Encased Columnar Inclusions in Soft Grounds - A Review

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ABSTRACT: Even before the evolution of soil mechanics, the research on mitigating the problems induced by soft soils has started. The granular column is one of the promising ground improvement technique widely accepted as a solution to soft soil problems all over the world. Recently the performance of it is improved by encasing with geosynthetic products like geogrid and geotextiles. This paper gives an insight into the technical aspects of encased granular columns by reviewing the advancements that have happened in the published literature. The focus of this paper is more on the problems associated with soft clay deposits, although granular columns can also be employed to mitigate liquefaction in saturated loose sand deposits. Discussions on the key technical aspects associated with encased granular columns and its applicability in the field are provided.

KEYWORDS: Ground improvement**,** Granular column, Soft soil, Geogrid, Encasement.

1. INTRODUCTION

Soft clay deposits which occur along the coastal regions are geologically young and remain unconsolidated for a long time. Often their moisture content is close to the liquid limit. The problems encountered by engineers when placing the structures on them include very low bearing capacity, high settlements which continues for longer durations, Instability of deep excavations for basement construction, Deep-seated slip failure in the case of embankments, lateral flow under surface loading etc., Soft clays are one such class of problematic soils that has to be improved in terms of its engineering behaviour by ground improvement techniques before erecting any structures. A variety of ground modification techniques by mechanical, hydraulic, physical and chemical means are practiced all over the world. Recently with the advancements in the polymer industry, improvements of the problematic soils by synthetic polymeric products (both planar and 3D) are also sorted to. Granular columns are one such forms of mechanical modifications in improving the in situ soft soils. They are basically cylindrical piers filled with stone aggregates or coarse-grained sand installed in soft clay deposits to carry flexible structures like oil storage tanks, embankments. The granular columns function in two aspects. Firstly they act as reinforcement in the in situ clay soil and secondly as permeable elements of dissipating the pore water pressure and hence increasing the carrying capacity and reducing the settlement of the foundations.

Granular Columns also referred as stone columns or aggregate piers, Granular piles were first used in France by 1830's as reported by Barksdale and Bachus (1983). When the load is applied, the granular column bulges and gets lateral support from the surrounding soil in the form of passive pressure, thus forming a composite soil/granular column system. The increase in the lateral stresses in the clay further leads to consolidation and subsequent relaxation of stresses. This process continues until the system reaches equilibrium. The soft clay soil confines the column and the passive resistance causes the granular column to resist the vertical deformation. This improves the stiffness of the granular column and increases the overall bearing capacity of the treated ground. Granular columns are usually analyzed by a unit cell concept. The granular column along with the surrounding tributary soil together constitutes the unit cell. Generally, the columns are installed in groups adopting different patterns of arrangement, two such patterns say square and a triangular pattern is indicated below in Figure 1. Out of these two patterns, the triangular pattern is commonly adopted as it provides better coverage of influence area by a single column than that of a square pattern. Although the tributary area forms a square or hexagon around the stone column it can be closely approximated as an equivalent circle having the same plan area. This equivalent circle has an effective diameter D_e of 1.05S & 1.13S for triangular and square patterns where "S" indicates the center to center spacing between the columns.

End bearing is not a strict requirement for granular columns; they can also be allowed to float. A long stone column (L>4D) with or without end bearing may fail by bulging. Whereas short columns installed with end bearing fail by shear. Short floating columns may undergo punching type shear failure. These failure mechanisms are illustrated in Figure 2.

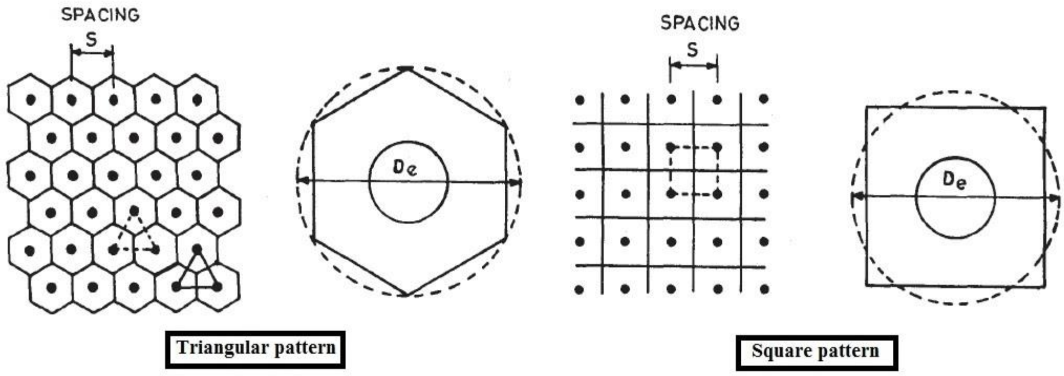

Figure 1 Various patterns of Stone Column Arrangement

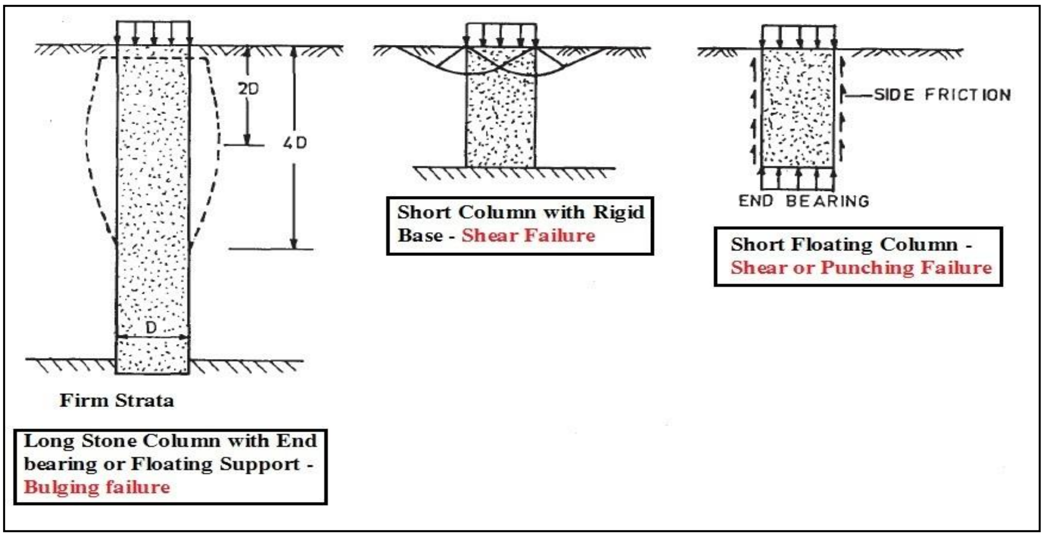

Figure 2 Failure Mechanisms of a Single Stone column

1.1 Advantages and Limitations of Granular Columns

Preloading with sand drains and stone columns are the extensively used ground improvement techniques in the Asian subcontinent. In certain time sensitive projects to achieve the desired degree of consolidation within the stipulated time, a stone column is the best alternative technique that can be opted for, apart from preloading technique. The Stone columns are generally cost effective and their installation is comparatively easy compared to other ground improvement techniques. The stone column also functions as a drain and serves the purpose of accelerating the process of consolidation by reducing the drainage path length. Nevertheless, it holds certain limitations. When conventional stone columns are installed in very soft clays (<10 kPa) and owing to the low confinement offered, the stones charged into the column may squeeze out of the column leading to loss of stones. This increases the quantity of the stones required to form the column. Further, the fine particles from the surrounding soft clay can contaminate the aggregates which in turn reduce their frictional property and drainage function of the column. The stone columns are generally dependent on the shear strength of surrounding in-situ clayey soil and hence the ultimate load carrying capacity cannot be improved beyond ~ 8 times the strength of soft clay as reported by (Chummar 2000 and Thorburn 1975). Hence the design would be uneconomical with closer spacing of the column in the case of higher loads. Additionally, the ordinary granular columns are incapable of taking higher loads as they predominantly fail by bulging. All the above said limitations can be rectified by encasing the stone column with appropriate geosynthetic. A clear schematic representation of encased stone column and its behaviour is indicated below in Figure 3.

2. GEOSYNTHETIC ENCASED GRANULAR COLUMNS

Though encased stone columns possess many advantages, this technique is not practiced widely as that of stone columns because of limited understanding of its response to applied load. Therefore it is felt that a detailed study on encased stone column is essential to bring out the mechanism with which the encasement provides strength to the column and the factors that influence its response. Based on the above discussion, this section describes review of literature based on the analytical, numerical, laboratory and Field studies of encased granular columns. The Discussion is more towards columns installed in cohesive deposits.

In this paper ordinary (Granular) stone columns are referred to as OSC and the encased stone columns are referred to as ESC. The word "encasement" strictly adheres to vertical encasement. Also, the word encased granular column seems to be apt to represent stone columns as many researchers have also used encased sand columns in their studies to depict the stone columns behaviour as a scaled down model.

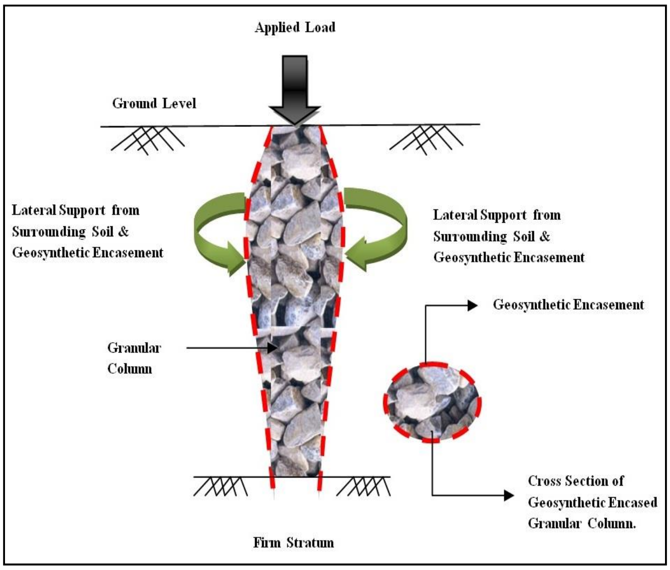

Figure 3 Single Encased Granular Column - Schematic Representation

2.1 Analytical Study on Encased Granular Columns

For design and calculation purposes of encased granular columns, different methods have been developed over the years. The Pioneering studies were attempted by Van Impe (1989). The analytical procedure estimates the required tensile strength of the encasement in the circumferential (ring) direction but doesn't consider the strain deformations into account nor consider the settlement aspects. This method has analyzed the problem from the point of view of the tensile strength of encasement ignoring the circumferential strain system as referred by Alexiew et al. 2000.

Raithel (1999) presented two new analytical design procedures on the basis of established design procedures for vibro-displacement compaction by Priebe (1995). The first one is called as simplified and the second one being precise. Procedures include a confining force in the ring direction of the encasement based not only on a tensile force at failure but on the complete stress-strain behaviour of the geosynthetic. This behaviour is defined by the tensile stiffness modulus J (kN/m). Consequently, it is possible to calculate from the ring strain the radial widening of the GEC and the resulting vertical settlement on top of the GEC that will be equal to the average settlement. Further assumptions and also the differences between the simplified and the more precise design procedure can be found in Raithel (1999). It is important to note that the stress-strain behaviour of the encasement is the key element for the performance of the system. The analytical model was published by Raithel and kempfert (2000) which is popular and widely accepted in engineering practice is indicated below in Figure 4.

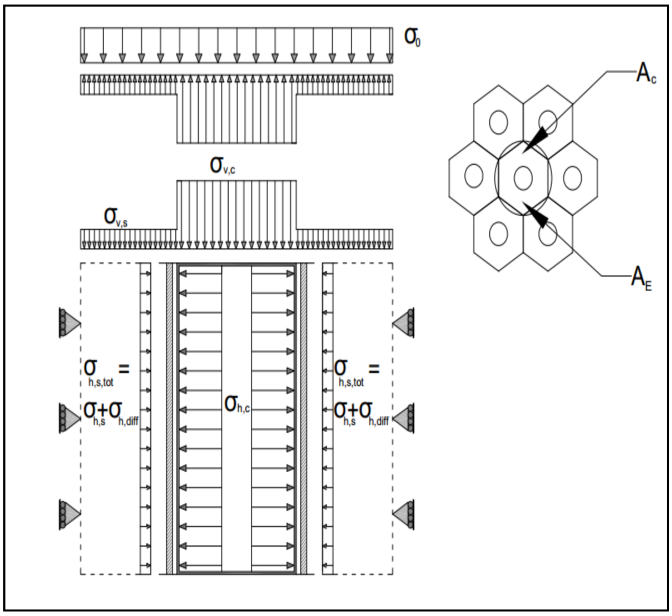

Figure 4 Analytical model of geotextile encased columns after Raithel & Kempfert 2000.

The average vertical stress from the overlying embankment σ_o acts over the hexagonal area of influence of a single column unit area A_E. This stress is equivalent to the higher stress imposed on the column $\sigma_{v,c}$ acting over the area of the column A_C plus the lower vertical stress $\sigma_{v,s}$ acting over the area of the adjacent soil A_E-A_C. The difference in vertical stresses acting over the column $\sigma_{v,c}$ due to concentration and the adjacent soil $\sigma_{v,s}$ creates a corresponding difference in the horizontal radial stresses σ_h in the column and in the adjacent soil resulting in a ring tensile force in the geotextile. This confining tensile force in the encasement provides the missing component for the state of equilibrium which was ignored by Van Impe (1989). It depends not only on the horizontal stresses and their differences but also on the strains through the ring tensile modulus J kN/m. In fact, this strain-dependence of the equilibrium is very specific for the encased column.

Pulko et al. (2011) presented an analytical model based on method characteristics for both ordinary and encased stone column. The regularly spaced end-bearing stone columns and the surrounding soil are modelled as a unit cell, consisting of elastic soil, elasto- plastic Mohr-Coulomb column material and elastic geosynthetic encasement. The dilation of the column material according to the Rowe stress-dilatancy theory is directly incorporated into the method. Elasto-plastic finite element study was performed by using commercial Plaxis 2D finite element program to compare with the analytical model. The parametric study conducted was concentrated on the important parameters that affect the composite soil - stone columns for both ordinary and encased, which include column spacing, stiffness of the encasement, peak friction angle of the column material, dilation angle of the column material, modular ratio i.e. the ratio of modulus of column upon soil and the loading levels. The study concludes that the selection of encasement stiffness should be based on column diameter, soil stiffness and the spacing between columns. The authors have suggested that the dilation of the column material has a beneficial effect on the settlement reduction and for conservative predictions it can be neglected.

Castro and Sagaseta et al. (2009, 2011, 2013) have investigated continuously on the analytical aspects of ordinary and encased stone columns. Initially (2009) the authors have presented a closed form solution for radial consolidation around stone columns under constant surcharge load. The solution considers the influence of vertical and radial deformation of the column either in elastic and elasto-plastic regimes with constant dilatancy angle in terms of average excess pore water pressure. The consolidation around encased stone column is generally a fully coupled problem and hence a reasonable solution is obtained in this study by using an average value of excess pore pressure along the radius of the column. As an extension in (2011), a new analytical solution was proposed to study the soft soil improvement by means of encased stone columns to reduce both settlement and consolidation time. The solution assumes the linear elastic behaviour of soil and linear elastic-perfectly plastic behaviour of encasement and column. Furthermore, the proper loading history is considered in this study (undrained loading and consolidation analysis), with equilibrium and compatibility conditions, both in vertical and radial directions, are fulfilled. *So, many of the limitations of (Raithel and Kempfert, 2000) are overcome in this study.* Speaking about the settlement reduction aspects, the encasement in stone columns are recommended in the case of very soft soils and for moderate loads. If the applied load is high, the encasement loses its tensile strength and its effectiveness is reduced. On the other hand, the settlement reduction introduced by the encasement was nearly the same for different area replacement ratios dealt with in this study. The analytical model was validated numerically and As a point of importance, the author's assumption on neglecting the elastic strains in the column during its plastic deformation has slightly affected the analytical solutions. Further addition of the above-mentioned assumption was taken into account in the next study (2013) which is basically an extension to the previous solution by the authors, Therefore, the model and assumptions were the same but the study included the elastic strains of the column during its plastic deformation. The solution is developed for a horizontal slice at a prescribed depth of the unit cell and consequently, shear stresses between slices at different depths are not considered. The vertical strain of the soil, column is the same for each slice. The overall behaviour of the whole unit cell is obtained by means of integration of the solution at the different depths. This is the same approach used by Pulko et al. (2011).

Zhang et al. (2011) developed a theoretical solution for consolidation of a composite foundation improved by geosynthetic encased stone columns. The solution includes both horizontal and vertical flows within the column and the soil. In the previous studies, the changes in the volume of the column were ignored nor only the vertical strain was included in the solution (Lo et al. 2009).The assumptions of the present study include equal strain hypothesis, the validity of Darcy's law, Instantaneous application of load. Most importantly the permeability of the geosynthetics is being described by permeability rate i.e. the ratio of permeability coefficient of geosynthetic upon the thickness of the geosynthetic. The geosynthetic encasement was found to play a minor role in the consolidation of the composite foundation. As it cannot decrease the volume of drainage and increase the pore water pressure gradient. However, the geosynthetics effectively can prevent the soil squeezing into the column which ensures the permeability of the column. In a sense, the geosynthetics can increase the drainage capacity of the column indirectly. The author's findings are in line with the previous observations by Castro and Sagaseta et al. (2011) wherein the consolidation problem of a composite foundation (geosynthetic encased) can be simplified as that of ordinary composite foundation because of the minor influence of geosynthetic encasement.

Wu and Hong (2014) presented a simplified approach for evaluating the bearing performance of encased granular columns. The approach discussed has its base on the tri-axial studies of sand specimens encapsulated with heat bonded non-woven geotextiles made of polypropylene filament, which yielded rigorous correlations to model soil characteristics especially for the volumetric strain of sand to predict encased granular column behaviour. Numerical analysis using rigorous regressive equations has predicted both deviatoric stress and volumetric strain in triaxially compressed sand columns. The present study proposes a simplified approach employing experimental results from a triaxial compression test of pure sand and proceeds to make satisfactory predictions for encased sand column response. The solution process is further simplified by assuming no volumetric change (Constant Volume assumption) during axial loading. Simple steps are proposed in the study for analysing the bearing performance of geosynthetic-encased sand columns. This assumption provides conservative, yet practically accurate results. The material properties and column geometry needed to complete the calculations are the encasement stiffness, strength, and column diameter. Except for encased granular columns with high encasement stiffness/column diameter ratio, the constant volume assumption was found to underestimate the confining pressure increment because this assumption ignores circumferential strain due to column dilation and associated expansion. Using Mohr-Coulomb yield criteria the axial stress of encased granular column can be evaluated from the confining pressure increment obtained from the simplified approach.

Zhang and Zhao 2014 worked on analytical solutions to predict the deformation behaviours of geotextile - encased stone columns based on unit cell concept. Under vertical loads at the top of the stone column, an axial compression occurs which is often accompanied by lateral expansion (bulging). The proposed analytical method incorporates the bulging characteristic of the encased column. The shear stress prevailing in between encased stone column and surrounding soil is also taken into consideration. The analogy of Passive earth pressure theory is used to analyse the confining pressure offered by the soil.

The study includes the following assumptions:

- Geotextile material behaves as an elastic material with constant stiffness modulus.
- Initial tension within the geotextile reinforcement caused by column installation is assumed to be constant along the whole length of the column.
- The shear stresses between the column and the geotextile and between the geotextile and soil in the circumferential direction are ignored.
- The lateral support from the soil to the column is induced mainly by the lateral pressure in the soil. (Raithel and Kempfert 2000)
- The stone column is assumed to rest on a hard stratum and then settlement of the bearing stratum is ignored.

Stress concentration ratio (SCR) is the ratio of vertical stress at the top of the column to that of the top of the soil is one of the input parameters in the study. Before providing a solution procedure for the encased stone columns, this analytical study investigates on lateral earth pressure, confining stress offered by the soil to the column, geotextile encasement, radial stress of the column, lateral bulging, axial deformation of the column and the depth of bulging. Validation of this study is done by analysing a hypothetical case of embankment supported by geotextile encased stone columns. The solution obtained is useful to compute the embankment settlement at different heights. The calculated settlements computed using the current method compare well with the solutions proposed by Raithel and Kempfert (2000) and Pulko et.al (2011). However, the analytical solutions provided by the latter can only be used to calculate the settlements at the top of the columns, whereas the former helps to predict the deformation behaviour all along the length of the column. The current analytical solution becomes inadequate when large deformations are applied. To investigate the influence of geotextile encasement a series of parametric analysis was also performed. Based on the results obtained from the parametric analysis the performance is improved significantly when the stone columns encased. When compared with ordinary stone columns, reduction in the settlement, column bulging are better for encased stone columns and are further reduced with increasing stiffness of the encasement. In the present study, the stiffness of the geotextile is varied from 2000 to 4000 kN/m. It is observed that increase in stone column diameter and reduction in column spacing can reduce considerably the settlement of the stone column foundation system. Hence the authors conclude that the stiffness of the encasement should be made based on column spacing and diameter.

2.1.1 Numerical Study on Encased Granular Columns

Many researchers have studied the behaviour of the encased stone columns numerically adopting various models. Discussed below are the prominent works related to encase stone columns in soft clay soils.

Raithel and Kempfert (2000) presented calculation models based on the numerical and analytical basis for dam foundations with geotextile coated sand columns. The numerical calculation was performed using PLAXIS. For the soft soil the Soft Soil Model (SSM), a model of the Cam-Clay type was used. For the sand and gravel of the column material the Hard Soil Model (HSM), a modified model on the basis of the Duncan-Chang model was used. In this numerical analysis, the three-dimensional problem is simplified and the calculation is split up into two separate models. For examining the single column based on the unit cell concept axial symmetric model is used and for investigating the deformation behaviour of the whole system i.e. for the entire dam foundation a cross model is used. As the geosynthetic reinforcement (coating) cannot be simulated directly a substitute shear parameter is defined for the column material after activating the ring tension forces. This study also includes a parametric study varying different parameters and the numerical calculations compared with a large-scale model test (scale 1:1).The authors have concluded that the advantage of the newly developed encased stone column foundation is its possibility to use in very soft soils like peat. This foundation system has helped the foundation engineers to build safe and flexible foundations with low settlements, which is attributed to enormous settlement reduction, acceleration of settlements and a due increase of shear strength.

Murugesan and Rajagopal (2006) studied the numerical evaluation of geosynthetic encased stone columns. In this study, the authors have conducted a detailed parametric study to investigate the effectiveness of the encasement in stone columns. The influence of the parameters such as stiffness, depth of encasement, the diameter of the stone columns and the shear strength of the surrounding soil. All the analysis in this investigation was performed using the finite element program 'GEOFEM' originally developed at Royal Military College Canada and Subsequently modified at Indian Institute of Technology Madras. In the FE models, the cylindrical unit cell can be idealized using the axisymmetric model with radial symmetry around the vertical axis passing through the center of the stone column The FE mesh shown below in Figure 5 was developed using 8-node quadrilateral elements for all the components in the system. The stone columns and the soft soil are modelled using hyperbolic non - linear elastic equation given in (Duncan and Chang, 1970).

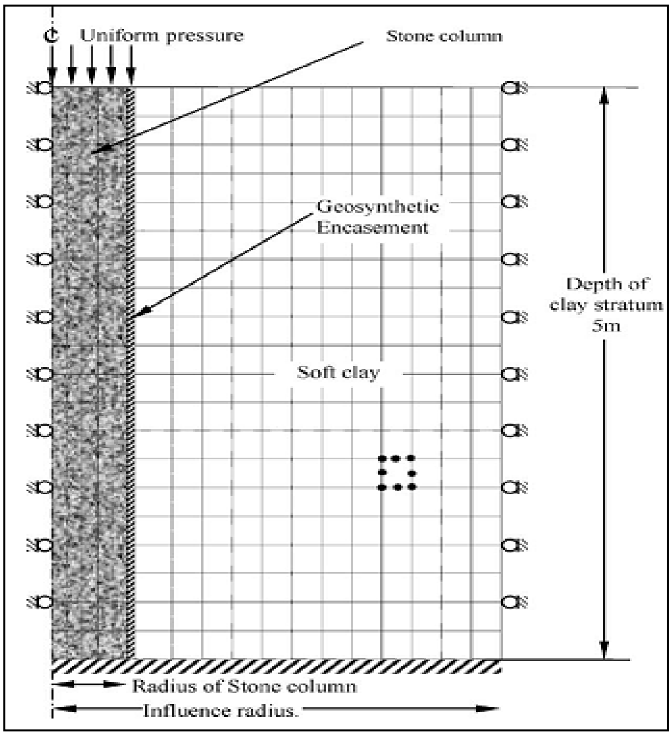

Figure 5 Typical Finite Element Mesh of Encased Stone Column after Murugesan and Rajagopal (2006)

While testing the effect of encasement in the parametric study it was found that the stone columns are confined and severe lateral bulging was significantly reduced. 0.6m and 1m diameter stone columns were used with and without encasement to quantify the effect of the encasement. The increase in confining pressure was observed all along the full height of stone column leading to the mobilization of higher vertical load carrying capacity in the encased stone columns. When the stiffness of the encasement was increased the bulging is observed to decrease due to the effect of lateral confinement. Interestingly smaller diameter encased stone columns were found to show a better pressure-settlement response because of the generation of larger additional confining stresses. When it comes to the depth of encasement, encasement length beyond twice the diameter (2D) of the column was not observed to yield further improvement in performance in the study conducted. The ordinary stone columns were found to rely on the strength of the surrounding soil whereas with increment in encasement stiffness the influence of the surrounding soil was observed to decrease. Additionally, studies were also conducted on stress transfer to the stone column from the embankment. A quantity termed as Stress Intensity Factor (SIF) was defined which is the ratio between average vertical stress in the stone column and the vertical stress corresponding to the height of the soil fill. As discussed earlier, with an increment of the encasement stiffness it was observed that overall stiffness of the encased stone column increases and hence higher stresses are transferred to it from the embankment.

Fattah and Majeed (2009, 2011, 2012) worked on the behaviour of both ordinary and encased floating stone column through numerical FE study. The program CRISP2D used in the analysis is capable of dealing with undrained, drained or fully coupled (Biot) consolidation analysis of two-dimensional plane strain or axisymmetric solid bodies. This program predicts the soil deformations considering Mohr-Coulomb failure criterion for elastic-plastic soil behaviour. 8 node isoparametric elements were employed for both soil and stone column whereas geogrid was modelled using 3 node bar elements capable of mobilizing only axial load. An isolated concrete footing of thickness 50 cm was placed at the top of the stone column with gradual uniform load application. The boundary conditions of this problem domain include no radial movement at the lateral sides without shear and prevention of the bottom boundary from both radial and vertical movement. Two terms namely the bearing improvement ratio (capacity of treated soil to that of untreated soil) and settlement ratio (settlement of treated to that of the untreated soil) were coined to quantify the level of improvement occurred in the stone column. From the parametric study conducted by varying the soil shear strength, length to diameter ratio, area replacement ratio, the authors have concluded that in the case of Ordinary floating stone columns, the area replacement ratio (a_s) and the undrained shear strength of the soil have significant effect on the bearing improvement ratio and settlement reduction. The maximum effective length to diameter ratio is found to be in the range of 7-8 for a Cu value of (20 -40 kPa) and for further reduction in soil shear strength to 10 kPa the L/d ratio rises to the range of (10-11). With respect to encased stone columns, the bearing improvement ratio is improved substantially for (a_s) greater than 0.25.The lateral displacement is also well arrested by encased columns when compared to that of ordinary stone columns. Interestingly for floating encased stone columns the bearing improvement ratio keeps increasing even beyond L/d = 8. This phenomenon indicates that there is no effective length to diameter ratio for floating encased stone columns. Further studies have been extended to portray the behaviour of end bearing stone columns (2011). The study revealed that with the increase in undrained soil shear strength the bearing improvement ratio increases for an L/d of 3 and 4 rather than for L/d of 5 and 6.The settlement reduction ratio and bearing improvement ratio are increased with the decrease in Cu values. This proves the fitness of the encased stone columns over ordinary stone columns in soft clay soils of less undrained shear strength. The authors have further attempted the same study (2012) using stone capping below the base of the footing. Irrespective of the L/d ratio adopted the bearing improvement ratio was found to show an increasing trend and reduction in settlement of the foundation system. The limiting thickness of the stone cap below the footing i.e. from the bottom face of the footing and above the floating stone column was found to be about 0.4 times the footing diameter.

Yoo and Kim (2009, 2010, 2015) conducted numerical studies on encased stone columns by different finite element modelling approaches. The model study includes an axisymmetric unit cell, a three-dimensional (3D) Column and a full 3D model. A commercial finite element code, ABAQUS (Abaqus 2006) was selected for the analysis for using the advantage of its robustness in numerical solution strategy for soil non-linearity and stress pore pressure coupled problems. The study has adopted Modified cam clay type model for the clay soil and Mohr-Coulomb model for the stone column and sand mat above the stone column. The geosynthetic was modelled as a linear elastic material. Further this study has investigated on the modelling aspects of geosynthetic encasement using continuum and membrane elements. Specific conclusions were drawn from the comparison of the above-mentioned approaches in terms of settlement, stresses, lateral deformation and geosynthetic strains. In particular, the results of the 3D column model showed good agreement with those from the full 3D model in all aspects say settlement, vertical stress, lateral deflection, excess pore pressure and geosynthetic strains. The axisymmetric unit cell model, however, yielded ~ 10-20 % larger results than the 3D models in particular for vertical effective stress, geosynthetic strains, and lateral deflection. It was also noted from the present study that the absolute magnitudes of discrepancies existing between axisymmetric unit cell model and 3D models are of little significance. In modelling the geosynthetic encasement, both continuum and membrane elements gave practically the same results and hence the authors have suggested continuum elements as alternatives of membrane elements. With geosynthetic encasement remarkable decrease in load induced excess pore pressure and vertical stresses leading to decreased settlements are observed.

Another interesting observation from the study includes the occurrence of lateral bulging at the bottom end of the encased stone column suggesting full encasement in order to achieve full encasement effect. *This trend is contrary to the reported critical encasement depth of 2-3 times diameter of the encased stone column.*

Further parametric investigations were continued numerically on the performance of geosynthetic encased stone columns in embankment construction by Yoo (2010). The governing factors in the study include consistency of the soft ground, geosynthetic encasement length, stiffness, embankment fill height and area replacement ratio. The study pertaining to this numerical investigations concludes that with geosynthetic encasement of the stone column lesser load is transferred from the embankment to the clay layer which in turn decreases the excess pore pressure generation. Similar conclusions from the previous study (2009) like considerable decrement in lateral bulging and full encasement of the stone column foundation is also reported. Additionally the critical encasement stiffness beyond which no further benefit of encasement was reported as J ~ 1500 - 2000 kN/m and was found to be independent of the area replacement ratio and embankment loading.

Numerical investigations on the settlement behaviour of an embankment on geosynthetic encased stone column installed in the soft ground were performed by Yoo (2015). A 3D stress pore - pressure coupled FE model was used in this study to simulate the construction process of the embankment. The parametric study conducted was same as that of Yoo (2010). Finally, design charts were presented which can be of use in estimating the maximum settlement and stress concentration ratio during the preliminary design. This study concludes that critical encasement length seems to exist only in the case of limited clay layer thickness. The critical encasement length for isolated column loading cannot be applied to the embankment loading condition. For smaller area replacement ratios; lesser soft clay consistencies; Thicker clay layers; The degree of settlement reduction with increasing encasement length and stiffness seems to be more pronounced. This phenomenon indirectly indicates increment in encasement length and stiffness is the site (problem) dependent and it's maximized when the stress intensity in the soft ground is larger. The above said parameters become more effective when the embankment load intensity to the soft soil consistency is greater. Hence the author has suggested considering the same as a design parameter.

Khabbazian et al. (2010, 2011, 2012, 2015) studied numerically the effects of geosynthetic encasement on the behaviour of granular columns. The numerical modelling consists of Mohr-Coulomb, Modified Cam Clay and Linear elastic model for the stone column, Soft soil and geosynthetic respectively. 3D Finite element analysis was performed using the program ABAQUS (2007) coupled with parametric studies by varying length and diameter of the granular column, stiffness and length of geosynthetic encasement and friction and dilation angle of the column material. The stress - settlement response was observed to improve with encasement of stone columns. For a given value of vertical settlement the lateral displacement for a geosynthetic encased column is much lower owing to the increased stiffness and in turn allowing larger loads to be transmitted at greater depths. Further, the lateral displacements were seen to be evenly distributed all along the length of the encased column. The load carrying capacity of the encased stone column was found to increase appreciably with an increase in friction and dilation angle. However, the authors insist on opting for higher encasement stiffness rather than to improve the stone column material properties. The optimum length of encasement in order to achieve the same performance of full encasement is dependent on two parameters namely the column settlement and the stress applied to the top of the column. The optimum length increases with increase in vertical settlements on top of the column.

Columns with smaller diameter were able to exhibit a better stress settlement response than larger diameter columns. The reason behind this phenomenon is that with the increase in column diameter, large lateral displacements were mobilized and it was noticeable only in the top portion of the encased stone column. This is in line with the previous study conducted by Murugesan and Rajagopal (2006). In the case of ordinary granular columns, the stress settlement response is not significantly affected by the increase in the length of the column as the failure occurs by lateral bulging only on the upper portion of the column. But for encased columns mobilized stress was observed to be larger for shorter columns than for the longer ones. The above said behaviour is similar to that of a short and long pile (concrete) behaviour in the aspect of the settlement. For a given load longer piles settle more than that of a short pile.

The authors have continued the numerical investigation on the performance of quasilinear elastic constitutive models in simulation of geosynthetic encased columns Khabbazian et al. (2011) Khabbazian et al. (2012). 3D finite element analysis utilizing three common functional forms of the hyperbolic model were investigated for single encased column in soft clay. Additionally, a single hardening constitutive model was also used along with the above-mentioned models to assess the performance of hyperbolic models. The results of the afore mentioned FE analysis showed significant differences between three versions of the hyperbolic model and single hardening model in simulating the behaviour of geosynthetic encased columns. For a given vertical displacement, the lateral displacement and stresses in the encased granular column predicted using hyperbolic models were significantly lower than those obtained by single hardening model. This disparity is mainly because the encased column was at near failure condition.

The authors have insisted the limitations of hyperbolic models in predicting the deformation behaviour of dilative soils because of their elastic nature and have suggested the usage of the same for conditions of monotonic nonlinear response and not when the behaviour of the soil mass is controlled to a large extent by elements of failure. The authors have finally commented that elastic models are not recommended to numerically simulate the behaviour of encased granular columns at any time.

In addition to the above study, unit cell concept has been validated for geosynthetic reinforced column supported embankments (2015). Full 3D, 3D unit cell, and axisymmetric unit cell analyses were carried out to validate the unit cell concept. The effect of degree of nodal constraint along the bottom boundary was also studied. The study resulted in arriving at the following conclusions.

Unit cell idealization provides reasonable approximations of the behaviour as obtained from the 3D analysis for geosynthetic reinforced column supported embankments that are constructed using geosynthetic encased columns.

The only exemption is the calculation of tensile forces that are induced in the geosynthetic reinforcement layer by the lateral spreading of the embankment in both the transverse and longitudinal directions.

Almeida et al. (2013,2014) worked on the performance of geosynthetic encased column in soft ground using numerical and analytical studies. The analytical model presented by Raithel and Kempfert (2000) and The axisymmetric FE Model using PLAXIS 2D (2002) are compared by means of parametric studies to assess the influence of various parameters on the overall behaviour of geosynthetic encased columns. The FE model was used to simulate the behaviour of geosynthetic encased stone column in soft clay loaded by an embankment by drained analysis. The results of 2D unit cell model showed good agreement with Analytical Model (AM) however unlike AM the FE model indicated that settlement is not the same for soft soil and encased column. Similarly, the tensile forces obtained from FE model compares well with AM. But an analytical model determines constant value along the depth whereas FE model exhibits variations over the entire depth showing dilated zones in the encased columns associated with maximum tensile forces. Pertaining to the current numerical study, the stress concentration factor does not change with soil thickness in the case of ordinary stone columns. Whereas for encased columns the same increases with increase in geosynthetic stiffness. The differential settlement (DS) calculated from the FE study revealed that with an increase in embankment height DS decreases and becomes zero at a given embankment height corresponding to full arching. This is called critical embankment height which is basically a function of the span between the columns and the column diameters.

Furthermore, the authors have studied numerically (2014) on the methods of reinforcing the stone columns using laminated discs in (horizontal) direction and full encasement (vertical) direction by PLAXIS (2010) software. Long term analysis (drained calculations) were performed to achieve maximum value of settlements and stresses. The Numerical study revealed that both the above-said methods help in reducing the settlement and improving the load carrying capacity of the stone column. In the case of geosynthetic disc type reinforcement the vertical spacing (S_v) between the reinforcement greater than 50 % of the column, diameter does not show significant improvement in on stress concentration than that of reinforcing by vertical full encasement. In the current investigation for a tensile stiffness of 2000 kN/m and for a vertical spacing of 25% of column diameter the settlement achieved for both the methods of reinforcement are same. It is to be remembered that for laminated disc type reinforcement closer spacing (at shorter vertical intervals) increases the settlement improvement for a given geosynthetic stiffness and embankment height. Howsoever when it comes to the preference of horizontally laminated disc or vertical encasement type reinforcement the latter improves the performance of the granular column for a given geosynthetic stiffness and area replacement ratio.

Lo et al.(2010) conducted numerical studies on geosynthetic encased stone columns in soft clay. The analysis has modelled the time-dependent interaction of encased stone column and surrounding soft clay by a fully coupled analysis. This study doesn't assume any particular form of geosynthetic. Stone columns were used to enhance the performance of the soft clay stratum in carrying a road embankment in the form of 4m fill. The stone column was modelled as a free draining material. A stone column element was incorporated into the finite element code, AFENA (1995). This element is, in fact, a modified Mohr–Coulomb elastic-plastic element with a nonlinear elastic part similar to that in the Duncan-Chang model (Duncan and Chang, 1970), but with the unloading and loading stiffness selected based on stress increment direction relative to the isotropic stress axes. It was observed that the role of stone columns in supporting the fill loading evolves with time and in order to adequately capture the behaviour of such a system coupled analysis or long term field monitoring is essential.

Keykhosropur et al (2012) numerically investigated geosynthetic encased stone column group in 3D forms. Encasement length was varied for different stone columns in a group and its effect in overall group behaviour is studied. The results were compared with those obtained from a group of fully encased group of columns. ABAQUS FE program was used in the analysis of the data presented from Raithel and Kempfert (2002). 800 mm diameter columns were modelled with 2m and 3m spacing's in the middle and sideways respectively. The length of the columns studied was 11.2 m. The encasement length was varied from (OSC) 0% to 100 % (ESC) with 25 % increment in length. The results from the study revealed that when settlements and lateral deformation are concerned it was sufficient to encase a selected set of columns without compromising the overall performance of the ground improvement system and it depends on the stiffness of the foundation and load distribution. With the increase in friction angle of the stone column, material increment in resistance of the columns against failure and decrement in the settlements of the column is noted. However when compared to the other variables discussed in the study influence of internal friction angle and elastic modulus of the stone column material are less sensitive for geosynthetic encased stone columns.

Elsawy (2013) observed the behaviour of soft ground improved by conventional and geogrid encased stone columns based on FE study. Full-scale models of unreinforced stone columns and the reinforced ones in Bremerhaven clay were analysed using PLAXIS 9. Noted observations from the study are similar to that of the results published by the earlier researches by Murugesan and Rajagopal (2006), Yoo and Kim (2009, 2010). The results of the analyses show that conventional stone columns significantly reduce total settlement and accelerate the consolidation of the clay. Using stone columns in soft clay reduces the values of the excess pore water pressure, and accelerates pore water pressure dissipation. In addition, the initial excess pore water pressure is reduced. The betterment in the soft soil is further improved with encased columns with lesser settlement and consolidation time. With an increase in embankment load and time of consolidation, more significance is noted for a reduction in the settlement. The excess pore water pressure in the clay reinforced with encased stone columns was dissipated in shorter intervals and considerably less as compared with conventional (ordinary) stone column. It's seen from the results that higher stress concentration is attracted in the case of encased stone columns than that of ordinary stone columns. Finally with the higher overall stiffness of the encased stone column foundation system, greater stress concentration in the column with greater reduction in the surrounding soft soil resulted in a quick acceleration of the soil consolidation.

Chen et al.(2015) numerically studied the failure mechanism of geosynthetic encased stone columns in soft soils under embankment by 3D and 2D FE analysis. Z_Soil FE software was used for the analysis. Experimental and 3D FE studies revealed a bending failure of encased columns rather than shear. 2D FE analysis was conducted for checking the stability of the embankment using equivalent bending and shears resistance out of which 3D FE analysis was found to coincide with the results of equivalent bending resistance portraying a bending failure of encased stone columns under embankment. The authors also suggested including one or more row(s) of columns in front of the toe of the embankment to increase its stability.

2.1.2 Laboratory Studies on Encased Stone Columns

A good amount of research work has been carried out in the laboratory in understanding the behaviour of encased stone columns in the past decades the most prominent ones are discussed below.

Malarvizhi and Ilamparuthi (2004) studied the load versus settlement relationship of ordinary and encased stone column through laboratory studies. The settlement decreased with increase in stiffness of the encasement. For smaller and higher loads the settlement reduction is better for ordinary and encased stone columns. The authors have also noticed that the L/d ratio is less sensitive in the case of floating columns when it comes to load bearing capacity. The ultimate bearing capacity of reinforced stone column and stone column treated beds were three times and two times that of the untreated bed.

Di Prisco et al. (2006) investigated geo-reinforced sand columns through small-scale experimental tests and showed how confining effect given by the geotextile improves both the stiffness and bearing capacity of the system.

Murugesan and Rajagopal (2007, 2008, 2010) conducted laboratory model tests on ordinary and encased stone columns extensively for both single as well as group and found that the encased stone column exhibited a stiffer response whereas the ordinary columns showed significant strain softening behaviour in terms of stress- strain behaviour. 50, 75, 100 mm diameter columns were used in the study. The lab test set up on unit cell testing is indicated below in Figure 6.

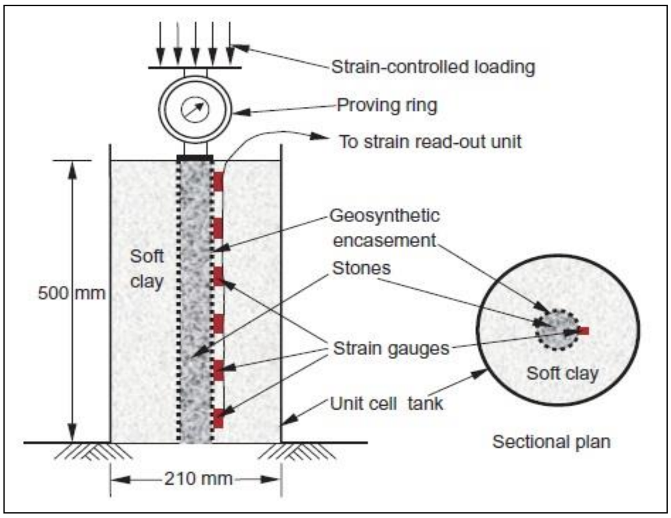

Figure 6 Unit cell load test on stone column after Murugesan and Rajagopal (2007)

Hoop strains were observed only near the top surface of the columns. Strain levels were noted to be smaller for larger diameter columns. The benefit of confinement was found to decrease with increase in diameter of stone columns. Limited investigations were also conducted on partially encased stone columns. Consequently, the authors have investigated the hoop strains by tension membrane theory and proposed a design methodology for selection of geosynthetic material as encasement is indicated below.

Guidelines for the Design of ESC:

1. For the given pressure loading (p_o) from the structure, suitable spacing (s) and diameter of the stone columns (d) are chosen. From the unit cell concept, the load coming over the unit cell is assumed to be carried fully by the stone column.
Load on the stone column = Applied pressure (p_o) $\times$ Area of the unit cell (A)

Area of the unit cell, $A = \pi \times (0.525s)^2$ for triangular grid and $A = \pi \times (0.564s)^2$ for square grid.

Load on the stone column = Load on the unit cell = $p_o \times A$

Pressure on the stone column = Load on unit cell / Area of the stone column, A_c

2. The limiting stress on an ordinary stone column, σ_v without encasement is computed by the equation

$$\sigma_v = (\sigma_{ro} + 4\,C_u)\,K_{pcol} \quad (1)$$

In which σ_{ro} is the initial effective radial stress computed at an average depth of twice the diameter of the column, C_u is the undrained cohesion of the surrounding soft clay. K_{pcol} is the coefficient of passive pressure of the aggregates in the stone column.

3. The additional confinement p_c required is calculated as

$$p_c = \frac{(po - \sigma v)}{Kpcol} \quad (2)$$

4. The corresponding hoop tension force in the encasement (T) can be estimated as $T = \frac{pc \times d}{2}$, where d is the diameter of the stone column.

5. The hoop strain ε_c in the encasement corresponding to the permissible (δ) in the stone column is computed using the following equation,

$$\varepsilon_c = \frac{1-\sqrt{1-\varepsilon_a}}{\sqrt{1-\varepsilon_a}} \quad (3)$$

In Which, ε_a is the axial strain in the stone column. This value can be evaluated from the surface settlement of the stone column treated ground, δ

$$\varepsilon_a = \frac{\delta}{4 \times d} \quad (4)$$

The effect of the surface loads was found to cause strains over a height of 4 times the diameter of the stone column (*4d*).

6. A suitable geosynthetic that can develop the long-term allowable design tensile strength (T) within a strain level of ε_c can be chosen for the encasement.

Based on the above design procedure, design chart indicated below Figure 7 is developed in non-dimensional form for a range of realistic soil parameters. Area replacement ratio is computed from spacing *s*, and diameter, *d* of the column.

Area replacement ratio = $0.907 \times \left(\frac{d}{s}\right)^2$ for triangular grid

Area replacement ratio = $0.786 \times \left(\frac{d}{s}\right)^2$ for square grid

For the design of geosynthetic encased stone column, the following steps will be of use along with the design chart.

- For the assumed spacing and diameter, calculate the area ratio.
- For the properties of the clay soil (c), friction angle of the stone aggregate (φ) and the area ratio, normalized tensile force [$T/(d \times p_o)$] required for the encasement is read from the chart. For other soil properties, linear interpolation may be used.

It is to be noted that in the above design procedure bearing support is conservatively removed as ESC are suited for extremely soft soils. The load improvement of encased stone columns was about 3-5 times that of the ordinary stone column depending on the stiffness of the encasement used. Stone column are normally seen in the aspect of taking vertical loads, at the same time because of the least lateral support provided by the surrounding soft soil shear loads are generated in the field especially in the case of embankments. In that aspect, Shear load capacity was examined (2008) by conducting laboratory experiments and encased stone columns were found to produce better results than ordinary stone columns. The encased stone column behaviour was like a semi-rigid pile.

Gneil and Bouazza (2009, 2010) conducted laboratory experiments to verify the effect of partial encasement in both single and group of stone columns. A steady reduction in vertical strain was observed for increase in length of encasement for the above-mentioned categories of stone columns. With increase in column stiffness, the decrease in strain was in the order of 80 %.
The authors have also studied the construction aspects of geogrid encased stone column through small-scale laboratory experiments. It was suggested to have an overlap of geogrid rather than having the connection through welding. Biaxial geogrids served better as per the investigation conducted. The authors finally commented that in order to achieve a sufficient level of fixity, columns should

generally be constructed with 100% circumferential overlap. From the findings, further research is recommended to refine this overlapping methodology and to determine the minimum number of junctions required in the section of overlap.

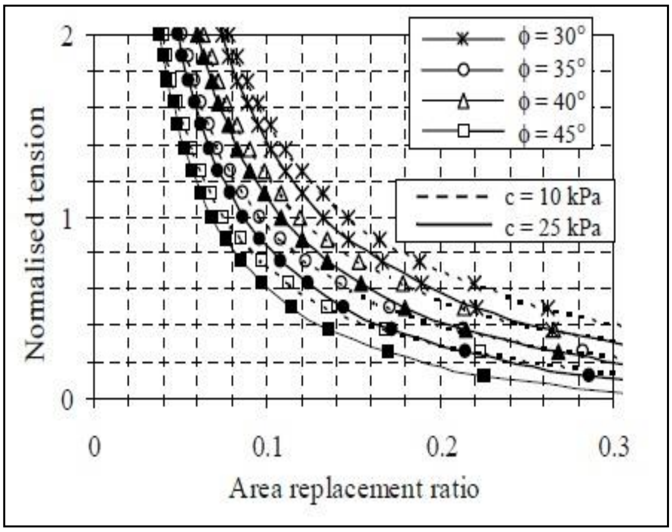

Figure 7 Design Chart for Geosynthetic Encased Stone Column after Murugesan and Rajagopal (2008)

Ali et al. (2010, 2012, 2014) extensively conducted laboratory experiments on stone columns with and without encasement on floating and full penetration basis. Parametric studies revealed that smaller diameter columns gave better performance and there was no improvement in bearing capacity for a stone column length greater than 6 times diameter in the study conducted.

The investigation was further continued by the authors with both floating and end bearing columns with geogrid encasement and horizontal strip reinforcement. The geogrid encasement offers improvement by providing lateral confinement and the strip by improvement of friction mobilization. For end bearing columns the wrapping of the entire column with geosynthetic seems to give better results than horizontal strips. But for floating columns both the types of reinforcement say full wrapping (vertical encasement) or horizontal strips yielded same results. The authors opine that full encasement increases the failure stress in the columns when compared to partial encasement.

Ghazavi and Afshar (2013) investigated the bearing capacity of encased (both single and group) stone columns through laboratory studies using three different diameters say 60,80,100 mm and validated the results numerically. It was observed that for single columns the failure was by bulging (usually occurring at a depth of D to 2D from column head) and for group, it was by both bulging and lateral deformation. Numerical results revealed that the load ratio (ultimate load from reinforced fill / ultimate load from soft soil without stone column) in encased columns with same area replacement ratio depends on the geometrical configuration of columns.

Dash and Bora (2013) observed the effect of reinforcement length on bearing capacity through laboratory experiments on floating and end bearing stone columns. The floating columns exhibited a 5 fold increment in capacity with 60 % coverage length of stone column, whereas the improvement was 3 fold for full coverage (length) of encasement. For end bearing columns, full encasement showed a better response than partial encasement.

Hong et al (2016) conducted model tests on individually encased stone columns varying encasement stiffness and strength. The analytical solutions provided by cavity expansion theory are in line with the calculated bearing stresses in the encased columns. For a column with low encasement stiffness, the failure is by bulging and for a high stiffness encasement failure in the form of uniform lateral deformation was observed. A column with ruptured geotextile still provides higher bearing capability than an uncased sand column.

The authors have insisted a field study to further validate the experimental findings.

2.1.3 Field studies on Encased stone columns.

Compared to laboratory and numerical studies field oriented studies are less in number. Discussed below are the few works on the field aspects of encased stone columns.

Raithel and kempfert (2000) worked on the practical aspects of the design of deep geotextile coated sand columns for the foundation of a dike on very soft soils. Tests were conducted on small and full scale and it was observed that the foundation adopted has considerably increased the shear strength by an average factor of 3.5.

Raithel and kempfert (2001) presented the implementation of a new foundation system 'Geotextile-Encased Columns' (GEC) for the foundation of a dike on very soft sludge for land reclamation at the Elbe River in Hamburg, Germany. The plant site of the airplane dockyard in Hamburg-Finkenwerder was enlarged by approximately 140 ha, in particular for the production of the new Airbus A 380. The area extension is carried out by enclosing the polder with a 2.4 km long dike. The necessary dike foundations were realized by about 60000 geotextile encased sand columns with a diameter of 80 cm, which was sunk to the bearing layers at depth between 4 and 14 m below the base of the dike footing. Due to the foundation system 'Geotextile Encased Sand Columns' (GEC) the dike could be constructed on the subsoil with very small shear strength and high deformability in a construction time of approximately 9 months.

Raithel et al.(2005) assessed the effectiveness of encased columns in relation to the conventional column foundation, the results of the test according to (Raithel 2000) and executed projects are compared with the results published on granular piles. By combining geotextile encasement and horizontal reinforcement (load transfer mat) it is proved that foundations can be constructed even in sludge. The authors insist a full-scale field study coupled with laboratory measurements to forecast settlement reduction.

De Mello et al. (2008) reported the first use of geosynthetic encased sand columns in South America. A double lane highway had to be extended along a relatively wide valley, where recent soft clayey and loose sand alluvial sediments, with a thickness of up to 10 m, were deposited in river meanders. On a 140m long final stretch, the road embankment had to be raised up to 8m height. In this stretch, different solutions were evaluated, and the most interesting proved to be use of the geosynthetic encased sand columns. To ensure lateral stability, a basal geogrid reinforcement was also incorporated in the solution.

The following construction sequence was used to build the embankment.

- Inclinometer Installation
- Geosynthetic encased sand column installation
- Load cell and Extensometer installation
- Basal geogrid installation
- Settlement gauges and Horizontal Inclinometer Installation
- Fill placement
- Pavement and superficial drainage construction.

Construction was finished, the highway is performing properly and the solution was considered successful.

Yoo and Lee (2012) conducted field load tests at two different sites to test the performance of geogrid encased columns in soft ground. The effect of the geogrid encasement length and column strain is investigated. In addition, isolated Geogrid Encased Stone Column (GESC) behaviour was compared to rammed aggregate pier (RAP) and conventional stone column (CSC) behaviour. The results show that additional confinement provided by the geogrid encasement increased the stiffness of the stone column and reduced the settlement of the soft ground. Also, bulging of the GESC was observed to occur directly beneath the base of the geogrid encasement. Geogrid hoop strain reaches its maximum value within a depth of 1.0D from the top of the column and decreases as the depth increases. By measuring hoop strain in this test results, it can be seen that the critical encasement length of geogrid is 2–3D. The improvement in the performance of GESC was found to be significant, even with partial encasement.

Alexiew et al.(2014) monitored a full-scale bridge abutment on soft soil supported by Geosynthetic Encased Columns. The field performance was monitored with pressure cells, electrical piezometers, inclinometers and settlement plates. The collected database is interpreted in order to estimate the horizontal earth pressure over bridge border foundation piles. Sand columns have proven to be useful in providing drainage for reducing the potential for building up of excess pore water pressures in the clay layer, in reducing the magnitude of settlements and in reducing the maximum horizontal earth pressure acting on structures adjacent to compacted fills.

Almeida et al. (2015) constructed an embankment of height 5.35 m in soft soil by geotextile encased sand columns. The construction was performed in four stages over 65 days, resulting in a total applied stress of around 150 kPa. The soft soil and the encased columns were instrumented to measure surface settlements, excess pore pressure, surface vertical stresses, and radial deformation of the geotextile encasement. Stress concentration and the difference in settlement between the top of the encased columns and the soft soil were studied. Results showed that the differential settlement increased as the embankment height increased and when the excess pore pressure was being dissipated. This contradicts the earlier conclusions drawn by the authors (2013, 2014) through numerical studies wherein the differential settlement decreases with increase in height of the embankment. Due to soil arching, the vertical stress supported by the encased column was over two times greater than the stress transmitted to the soft soil. Also, vertical stress on the encased column increased as consolidation progressed, whereas it did not vary significantly on the soft soil.

3. Observations from the Published Literature

From the above-detailed discussions on the analytical, numerical, lab and field-based studies by various researchers on encased stone columns, significant observations noted in the study. In order to have a good understanding of the encased granular column behaviour, it's quite necessary to assess the various parameters which are of importance namely, The undrained shear strength of the soft clay, Friction angle of the aggregates, Diameter and Length of the stone column, Modulus and Length of the Geosynthetic Encasement, Method of Reinforcement, Method of Loading. The aforesaid parameters are discussed briefly in comparison with ordinary granular columns to appreciate the advantage and also to gear up the use of encased granular columns as foundation elements.

3.1 Undrained Shear strength of Soft clay

One of the most significant factors that influence the ordinary granular column behaviour is the in situ- undrained shear strength C_u. In fact, the innovation of encased stone column using geosynthetics started when the ordinary stone columns started losing its drainage characteristics when loaded via intermixing with the in situ soft clay leading to clogging of the aggregates resulting in loss of aggregates and reduced load bearing capacities. In the case of encased stone columns, the above said limitation is overcome as researchers have reported the installation of geosynthetic encased columns in a soft sludge of (C_u < 15 kPa) Raithel and Kempfert 2001.Its also to be noted that in the case of laboratory studies under controlled environment encased stone columns can be installed even at a Cu ~ 5 kPa Malarvizhi and Ilamparuthi (2007) (Murugesan and Rajagopal (2007) and others which are in fact a slurry rather than a soil. Encased granular columns can perform well even with soils like peat Raithel and Kempfert (2000). Hence it gives a feel that no lower limit on undrained shear strength exists for encased stone column installation. However, from the authors view point a min of around C_{uu} ~ (20 - 30) kPa is necessary for the safe operation of installation equipment and construction workers.

3.1.1 Friction angle of aggregates

The aggregate friction angle is an important member which helps the stone column to carry the imposed structural load. It's a known fact that the friction angle is expected to vary based on angularity, density and surface characteristic of the aggregate. In general, with the increase in friction angle of the granular medium, the load carrying capacity is found to improve with respect to an ordinary granular column. When it comes to encased granular column not much of the influence was observed on load carrying aspects from the studies as compared to that of the other parameters/variables described below. The numerical investigations conducted by keykhosropur et al (2012) by varying the friction angle from 30°-45° yielded similar results. Khabbazian et al.(2010) also concluded to increase the geosynthetic stiffness rather than improving columns properties for better load-settlement behaviour.

3.1.2 Diameter of the encased stone column

In the case of ordinary granular columns, stone column installation is itself a self-compensating process, which means softer the soil and greater will be the diameter required. This increase in diameter is to account for the loss of aggregate and to improve the drainage function in extremely soft soils. So in granular columns greater the stone column diameter, higher the capacity.

In the case of encased granular columns it is the other way around, lesser the diameter higher is the load bearing capacity. The reason owes to the inability of large diameter stone column to offer additional confining stress Murugesan and Rajagopal (2007) and others. But significant increase in failure stress is reported with an increase in diameter of both ordinary and reinforced granular columns Ali et al (2012).

3.1.3 Length of the stone column

Mostly Ordinary granular columns are preferred with longer lengths (end bearing) rather than short floating columns to avoid punching shear failure under excessive loading. As mentioned earlier, end bearing is again not a strict requirement for granular columns as the requirement is only to bye-pass the compressible layer if any in between. On an average, the length of stone columns accomplished in South Asian Countries like India is ~ 15m IS 15284 part 1 (2003). The failure mechanism of an ordinary granular column in the cases for short, long, end bearing and floating are indicated in Fig.2

In the case of encased granular columns, end bearing columns are expected to perform better in load sharing aspects Ali et al.(2012, 2014) when compared to that of floating columns a behaviour, similar to that of ordinary granular columns is seen. Unfortunately, very few research has been conducted on floating encased granular columns Ali et al (2012, 2014) Dash and Bora (2013). The former has noticed that irrespective of whether ordinary or geosynthetic reinforced granular column the floating columns fail by punching shear failure, which witnesses that long encased end bearing granular columns are much beneficial over floating columns. Moreover, failure stresses were observed to be the same for both floating and end bearing columns when the length of the granular column $L \geq 9D$. The ideal length of encased granular columns may be about ~ 8D to10D as observed from the studies conducted. Also, geogrids were found to be ideally suited for end bearing type and geotextiles being suited for floating type of columns.

3.1.4 Modulus of the geosynthetic encasement

One of the prime factor which dominates over the other factors of encased granular column behaviour is the geosynthetic stiffness. Many researchers have worked on this aspect through their parametric studies. a wide range of values was tested by Murugesan and Rajagopal (2006) and others starting from 50 kN/m till 10,000 kN/m. The observations include that the overall stiffness of the foundation is increased with increase in stiffness values of the geosynthetic. Additionally, a large amount of lateral (confining) stresses are being mobilized with increment in stiffness leading to sharp decrement in the lateral bulging.

Interestingly the influence of shear strength of the in-situ surrounding soil and granular column friction angle properties on encased granular column is noticed to be less with the increase in stiffness values of geosynthetics. From this aspect, it is clear that encased granular columns with high geosynthetic stiffness can mask over the performance of shear strength of the soil and granular column properties. Also with encasement, the end bearing granular columns attract more stress concentration leading to an efficient load transfer to competent strata.

There is another school of thought by Pulko et al.(2011), Zhang and Zhao (2014) that selection of geosynthetic selection should be based on stone column diameter, shear strength of the soil and column spacing. Yoo (2010) reported the critical encasement stiffness beyond no further increase in load capacity to be ~1500 - 2000 kN/m.

3.1.5 Length of Geosynthetic Encasement

In the case of ordinary granular columns the depth of lateral bulging accounts to ~ 4D from GL with the maximum at 2D where (D) being the diameter of the column as depicted from Fig.2. One of the primary aims of the geosynthetic employed is to arrest the lateral bulging in a way to effectively perform in increasing the load sharing capability.

Encased and partially encased granular columns are reported to perform better than ordinary granular columns. A variety of studies have been reported in full as well as partial encasement of granular columns in both floating and end bearing aspects. Murugesan and Rajagopal (2007), Khabbazian et al.(2010), Yoo and Lee (2012) observed from their research that the effective (height) length of encasement from the top surface of the column is around 2D-3D beyond which no appreciable improvement is noticed and have concluded that encasement length is effective only till the depth of bulging and that is where confinement is needed.

Contradicting the above study Yoo and Kim (2009) have reported that with encasement in the granular column, the lateral bulging shifted towards the bottom which necessitates the coverage length till the bottom rather than that of partial encasement.

Ali et al.(2012) also presented similar results in support of full-length encasement to achieve higher failure stresses irrespective of whether it is floating or end bearing. Fattah and Majeed (2009) have reported similar observations like Ali et al. (2012) as the bearing capacity improvement was observed even for a length equivalent to 8 times diameter. Dash and Bora (2013) identified from their laboratory studies that partially encased floating stone columns perform better than fully encased columns. This clearly shows that further laboratory and field studies are needed to have a better understanding and reliability.

3.1.6 Method of Reinforcement

The reinforcement methods are of two types with respect to geosynthetics in granular columns from the reported literature. Majorly the vertical wrapping or encapsulating type is being reported and guaranteed with promising results. The other minor one being horizontal strip type or laminated Disc type reinforcement spaced at regular vertical intervals.

Very few researches have been reported with horizontal strip/disc type reinforcements like Ali et al. (2012,2014) and Almeida et al.(2014). With both the types of reinforcements improvement in bearing capacity and reduction in settlements are observed, but for a given geosynthetic stiffness and area replacement ratio vertical encasement (wrapping) functions better than horizontal strip or disc type reinforcement. Nevertheless, the optimum vertical spacing S_v required in horizontal disc type reinforcements to achieve the same performance as that of vertical encasement is reported to be dependent on stiffness of reinforcement and length of the column. Ali et al. (2012)from their studies have reported the best configuration of placement of horizontal strip is up to 50 % of the column length with a vertical spacing equal to 0.5D and the same is reported as 0.25D by Almeida et al.(2014).

3.1.7 Method of Loading

The loading of granular columns both ordinary and reinforced can be either one of the two.

a) Loading of the Granular column alone.

b) Embankment type of loading.

Granular columns are seldom loaded alone and most of the time embankment type of flexible loading is expected to be shared by granular columns. As said earlier, the parameter of stress concentration ratio (n) becomes essential in this discussion as encased granular columns attract higher stress concentration ratio than the ordinary granular columns.

Critical encasement length is reported to be not applicable for embankment loading type encased columns Yoo (2015). Further, Lo et al (2010) concluded that the role of stone columns in taking fill loading evolves with time and long term field monitoring is essential. This suggests the research community have more real-time field studies in portraying the stress distribution behaviour of encased stone columns, especially in embankment loadings.

4. CONCLUSIONS

It's evident from the above discussions that granular columns, when encased, have multiple benefits. But still, for a better understanding of the interdependence of parameters like Soft soil, Granular aggregates, Geosynthetic member and loading on one another more laboratory and field oriented studies are necessary which can, in turn, bring a better understanding and promote the usage of the same in the construction Industry.

1. Smaller diameter encased columns perform better compared to larger diameter columns.

2. Partial encasement has brought significant load sharing performance like fully encased columns and is even better solutions than ordinary granular columns in soft grounds.

3. End bearing stone columns with full encasement share higher loads over floating granular columns. Encapsulation is better than horizontal reinforcement layers for improving the performance of granular columns.

4. More full-scale instrumented field studies are necessary to have a better understanding of the encased granular columns.

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