Reinforced granular column for deep soil stabilization: A review

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ABSTRACT

The engineering structures constructed on thick deposits of soft soil strata have problems of low bearing capacity, excessive total and differential settlement, lateral spreading etc. To mitigate such problems, different ground improvement techniques are available namely; vertical drains, lime/cement column, stone (granular) column etc. in view of their proven performance, short time schedule, durability, constructability and low costs. Stone column technique seems to be very suitable and favourable ground improvement technique for deep soft soil improvement. Further to prevent excessive bulging, squeezing of stone into soft soil, stone column can be encased with suitable geosynthetic. Another advantage of encasement is having high load carrying capacity and lesser settlement of composite foundation. This paper presents the current state of the geosynthetic encased stone column as a ground improvement technique. A review is provided aiming to: (a) identify key considerations for the general use of encased stone columns, (b) provide insights for design and construction, (c) compile the latest research developments. Case histories of field applications and observed field performance are cited to portray different stone column applications and observed effectiveness. The paper identifies areas where more research is needed and includes recommendations for future research and development.

Key words: Soft soil, Ground Improvement, Stone Column, Geosynthetic.

1. Introduction

The increasing infrastructure growth in urban and metropolitan areas has resulted in a dramatic rise in land prices and lack of suitable sites for development. As a result, construction is now carried out on sites which, due to poor ground conditions, would not previously have been considered economic to develop (Gniel and Bouazza, 2009).

Structures constructed on soft soils may experience problems, such as excessive settlements, large lateral flow sand slope instability (Abdullah and Edil, 2007).

A number of methods are available to improve the soft clay soils, such as stone (or granular) columns (Greenwood, 1970; Hughes et al., 1975) vacuum pre-consolidation (Indraratna et al.,2004), soil cement columns (Rampello and Callisto, 2003), pre-consolidation using pre-fabricated vertical drains (Shen et al. 2005), lime treatment (Rajasekaran and Rao, 2002) etc.

Among all these methods, the stone column technique is preferred because it gives the advantage of reduced settlements and accelerated consolidation settlements due to reduction in flow path lengths.

Another major advantage with this technique is the simplicity of its construction method (Murugesan and Rajagopal, 2006).

When the stone columns are installed in very soft soils, they may not derive significant load capacity owing to low lateral confinement. McKenna et al. (1975) reported cases where the stone column was not restrained by the surrounding soft clay, which led to excessive bulging, and also the soft clay squeezed into the voids of the aggregate. The squeezing of clay into the stone aggregate ultimately reduces the bearing capacity of stone column. Also the lower undrained cohesion value demand more stone column material.

Compacted gravel column techniques are usually limited to soft soils with undrained cohesion (undrained, unconsolidated shear strength) c_u or s_u 15 kN/m². The problem can be solved by confining (Figure 1) the compacted sand or gravel column in a high-modulus geosynthetic encasement (Raithel et al. 2000, Alexiew et al. 2005, di Prisco et al., 2006, Murugesan and Rajagopal, 2006).

Van Impe and Silence (1986) was probably the first to recognize that columns could be encased by geotextile. They produced an analytical design technique that was used to assess the required geotextile tensile strength. Earlier, details on this technique were provided by confining (Figure 1) the compacted sand or gravel column in a high-modulus geosynthetic encasement (Raithel et al. 2000, Alexiew et al. 2005, di Prisco et al., 2006, Murugesan and Rajagopal, 2006).

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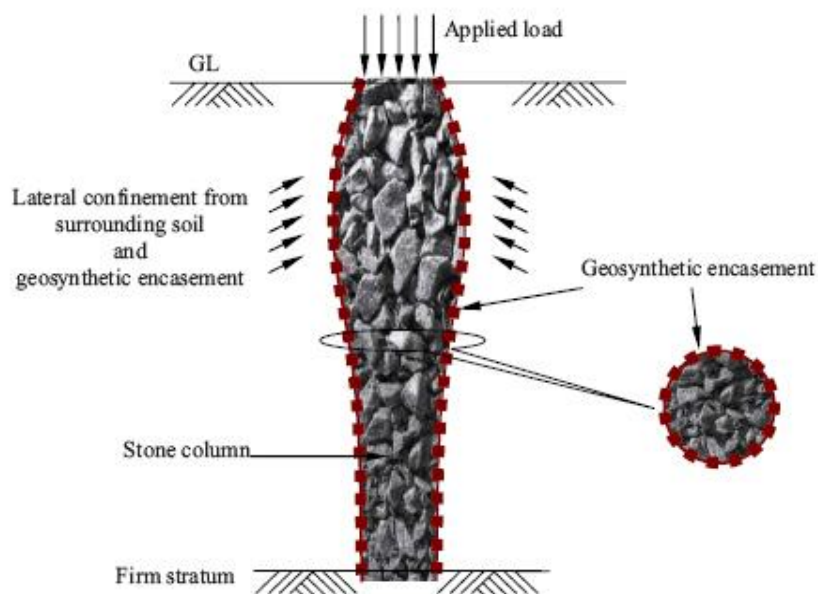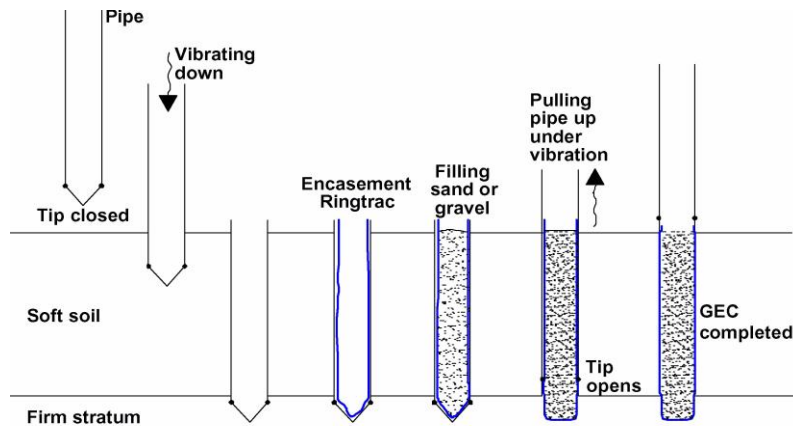

Figure 1: Schematic of geosynthetic encased stone column (Murugesan and Rajagopal 2006).

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2. Installation Methods

Two ways of installation of the geosynthetic encased stone columns are possible as explained in the following sections.
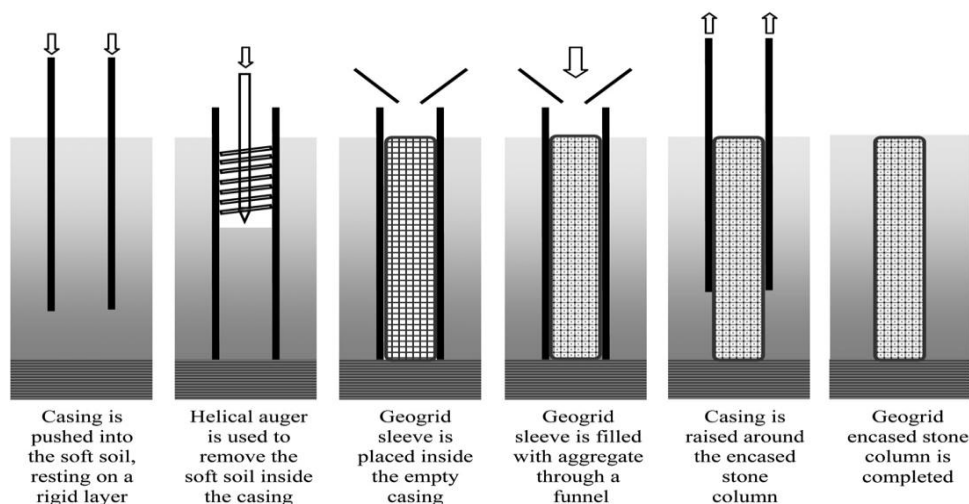
2.1 Displacement Method

Figure 2: Displacement Method (Alexiew, 2005).

The first option is the displacement method where a closed-tip steel pipe is driven down into the soft soil followed by the insertion of the circular weave geotextile and sand or gravel backfill. The tip opens, the pipe is pulled upwards under optimized vibration designed to compact the column. The displacement method is commonly used for extremely soft soils (e.g. $c_u < 15$ kN/m²).

2.2 Replacement Method

With the replacement method, an open steel shaft (usually diameter = 150 cm) is driven deep into the bearing layer and the soil within the shaft is removed by auger boring. The replacement method is preferred for soils with relatively higher penetration resistance or when vibration effects on nearby buildings and road installation have to be minimized.

Figure 3: Replacement Method (Gniel and Bouazza, 2010).

3. Model Testing

Al-Joulani (1995) investigated the performance of sleeve-reinforced stone columns through laboratory uniaxial and triaxial compression tests. Also, Wu and Hong (2009) carried out series of laboratory triaxial compression tests (140mm high $\times$ 70mm diameter) on sand columns (relative density 60% & 80%) encapsulated by geotextiles. They studied the effect of encapsulating sleeve on the deviatoric stress increase and the volumetric reduction. The mobilized cohesion and friction angle corresponding to various axial strains were studied to interpret the reinforcing effect.

Kempfert and Gebreselassie (2006) carried out small scale and large scale model tests in slight fiberous peat and medium grained sand to study the effect of heightening of groundwater level. They concluded that the horizontal support of the column and therefore the bearing deformation of the system slightly changed by the heightening of groundwater level.

Ayadat and Hanna (2005) conducted small-scale tests to study the performance of stone columns in collapsible soil, and presented theoretical models to predict the carrying capacity and settlement of these columns. It was observed that the collapse potential (CP) which is defined as the ratio of the settlement of the foundation on collapsible soil with/without stone column to the thickness of the collapsing layer, was remarkably reduced by the installation of a encapsulated stone column system.

Murugesan and Rajagopal (2007) conducted 1g model tests on single geosynthetic encased stone columns (ESC) & ordinary stone columns (OSC) having length to diameter ratio 5, 7 and 10. They concluded that the ESC having three to five times larger load carrying capacity than OSC. Malarvizhi and Ilamparuthi (2007) reported that the bearing capacity of encased stone column was 1.5 to 2 times that of ordinary stone column for length to diameter ratio of encased stone column equal to 9 and area replacement ratio equal to 17%. The comparison between the end bearing column and floating column revealed that the end bearing column having load carrying capacity twice that of floating column (Murugesan and Rajagopal 2008).

In the study of Kempfert and Gebreselassie (2006), it was found that as the area replacement ratio along with the geosynthetic stiffness has significant influence on the settlement reduction. The relationship between the modular ratio (ratio of modulus of encased stone column to modulus of clay) and the settlement for the various area replacement ratio was brought in the form of chart by Malarvizhi and Ilamparthi (2007).

Stiffness of the encased stone column (Murugesan and Rajagopal 2010) increases with the increase in the tensile strength of geosynthetic used for encasement as shown in figure 4. This is accordance with the finding of Malarvizhi and Ilamparthi (2007).
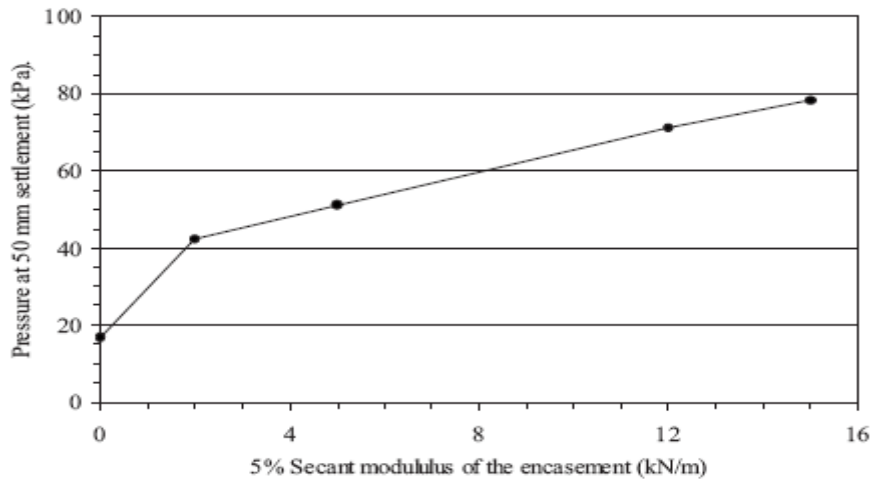
Figure 4: Influence of the modulus of encasement on the performance of the encased column (Murugesan and Rajagopal, 2010).

Gneil and Bouazza (2010) ascertained that biaxial geogrids are best suited to encased column construction, with higher strength of geogrids providing the stiffest column response and greatest robustness of the different encasement materials tested.

In the study of Murugesan and Rajagopal (2007), higher hoop strain was observed in the portion of bulging nearer to top of the stone column and going to decrease with depth. Similar results were quoted by Malarvizhi and Ilamparthi (2007) in their study, having maximum hoop stress at depth one diameter of stone column. Study revealed that as the diameter of stone column increases, the benefit of encasement decreases due to the reduction of hoop strain in the encasement.

The predicted stress concentration ratio on the encased stone column about five was observed by Murugesan and Rajagopal (2010).

Malarvizhi and Ilamparthi (2007) found that the hoop stress in the geogrid is less if the angle of shearing resistance in the column is more.

Murugesan and Rajagopal (2008) developed special test set up to closely simulate the stone columns subjected to lateral soil movements under embankment loadings in soft clay foundation soils. They observed that the ordinary stone columns were under gone shear rupture under lateral soil movement, on the other hand encased stone column were remain intact and have deflected similar to flexible pile.

The studies on the deformation behaviour of isolated, group encased stone columns were undertaken in the study of Gniel and Bouazza (2009). They observed that the isolated columns were failed by radial expansion below the level of encasement where as in partially encased group column, bulging was occurred along the full length of non encased section.

4. Numerical and Analytical Investigations

Khabbazian et al. (2009) carried out three dimensional finite element analysis of a single, end bearing geosynthetic encased stone column using computer program ABAQUS considering the influence of geosynthetic stiffness, column diameter, the elastic modulus and friction angle of the column material. It was concluded that effect of angle of internal friction and elastic modulus of stone column material was negligible on load carrying capacity of stone

column as compare to other parameters. The study depicted that maximum bulging occurs at a depth approximately equal to one diameter of the stone column. They observed, maximum bulging at twice the diameter of stone column as depicted in Figure 5.

Yoo and Kim (2009) reported that encased stone column reduced settlement about 50% that of untreated soil. Similar observation was reported by Alexiew et al. (2005), said that geosynthetic encased column foundation can reduce settlements up to 3 times more in comparison to solutions without treatment.

Fattah and Majeed (2009) found that the increase in strength of stone column occurs when it was encased by geogrid for (length/diameter) L/d = 8.
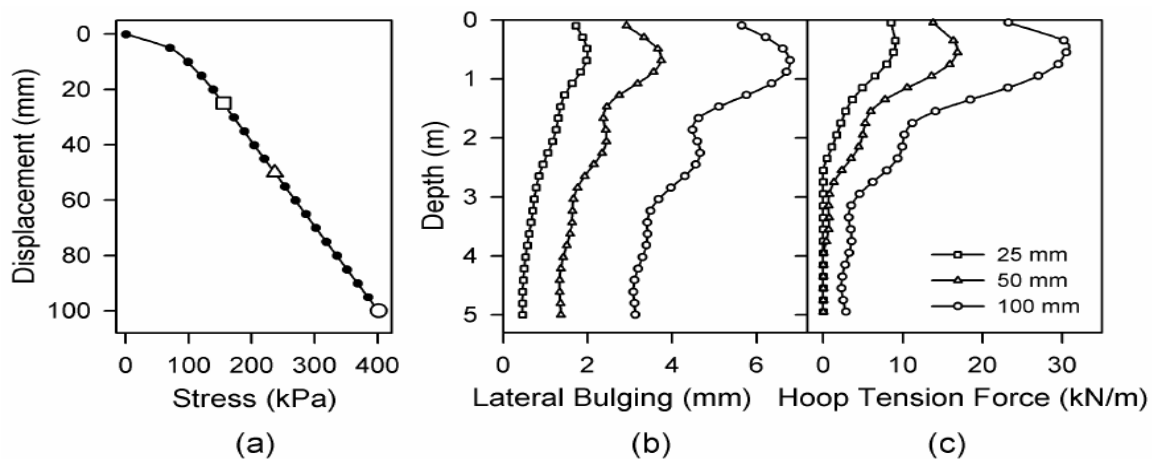
Figure 5: Stone column response: (a) displacement vs. stress, (b) depth vs. lateral bulging, and (c) depth vs. resultant hoop tension force (Khabbazian et al. (2009).

In the 3D numerical analysis done by Yoo and Kim (2009), it was observed that with encased stone column pore pressure developed was 3 times lesser than ordinary stone column.
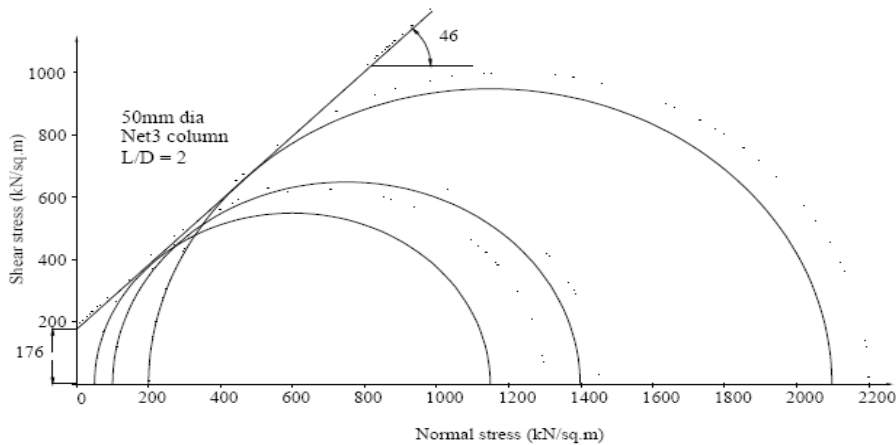
Murugesan and Rajagopal (2006) concluded that the encasement beyond depth equal to twice the diameter of the column does not lead to further improvement in performance. The report of Yoo (2009), suggests that the different encasement depths should be adopted for different loading condition i.e. short and long term. The governing equation for adequate geosynthetic depth (Z_f) was described by Wu et al., 2009 as under.

$$Z_f = \frac{2C_u + \sigma_f}{\gamma'_{clay}k_o + \gamma_w}$$

(1)

Where C_u = unconsolidated undrained cohesion, σ_f = confining pressure acting on the column provided by the expanded sleeve, γ'_{clay} = the submerged soil unit weight, γ_w = water unit weight, k_o = at rest earth pressure coefficient.

Triaxial tests on encapsulated stone column were simulated (Malarvizhi and Ilamparuthi, 2008) with finite element based software PLAXIS revealed that due to provision of encasement there was an apparent increase in cohesion (Figure 6) of the encased stone

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column. The smaller columns are stiffer and therefore the strength increase is more which is in tune with the finding of Khabbazian et al. (2009), Murugesan and Rajagopal (2006).

Figure 6: Mohr-Coulomb plot of 50mm diameter composite columns
(Malarvizhi and Ilamparuthi, 2008)

Additional studies on this topic include those of Kempfert and Gebreselassie (2006), Wu et al. (2009), Murugesan and Rajagopal (2010), Malarvizhi and Ilamparthi (2008), Lo (2008) and Pulko et al. (2010) discuss the various analytical approaches for the design of encased stone column.

5. Field Case Histories

The first application of geosynthetic encased stone column was reported by Raithel and Kirchner (2008) for the land reclamation of the airplane dockyard (EADS) in Hamburg approximately 346 acres for the production of the new Airbus A380. Table 1 summarised the completed project on the encased stone column.

Table 1: Accomplished project with geotextile encased gravel/sand columns

Year	Construction	Soft soil depth (m)	Diameter of Stone column (m)	Area replacement ratio (%)	Reference
1996	railroad embankment	5	0.154	25-30	Raithel et al. 2008
1996	railroad embankment	10	0.65	20	Raithel et al. 2008
1998	road embankment	5	0.80	20	Raithel et al. 2008
1998	railroad embankment	10	0.80	17	Raithel et al. 2008
1998	highway embankment	10	0.80	10	Raithel et al. 2008
1998	highway embankment	7	0.80	14	Raithel et al. 2008
1999	railroad embankment	11	0.80	15	Raithel et al. 2008
1999	highway embankment	10	0.80	10	Raithel et al.

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Year	Application				Reference
					2008
2000	bridge ramp	7	0.80	13-20	Raithel et al. 2008
2000	railroad embankment	6.5	0.80	15	Raithel et al. 2008
2000	railroad embankment	7	0.80	15	Raithel et al. 2008
2001	test field	10	0.80	5-20	Raithel et al. 2008
2001	test field	10	0.80	15	Raithel et al. 2008
2001	bridge ramp	15	0.80	13-18	Raithel et al. 2008
2001	bridge ramp	8	0.80	10-15	Raithel et al. 2008
2001	bridge ramp	8	0.80	15	Raithel et al. 2008
2001	flood protection dike	14	0.80	10-20	Raithel et al. 2008
2002	railroad embankment	6	0.80	15	Raithel et al. 2008
2003	railroad embankment	6	0.60	15	Raithel et al. 2008
2004	flood protection dike	12	0.80	15	Raithel et al. 2008
2008	landscape embankments	7.5	0.80	15	Brokemper et al., 2008
2008	test field	5	0.80	-	Lee et al., 2008
2009	foundation of a coal/cake stockyard	20	0.78	12	Alexiew, 2009
2009	test field	8.5	0.40	-	Araujo et al., 2009
2008	landscape embankments	7.5	0.80	15	Brokemper et al., 2008
2008	test field	5	0.80	-	Lee et al., 2008
2009	foundation of a coal/cake stockyard	20	0.78	12	Alexiew, 2009
2009	test field	8.5	0.40	-	Araujo et al., 2009

Additional case histories on the use of this technique to improve soft soil are reported by Nods (2005), Lee et al. (2008), Trunk et al. (2004) and Koerner (2008) etc.

6. Conclusions

Some of the major conclusions include:

1. The performance of encased stone column of smaller diameters is superior to that of larger diameter stone columns for the same encasement because of mobilization of higher confining stresses in smaller diameter stone columns.

2. The ultimate load capacity of the reinforced column increases with the stiffness of the reinforcement.

3. Geosynthetic encased stone column reduces settlement almost half that of untreated ground.

4. The ultimate bearing capacity of reinforced stone column and stone column treated beds are about three times and two times that of the untreated bed.

5. While theoretical analyses and model testing results indicate that geosynthetic encased stone column methods can be efficient for soft soil improvement, well-documented case histories of successful utilization are rather limited. There remains a great need for well-documented data sets of field performance scenarios.

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