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Field behaviour geotextile reinforced sand column

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Abstract. Stone columns (or granular column) have been used to increase the load carrying capacity and accelerating consolidation of soft soil. Recently, the geosynthetic reinforced stone column technique has been developed to improve the load carrying capacity of the stone column. In addition, reinforcement prevents the lateral squeezing of stone in to surrounding soft soil, helps in easy formation of stone column, preserve frictional properties of aggregate and drainage function of the stone column. This paper investigates the improvement of load carrying capacity of isolated ordinary and geotextile reinforced sand column through field load tests. Tests were performed with different reinforcement stiffness, diameter of sand column and reinforcement length. The results of field load test indicated an improved load carrying capacity of geotextile reinforced sand column over ordinary sand column. The increase in load carrying capacity depends upon the sand column diameter, stiffness of reinforcement and reinforcement length. Also, the partial reinforcement length about two to four time's sand column diameter from the top of the column was found to significant effect on the performance of sand column.

Keywords: soft soil; ground improvement; ordinary sand column; geosynthetic reinforced sand column; field load test

1. Introduction

Men do not have any control on the process of soil formation. The existing soil on a given site may not be suitable for supporting the desired facilities such as buildings, bridges, dams, and so on because safe bearing capacity of a soil may not be adequate to support the given loads. The soil properties of such deposit have to be improved in order to make them suitable to support the given loads. Various ground improvement techniques have been developed to improve the soil properties in these sites (Chu *et al*. 2000, Rampello and Callisto 2003, Indraratna *et al*. 2004, Abuel-Naga *et al*. 2006, Bergado and Teerawattanasuk 2008, Chen *et al*. 2008, Rowe and Taechakumthorn 2008, Vashi *et al*. 2013).

One of the methods extensively used in soft soils is stone column (or granular column). Stone column derives its load capacity through passive pressure from the surrounding soil due to bulging of stone column. When installed in very soft soil, the load carrying capacity of the stone column reduces owing to the lower lateral confinement in the top portion of the column (Greenwood 1970,

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Barksdale and Bachus 1983). To overcome this limitation, stone column is reinforced (or encased) using geosynthetic. Further, reinforcement prevent clogging of the stone aggregate by surrounding soft soil, so drainage of column is not affected (Alexiew *et al*. 2005, Brokemper *et al*. 2006, Kempfert and Gebreselassie 2006).

The concept of encasement of stone column by geosynthetic was first suggested by Van Impe and Silence (1986). Raithel and Kirchner (2008) reported that the first load test on encased columns was carried out in Germany in 1994. Kempfert and Wallis (1997) reported the first application of 'geotextile encased columns' for widening an about 5 m high railroad embankment on peat and clay soils in Hamburg. Later on, this foundation system has been successfully applied in different projects (Kempfert and Raithel 2002, Raithel *et al*. 2005, Nods 2005, De Mello *et al*. 2008, Koerner and Wong 2008).

Raithel *et al*. (2002) reported the application of geotextile-encased columns to stabilize a dyke built on a soft soil layer having undrained shear strength 0.4 to 10 kPa. Trunk *et al*. (2004) performed series of medium scale unconfined compression tests and addressed successful installation of the geogrid encased stone columns in the field. Paul and Ponomarjow (2004) did comparative study on the load carrying capacity behaviour of reinforced crushed stone columns and non-reinforced concrete pile foundations.

Numerous researchers have evaluated the behaviour of ordinary stone columns without encasement and geosynthetic encased stone columns through laboratory tests. Bauer and Nabil (1996) performed uniaxial and triaxial compression tests on ordinary stone column and sleeve reinforced stone columns. They concluded that cylindrical sleeve increase the stiffness of the column. Malarvizhi and Ilamparuthi (2004) investigated the behaviour of end bearing and floating reinforced and unreinforced stone columns through laboratory model tests. Benefits of encasing stone columns installed in collapsible soils were reported by Ayadat and Hanna (2005). Di Prisco *et al*. (2006) have reported the results from laboratory small-scale model tests on the load capacity of sand columns against vertical non-monotonic loading and brought out the qualitative improvements in their load capacity. Lee *et al*. (2007) examined the load carrying capacity and failure mechanism of geogrid encased stone column by model tests. A parametric study was conducted by Murugesan and Rajagopal (2007, 2010) on single and group of stone columns to study the effects of column diameter, geosynthetic stiffness, and length of encasement on the load carrying capacity of geosynthetic encased stone columns. They reported that the performances of partially encased columns are very close to that of fully encased columns. Gniel and Bouazza (2009) provided comparative study on the performance of single and the group of stone columns and indicated a steady reduction in vertical strain with increasing encased length. Triaxial compression tests were conducted by Wu and Hong (2009) on unreinforced and reinforced sand columns. These tests showed that reinforcement induced apparent cohesion to stone column material.

Many researchers have done numerical analysis for understanding the behaviour of encased columns. Murugesan and Rajagopal (2006) performed axisymmetric finite element analyses to examine the behaviour of ordinary stone columns (OSCs) and geosynthetic encased stone columns (ESC_S). They reported that the depth of encasement equal to two times the diameter of stone column is adequate to substantially increase its load carrying capacity. Malarvizhi and Ilamparuthi (2007) also performed axisymmetric finite element analyses on single ordinary and the encased stone column stabilized clay bed to bring out the influence of the various column parameters. They suggested that the bearing capacity encased stone columns stabilized clay bed is not effective beyond length to diameter ratio of column of 10 and geogrid stiffness over 2000 kN/m, respectively. Khabbazian *et al*. (2009) carried out 3D finite element analyses to simulate the behaviour of a single geosynthetic-encased stone column in a soft clayey soil. They suggested that it is more efficient to select encasement with higher stiffness rather than to improve the stone column material. The study on the comparison of different modelling approach (i.e., axisymmetric, 3-d unit cell, and fully 3-d) was carried out by Yoo and Kim (2009). They noted that the results of 3-d unit cells were in good agreement with those from the fully 3-d model. Yoo (2010) numerically investigated the performance of geosynthetic-encased stone columns installed in soft ground for embankment construction. He reported that full encasement may be necessary to ensure maximum settlement reduction when implementing geosynthetic encased stone column under an embankment loading condition.

Many researchers have proposed analytical approaches for estimating bearing capacity and settlement of reinforced foundations by encased stone columns. Based on the assumption of unit cell behaviour, equal settlement for the column and soft surrounding soil, volume of the column remains constant, an analytical method was proposed by Raithel and Kempfert (2000). Wu *et al*. (2009) developed an analytical procedures to examine the axial stress-strain response of geosynthetic encased stone column adopting Duncan and Chang model to describe the mechanical characteristics of the stone column materials. Zhang *et al*. (2011) developed a theoretical elastic solution of stresses and displacements of foundation reinforced with encased column adopting unit cell approach. An updated elasto-plastic solution for a fully encased column was proposed by Pulko *et al*. (2011). They have ignored the effect of the radial stresses at different locations on the radial deflection of the soil. Recently, a closed form solution was proposed by Castro and Sagaseta (2011) to study the settlement reduction and the acceleration of consolidation caused by encased stone columns. They concluded that the column reinforcement has negligible effect for an elastic column and starts to be useful only after column yielding. Apart from above analytical methods, a simple analytical solution based on the hoop tension theory was developed by many authors (Van Impe 1989, Ayadat and Hanna 2005, Murugesan and Rajagopal 2010).

Although the behaviour of the geosynthetic encased stone columns have been investigated by many researchers through laboratory and filed load tests, numerically and analytically, there have been few systematic investigations to understand the behaviour of reinforced sand columns in the field. As part of an effort to understand the behaviour of unreinforced and reinforced sand columns in the field and to bring out the parameters which play an important role in increasing the load carrying capacity and settlement reduction of sand column, a prototype axial load test programme on sand column was performed. An extensive parametric study was carried out to understand the influence of diameter of column, the stiffness of reinforcement and reinforcement length on settlement and load carrying capacity. As a follow-up load carrying capacity of sand columns were compared with the existing theory.

2. Site characteristics, materials and testing methodology

All the tests were performed nearer to Althan creek, Surat city, in the state of Gujarat, India. The test programme was aimed at developing an efficient foundation design on sites adjacent to the test site. A schematic soil profile with standard penetration test (SPT) blow counts is presented in Fig. 1. Standard penetration test blow counts for a site vary typically between 3 and 38, ranging from 3 to 5 in the first 4 m of depth.

The boring logs indicate that test area is underlain by a 0.5 m-thick layer of highly plastic clay.

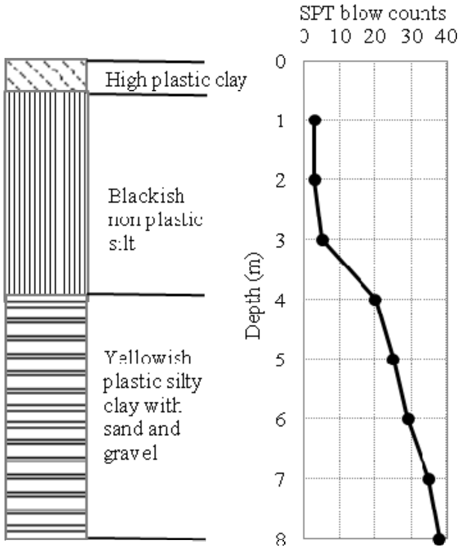

Fig. 1 Soil profiles with SPT blow counts

Table 1 Properties of geotextile used for reinforcement

Characteristic/ property	Geotextile 1	Geotextile 2
Polymer type	Polypropylene	Polyester
Thickness (mm)	0.68	0.90
Ultimate tensile strength (kN/m)	59.20	106.25
10% secant stiffness, J (kN/m)	121.90	450

This clay layer is underlain by a 3.5 m-thick layer of blackish non-plastic silt. The silt layer is underlain by yellowish plastic silty clay with sand and gravel extending well below the zone of interest. The ground water table was not observed upto a depth of 8 m. Laboratory testing on soil samples showed the degree of saturation ranges from 77 % for high plastic clay, 81% for blackish non-plastic silt and 80 % for yellowish plastic silty clay with sand and gravel. Other properties of the foundation soil at different depth are illustrated in Fig. 2. Unconfined compression test on high plastic clay provided value of undrained cohesion of 21.50 kPa. Angle of internal friction for non-plastic silt, determined from series of undrained triaxial shear tests was 26°. Undrained triaxial shear tests on undisturbed samples provided average values of cohesion 82 kPa and friction angle 12° along the 4-8 m soil depth. The Young moduli obtained from triaxial test were 4300, 2542 and 50752 kPa for highly plastic clay, non-plastic silt and yellowish clay, respectively.

Two woven geotextile of different tensile strength was used to reinforce the sand column in the present study. Fig. 3 shows the geotextile used in the tests. The tensile strength properties of these geotextile, determined from standard wide-width tension tests (ASTM D 4595 1986), and other geometrical properties are listed in Table 1. Geotextile in the form of tube was made by bonding the section with epoxy-resin, as reported by Gniel and Bouazza (2009). The load deformation behaviour observed from wide-width tension tests on bonded geotextile is shown in Fig. 4.

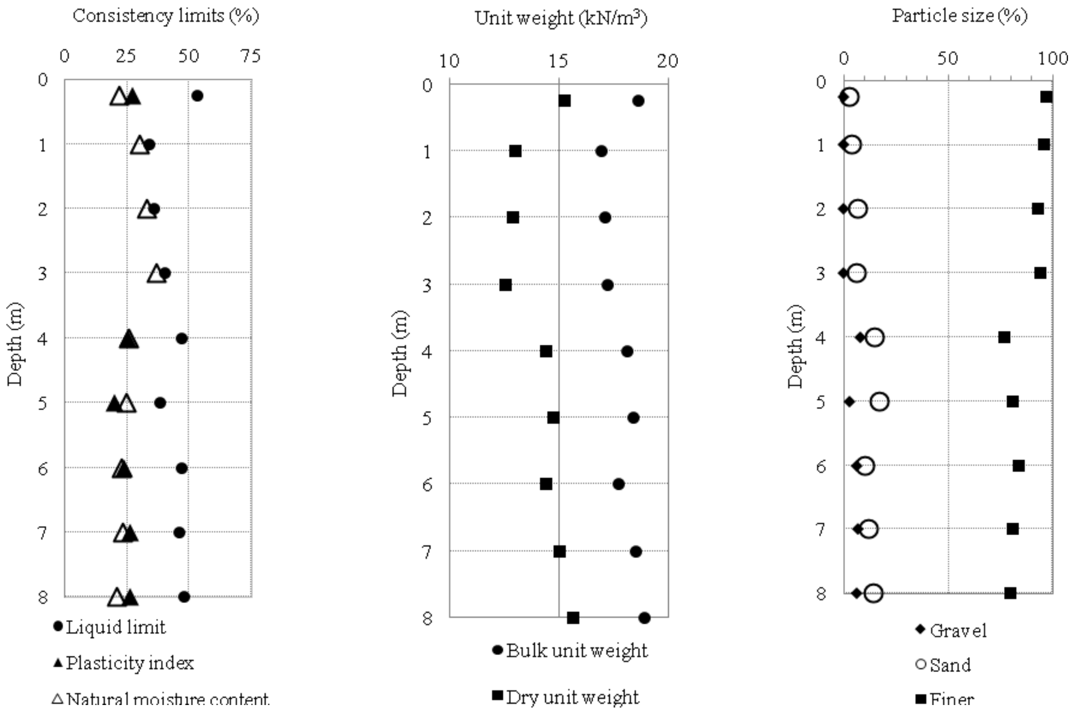

Fig. 2 Summary of foundation soil properties

Fig. 3 Geotextile used to reinforce the sand column

The sand used is clean river sand with particle size distribution as shown in Fig. 5. Other properties of the sand for the sand column are given in Table 3. The angle of internal friction has been determined using a direct shear box. The sand for the column was compacted to a density of approximately 1.77 g/cm^3. The Young modulus of sand used for the column was 35625 kPa.

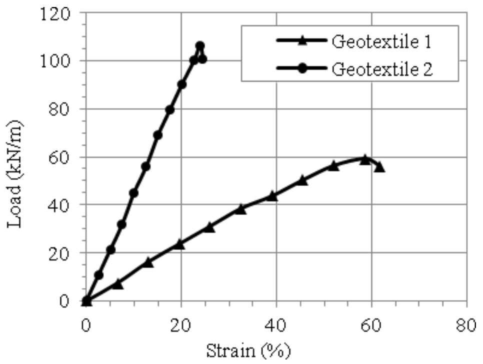

Fig. 4 Tensile load-strain behaviour of geotextile samples

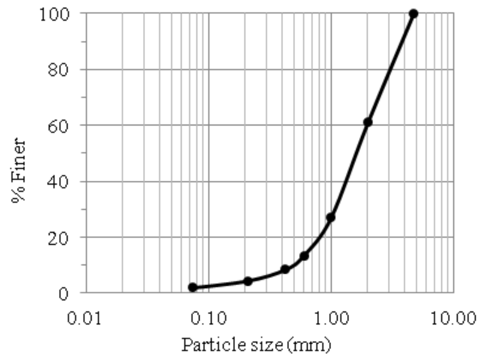

Fig 5 Grain size distribution for sand

Table 2 Properties of sand used in sand columns

Parameter	Value
Minimum dry density (g/cm^3)	1.56
Maximum dry density (g/cm^3)	1.88
Compacted dry density (g/cm^3)	1.77
Angle of internal friction (deg)	36

Table 3 Experimental programme

Test number	Diameter of column (m)	Reinforcement length (m)	Length of column (m)	Type of reinforcement	Type
1	0.30	-	-	-	Without treatment
2	0.30	-	4	-	OSC
3	0.30	0.6	4	Geotextile 1	RSC
4	0.30	1.2	4	Geotextile 1	RSC
5	0.30	4	4	Geotextile 1	RSC
6	0.30	0.6	4	Geotextile 2	RSC
7	0.30	1.2	4	Geotextile 2	RSC
8	0.30	4	4	Geotextile 2	RSC
9	0.45	-	4	-	OSC
10	0.45	0.9	4	Geotextile 1	RSC
11	0.45	1.8	4	Geotextile 1	RSC
12	0.45	4	4	Geotextile 1	RSC
13	0.45	0.9	4	Geotextile 2	RSC
14	0.45	1.8	4	Geotextile 2	RSC
15	0.45	4	4	Geotextile 2	RSC

(a) (b)

Fig. 6 Photograph of one of the loading tests: (a) General view; (b) Close view of sand column top

In the current research project, two 4 m long ordinary sand columns (OSCs) and twelve 4 m long geotextile reinforced sand column (RSCs) were constructed. The overall experimental programme is given in Table 3. All sand columns were constructed by a replacement method. An open-ended steel pipe (casing) having thickness of 6 mm was pushed into the soil upto the required depth. The soil within the casing was scooped out using a helical auger followed by the insertion of the geotextile tube. The quantity of the sand required to form the sand column was pre-measured and charged into the casing pipe in layers to achieve a compacted height of 30 cm. The casing was then raised in stages ensuring a minimum of 15 mm penetration below the top level of the placed sand. This was to prevent necking of the geotextile reinforcement. This method of installation ensures the continuity of the sand columns. This method of compaction of each layer of sand was done by ramming method as suggested by Datye and Nagaraju (1981). The corresponding density was found to be 1.77 g/cm^3. The procedure was repeated until the column is completed to the full height.

After the construction of the sand column, the load-settlement behaviours of the columns were studied by applying vertical load in a loading frame. To load the sand column area, a loading plate with diameter equal to that of the column, was used. This plate was used to transfer the vertical loads from a hydraulic cylinder to the sand column top.

Three series of tests were conducted. The first series of tests was performed on the soil without any treatment. A second series of tests was performed on ordinary sand columns (OSCs) without any reinforcement. The third series of tests was performed on geosynthetic reinforced sand columns (RSCs) with different diameters, reinforcement stiffness and length.

All the field load tests were performed as per the method suggested by Indian Standard for load tests on soils (IS: 1888). The vertical load was applied to the column top in stages with the following load stage being applied only after the rate of settlement is reduced to a value of 0.02 mm/min. All the tests were continued till a settlement of 50 mm. Reaction to the vertical loads applied at the column top was provided by kentledge method. A photograph of one of the loading tests is shown in Fig. 6.

3. Results and discussion

3.1 Effect of geotextile reinforcement

The stress-settlement responses observed for soil without treatment, ordinary sand column (OSC), reinforced sand column (RSC) with secant stiffness (J) of 450 kN/m are shown in Fig. 7. These results were obtained by loading the sand column area only or an equivalent area in the case of the soil without treatment. RSC was not fail even at a settlement of 50 mm. The compression of RSC was due to the elongation of the geotextile reinforcement. The stress on RSC corresponding to 40 mm of settlement is found to be 70 % greater than that of OSC for a column diameter of 0.30 m.

3.2 Analytical solution

The filed load tests results are compared with the analytical solution proposed by Murugesan and Rajagopal (2010). The analytical method for computing the stress on the OSC and RSC is explained in the following paragraphs.

The ultimate load carrying capacity of a sand column installed in a soil mass is governed by the lateral confining earth pressure mobilized in the surrounding soil. The limiting (yield) axial stress in the OSC constructed in clay is given by Eq. (1) (Hughes *et al*. 1975, Indian Standard (IS) 2003). Similarly axial stress in the OSC constructed in cohesionless (here silt) soil is given by Eq. (2). The ultimate load carrying capacity of the ordinary stone column (i.e., q_{OSC}) is computed by the Eq. (3). In the below, initial effective radial stress (σ_{ro}) was computed at an average depth of twice the column diameter.

$$\sigma_{v1} = \left(\sigma_{ro} + 4C_u\right)\cdot \tan^2\left(45 + {\varphi_C}/{2}\right) \tag{1}$$

$$\sigma_{v2} = \left(\sigma_{vo} \cdot \frac{1+\sin\varphi}{1-\sin\varphi}\right)\cdot \tan^2\left(45 + {\varphi_C}/{2}\right) \tag{2}$$

$$\sigma_{osc} = \left(\sigma_{vo} + 4C_u + \sigma_{vo} \cdot \frac{1+\sin\varphi}{1-\sin\varphi}\right)\cdot \tan^2\left(45 + {\varphi_C}/{2}\right) \tag{3}$$

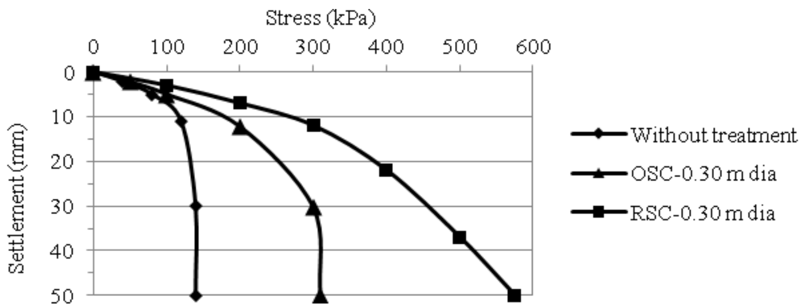

Fig. 7 Effect of geotextile reinforcement on stress-settlement response

where

σ_{ro} = *initial effective radial stress* = $K_0\ \sigma_{vo}$
C_u = *undrained shear strength of clay surrounding the column*
σ_{vo} = *average initial effective vertical stress*
K_0 = *average coefficient of lateral earth pressure for clays* (*assumed 0.6*)
φ_c = *angle of internal friction of sand column material*
φ = *angle of internal friction of soil surrounding the column*

A sand column reinforced in a geosynthetic material can be simulated by a cylindrical element made of a cohesionless material and subjected to triaxial loading. The confining pressure is the total of the lateral resistance of the soil and the geosynthetic enveloping the column. The geosynthetic provide confining stress to column. This confining stress can be estimated based on the tensile strength of geosynthetic. A simple closed from solution proposed by Van Impe (1989) and Ayadat and Hanna (2005) based on the hoop tension theory in a thin cylindrical container subjected to internal pressure was used to predict the axial stress on the RSC. It is well established that the bulging of column occurs mostly over a height equal to four times the diameter of column from top (Greenwood 1970, Hughes *et al*. 1975). The vertical strain developed in the column could be assumed due to bulging of column. Assuming, no volume change of column, the hoop strain (ε_c) developed in the geosynthetic is predicted from the axial strain (ε_a) relation as reported by (Henkel and Gilbert 1952, Bathurst and Karpurapu 1993, Rajagopal *et al*. 1999, Latha *et al*. 2006).

$$\varepsilon_c = \frac{1-\sqrt{1-\varepsilon_a}}{\sqrt{1-\varepsilon_a}} \tag{4}$$

The vertical strain of the column was calculated based on the measured vertical settlement at the column top divided by a column height equal to four times the diameter of column. The load corresponding to hoop strain is predicted from the load-strain curve obtained from wide-width tension tests on geotextiles. Based on this tension force the additional confining pressure (σ_{3geo}) provided by geotextile is calculated as

$$\sigma_{3geo} = \frac{2T}{d} \tag{5}$$

Combining Eqs. (1), (2) and (5), the ultimate load carrying capacity of the RSC can be calculated by the following equation.

$$q_{RSC} = \left(\sigma_{ro} + 4C_u + \frac{1+\sin\varphi}{1-\sin\varphi} + \frac{2T}{d}\right)\tan^2\left(45 + {\varphi_C}/{2}\right) \tag{6}$$

3.3 *Effect of diameter of sand column* (*d*)

Stress-settlement response of 0.30 m and 0.45 m diameter OSC and RSC of secant stiffness 450 kN/m were plotted in Fig. 8. It is seen in Fig. 8 that the stress-settlement responses of the OSC of different diameters are almost the same. The stress developed in the RSC increased with a decrease in the diameter of the column. This phenomenon is due to the development of larger confining stresses in smaller diameter reinforced sand column. A similar trend was observed by

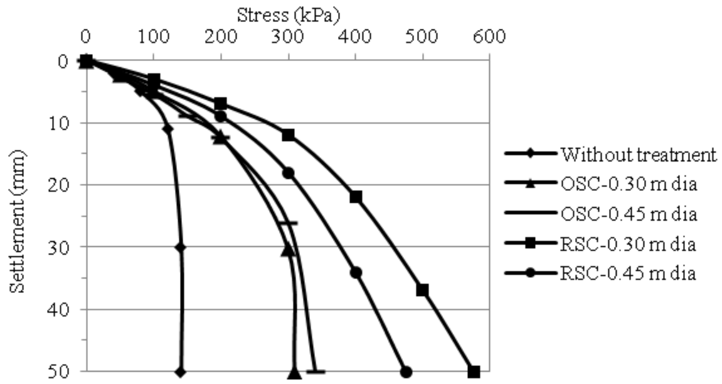

Fig. 8 Effect of diameter of sand column on stress-settlement response

Murugesan and Rajagopal (2006), based on numerical analysis.

The relationship between the diameter of sand column and stress corresponding to a vertical settlement of 50 mm is compared in Fig. 9 with analytical solution. The present work predicts a slightly lower stress than the analytical results for the OSCs and RSCs.

Fig. 10 shows the percent reduction in settlement of RSCs over that of OSCs for two diameters (0.30 and 0.45 m) of sand columns under a vertical stress of 300 kPa. In Fig. 10, it can be seen that percent reduction in settlement of sand column tends to sharply increase by decreasing diameter of sand column for secant stiffness of 450 kN/m. This is because with increase in column diameter, the stresses are mobilized in the top portion of the column, which cause larger lateral bulging and eventually leads to more vertical settlement. Murugesan and Rajagopal (2010) also observed similar behaviour with single reinforced stone column in the laboratory model tests. However, for reinforcement stiffness of 121.90 kN/m, settlement reduction was insignificant with diameter.

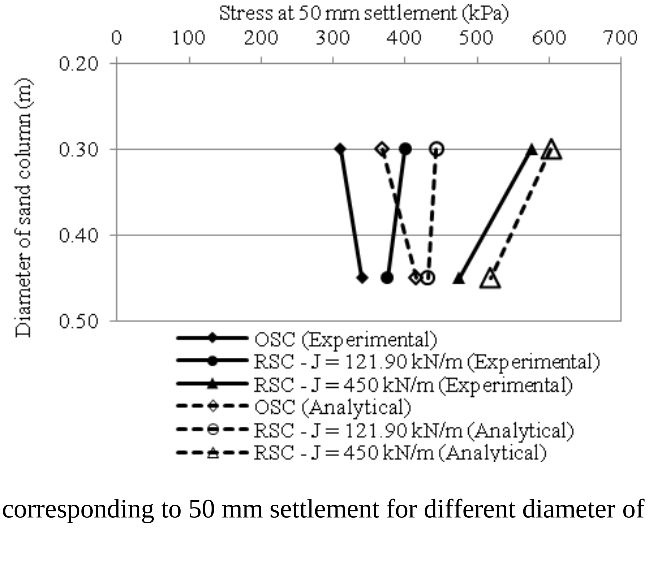

Fig. 9 Stress corresponding to 50 mm settlement for different diameter of sand columns

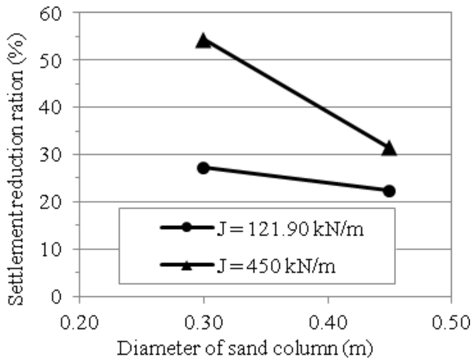

Fig. 10 Settlement reduction with decreasing diameter of RSC

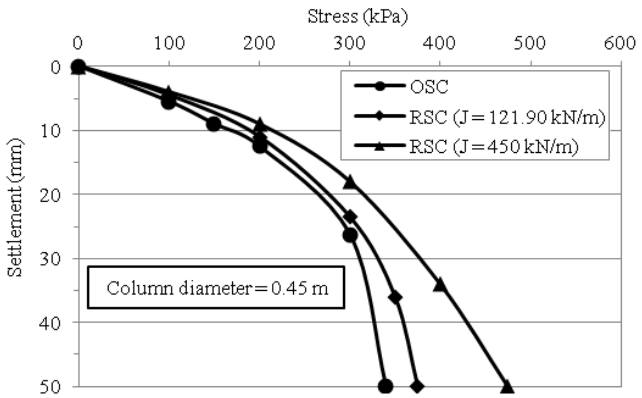

Fig. 11 Effect of stiffness of geotextile on performance of reinforced sand column

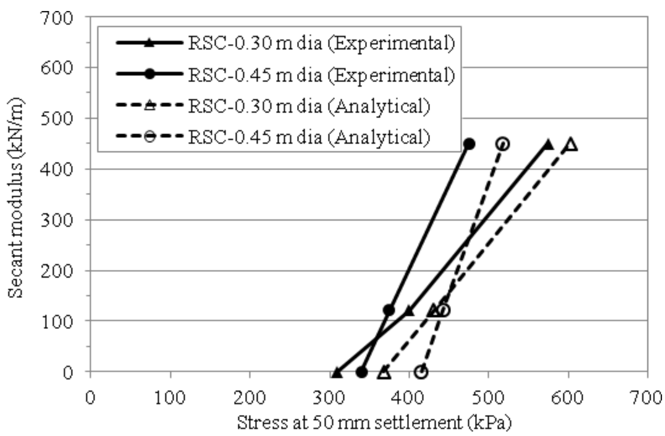

Fig. 12 Stress corresponding to 50 mm settlement for different secant modulus of geotextile reinforcement

3.4 Effect of stiffness of reinforcement

The effect of geotextile stiffness on load carrying capacity of column was studied for two different secant stiffness of reinforcement of 121.90 and 450 kN/m. Fig. 11 shows a comparison of vertical stress versus settlement behaviour of an OSC and RSCs of 0.45 m column diameter for different geotextile stiffness. As can be seen, stress on the reinforced sand columns increases with an increase in the secant stiffness of the geotextile used for reinforcement. The improved characteristics of RSCs with higher stiffness were due to larger confining (lateral) stress developed in the sand columns.

Fig. 12 shows the relationship between the vertical stress at 50 mm settlement and the secant stiffness of geotextile for different diameter of sand columns. Form the figure, it can be seen that as the stiffness of geotextile increases, the vertical stress on the stone column increases. The hoop stresses in the geotextile lead to an increase in the confining pressures in the sand columns. Hence, geotextile with a higher stiffness will induce larger confining pressures, leading to a stiffer and stronger response of the sand columns. The experimental results for the carrying capacities of reinforced sand columns at 50 mm settlement were compared with the analytical study in Fig. 12. It can be seen from Fig. 12 that the experimental study underestimates the results by about 5-20%.

3.5 Effect of reinforcement length

In the literature, it can be found that the bulging of sand columns will be predominant within top portion of the column (Greenwood 1970, Hughes *et al*. 1975). Hence, only the top portion of the sand column needs more lateral confinement in order to improve its performance. Hence, it was decided to investigate the effect of the reinforcement length on the response of the sand columns. Figs. 13 and 14 show the stress-settlement response of 0.30 m diameter RSCs with the reinforcement length for $J = 121.90$ and 450 kN/m respectively. It can be seen that sand column reinforced (with $J = 450$ kN/m) upto two times diameter of column exhibit much higher load carrying capacity than an OSC.

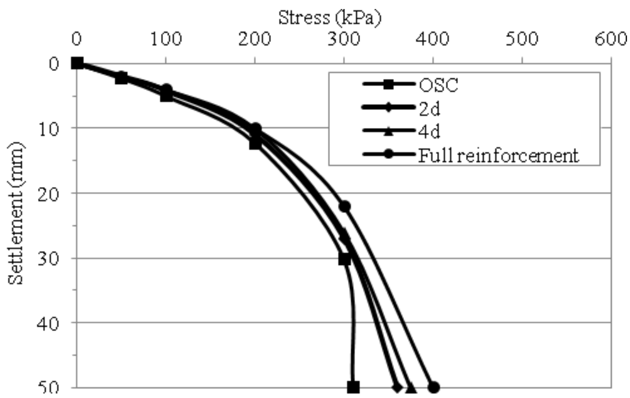

Fig. 13 Effect of reinforcement length on the performance of reinforced sand column (d = 0.30 m, J = 121.90 kN/m)

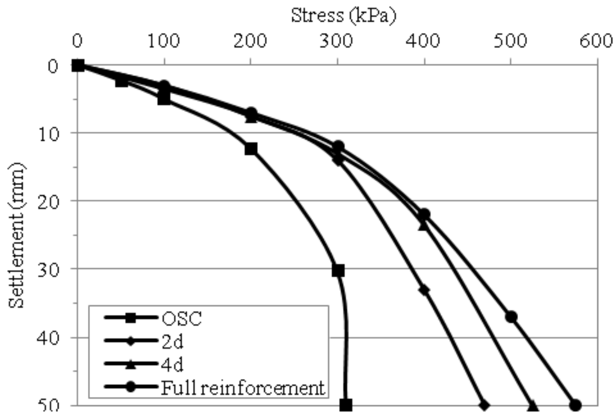

Fig. 14 Effect of reinforcement length on the performance of reinforced sand column (d = 0.30 m, J = 450 kN/m)

The stress improvement factor is derived as stress of treated ground divided by stress of untreated ground at 50 mm settlement. As can be seen from Fig. 15, the stress improvement factor is not change remarkably with reinforcement length for geotextile stiffness of 121.90 kN/m. However, stress improvement factor rapidly increases for reinforcement length upto four times the diameter of sand column form the top of the column, then after increase in stress improvement factor is gradual. It shows that the reinforcement at the top portion of the sand column is sufficient for improved performance.

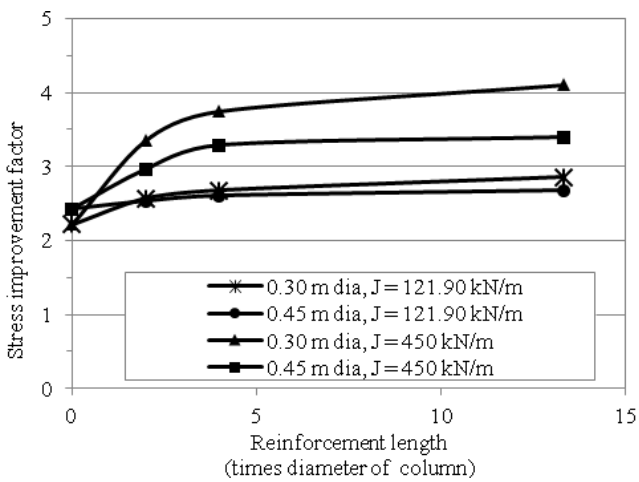

Fig. 15 Variation of stress improvement factor with reinforcement length, diameter of column and stiffness of reinforcement

4. Conclusions

The present work describes field load tests carried out to study the effect of diameter of sand column, reinforcement stiffness and reinforcement length on the behaviour of sand columns. Load tests were carried out by loading the column area alone to study the limiting axial stress on the sand column. From the results of these tests, the following conclusions can be drawn. Here, conclusions 1 to 3 deals with reinforced sand column of full reinforcement length.

(1) Depending upon the reinforcement stiffness and diameter of column, the load carrying capacity of reinforced sand columns are 20-85 % more than that of ordinary sand columns and settlement of reinforced sand columns reduced by 20-54% that of ordinary sand columns.

(2) Decreasing the diameter of a reinforced sand column increase the ultimate stress on the column. When the diameter of the reinforced sand column (with $J = 450$ kN/m) was changed from 0.45 m to 0.3 m, the resultant stress on top the column at a settlement of 50 mm increased by 21%.

(3) The ultimate stress on the reinforced column increases with the stiffness of the reinforcement. This phenomenon is due to generation of higher confining stresses for stiffer reinforcements. By changing the reinforcement stiffness from 121.90 to 450 kN/m, the stress on column increased about 27-44 % for a vertical settlement of 50 mm.

(4) The optimum reinforcement length require to substantially increase load carrying capacity of reinforced sand column is found to be approximately four times the diameter of sand column.

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References

Abuel-Naga, H.M., Bergado, D.T. and Chaiprakaikeow, S. (2006), “Innovative thermal technique for enhancing the performance of prefabricated vertical drain system”, *Geotext. Geomembr.*, **24**(6), 359-370.

Alexiew, D., Brokemper, D. and Lothspeich, S. (2005), “Geotextile encased columns (GEC): Load capacity, geotextile selection and pre-design graphs”, *Proceedings of the Geo-Frontiers Conference, ASCE Geotechnical Special Publication No. 130-142*, Austin, TX, USA, January, pp. 497-510.

ASTM D 4595 (1986), *Standard Test Method for Tensile Properties of Geotextiles by Wide-Width Strip Method*, ASTM International, West Conshohocken, PA, USA.

Ayadat, T. and Hanna, A.M. (2005), “Encapsulated stone columns as a soil improvement technique for collapsible soil”, *Ground Improve.*, **9**(4), 137-147.

Barksdale, R.D. and Bachus, R.C. (1983), “Design and construction of stone columns”, Rep. No. FHWA/RD-83/026, Office of Engineering and Highway Operations Research and Development, *Federal Highway Administration*, Washington, D.C., USA.

Bathurst, R.J. and Karpurapu, R. (1993), “Large scale model triaxial compression testing of geocell-reinforced granular soils”, *ASTM Geotech. Test. J.*, **16**(3), 296-303.

Bauer, G.E. and Nabil, A.J. (1996), "Laboratory and analytical investigation of sleeve reinforced stone columns", *Geosynthetics: Application-Design and Construction – Proceedings of the First European Geosynthetics Conference*, *EUROGEO 1*, Netherlands, pp. 463-466.

Bergado, D.T. and Teerawattanasuk, C. (2008), "2D and 3D numerical simulations of reinforced embankments on soft ground", *Geotext*. *Geomembr*., **26**(1), 39-55.

Brokemper, D., Sobolewski, J., Alexiew, D. and Brok, C. (2006), "Design and construction of geotextile encased columns supporting geogrid reinforced landscape embankments; Bastions Vijfwal Houten in the Netherlands", *Proceedings of the 8th International Conference on Geosynthetics*, Yokohama, Japan, October, pp. 889-892.

Castro, J. and Sagaseta, C. (2011), "Deformation and consolidation around encased stone columns", *Geotext*. *Geomembr*., **29**(3), 268-276.

Chen, Y.M., Cao, W.P. and Chen, R.P. (2008), "An experimental investigation of soil arching within basal reinforced and unreinforced piled embankment", *Geotext*. *Geomembr*., **26**(2), 164-174.

Chu, J., Yan, S.W. and Yang, H. (2000), "Soil improvement by the vacuum preloading method for an oil storage station", *Geotechnique*, **50**(6), 625-632.

Datye, K.R. and Nagaraju, S.S. (1981), "Design approach and field control for stone columns", *Proceedings of the 10th International Conference on SMFE*, Stockholm, Sweden, June, Vol. 3, pp. 637-640.

De Mello, L.G., Mondolfo, M., Montez, F., Tsukahara, C.N. and Bilfinger, W. (2008), "First use of geosynthetic encased sand columns in South America", *Proceedings of the 1st Pan-American Geosynthetics Conference*, Cancun, Mexico, March, pp. 1332-1341.

Di Prisco, C., Galli, A., Cantarelli, E. and Bongiorno, D. (2006), "Georeinforced sand columns: small scale experimental tests and theoretical modeling", *Proceedings of the 8th International Conference on Geosynthetics*, Yokohama, Japan, September, pp. 1685-1688.

Gniel, J. and Bouazza, A. (2009), "Improvement of soft soils using geogrid encased stone columns", *Geotext*. *Geomembr*., **27**(3), 167-175.

Greenwood, D.A. (1970), "Mechanical improvement of soils below ground surface", *Proceedings of Confernce on Ground Engineering*, Institution of Civil Engineers, London, UK, January, pp. 11-22.

Henkel, D.J. and Gilbert, G.D. (1952), "The effect of the rubber membrane on the measured triaxial compression strength of clay samples", *Geotechnique*, **3**(1), 20-29.

Hughes, J.M.O., Withers, N.J. and Greenwood, D.A. (1975), "A field trial of the reinforcing effect of a stone column in soil", *Geotechnique*, **25**(1), 31-44.

Indian Standard (IS) (1982), *Method of Load Test in Soils IS: 1888*, Bureau of Indian Standards, New Delhi, India.

Indian Standard (IS) (2003), *Design and Construction for Ground Improvement-Guidelines*. *Part 1: Stone columns*, *IS:15284*, Bureau of Indian Standards, New Delhi, India.

Indraratna, B., Bamunawita, C. and Khabbaz, H. (2004), "Numerical modelling of vacuum preloading and field applications", *Can*. *Geotech*. *J*., **41**(6), 1098-1110.

Kempfert, H.G. and Gebreselassie, B. (2006), *Excavations and Foundations in Soft Soils*, Springer-Verlag, Berlin, Germany.

Kempfert, H.G. and Raithel, M. (2002), "Experiences on dike foundations and landfills on very soft soils", *Technical Committee TC 36 Soft Soils Foundation Engineering*, *International Symposium on Soft Soils Foundation Engineering*, Mexico.

Kempfert, H.G. and Wallis, P. (1997), "Geokunststoffummantelte Sandsäulen – ein neues Gründungsverfahren im Verkehrswegebau", *Geotechnik Sonderheft zur 5*, *Informations – und Vortragsveranstaltung über Kunststoffe in der Geotechnik*, München, Germany.

Khabbazian, M., Kaliakin, V.N. and Meehan, C.L. (2009), "3D analyses of geosynthetic encased stone columns", *Proceedings of the International Foundations Congress and Equipment Expo 09* (*IFCEE09*), *Contemporary Topics in Ground Modification*, *Problem Soils*, *and Geo-Support*, *Geotechnical Special Publication No*. *187*, New York, USA.

Koerner, R.M. and Wong (2008), "Geosynthetic supported basal reinforcement over deep foundations emphasizing geogrid encased stone columns and geotextile encased sand columns", *Proceedings of the*

23rd Central Pennsylvania Geotechnical Conference, Hershey, CA, USA, p. 26.

Latha, G.M., Rajagopal, K. and Krishnaswamy, N.R. (2006), "Experimental and theoretical investigations on geocell-supported embankments", *Int. J. Geomech.*, **6**(1), 30-35.

Lee, D., Yoo, C. and Park, S. (2007), "Model tests for analysis of load carrying capacity of geogrid encased stone column", *Proceeding of the 17th International Offshore and Polar Engineering Conference*, Lisbon, Portugal, July, pp. 1632-1635.

Malarvizhi, S.N. and Ilamparuthi, K. (2004), "Load versus settlement of clay bed stabilized with stone and reinforced stone columns", *Proceedings of GeoAsia-2004*, Seoul, Korea, pp. 322-329.

Malarvizhi, S.N. and Ilamparuthi, K. (2007), "Comparative study on the behaviour of encased stone column and conventional stone column", *Soil. Found.*, **47**(5), 873-885.

Murugesan, S. and Rajagopal, K. (2006), "Geosynthetic-encased stone columns: Numerical evaluation", *Geotext. Geomembr.*, **24**(6), 349-358.

Murugesan, S. and Rajagopal, K. (2007), "Model tests on geosynthetic encased stone columns", *Geosynth. Int.*, **14**(6), 346-354.

Murugesan, S. and Rajagopal, K. (2010), "Studies on the behaviour of single and group of geosynthetic encased stone columns", *J. Geotech. Geoenviron. Eng.*, **136**(1), 129-139.

Nods, M. (2003), "Put a sock in it", *Ground Eng.*, pp. 13-15.

Paul, A. and Ponomarjow, A. (2004), "The bearing behaviour of geogrid reinforced crushed stone columns in comparison to non-reinforced concrete pile foundations", *EuroGeo3: Geotechnical Engineering with Geosynthetics*, Munich, Germany, 285-288.

Pulko, B., Majes, B. and Logar, J. (2011), "Geosynthetic-encased stone columns: Analytical calculation model", *Geotext. Geomembr.*, **29**(1), 29-39.

Raithel, M. and Kempfert, H.G. (2000), "Calculation models for dam foundations with geotextile-coated sand columns", *Proceedings of International Conference on Geotechnical and Geological Engineering, GeoEng 2000*, Melbourne, Australia, pp. 347-352.

Raithel, M. and Kirchner, A. (2008), "Calculation techniques and dimensioning of encased columns-design and state of the art", *Proceedings of the 4th Asian Regional Conference on Geosynthetics*, Shanghai, China, June, pp. 718-723.

Raithel, M., Kempfert, H.G. and Kirchner, A. (2002), "Geotextile-encased columns (GEC) for foundation of a dike on very soft soils", *Proceedings of the 7th International Conference on Geosynthetics*, Nice, France, September, pp. 1025-1028.

Raithel, M., Kirchner, A., Schade, C. and Leusink, E. (2005), "Foundation of construction on very soft soils with geotextile encased columns-state of the art", *Proceedings of GeoFrontiers 2005*, Austin, TX, USA, January.

Rajagopal, K., Krishnaswamy, N.R. and Latha, G.M. (1999), "Behaviour of sand confined with single and multiple geocells", *Geotext. Geomembr.*, **17**(3), 171-184.

Rampello, S. and Callisto, L. (2003), "Predicted and observed performance of an oil tank founded on soil-cement columns in clayey soils", *Soil. Found.*, **43**(4), 229-241.

Rowe, R.K. and Taechakumthorn, C. (2008), "Combined effect of PVDs and reinforcement on embankments over rate-sensitive soils", *Geotext. Geomembr.*, **26**(3), 239-249.

Trunk, U., Heerten, G., Paul, A. and Reuter, E. (2004), "Geogrid wrapped vibro stone columns", *Proceedings of the 3rd European Geosynthetics Conference; Geotechnical Engineering with Geosynthetics*, Munich, Germany, March, pp. 289-294.

Van Impe, W.F. (1989), *Soil Improvement Techniques and Their Evolution*, (A.A. Balkema), Rotterdam, Netherlands.

Van Impe, W. and Silence, P. (1986), "Improving of the bearing capacity of weak hydraulic fills by means of geotextiles", *Proceedings of the 3rd International Conference on Geotextiles*, Vienna, Austria, April, pp. 1411-1416.

Vashi, J.M., Desai, A.K. and Solanki, C.H. (2013), "Behaviour of geotextile reinforced flyash + clay-mix by laboratory evaluation", *Geomech. Eng.*, **5**(4), 331-342.

Wu, C.S. and Hong, Y.S. (2009), "Laboratory tests on geosynthetic encapsulated sand columns", *Geotext.*

Geomembr., **27**(2), 107-120.

Wu, C.-S., Hong, Y.S. and Lin, H.C. (2009), "Axial stress-strain relation of encapsulated granular column", *Comput*. *Geotech*., **36**(1-2), 226-240.

Yoo, C. (2010), "Performance of geosynthetic-encased stone columns in embankment construction: numerical investigation", *J. Geotech*. *Geoenviron*. *Eng*., **136**(8), 1148-1160.

Yoo, C. and Kim, S.B. (2009), "Numerical modeling of geosynthetic encased stone column-reinforced ground", *Geosynth*. *Int*., **16**(3), 116-126.

Zhang, Y.P., Li T. and Wang, Y. (2011), "Theoretical solutions for foundations improved by geosynthetic-encased stone columns", *Geosynth*. *Int*., **18**(1), 12-20.

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