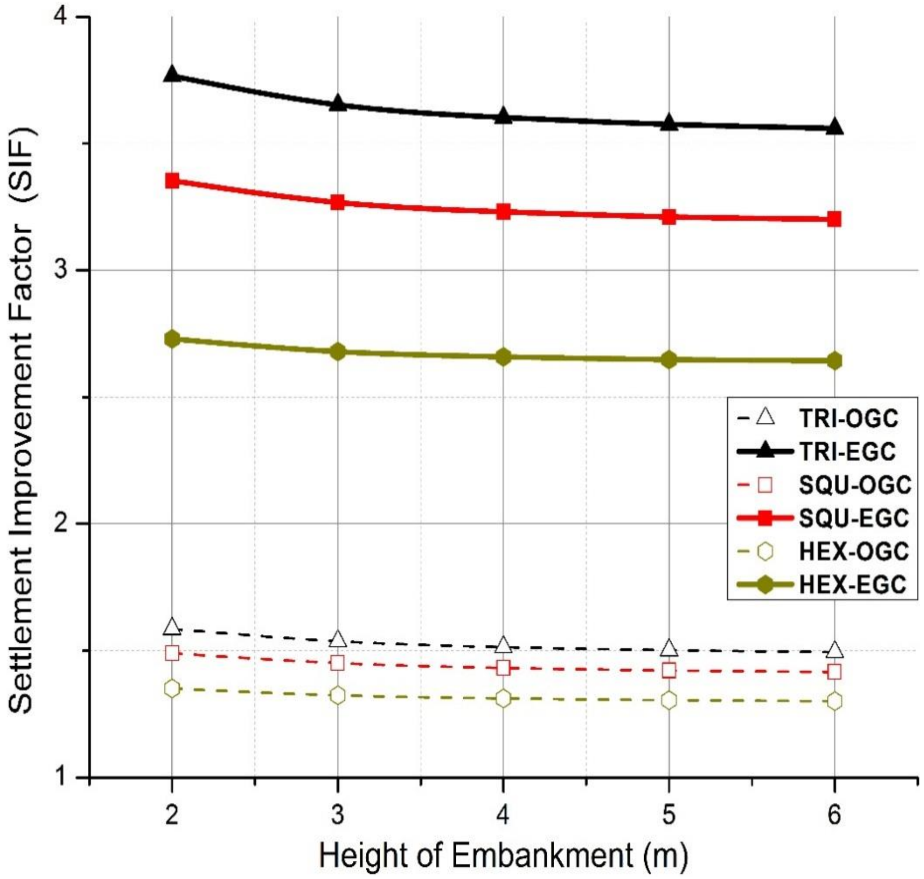


Fig.10. Effect of increase in Height of Embankment on the settlement behaviour of OGC& EGC

Modulus of the geosynthetic encasement (J). The variation of SIF with tensile modulus of the geosynthetic encasement for different column arrangements is shown in Fig. 11. A linear response is observed between SIF and the tensile modulus of the geosynthetic. This linear response clearly shows the control offered by geosynthetic modulus (J) on the performance of the EGC's. So, higher the (J) value, higher is the level of confinement offered in resisting the hoop stresses and consequently higher is the SIF. The secant modulus values usually adopted in the design calculations normally range between 1500 to 6500 kN/m at about 5 to 10% strains, [22]. Further, it can be seen from Fig.11 that the effect of plan arrangement with respect to SIF is noticeable only for (J) values greater than 3500 kN/m. When compared to other parameters discussed above, the secant modulus of the geosynthetic encasement is the key parameter which strongly influences the SIF.

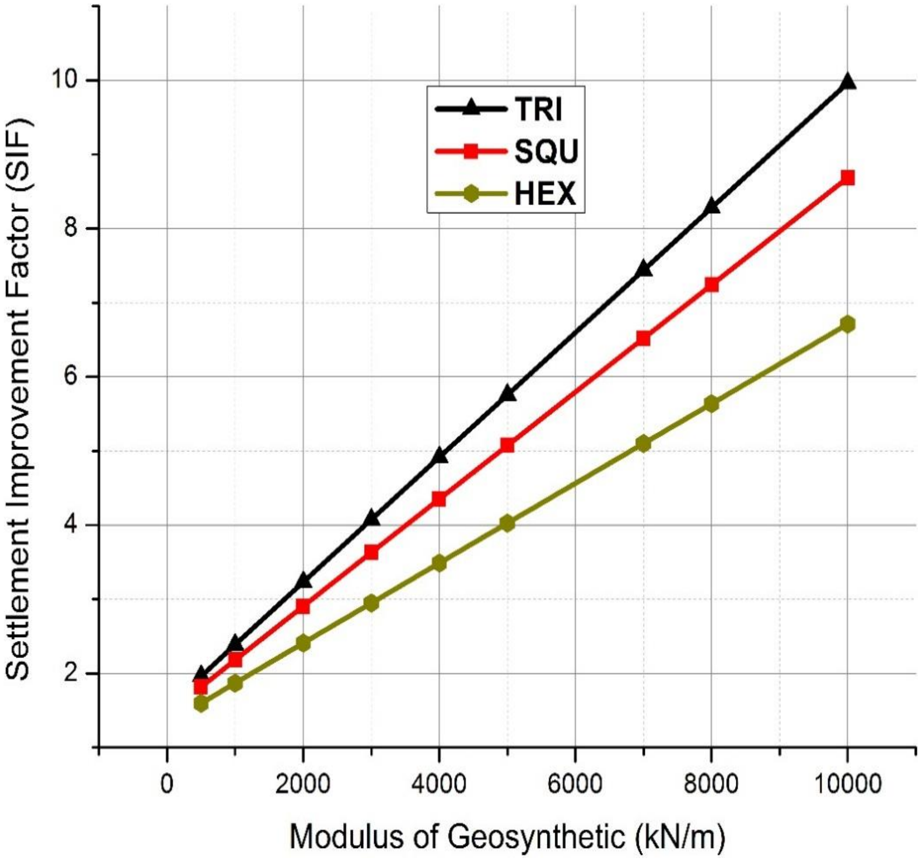


Fig.11. Effect of the increase in modulus of geosynthetic encasement

Design chart for geosynthetic encased granular column. The Design chart presented in Fig.12 shows the SIF with increase in area ratio for different plan arrangements pertaining to 0.75 m diameter granular columns. The markers are used appropriately for the three different plan arrangements. The ordinary and geosynthetic encased granular columns were analysed for (S/D) ratio ranging between 2 to 4. The friction angle of the granular aggregates was varied between 35° and 45°. The term "area ratio" is the inverse of area replacement ratio(a_s), [23]. This terminology was used to compare the present results with previously published design charts by [23]. It can be seen from Fig.12 that the present results are in good agreement with the studies reported by [23]. This design chart is quite comprehensive when compared to the one published by [24], as for a given diameter, c/c spacing, friction angle and the secant modulus of the geosynthetic encasement the design engineer can quickly anticipate the likely improvement expected out of ordinary and encased granular columns.

Limitations and Insights. Though, the triangular arrangement is generally preferable for both ordinary and encased granular columns due to higher area replacement and better degree of packing, other patterns namely the square and hexagon can also be chosen based upon the project requirements. By doing so, the area replacement ratio gets reduced and considerable savings can be expected out of lesser quantity of aggregates. Further, the design procedure by [5] is limited to soft clay treatment with end bearing type EGC's. When flexible structures like embankments, oil storage tanks are to be constructed near coastal areas (e.g. Ports) where there is a possibility of occurrence of deep deposits of soft marine clays the current design procedure [5] cannot be applied. The maximum length of EGC accomplished till date in field projects is around 28 m [22].

3 Part B: Design of EGC's Using Modified IS 15284 part I [25]

3.1 Estimation of the Load carrying capacity of granular columns

For wide spread loads from flexible loaded structures like oil storage tanks and embankments, the load carrying capacity of the ordinary granular column treated ground may be obtained by summing up the contribution of the following:

- Capacity of the granular column resulting from the passive resistance offered by the surrounding soft clay against its bulging under axial load.
- Capacity of the granular column resulting from increase in resistance offered by the surcharge acting on the surrounding soil.
- Bearing support provided by the intervening soil between the columns.

Suggested modification. Murugesan and Rajagopal [8] have used the following equation proposed by Henkel and Gilbert [26] to calculate the increase in the additional confining pressure ($\Delta\sigma_3$) in the granular columns in terms of the geosynthetic modulus (M or J), diameter of the column (D) and the allowable axial strain (ε_a),

$$\Delta\sigma_3 = \frac{2M}{D}\left(\frac{1-\sqrt{1-\varepsilon_a}}{1-\varepsilon_a}\right) \tag{15}$$

This additional confining pressure offered by the geosynthetic encasement was added to the confining pressure offered by the surrounding soil as discussed in [25] to extend the design procedure of OGC to EGC.

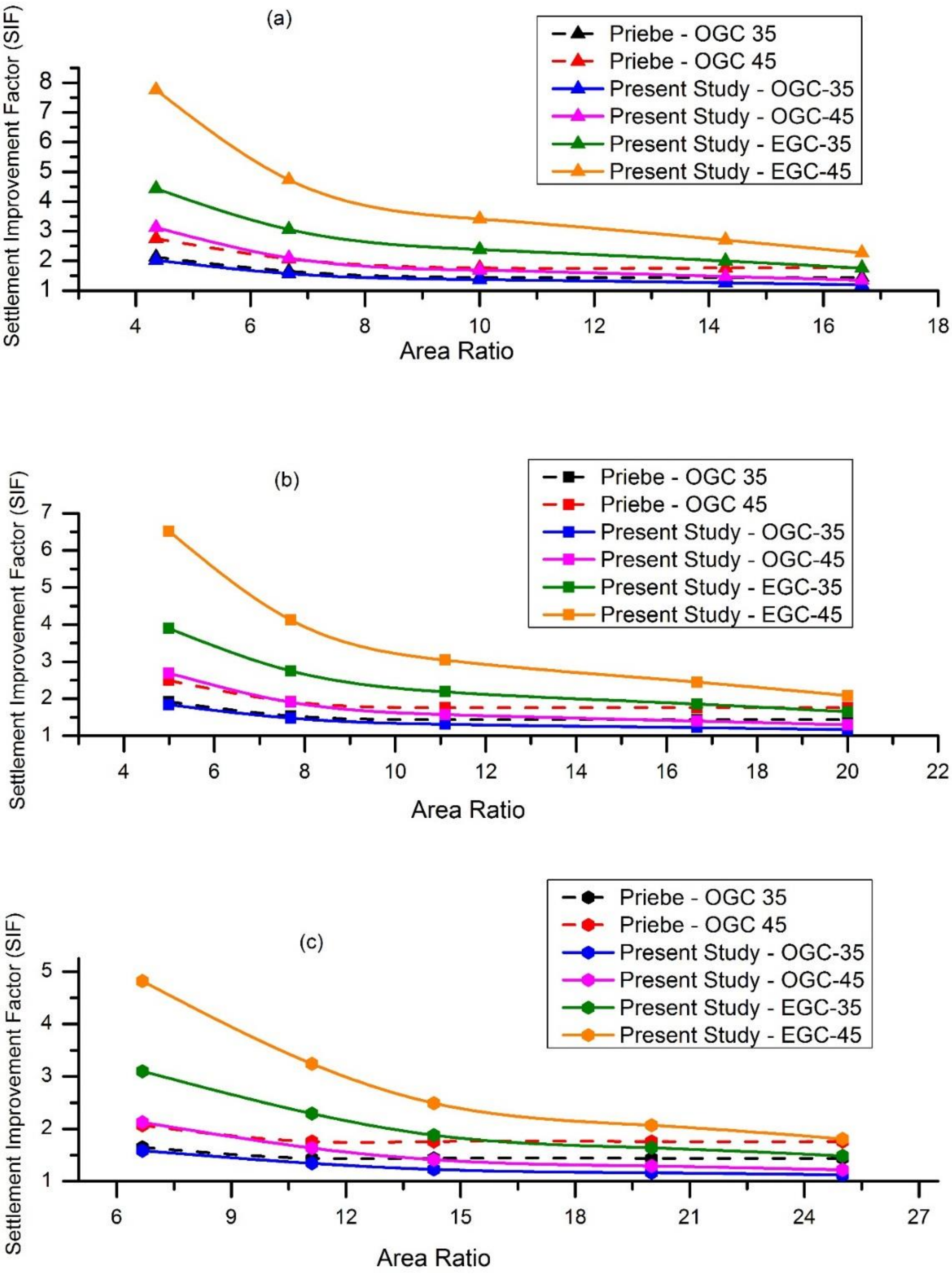


Fig.12. Design chart for 750 mm diameter EGC's based on different plan arrangements (a) Triangular (b) Square (c) Hexagonal

3.2 Parametric evaluation

Similar to the method discussed previously, a wide variety of parameters influencing the behaviour of granular columns were varied to understand the response of OGC and EGC in soft clays. The parameters are diameter of granular column, friction angle of the aggregates, plan arrangement, c/c spacing, undrained shear strength of soft clay, tensile modulus of the geosynthetic encasement. The equations provided in [25] along with the suggested modification was coded in an EXCEL spread sheet program to evaluate the settlement response of granular columns with and without ground improvement. The aim of this parametric evaluation was to develop a design chart for the use of EGC in soft clays. The settlement improvement factor and Improvement factor are one and the same which is defined as the inverse of settlement reduction ratio (β). The results obtained from these parametric studies are summarized in Figures 12 and 13.

4 Granular Columns Subjected to Vertical And Lateral Loads

The granular columns installed below embankments may be subjected to both vertical and lateral loads. The columns near the centre line are subjected to predominantly vertical compression type loading while the columns near the toe of the embankments are subjected to both vertical and lateral loads as illustrated in Figure 14. The strength of granular columns subjected to shear loading was studied by Mohapatra et al. [27] through large-scale direct shear tests. They have reported that the geosynthetic encasement increases the shear strength of the columns and the integrity of the encased columns was found to be preserved even at large lateral deformations.

The behaviour of granular columns subjected to combined vertical and lateral loading under an embankment was investigated through 3-dimensional numerical analyses. The influence of geosynthetic encasement on the response of encased granular columns was studied through the factor of safety analysis of the embankments supported on granular columns. All the analyses were performed using FLAC^{3D} program which is based on finite difference method. This program has capability to capture the nonlinear and inelastic behaviour of soils, incremental geotechnical constructions and the interaction between different materials like geosynthetic and granular material.

An embankment of height 5 m with side slope of 26.6° (2H:1V) resting on 10 m thick soft clay layer was considered for all the analyses. The side slope of the embankment was kept low to promote deep seated failure to bring out the contribution of the granular columns. The base and crest width of the embankment are 40 m and 20 m, respectively (Fig. 15). Only half the section of the embankment with single row of granular columns was considered for numerical analyses in the present study. The single row of granular column represents the square arrangement of granular column in the field. The centre to centre spacing of the granular columns varies between 2 to

3 times the diameter of the column. For the present analyses, granular columns of 1 m diameter (*d*), spaced at 2.5m centre to centre (2.5*d*) are considered. These geometric properties of the granular columns correspond to an area replacement ratio (a_s) of 12.6%. The influence of area replacement ratio was studied by varying its value from about 8% to 24%.

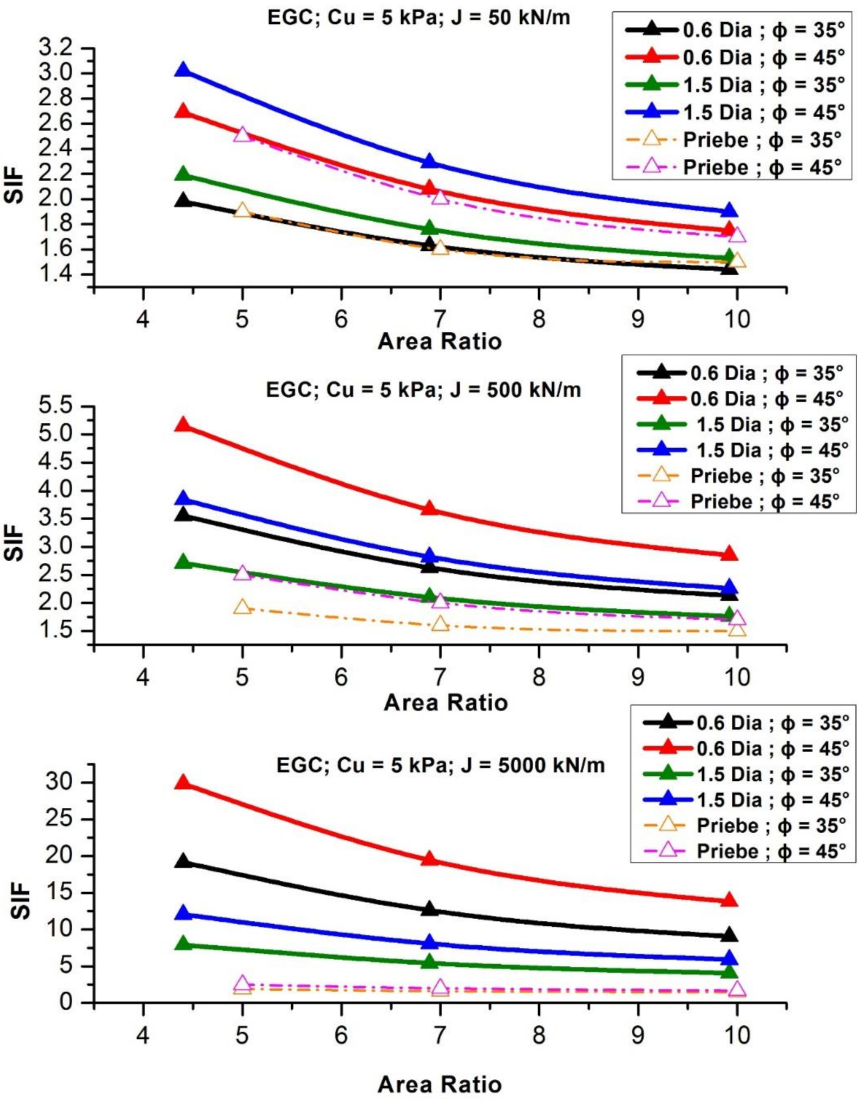


Fig.13. Variation of Settlement Improvement factor (SIF) with Area Ratio for EGC – Triangular Arrangement

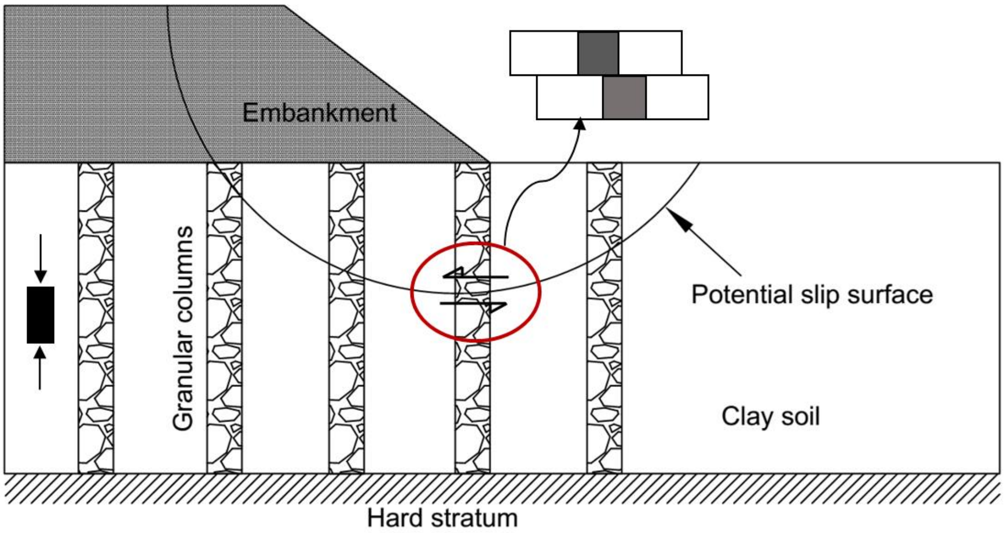


Fig 14. Loading on granular columns below embankments

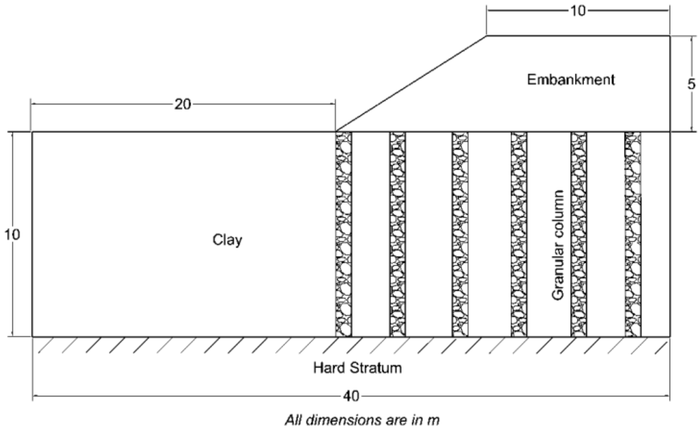


Fig.15. Schematic of the embankment supported on granular columns

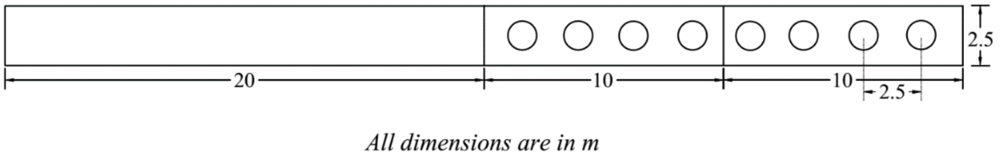
The vertical boundary was fixed at twice the depth of soft clay layer such that the most critical slip surface is contained within the analysis domain. The generated mesh for the numerical analyses is shown in Figure 16. The perspective view of the mesh is shown in Figure 16a and the plan view is shown in Figure 16b. The generated mesh was chosen after several trials with finer meshes until the results did not change any further. Very fine meshing was provided in the regions with large shear strains, e.g. near the toe while coarser mesh was provided at the mid-section where the strains are predominantly compressive normal strains. All the nodes on the vertical boundaries are prescribed with zero displacement in the normal direction to simulate smooth rigid vertical boundaries. The nodes on the bottom boundary were fixed in all directions to represent rough rigid boundary. The water table was fixed at the ground level to simulate soft clay conditions.

The granular columns were generated using cylindrical-shaped mesh and the soft soil was generated using radially graded mesh. The geosynthetic-soil interface parameters were calculated based on the size of the grid around the interface and the modulus of the soil, Itasca Consulting Group, Inc. [28] and Mohapatra and Rajagopal [29]. The values of normal stiffness (k_n) and shear stiffness (k_s) used to model the interface are reported in Table 2.

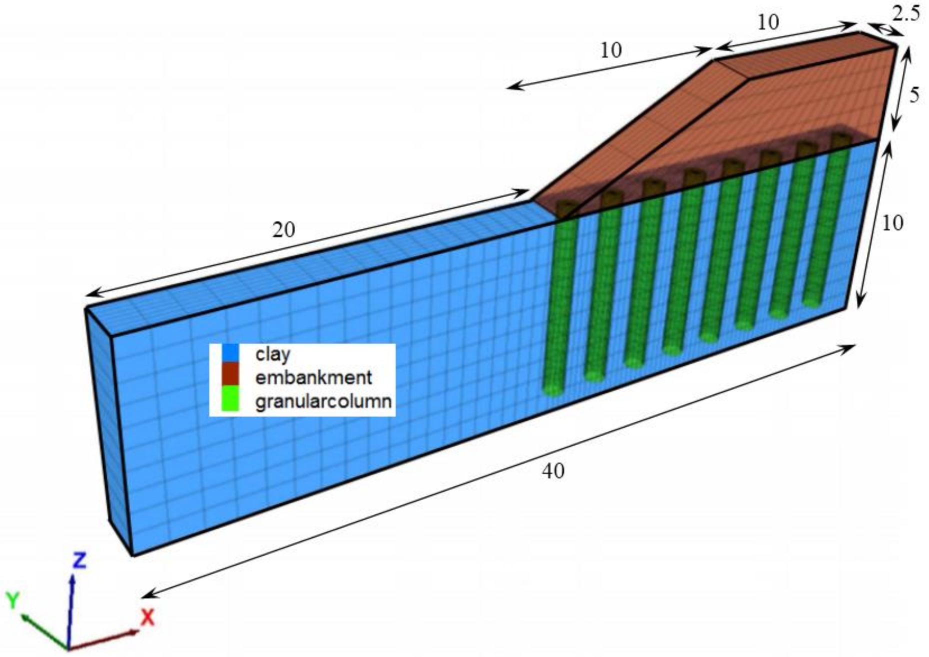
The constitutive behaviour of different materials like embankment soil, soft clay and stone aggregates in columns was simulated using Mohr-Coulomb model. The interface between the geosynthetic and soil was modelled using frictional based Coulomb's law. The properties of different materials are listed in Table 2.

Table 2. Properties of different materials used for numerical modelling in the baseline case

Parameter	Unit	Granular column	Soft clay	Embankment fill
Constitutive model	--	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb
Height/Depth	m	10	10	5
Bulk unit weight	kN/m^3	19	15	18
Poisson's ratio	--	0.3	0.45	0.3
Friction angle	°	38	0	32
Cohesion	kPa	0	10	0
Young's Modulus	kPa	50,000	2500	20,000
Geosynthetic encasement	J=500 kN/m	ν=0.33	t=1 mm	
Interface properties		$k_s = k_n = 5.0 \times 10^3$ MPa/m		



a) Plan view of the model



b) 3-dimensional view of the model

Fig. 16. Numerical model of embankment supported on granular column treated ground

The factor of safety of the embankment resting on granular column treated ground was determined using strength reduction technique as proposed by Dawson et al. [30]. The program estimates the factor of safety by gradually bringing the slope to a state of limit equilibrium by reducing the shear strength of the materials as given below,

$$\bar{c} = \frac{c}{FS} \tag{16}$$

$$\bar{\phi} = \tan^{-1}\frac{\tan\phi}{FS} \tag{17}$$

In the above equations, the c and ϕ are the actual cohesion and friction angle values, respectively while $\bar{c}$ and $\bar{\phi}$ are the reduced cohesion and friction angle values respectively which bring the slope to the verge of limit state. It is assumed that both cohesion and friction angle are reduced proportionally for the calculation of FS value. On the other hand, if the slope is initially unstable, the value of $\bar{c}$ and $\bar{\phi}$ are increased progressively to reach a state of limit equilibrium (i.e. the FS value is decreased).

As the strength of the materials is gradually reduced, the system will reach a limit state with large deformations and formation of continuous rupture surface for the formation of a slip circle failure mechanism. When the ground was treated with ordinary granular columns or with low area replacement ratios, the embankments failed by deep seated failure with shear movements in the granular columns as shown in Figure 17. When the columns were encased with strong geosynthetics, the failure mechanism changed from deep seated failure to toe failure mode as illustrated in Figure 18. The use of geogrid encasement for granular columns has resulted in increase of loads transferred to the columns and reduction of pressures transferred into the foundation soil as illustrated in Figure 19. It is clearly seen from this diagram that the pressures are higher in encased columns compared to the ordinary columns. This is because of higher soil arching that took place around stronger and stiffer encased granular columns

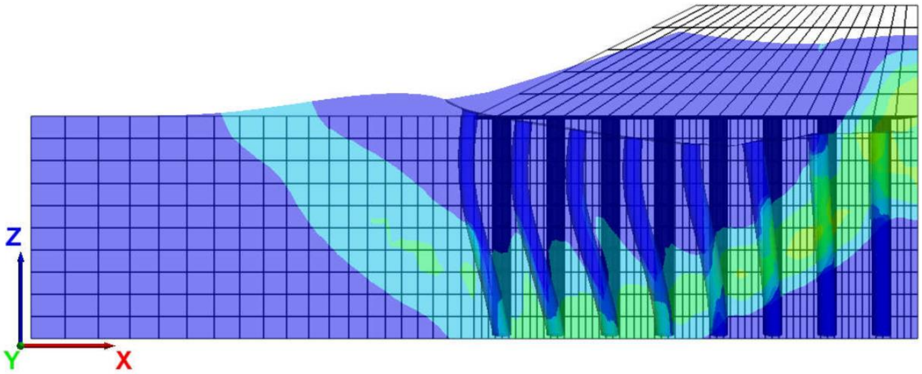


Fig. 17. Deep seated slip circle in ordinary granular columns treated ground

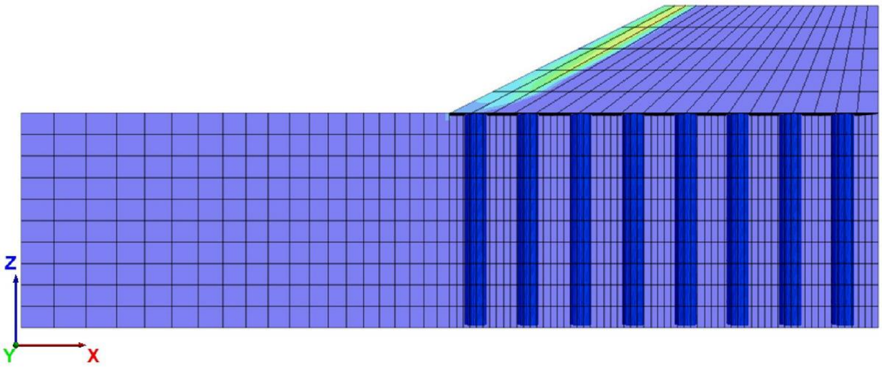


Fig.18. Toe failure in encased granular column treated ground with modulus of 2500 kN/m

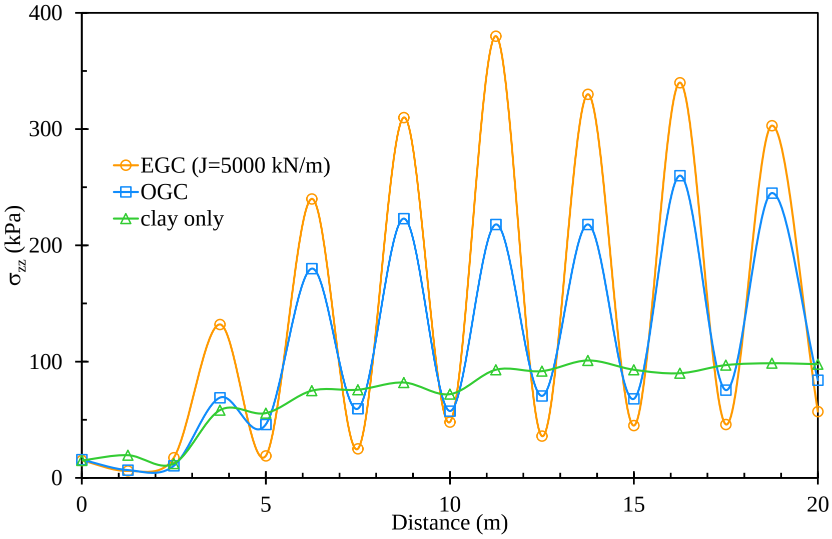


Fig.19. Pressure on foundation soil with different types of ground treatment

The factors of safety values with different configurations are reported in Table 2. As very soft soil was considered for the foundation, the factor of safety for the OGC treated ground is very low even with 24% area replacement ratio. On the other hand, the use of geosynthetic encasement has increased the factor of safety even with low area replacement ratios. Beyond a certain limit of geosynthetic modulus and area replacement ratio, the factor of safety did not increase any further in EGC cases as the critical slip surface passed through the toe of the embankment.

Table 3. Variation of FS with a_s in case of OGC and EGC supported embankment

a_s (%)	FS			
		EGC		
	OGC	J=500 kN/m	J=1000 kN/m	J=2500 kN/m
8.04	0.83	0.98	1.00	1.29
12.56	0.93	1.03	1.08	1.29
18.09	0.97	1.14	1.20	1.30
24.62	1.02	1.24	1.27	1.30

5 Conclusions

A series of parametric investigations were performed to capture the response of geosynthetic encased granular columns by two different methods. The present study limits the discussions on the EGC treated soft clays with respect to the effect of pattern and other relevant design parameters. However, these results need to be supplemented by full scale instrumented field trials. Some of the major conclusions from this study are as follows:

1. The settlement reduction is higher with geosynthetic encased granular columns compared to ordinary granular columns.
2. The settlement improvement factor for ordinary granular columns increases with increase in diameter of the granular column (for the same c/c spacing of columns). However, the geosynthetic encased columns show higher better performance with smaller diameters due to larger hoop confinement effects.
3. The granular material with higher friction angles resulted in higher settlement improvement factors for columns with and without encasement.
4. The influence of installation pattern on the settlement improvement factor was significant only with encased granular columns.
5. The influence of the encasement on the settlement improvement factor is more significant in the case of softer soils as they cannot provide adequate lateral support on their own.
6. The geosynthetic encasement of granular columns has obstructed the slip surfaces passing through them leading to larger factor of safety values.

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List of Abbreviations:

OGC **-** Ordinary Granular Column
EGC **-** Encased Granular Column
SIF- Settlement Improvement Factor

List of Symbols

a_s - Area replacement ratio
h - Thickness of the soil
C - Constant applied for a given granular column arrangement.
D - Diameter of the granular column
D_s - Constrained modulus of the soil
E_s - Elastic modulus of the soil
S - Spacing of the granular column at c/c
H - Height of the Embankment
$M\ or\ J$ - Modulus of the geosynthetic encasement
$K_{0,s}$ - At-rest earth pressure coefficient in the soft clay soil
S_u – Undrained shear strength of the soft clay.
S_{sl} – Settlement of the soft soil
S' - Settlement of the improved ground with granular column with or without encasement
T_g – Hoop tensile force in the geosynthetic encasement.
r_g – Radius of the geosynthetic element
r_c – Radius of the granular column
φ'_c – Effective friction angle of the granular column
φ'_s – Effective friction angle of the soft soil
ϑ_s – Poisson's ratio of the soil
$\sigma_{z0,c}$ - Overburden stress of the granular column;
$\sigma_{z0,s}$- Overburden stress of the soft clay soil;
$\Delta\sigma_c$ - Additional vertical stress in the column
$\Delta\sigma_s$ - Additional vertical stress in the soft clay soil
$\Delta\sigma_r$ – Radial stress difference between column and soil
σr_g – Radial stress in the geosynthetic element

σr_c – Radial stress in the granular column
γ_s – Unit weight of soil
γ_w – Unit weight of water
γ_e – Unit weight of embankment or fill