Analysis of the performance of encased granular columns based on laboratory and field test data

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ABSTRACT: The coastal deposits all around the world are often marine clays which are in soft to very soft consistencies. They are one such variety of problematic soils characterized by low bearing capacity and high compressibility that necessarily require treatment to enhance their strength and stiffness properties. A wide variety of ground improvement techniques are practiced currently in enhancing the engineering behaviour of problematic soils which include surcharge pre-loading, PVD, granular columns, lime stabilization and recently Vacuum methods etc. Out of these methods, the granular columns have provided promising solutions in soft clay deposits. More recently with the advancements in polymer industry synthetic planar and 3D products have emerged in the field of geotechnical engineering which is indeed an added advantage nowadays in combination with the conventional methods. Geosynthetic encased granular columns are one such recent advancements that can effectively tackle soft soil problems. Very small numbers of field based trials related to geosynthetic encased granular columns are reported in the literature which indirectly indicates the lack of understanding the mechanism of the same. This paper will discuss concisely on the parameters which influence the effectiveness of geosynthetic encased granular columns in soft grounds by reviewing the data collected from published literature. Discussions on the key parameters like the shear strength of soft soil, diameter, length of the granular column, length of the geosynthetic encasement etc., will be included. The analysis will include comparison of the data with the procedures given in German design code (EBGEO) for encased granular columns.

Keywords: Granular Columns, Encased, performance, EBGEO

1 INTRODUCTION

Soft clay deposits are geologically young and are found in several parts of the world. Often their natural moisture content is close to or greater than their liquid limit values. They are usually problematic for a civil engineer due to their low bearing capacities and excessive settlements. These weak deposits require one or more ground improvement (modification) techniques to efficiently tackle the applied loads. Many ground improvement techniques are adopted to improve their mechanical behaviour out of which granular column (also known as stone column, aggregate pier) have given promising and effective solutions in addressing the problems of soft soils. The advantages of the granular column technique include simplicity, functionality as a drain, acceleration of the consolidation rate, etc. Nevertheless, when these granular columns are installed in very soft clays (< 15 kPa), the column formation is difficult resulting in loss of aggregates leading to a non-uniform diameter of the column and contamination of the granular medium with soft clay soil leading to reduction in strength and permeability. These limitations can be effectively tackled by encasing the granular column within a geosynthetic.

This paper discusses the mechanism and advantages of the geosynthetic encased granular column from published literature. Recently German Geotechnical Society has published the Recommendations for Design and Analysis of Earth structures using Geosynthetic Reinforcements – EBGEO (2011) which is the only code available for the design of geosynthetic encased granular columns. A discussion on the same is also included briefly.

2 LABORATORY AND FIELD BASED STUDIES ON GEOSYNTHETIC ENCASED GRANULAR COLUMN

Pioneering attempts on geosynthetic encased granular column studies were initiated by **Van Impe (1989)**. This analytical procedure focuses on the tensile strength of the reinforcement. Then after the laboratory studies have started budding followed by field studies as early as 1994. The key concept of the inter-dependence of granular column, soft clay and the reinforcement with respect to encased granular column is discussed in the following sections.

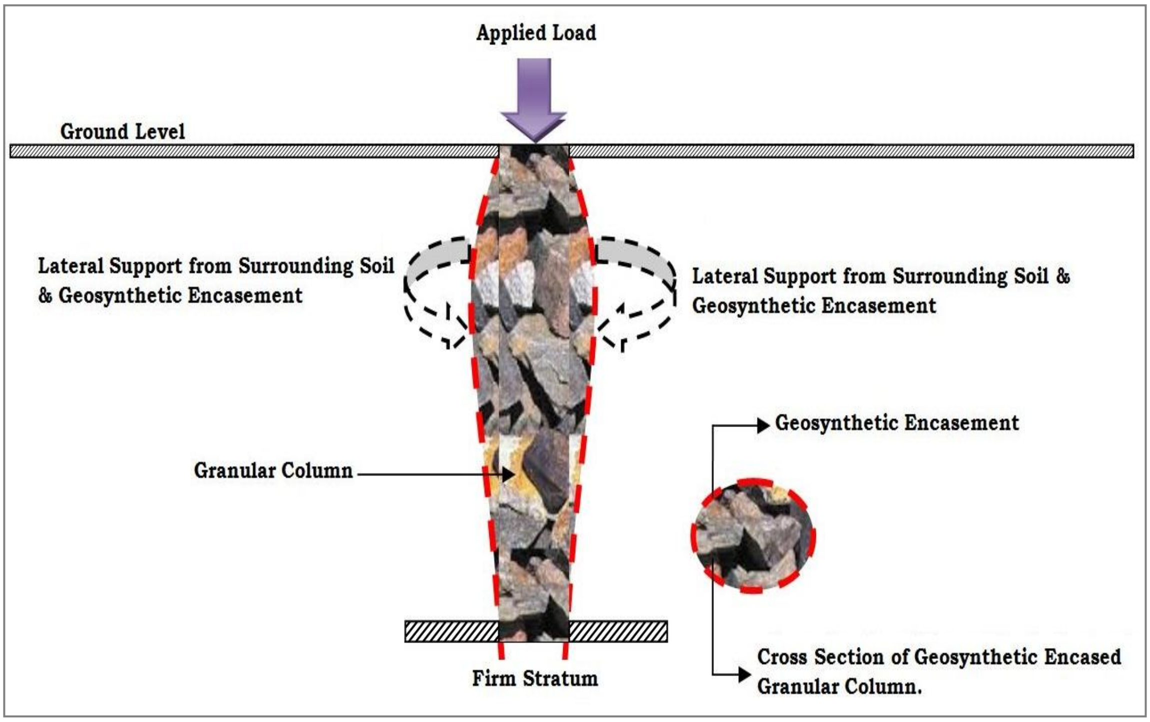

Figure.1. Single Geosynthetic Encased Granular Column – Schematic Representation.

2.1 *Laboratory Studies*

Very large numbers of papers were published in the past from laboratory model tests on granular and encased granular columns. Some of these papers are discussed here.

Sivakumar et al. (2004) conducted triaxial tests on model sand columns in clay. Two series of tests were conducted out of which the first series include tests on ordinary sand columns without reinforcement and the second with encasement using geogrid reinforcement. Kaolin clay with undrained strength of 30 kPa was used in the study. The ℓ/d ratio (length to diameter ratio) adopted was 3.75 and 6.25. Load bearing capacities increased with increase in column length. Geogrid reinforcement produced significant increase in load carrying capacity.

Malarvizhi and Ilamparuthi (2004) presented the load versus settlement behaviour of clay bed stabilized with encased and conventional stone column. Marine clay with high plasticity reinforced with compacted granite chips was used in the study. Investigations were conducted for end bearing and floating stone columns. An increase in load carrying capacity irrespective of whether the column is end bearing or floating was observed. The ℓ/d ratio of floating columns had less effect on the carrying capacity of stone columns.

Black et al. (2007) conducted laboratory tests on 80 mm diameter reinforced stone columns in weak deposits. A tubular wire mesh was used to encase the aggregate column installed in peat. The peat was sandwiched between two sand layers. The soil bed was formed first followed by installation of stone column without vibration. A large steel framed wooden box of dimensions 1500 mm x 700 mm x 700 mm was used in the study. A considerable improvement in load and settlement response was noted.

Gneil and Bouazza (2009) performed laboratory tests in kaolin clay using an enlarged consolidation cell. The study used frozen sand columns of 51 mm diameter. The sand columns were encased with fiber glass and aluminium mesh. Replacement technique was adopted for installing the columns. A substantial radial bulging was noticed directly below the base of the encasement. For columns with partial encasement bulging was noticed all along the non - encased section.

Based on the laboratory testing, the authors have presented a proposal for the construction of geogrid encased stone columns (2010).The outcomes from the study indicated that biaxial geogrids are best suited for the encased stone column foundation system. The column stiffness and capacity was found to increase with increase in encasement stiffness.

Murugesan and Rajagopal (2007, 2008, and 2010) conducted experiments extensively on ordinary and encased stone columns in both single and group. The marine clay located in the lake bed of the IIT campus was used in the study. The ordinary stone columns were found to exhibit a strain softening behaviour on par with the stiff response observed from the encased granular columns. The circumferential (hoop) strains were observed only near the top of the stone columns. The encasement effect of a smaller diameter column was better over the larger diameter columns. A picture showing the unit cell load test on stone column is shown below.

Though the stone columns are designed for carrying vertical loads, soil movements occurring in the field can induce shear deformations in the stone columns. The authors (2008) have investigated the shear loading capacity of ordinary and encased granular columns. The encased granular columns act like semi-rigid pile by confining the aggregates. A qualitative improvement in the shear stiffness of the stone column due to geosynthetic encasement was observed.

Sivakumar et al. (2010) observed the effects of granular columns in compacted fills. The 1-d tests were conducted using crushed basalt as stone column. The diameter and *ℓ/d* ratio were correspondingly 32 mm and 7.81. A notable increase in bearing pressure and decrease in settlement was noticed.

Ali et al. (2010, 2012, and 2014) studied the behaviour of ordinary and encased stone columns for both end bearing and floating columns through laboratory experiments. The performance of the granular columns in terms of carrying capacity ceased when the length of the column was increased beyond 6 times the diameter of the column. Additionally, the fully encased granular columns were able to have higher failure stresses over partial encasement.

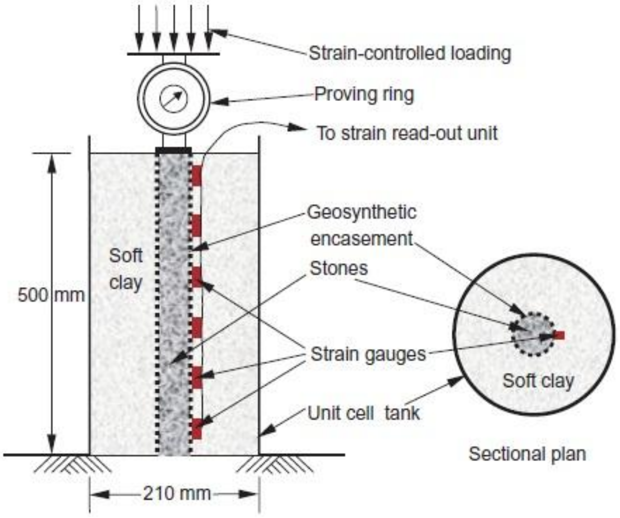

Figure.2. Unit cell load test on stone column after Murugesan and Rajagopal (2007).

Najjar et al. (2010) observed the effects of sand columns on the undrained response of soft clays. CU Triaxial tests were conducted in sand columns of 20 mm and 30 mm diameter. The area replacement ratios adopted for the study are 8% and 18% respectively. Replacement method was adopted for constructing the frozen sand column. The encasement of sand columns with a geotextile fabric improved the apparent cohesion of the composite system in particular for small area replacement ratios.

Dash and Bora (2013) performed laboratory studies to understand the influence of geosynthetic encasement on the stone columns floating in soft clay. The authors observed that short ordinary granular columns (ℓ≤ 3d) punched inside the soft clay and long columns (ℓ>3d) resisted the foundation pressure without considerable movement and underwent large scale bulging. Significant improvement in bearing capacity was obtained from the test results when the granular columns were encased with geosynthetics. The superior performance of partially encased floating granular columns over fully encased floating granular columns was observed.

Ghazavi and Afshar (2013, 2014) studied the bearing capacity of geosynthetic encased stone columns through laboratory experiments. The main scope of the paper was to compare the effectiveness of vertical encapsulation of stone columns for various stone column diameters 60, 80 and 100 mm. The laboratory studies were accompanied by numerical analysis to study the scale effects of the tested stone columns. The observations from the studies include improved performance of geosynthetic encased columns and increment in stress concentration ratio of columns.

The authors continued to study (2014) the effectiveness of the vertical and horizontal reinforcements in granular columns. The bearing capacity was found to increase with both horizontal and vertical reinforcements and in particular with increased strength of reinforcements. The governing failure mechanism observed in both the type of reinforcements was lateral bulging and it is reduced with increased strength of geosynthetic.

Hasan and Samadhiya (2016) presented the results of experimental and numerical analysis on geosynthetic reinforced floating granular piles in soft clays. Laboratory experiments were conducted on vertical, horizontal and combined vertical-horizontal reinforced granular piles. Unit cell concept was simulated around each granular pile by assuming piles in a triangular pattern. The diameters of the granular piles were 75 and 90mm respectively. For vertical encapsulation, a seamless woven geotextile throughout the length of the pile was adopted. For horizontal case, a circular geogrid strip having lesser diameter (10 mm) than that of the granular piles was adopted in the study. Improved performance of geosynthetic encased granular piles was observed from the laboratory studies. Additionally, for combined vertical and horizontal reinforcement the spacing of geogrid strips had negligible effect on ultimate load intensity.

2.2 *Field Studies*

The ultimate aim of any analytical, laboratory, numerical study is to transfer the same to the field practice. Discussed below are the very few field studies that have been conducted on the geosynthetic encased granular columns.

Raithel et al. (2002, 2005) reported the design and construction of the foundation of a dike on very soft soils using geotextile encased columns. It was a land reclamation project for production of new Airbus A 380 at the Elbe River in Hamburg, in Germany. The area extension was carried out by enclosing a polder with a 2.4 km long dike. The necessary geotextile encased column foundations were decided to be executed with 60,000 geotextile encased sand columns of 0.8 m diameter and 14 m length below the base of the dike footing. Appropriate instrumentation was used in the project like piezometers to measure the pore pressures and inclinometers for measuring the lateral ground movements. The authors have also presented the increase in undrained shear strength of soft soil between columns in comparison before and after column installation. Additionally, the authors have reported (2005) the state of the art report on construction on very soft soils with geotextile encased columns. Discussion on both FEM and analytical methods of design of encased columns are presented along with a table showing accomplished project with geotextile encased gravel/sand columns from 1996 to 2003. The effectiveness of the system in terms of settlement was assessed by plotting the area replacement ratio against improvement factor.

de Mello et al.(2008) presented the first use of geosynthetic encased stone columns in South America. The soil profile of the site includes recent soft clay deposits followed by loose sand alluvial sediments deposited by river meanders. Geosynthetic encased sand columns were provided as a solution along with a basal geogrid to ensure lateral stability. Analytical design methods proposed by **Raithel (1999)** were used in this project for the stone column design. The basis of this design method has its formulations from

Gionna and Jamiolkowski (1981). The formulations include the following simplified hypothesis,

1. Compatibility of vertical displacements of the column and of the adjacent soft soil.
2. Vertical displacement of the toe of the sand column and its settlement are negligible.
3. The geotextile has linear elastic behaviour.
4. The soft soil has an elastic behaviour with increasing stiffness with depth.

The design requirements are as explained. The maximum allowable settlement is 400 mm over a period of 30 years. Operational traffic load is 10 kPa. At the end of construction, the required safety factor for the embankment slopes is 1.25. The geosynthetic encased stone columns were successfully installed and from a practical view point, the performance of the foundation system was considered fully adequate and in compliance with the predicted behavior. The authors have reported significant differences between predicted and measured values of settlements and loads. The possible reasons for the attributed differences are due to placement of extensometers inside the column which has affected their stiffness. This technical paper concludes that the load transfer mechanisms between the embankment, soft soil and the granular columns is not fully clear and necessitates further research.

Yoo and Lee (2012) investigated the performance of geogrid encased stone columns in soft ground through full-scale load tests. Instrumented geogrid encased stone columns were installed in two different sites namely Gimhae and Pohang in Korea. The 0.76 m diameter stone column was constructed using crushed stones having uniformity coefficient Cu value of 2 and coefficient of curvature Cc of 0.2. Bi-axial geogrids with rectangular apertures were used as encasements. Instrumentation in the sites included the load cell, telltale reference plate, displacement transducer, inclinometer casing and strain gauge. Strain gauges were placed at different locations along the column length. Full-scale compressive load tests were performed using steel reaction beams with pairs of anchors. For applying the load over the circular footing resting on geosynthetic reinforced partially encased stone columns, a 300-ton capacity hydraulic jack was used. The authors have also discussed on the lateral displacement, hoop strain, ring tension force in the geogrid, where in which the maximum hoop strain of the geogrid encasement occurred at a depth equal to 0.7 times the diameter of the column. This supports the results from the laboratory analysis conducted by Murugesan and Rajagopal (2007). The critical encasement depth for a geosynthetic encased stone column was found to be between 2 to 3 times the diameters of the stone column.

Almeida et al. 2015 observed the behaviour of geotextile encased granular columns supporting test embankment on a soft deposit at Rio de Janeiro, Brazil. The height of the embankment was 5.35 m constructed in 4 stages applying a total pressure of 150 kPa. The granular columns and soft soil were instrumented to measure surface vertical stress, settlement, excess pore pressure and radial deformation of the encasement. Based on the study conducted it was observed that differential settlements occurred between column and surrounding soil due to soil arching and it increases steadily with increase in height of embankment and with consolidation of the soft soil. This behaviour was reported in the analytical solutions proposed by Raithel and Kempfert (2000). Additionally, the stress concentration values observed from the field test conducted revealed that the vertical stress carried by encased stone columns is 2.3 times as that of soft soils.

Schnaid et al. (2017) presented a case study on the usage of geotextile encased columns (GEC) as pressure-relief system for an instrumented bridge abutment in soft soil. This paper details out the entire monitoring program of a full –scale bridge abutment on soft soils supported by GEC and geogrid reinforced system. The field performance was monitored with appropriate instrumentation say with pressure cells, electrical piezometers, inclinometers and settlement plates. The diameter and tensile stiffness of the geotextile were 0.8m and 1900 kN/m. The installed sand columns have proved its usefulness in providing drainage to reduce the potential for building up of excess pore pressures in clay layers. Apart from the drainage function, the GEC's have reduced the maximum horizontal earth pressure acting on the structures. Finally, the 2D FEA (PLAXIS) has estimated the performance of the field instrumented embankment to a reasonable accuracy by capturing the characteristics of the soil and the extent of the reinforcement.

2.3 *Factors influencing the performance of geosynthetic encased granular columns*

The main factors influencing the performance and behaviour of the encased stone column are the undrained shear strength of the soft clay, aggregate friction angle, diameter and length of the granular column, tensile strength, length of the geosynthetic encasement, method of encasement etc.

The undrained shear strength of the soft clay is one of the prominent factors that necessitate the use of granular and encased granular columns. The shear strength range below which there is a difficulty in granular column formations as mentioned by **FHWA (1980)** is a C_u value less than 15 kPa. However the field studies have presented the installation of encased granular columns for a value as low as 5 kPa **Raithel et al. (2002)**. A nominal range may be between 10-15 kPa for avoiding the problems related to column formation and for mobilizing the equipment for column installation. The second important member which has a predominant influence over the other properties in terms of strength aspects of the encased granular column is the granular aggregate. Higher the friction angle of the aggregate, higher is the strength of the granular column. The nominal range of the friction angle is between 38^o to a maximum of 42^o. A slight increment in friction angle values is possible with ramming and compaction of the aggregates indeed it's difficult to implement it at the site. The average diameter of the encased granular column adopted in the field is around 800 mm to a maximum of 1540 mm as reported by **Raithel et al (2005)**. It is to be noted that the encasement has more effect on smaller diameter columns compared to larger diameter columns, **Murugesan and Rajagopal (2007).** The length of encased granular columns installed in various projects ranged between 15 m to 28 m.

The most dominant member that influences the encased stone column performance is the tensile modulus of the geosynthetic reinforcement. The reduction in lateral deformation of the encased granular column is mainly due to the confinement offered by the geosynthetic. The nominal range of values reported is from 100 - 4000 kN/m. Higher the tensile modulus of the geosynthetic higher is the resistance provided by the encased granular column against deformation. The predominant method of geosynthetic encasement in reinforcing the granular column is by vertical encapsulation. However, some laboratory studies have been reported by placing horizontal circular discs at equal vertical intervals. The vertical encapsulation type reinforcement is more frequently adopted in almost all the field studies.

3 RECOMMENDATIONS FOR DESIGN AND ANALYSIS OF EARTH STRUCTURES USING GEOSYNTHETIC REINFORCEMENTS –EBGEO (2011)

As mentioned earlier the EBGEO is the most recent and the one codal provision available for the design of encased granular columns. The formulation of design had its basis from **Ghionna and Jamiolkowski (1981), Raithel et al (1999)**. The Discussions on the geosynthetic encased column design is brought out under various heads starting from the method with which the column works. In general, the limiting values prescribed by the code are in line with the laboratory and field studies discussed above say, the undrained shear strength values are between 3 kPa – 30 kPa. The stiffness of the granular column is recommended to have 10 times of the higher values over the surrounding soft soil. A minimum column diameter of 0.4 m is recommended for the safe activation of governing circumferential tensile forces. The commonly adopted column diameter falls in the range of 0.5 m – 1.5 m. The length of the granular column is indirectly determined from the depth of the soft strata and is normally recommended to be from 3 m to 20 m. The axial stiffness of the geosynthetic has a governing impact over the other factors and it generally ranges from 1000 – 4000 kN/m.

The code does refer to the design recommendations stipulated to the encased granular columns like the provision of a minimum area replacement ratio of 10% and a minimum granular cover of approximately 1 m above the columns. In particular, a prior planning or analysis on foundation deformations during and after load applications by suitable measurements on a case to case basis is suggested. Additionally, placement of planar reinforcement at 0.3 m above the embankment base for providing global stability and to support load transfer in to encased columns is recommended. The planar reinforcement also acts as a supporting member in reducing the settlements.

4 CONCLUSIONS

Based on the discussions above, it can be understood that the geosynthetic encased granular column is a promising and an innovative technique especially for improving the capacity of soft soils on par with ordinary granular columns. The performance of the encased column is actually based on the interaction between the in situ soft clay, granular aggregates, geosynthetic member and the loading conditions. A Proper understanding of the interdependence of the above stated parameters is the key for predicting the bearing capacity and settlement behaviour to a reasonable accuracy. Hence further research and understanding is necessary especially on the load settlement behaviour of encased granular columns.

1. Encased granular column is an innovative technique useful especially for improving the capacity of soft clay deposits.
2. End bearing encased stone columns share higher loads over floating granular columns.
3. Partial encasement of the granular column has provided significant load sharing performance like fully encased columns. Nevertheless, full encasement can increase the failure stress.
4. Vertical encasement (encapsulation) of the granular column has provided better response and also advantageous over horizontal disc type reinforcements.
5. More full-scale field studies are necessary for understanding the behaviour of encased granular columns.

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