Investigations on the behaviour of geosynthetic encased stone columns

Les enquêtes sur le comportement de geosynthetic encased les colonnes en pierre

S.Murugesan

Garware Wall Ropes Ltd., Pune 411019, India. Email:smurugesan@garwareropes.com

K.Rajagopal

Professor, Department of Civil Engineering, Indian Institute of Technology Madras, Chennai – 36, India. Email: gopalkr@iitm.ac.in

ABSTRACT

Stone column (or granular pile) technique is an ideal ground reinforcement for supporting flexible structures like embankments, storage tanks on soft soils. The axial load capacity of stone columns is mobilized by passive pressure from the surrounding soft soils. In very soft soils, this lateral confinement may not be adequate, which leads to excessive bulging resulting in undue surface settlements. Wrapping the individual stone columns with a suitable geosynthetic would be an ideal remedy for such situations. This encasement, apart from increasing the load capacity significantly, makes the stone column to act as semi-rigid and end bearing element. This paper investigates the improved performance of encased stone columns through laboratory model tests. It is observed that the increase in the axial load capacity is dependent on the modulus of the encasement and the diameter of the stone column. Results from the tests were used to develop guidelines in the form of design charts for the design of geosynthetic encased stone columns.

RÉSUMÉ

La colonne en pierre (ou le tas granuleux) la technique est un renforcement de terre idéal pour soutenir des structures flexibles comme les digues, les réservoirs d'entreposage sur les sols mous. La capacité de charge axiale de colonne en pierre est mobilisée par la pression passive des sols mous entourants. Dans les sols très mous, cet emprisonnement latéral peut ne pas être adéquat, qui cause le renflement excessif s'ensuivant dans les règlements indus de surface. Le papier d'emballage des colonnes en pierre individuelles avec geosynthetic convenable serait un remède idéal pour de telles situations. Ce revêtement, sauf l'augmentation de la capacité de charge de façon significative, fait la colonne en pierre pour agir comme semi-rigide et la fin en portant l'élément. Ce papier enquête sur la performance améliorée de colonnes en pierre encased par les épreuves modèles de laboratoire. Il est remarqué que l'augmentation dans la capacité de charge axiale dépend du module du revêtement et du diamètre de la colonne en pierre. Les résultats des épreuves ont été utilisés pour développer des directives dans la forme de graphiques de design pour le design de geosynthetic encased les colonnes en pierre.

Keywords: stone column, geosynthetics, geosynthetic encasement, soft clay soils, settlements

1. INTRODUCTION

The stone columns are vertical columnar elements formed below the ground level with compacted and uncemented stone fragments or gravels. When the stone columns are installed in very soft clays, they may not derive significant load capacity due to the low lateral confinement. McKenna *et al.* (1975) reported cases where the stone column was not restrained by the surrounding soft clay which lead to excessive bulging and also the soft clay squeezed into the voids of the aggregate. In such situations, the stone column itself may need to be reinforced for its improved performance. One ideal form of reinforcing the stone column could be by wrapping the individual stone columns using suitable geosynthetic. This encasement imparts additional confinement to the stone column and brings in several advantages like increased stiffness of column, preventing the loss of stones into the surrounding soft clay, preserving the drainage and frictional properties of the stone aggregates etc. as described by Raithel *et al.* (2002), Kempfert and Gebreselassie (2006) Murugesan and Rajagopal (2006, 2007).

In spite of many advantages of this technique, there are only limited investigations reported in the literature to understand the behaviour of Geosynthetic Encased Stone Columns (ESC). This paper reports the results from a series of laboratory tests performed on ESCs as well as OSCs (Ordinary Stone Columns without encasement) installed in clay bed formed in a model test tank. The results mainly quantify the improvements achieved in the load capacity over OSC due to the encasement by the geosynthetic.

2. DESCRIPTION OF EXPERIMENTS

2.1 *Preparation of Clay Bed*

The clay bed for the tests was prepared in a large test tank of plan dimensions 1.2 m×1.2 m and 0.85 m in depth. The clay soil was obtained from a lake bed and was made into slurry to be free from stress histories. This slurry was consolidated in-situ in the test tank under a pressure of 10 kPa. The consolidation of the clay bed was continued for a period of 8 to 10 days until the rate of settlement was less than 1 mm per day. This procedure yielded clay beds of uniform moisture content and consistency. After consolidation of the clay bed, its top surface was trimmed level to a have 600 mm depth of clay soil in the tank. The clay bed was prepared afresh by this method for every test. The properties of the clay bed prepared by this method are listed in Table 1.

Table 1. Properties of clay soil

Properties	Value
Liquid limit	49%
Plastic limit	17%
Specific Gravity	2.59
In-situ moisture content	47±1%
In-situ vane shear strength (kPa)	2.5
Dry unit weight (kN/m^3)	11.6
USCS classification symbol	CL
Degree of Saturation	96%

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-2411

2.2 *Material Properties*

The stone aggregates used to form the stone columns were angular granite chips of size 2 to 10 mm, having a peak angle of frictional resistance of 41.5°. The dry density, specific gravity and the USCS classification symbol are 1.6 g/cc, 2.65 and GP respectively.

Four different types of geosynthetics were used to encase the stone columns in the present study, namely woven geotextile, nonwoven geotextile, and soft meshes having two different aperture opening sizes, soft grid-1 and soft grid-2. The tensile strength properties of these geosynthetics determined from standard wide width tension tests (ASTM-D4595, 1986) are listed in Table 2. As the geosynthetics were stitched to form the tube for encasing the stone column, the seam strength of the geosynthetic was also determined.

Table 2. Properties of geosynthetics used as encasement

Strength Properties	Woven geotextile	Nonwoven geotextile	Soft Grid 1	Soft Grid 2
Ultimate tensile strength (kN/m)	20	6.8	2.5	1.5
Ultimate seam strength (kN/m)	4	5.1	2	1
Initial modulus (seam) (kN/m)	17.5	12	9.6	1.5
5% secant modulus (seam) (kN/m)	15	12	4	1.5

2.3 *Installation of Stone Column*

All the load tests were conducted on the stone column installed at the centre of the clay bed prepared in the large test tank (Figure 1).

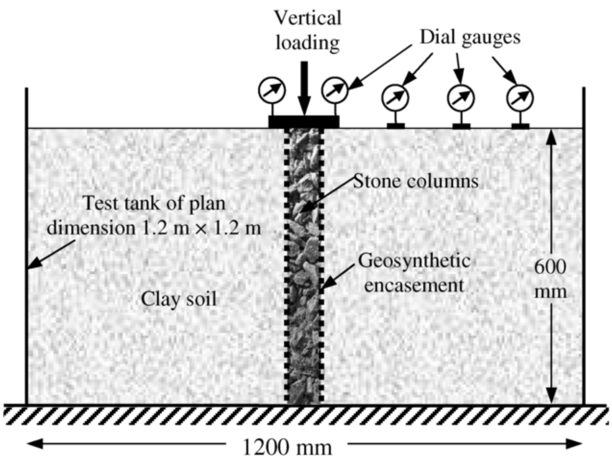

Figure 1. Schematic of Load test on single stone column

The stone columns were installed by displacement method up to the bottom of the tank. A casing pipe having an outer diameter equal to the diameter of the stone column was used to install the stone columns. The casing pipe was pushed into the soil till the bottom of the tank along with a base plate in order to prevent the soil from entering into the casing pipe. When the casing pipe is pulled out, the base plate remains in the soil.

2.4 *Load Tests on Stone Columns*

The stone column thus formed in the clay bed was subjected to vertical loading through a loading plate displaced at a constant strain rate of 1.2 mm per minute. The loading plates used in the tests were circular having a diameter twice that of the stone column, Figure 1. This method was adopted as per the guidelines given in IS:15284, Part-I (2003). The loads corresponding to different displacements (in the stone column) were measured through a pre-calibrated proving ring (having a least count of 0.8 N). As the loading is quick, it is essentially an undrained loading, which simulates the loading condition immediately after the construction.

Four series of tests were conducted by varying the diameter of the stone column. First series of tests were performed on the clay bed without any stone columns. Second series of tests were performed on OSCs without any encasement. Third series of tests were performed on ESCs with different diameters and type of geosynthetic encasement. Load tests were conducted on OSC and the geosynthetic ESCs to directly compare their relative performance. As the confinement effect is highly dependent on the diameter of the stone column, three different diameters of stone columns viz. 50, 75 and 100 mm were considered for the present study.

3. RESULTS AND DISCUSSIONS

3.1 *Effect of Geosynthetic Encasement*

The pressure-settlement responses observed from load tests on clay bed, OSCs and ESCs of different diameters encased in nonwoven geotextile are shown in Figure 2. The loading on the OSCs show a clear failure indicating ultimate load, while the ESCs did not show any signs of failure even at large settlement levels. The pressure on the ESCs corresponding to 10 mm settlements is found to be 3 to 5 times greater than that on the OSCs. The failure of the ESCs was not observed even at a settlement of 50 mm in the present investigations. The ESCs behaved like semi-rigid flexible piles. In the case of ESCs the compression of the stone column was mainly due to the elongation of the geosynthetic encasement caused by the bulging of the stone aggregates.

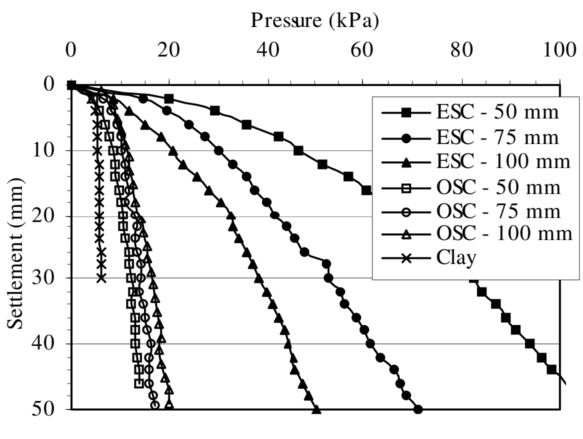

Figure 2. Pressure settlement responses of OSCs and ESCs (nonwoven)

3.2 *Influence of the Diameter of the Stone Column*

It could be seen in Figure 2 that the pressure-settlement responses of the OSC of different diameters are almost the same. The ESCs have developed much higher pressures compared to the OSCs. The pressures developed in the ESC decrease with increase in diameter of the column. This is in line with the findings by Murugesan and Rajagopal (2006 and 2007) and Murugesan (2007) based on numerical and laboratory model tests on stone columns installed in unit cells. The pressure-settlement response of columns encased in woven geotextiles have also shown similar trend of decreasing pressures with increasing diameter for the same modulus of the geosynthetic encasement.

3.3 *Influence of Stiffness of Geosynthetic Encasement*

Figure 3 shows a comparison of pressure-settlement responses of 75 mm diameter stone columns with different types of encasements. It can be observed that the stiffness of the ESCs increases with the increase in the secant modulus of the geosynthetic used for encasement. The improved performance due to the encasement can be attributed to the enhancement of overall stiffness of the columns due to larger confining stresses developed in the stone columns. The hoop stresses in the geosynthetic lead to increase in confining pressures in the stone columns as described by Murugesan and Rajagopal (2006). Hence the geosynthetics with higher modulus will induce larger confining pressures leading to stiffer and stronger response of the stone columns.

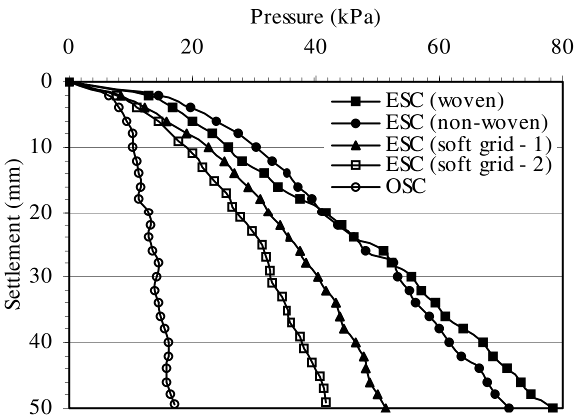

Figure 3. Responses of 75 mm diameter stone columns encased in different types of geosynthetics

3.4 *Theoretical Predictions*

The maximum load that can be applied on the OSC treated clay bed was obtained by using the method given in IS:15284 – Part-I (2003).

(i) The maximum pressure on OSCs, i.e. limiting axial stress (σ_v) on the stone column is given by Equation 1 (Hughes *et al.* 1975 and IS 15284 - Part 1, 2003).

$$\sigma_v = (\sigma_{ro} + 4c_u) Kp_{col} \tag{1}$$

In the above, σ_{ro} is the initial effective radial stress computed at an average depth of twice the diameter of the column. $Kp_{col} = \tan^2(45 + (\phi/2))$, where ϕ is the angle of internal friction of the stone aggregate. The limiting axial stress on the column was estimated by assuming a K_o of 1.0 for the soft soil and using the properties of the soft clay and the aggregate reported earlier in the paper. The bearing support offered by the clay soil in contact with the loading plate was obtained from the following equation.

$$q_u = c_u N_c \tag{2}$$

The total limiting stress was computed and compared with the maximum stress obtained from the experiments for different diameters of the OSC. The comparison between the experimental results and the analytical values matched very well as shown in Figure 4. Some of the tests were repeated in order to verify the consistency of the data. The comparison was found to be excellent with less than 5% variation in the results between the different tests.

A simple analytical model based on the hoop tension theory was used to predict the vertical pressure on the ESCs (Van Impe 1989). It is proven that the bulging of the stone columns occurs predominantly in the top portion over a height equal to about 4 times the diameter (Greenwood 1970 and Hughes *et al.* 1975). Accordingly, the predominant vertical strains in the stone columns could be assumed to be due to the compression in this zone of the column. Assuming the stone aggregate to deform without volume changes, the hoop strain ε_c (circumferential strain) in the geosynthetic is calculated from the vertical strain (i.e. axial strain ε_a) using the relation,

$$\varepsilon_c = \frac{1 - \sqrt{1 - \varepsilon_a}}{\sqrt{1 - \varepsilon_a}} \tag{3}$$

The axial strain ε_a in the column was estimated based on the measured surface displacements divided by a column height equal to 4 times the diameter. The tensile load corresponding to this strain in the geosynthetic is obtained from the load strain response from the wide width tension tests performed on the seamed geosynthetic. Knowing the tensile load (T) in the geosynthetic, the additional lateral confining stress p_c (hoop compression) exerted by the geosynthetic is calculated as,

$$p_c = (2 \times T)/d \tag{4}$$

in which d is the diameter of the column. As the diameter increases, the additional confining pressure decreases as evident from Equation 4. The vertical stress on the ESC can be calculated using the relation,

$$\sigma_v = (\sigma_{ro} + 4c_u + p_c) Kp_{col} \tag{5}$$

The vertical stress on the ESCs corresponding to a vertical settlement of 50 mm for the different stone columns was calculated and compared with those obtained from the experimental results, Figure 4. A reasonably good agreement is obtained between the two as could be seen from the figure.

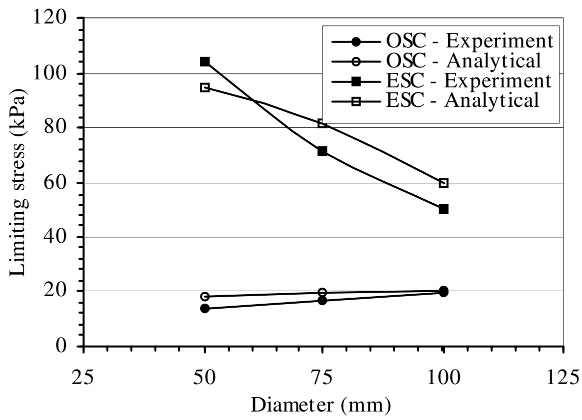

Figure 4. Comparison of analytical and experimental results

4. GUIDELINES FOR THE DESIGN OF ENCASED STONE COLUMNS

Based on the excellent comparison obtained between the analytical and experimental results, guidelines are developed for the design of geosynthetic ESCs. The bearing support from the soft soil is conservatively ignored in this methodology as the ESCs are specially suited for the case of extremely soft soils.

1. For the given pressure loading p_o from the structure, suitable spacing (s) and diameter (d) of the stone columns are chosen. A typical unit cell consisting of a stone column and the contributing surrounding soil is considered among the grid of stone columns. The load coming over the unit cell is assumed to be carried fully by the stone column in the unit cell.

Load on the stone column = Applied pressure, p_o × Area of the unit cell, A

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

where s is the spacing of the stone column.

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

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

2. The limiting stress on an OSC without encasement is computed by using the Equation 1.

3. The additional confinement p_c required is calculated as

$$p_c = (p_o - \sigma_v)/Kp_{col} \tag{6}$$

4. The corresponding hoop tension force in the encasement (T) can be estimated using Equation 4.

5. The hoop strain ε_c in the encasement corresponding to the permissible settlement (δ) in the stone column is computed using the following Equation 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 (i.e. permissible settlement).

$$\varepsilon_a = \delta/(4 \times d) \tag{7}$$

The effect of the surface loads was found to cause strains over a height of 4 times the diameter of the stone column as discussed by Murugesan and Rajagopal (2007).

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.

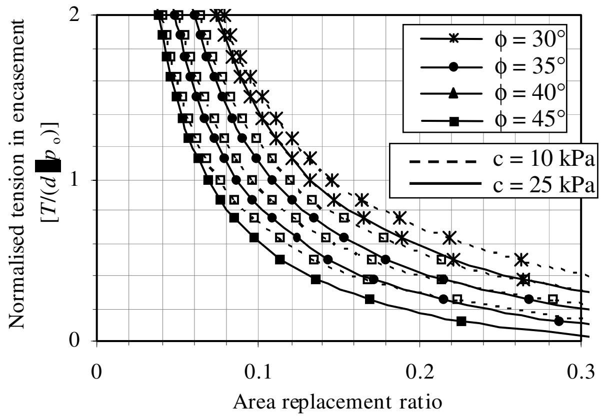

Figure 5. Design charts for the geosynthetic encased stone columns

4.1 *Design Charts*

Based on the above design procedure developed for the ESCs, design charts have been prepared in non-dimensional form applicable for a range of realistic soil parameters, Figure 5. The area replacement ratio in this figure is calculated from the spacing, s and diameter of the stone column, d as,

$$\text{Area ratio} = 0.907 \times (d/s)^2 \quad \text{- for triangular grid.} \tag{8}$$

$$\text{Area ratio} = 0.786 \times (d/s)^2 \quad \text{- for square grid.} \tag{9}$$

The methodology for using the design charts is as follows:

(i) For the assumed spacing and diameter of the stone column, the area ratio is calculated.

(ii) For the properties of clay soil (c), friction angle of the stone aggregate (ϕ) and the area ratio, normalised tensile force required for the encasement is read from the chart. For other soil or aggregate properties, linear interpolation may be used.

(iii) From the normalised tension in the geosynthetic encasement, the tensile strength of the geosynthetic required is estimated for the maximum applied pressure.

(iv) From the settlement criterion the axial strain in the stone column is calculated. The hoop strain corresponding to this axial strain is computed.

A suitable geosynthetic having long term allowable design tensile strength is then selected for the encasement.

5. CONCLUSIONS

The results of the testing program give some important insight into the performance of the Geosynthetic Encased Stone Columns. The major conclusions drawn from the present study are (i) The geosynthetic encased stone columns exhibit stiffer and stronger response. (ii) The benefit of encasement decreases with increase in the diameter of the stone columns. (iii) The elastic modulus of the geosynthetic encasement plays an important role in enhancing the load capacity and stiffness of the encased columns. (v) The design procedures and design charts developed in this paper enable easy design of geosynthetic encased stone columns. Due to the geosynthetic encasement either the spacing of the stone column can be increased or the diameter can be decreased for the same applied pressure.

REFERENCES

ASTM D4595 (1986) Standard test method for tensile properties of geotextiles by wide–width strip method, American Society for Testing and Materials. ASTM International.

Greenwood D.A. (1970) Mechanical improvement of soils below ground surface. *Ground Engineering Proceedings Conference Organised by the Institution of Civil Engineers, London,* pp 11–22.

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) pp 31–44.

IS:15284 (2003) Design and construction for ground improvement – Guidelines. Part – 1, Stone Columns. *Indian Standard*.

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

McKenna, J.M., Eyre, W.A. and Wolstenholme, D.R. (1975) Performance of an embankment supported by stone columns in soft ground. *Geotechnique,* **25** (1), 51-59.

Murugesan, S. (2007) Geosynthetic Encased Stone Columns as Ground Reinforcement of Soft Soils. *A Ph.D. Thesis submitted to Indian Institute of Technology Madras, India.*

Murugesan S. and Rajagopal K. (2006) Geosynthetic-encased stone columns: Numerical evaluation. *Geotextiles and Geomembranes,* **24** (6), 349–358.

Murugesan, S. and Rajagopal, K. (2007) Model tests on geosynthetic encased stone columns. *Geosynthetic International*, **24** (6), 349-358.

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 Seventh International Conference on Geosynthetics, Nice, France*, 1025-1028.

Van Impe W.F. *Soil improvement techniques and their evolution. A.A. Balkema, Rotterdam, Netherlands. 1*989.