

Geosynthetic-encased stone columns: Numerical evaluation

S. Murugesan, K. Rajagopal*

Department of Civil Engineering, Indian Institute of Technology Madras, Chennai 600036, India

Abstract

Stone columns (or granular piles) are increasingly being used for ground improvement, particularly for flexible structures such as road embankments, oil storage tanks, etc. When the stone columns are installed in extremely soft soils, the lateral confinement offered by the surrounding soil may not be adequate to form the stone column. Consequently, the stone columns installed in such soils will not be able to develop the required load-bearing capacity. In such soils, the required lateral confinement can be induced by encasing the stone columns with a suitable geosynthetic. The encasement, besides increasing the strength and stiffness of the stone column, prevents the lateral squeezing of stones when the column is installed even in extremely soft soils, thus enabling quicker and more economical installation. This paper investigates the qualitative and quantitative improvement in load capacity of the stone column by encasement through a comprehensive parametric study using the finite element analysis. It is found from the analyses that the encased stone columns have much higher load carrying capacities and undergo lesser compressions and lesser lateral bulging as compared to conventional stone columns. The results have shown that the lateral confining stresses developed in the stone columns are higher with encasement. The encasement at the top portion of the stone column up to twice the diameter of the column is found to be adequate in improving its load carrying capacity. As the stiffness of the encasement increases, the lateral stresses transferred to the surrounding soil are found to decrease. This phenomenon makes the load capacity of encased columns less dependent on the strength of the surrounding soil as compared to the ordinary stone columns.

Keywords: Stone column; Geosynthetic encasement; Granular pile; Finite element analysis; Soft soil; Hyperbolic non-linear elastic

1. Introduction

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) and lime treatment (Rajasekaran and Rao, 2002). 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. The stone columns develop their load carrying capacity through bulging and

thereby inducing near-passive pressure conditions in the surrounding soil (Greenwood, 1970). Several papers have been published in the past on the stone column as a ground reinforcing technique. Bergado et al. (1990) found from field studies that the installation of granular piles increased the bearing capacity by as much as four times and increased the factor of safety of slopes by approximately 25%. They also reported the improved performance of stone columns compared to prefabricated vertical drains.

Further development in the stone column technique is reinforcing the column using either horizontal layers of reinforcement (Sharma, 1998; Sharma et al., 2004) or encasing the individual stone column by geosynthetics (Raithel and Kempfert, 2000; Raithel et al., 2002) over the full or partial height of the column. The geosynthetic encasement will increase the load carrying capacity of stone columns by many folds due to the additional confinement from the geosynthetic. The geosynthetic encasement also prevents the lateral squeezing of stones when the stone

*Corresponding author. Tel.: +91 44 2257 4263; fax: +91 44 2257 0509.
E-mail addresses: smgsoil@sify.com (S. Murugesan),
gopalkr@iitm.ac.in (K. Rajagopal).

Nomenclature

c	cohesion
d_o, \varnothing	diameter of the stone column
E	Young's modulus
ESC	geosynthetic-encased stone column
E_t	tangent elastic modulus
h	depth of encasement from the ground level (top of stone column)
H	total height of stone column
J	modulus of stiffness of geosynthetic
K	Young's modulus number
M	secant stiffness of the geosynthetic
m	Young's modulus exponent
OSC	ordinary stone column (without any encasement)

p_a	atmospheric pressure
R_f	failure ratio
r_o	original radius
s	centre to centre spacing between stone columns
SIF	stress intensity factor
t	thickness of geosynthetic elements
u	radial deformation
z	depth of soil layer
γ	unit weight of material
$\Delta\sigma_3$	increase in confining pressure
Δ_z	increase in radius of stone column
ε_a	axial strain
ε_θ	hoop strain
μ	Poisson's ratio
ϕ	angle of internal friction
σ_1, σ_3	major and minor principal stresses

column is installed in some extremely soft soils, leading to minimal loss of stones and quicker installation. The published literature on the performance of encased stone columns is limited. [Katti et al. \(1993\)](#) proposed a theory for the improvement of soft ground using stone columns with geosynthetic encasement based on the particulate concept. [Malarvizhi and Ilamparuthi \(2004\)](#) reported the improved performance of geosynthetic-encased stone columns based on small-scale laboratory tests on end bearing as well as floating columns. It was found that the ultimate bearing capacity of reinforced stone column treated beds is three times that of the untreated beds. [Raithel and Kempfert \(2000\)](#) and [Raithel et al. \(2002\)](#) studied the performance of geosynthetic-encased sand columns through numerical and analytical models. [Ayadat and Hanna \(2005\)](#) performed experimental investigation on the load carrying capacity and settlement of stone columns encapsulated in geogrid textile material and concluded that the ultimate carrying capacity of a stone column increases with an increase in the stiffness of the geofabric material used to encapsulate the sand column.

In the present study, the effectiveness of geosynthetic encasement on the stone columns is investigated through parametric study carried out by finite element analysis. The influence of the parameters such as the stiffness of geosynthetic encasement, the depth of encasement from ground level, the diameter of stone columns and shear strength of the surrounding soil is analysed.

2. Numerical analyses

All the analyses in this investigation were performed using the finite element program 'GEOFEM' which was originally developed at the Royal Military College of Canada ([Rajagopal and Bathurst, 1993](#)) and subsequently modified at Indian Institute of Technology Madras. The stone columns are usually installed in square or triangular plan patterns in the field. For design and analysis purposes,

a cylindrical unit cell is considered, consisting of stone column and soil from the influence area. The influence areas for stone columns installed in square and triangular plan patterns are calculated from that of an equivalent square or hexagonal area, respectively. The radius of the circular influence area is related to the centre to centre spacing 's' between the stone columns as 0.564s and 0.525s for square and triangular patterns, respectively, [Barron \(1948\)](#).

In finite element models, the cylindrical unit cell can be idealised using axisymmetric model with radial symmetry around the vertical axis passing through the centre of the stone column. The finite element mesh was developed using 8-node quadrilateral elements for all the components in the system as shown in [Fig. 1](#). The stone columns and the soft soil are modelled using hyperbolic non-linear elastic equation as given in Eq. (1) ([Duncan and Chang, 1970](#)). It was decided to use this simple model because of its ability to relate the modulus of the soil to the confining pressure and the mobilised shear strength of the soil.

$$E_t = \left[1 - \frac{R_f(1 - \sin \phi)(\sigma_1 - \sigma_3)}{2c \cos \phi + 2\sigma_3 \sin \phi} \right]^2 K p_a \left(\frac{\sigma_3}{p_a} \right)^m, \quad (1)$$

where E_t is the tangent elastic modulus, c and ϕ are the cohesion and the friction angle of the foundation soil or stone column, K is a non-dimensional Young's modulus parameter, m is the Young's modulus exponent which governs the stress dependence of K on σ_3 , R_f is the failure ratio which defines the shape of the stress-strain curve, σ_1 and σ_3 are the major and minor principal stresses and p_a is the atmospheric pressure. More details on this model can be found in [Duncan and Chang \(1970\)](#). The hyperbolic material properties for different materials were selected from the database of hyperbolic parameters published by [Duncan et al. \(1980\)](#) and are listed in [Table 1](#). The geosynthetic encasement around the stone column was modelled as linear elastic material and discretised as continuum elements around the stone column (considering

effects due to encasement. Later, analyses were performed by constructing layers of soil above the stone-column-reinforced foundation soil. Detailed parametric analyses were performed by varying the diameter of the stone column, stiffness of the geosynthetic used for encasement, depth of encasement from the top of the stone column and cohesion value of the surrounding clay soil. All cases were idealised through axisymmetric modelling. The improved performance was quantified based on the reduction in settlement of the stone column and lateral bulging of the stone column. The foundation soil in all the cases is assumed to be a 5 m thick soft clay layer underlain by a rigid hard stratum.

The typical finite element mesh consisted of 1750 nodes and 550 8-node quadrilateral elements. The external loading was applied in small increments. The solution at each step was iterated to reduce the norm of out-of-balance force to less than 0.1% or 25 iterations, whichever happens earlier. The stiffness matrix of the system was updated at every iteration in view of the dependence of the modulus on the stress state.

4. Results and discussion

4.1. Effect of encasement of stone column

The improvement in the performance of the stone column due to encasement was studied by applying pressure only over the stone column area. By encasing, it is found that the stone columns are confined and the severe lateral bulging has significantly reduced. The lateral bulging observed in the stone columns of two sizes (0.6 and 1 m diameters) with and without encasement is compared in Fig. 3. In the figure, the lateral bulging at various depths is presented in terms of the increase in radius ' Δ_r ' at different depths normalised with original radius of the stone column (r_o). This value is also equal to the hoop strain (ϵ_θ) in percent (because $\epsilon_\theta = u/r_o$ in which ' u ' is the radial displacement). It is observed that in OSCs,

there is severe bulging near the ground surface up to a depth equal to twice the diameter of the stone column. On the other hand, the encased stone columns have undergone much lesser lateral expansion near the ground surface. The encased columns have undergone slightly higher lateral expansions at deeper depths as compared to the OSCs. This could have happened because the applied surface load is transmitted deeper into the column due to encasement effects.

The lateral confining stresses mobilised along the height of the 1 and 0.6 m diameter stone columns (both ordinary and encased) are illustrated in Fig. 4. It is clear that the lateral stresses are higher in the encased column as compared to the corresponding lateral stresses in OSCs. The increase in confining pressure can be seen over the full height of the stone column, which leads to mobilisation of higher vertical load capacity in the encased columns. The lateral stresses mobilised in the OSCs without geosynthetic encasement are found to be the same for both diameters of the stone columns (0.6 and 1 m). On the other hand, the lateral stresses mobilised in encased stone columns are higher for smaller diameter columns. The reasons for this are discussed later.

Figs. 5(a) and (b) show the contours of mobilised shear strength ratio in ordinary and encased stone columns of 1 m diameter, respectively. For clarity purposes, only the contours around the loaded area are shown in the figures. The mobilised shear strength ratio is defined as the ratio between the shear stress and the shear strength $[(\sigma_1 - \sigma_3)/(\sigma_1 + \sigma_3)]$, whose value ranges from 0 to 1. It could be observed that in the case of OSCs (without encasement), the full shear strength of the stones in the column is mobilised up to a depth of almost two times the diameter below the surface. On the other hand, in the case of encased stone column ($J = 2500 \text{ kN/m}$), only 90% of the shear strength is mobilised. It is interesting to note that much higher shear strength is mobilised in the clay soil adjacent to the ordinary stone column as compared to that of encased stone column. Due to the lateral confinement in

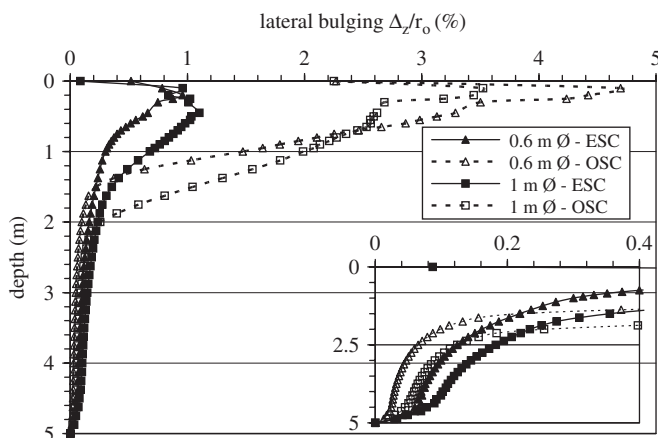


Fig. 3. Lateral bulging observed in stone columns.

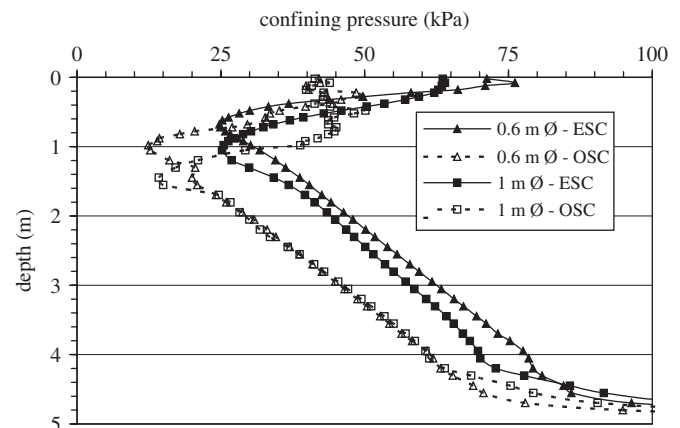


Fig. 4. Variation in confining pressure along the height of stone column.

encased stone columns, lesser lateral stresses are transferred to the surrounding soil.

4.2. Influence of stiffness of encasement

The influence of the tensile stiffness of the geosynthetic used for encasement on the performance of the stone column was investigated by varying the stiffness of geosynthetic over a wide range of values (up to 10,000 kN/m), while all other parameters were kept constant. Some recent geosynthetic products made of high tenacity polyester yarns have tensile strengths of the order of 10,000 kN/m at a strain of about 5% with a secant stiffness of 200,000 kN/m (e.g., high strength geotextiles made by Huesker, USA). Fig. 6 shows the pressure settlement behaviour of 1 m diameter stone column encased with geosynthetic of different stiffness values. The improved performance due to the encasement can be attributed to the enhancement of overall stiffness of the columns due to larger lateral stresses (confining stresses) mobilised in the column, which is illustrated in Fig. 7. It is clearly seen from Fig. 7 that increasing stiffness of geosynthetic encasement mobilises larger lateral stresses in the stone columns. The increase in the lateral stresses in the columns due to geosynthetic encasement can be calculated using Eq. (2) shown below (Bathurst and Karpurapu (1993);

Rajagopal et al. (1999); Latha et al. (2006)).

$$\Delta\sigma_3 = \frac{2M}{d_o} \left[\frac{1 - \sqrt{1 - \varepsilon_a}}{1 - \varepsilon_a} \right]. \quad (2)$$

The above equation estimates an increase in confining pressure in the range of 10–20 kPa for the different stiffness values of geosynthetics at vertical pressure of 200 kPa. These estimates are within the range of lateral stress increase for encased columns shown in Fig. 7. The percent reduction in settlement of encased stone columns over that of the uncased column for different tensile stiffness values of geosynthetics under a particular vertical pressure of 200 kPa is shown in Fig. 8 for two diameters (1 and 0.6 m) of stone column.

22 kN/m for different stiffness values of the geosynthetic. These tensile forces are much lower than the ultimate long-term tensile strength of most commercially available geosynthetics. Hence, the assumption of linear-elastic behaviour for the encasement elements in this paper is justified. For the same reason, the creep effects can also be assumed to be negligible. The tensile forces developed will be lower for smaller diameter stone columns as illustrated in Fig. 12.

4.4. Influence of diameter of stone column on encasement effect

The influence of the diameter of the stone column was investigated by performing analyses with diameters of 0.6 and 1 m by applying pressure loading only on the stone column surface, while keeping the influence radius constant at 3 m. The analyses were performed for two different stiffness values of encasement of 500 and 1000 kN/m. The pressure-settlement diagrams for the different cases are presented in Fig. 13. It is seen that the pressure-settlement responses of the OSCs are almost the same for both the

diameters. But in case of encased stone columns, the performance of 0.6 m diameter encased stone columns is superior to that of 1 m diameter columns. The reason for this is the development of larger additional confining stresses in smaller diameter encased columns as discussed earlier (Eq. (2) and Fig. 4). Eq. (2) suggests that lesser confining pressures are generated for larger diameter columns as the diameter (d_o) is in the denominator. The same can also be observed in the results presented in Fig. 4.

4.5. Influence of depth of encasement

It is well established that the bulging of stone column upon loading will be predominant up to a depth of 1.5–2 times the diameter of stone column from the ground surface. Hence, only the top portion of the stone column needs more lateral confinement in order to improve its performance. Especially, for very long stone columns, it may not be necessary to provide encasement over the full height. Hence, it was decided to investigate the influence of the encasement depth on the response of the stone columns. Analyses were performed using encasement stiffness of 2500 kN/m and by varying the depth of encasement from the ground level. Fig. 14 shows the pressure-settlement response of 0.6 m diameter stone columns with different depths of encasement. The variation in settlement reduction over uncased stone column with depth of encasement for two diameters of stone column (0.6 and 1 m) is shown in Fig. 15. From this it is observed that the encasement beyond a depth equal to twice the diameter of the column does not lead to further improvement in performance. It shows that the confinement at the top portion of the stone column is adequate for improved performance. The settlement reduction for 0.6 m diameter stone column is higher because of the higher confining pressures (consequently higher stiffness) developed in the stone column for lower diameter of the encased columns.

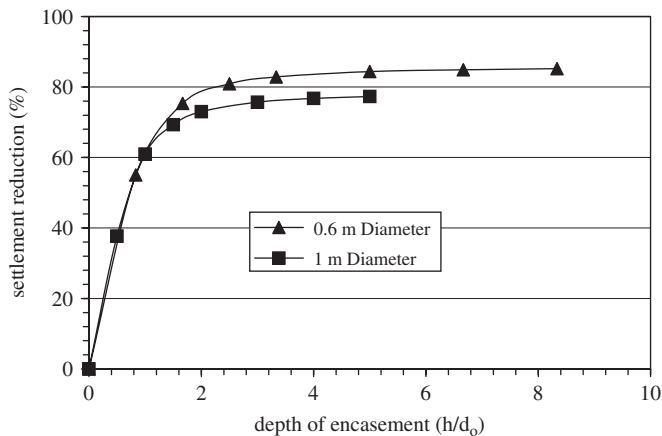


Fig. 15. Influence of depth of encasement on compression of stone column.

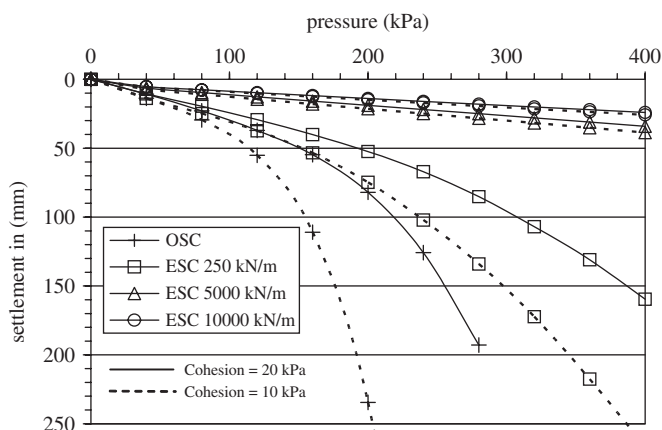


Fig. 16. Influence of the shear strength on foundation soil.

4.6. Influence of strength of foundation soil

The influence of the strength of foundation soil was studied by performing analyses for two cohesive strength values of 10 and 20 kPa. The analyses were performed for two diameters of columns, 0.6 and 1 m, and encasement stiffness of 250, 5000 and 10,000 kN/m. The load–deformation responses observed are shown in Fig. 16. It is seen that the load capacity of ordinary stone column is very much dependent on the cohesive strength of the surrounding clay soil. On the other hand, the influence of the strength of surrounding soil on the capacity of the encased stone columns gradually decreases as the stiffness of the geosynthetic increases. When the encasement stiffness is increased to 10,000 kN/m, the pressure–settlement response of encased column is practically independent of the strength of the surrounding clay soil. As the stiffness of the encasement increases, the lateral bulging of the stone column reduces (Fig. 10), thereby reducing the stresses propagated into the surrounding soil. Hence, the contribution of the surrounding soil to the stability of the encased stone column reduces as the stiffness of the encasement

increases. This phenomenon makes the capacity of encased columns practically independent of the strength of the surrounding soil for very stiff encasement.

4.7. Influence of encasement on load transfer into the columns

All the earlier analyses were performed by applying pressure directly over the top surface of the stone column in order to study the effect of encasing the stone column with geosynthetic. Further analyses were performed by constructing layers of soil on top of the stone column reinforced foundation soil to study the effect of encasement on the load transfer into the stone column. Fig. 17 shows the schematic of the finite element mesh employed for these analyses. All the analyses were performed using axisymmetric idealisation of a cylindrical unit cell consisting of both stone column and soil. The height of the soil layer was varied from 1 to 5 m. The soil fill properties are listed in Table 1. The construction of soil layer was simulated in the analysis by constructing it in layers of 250 mm height in 25 load steps each and maximum 25 iterations per load step.

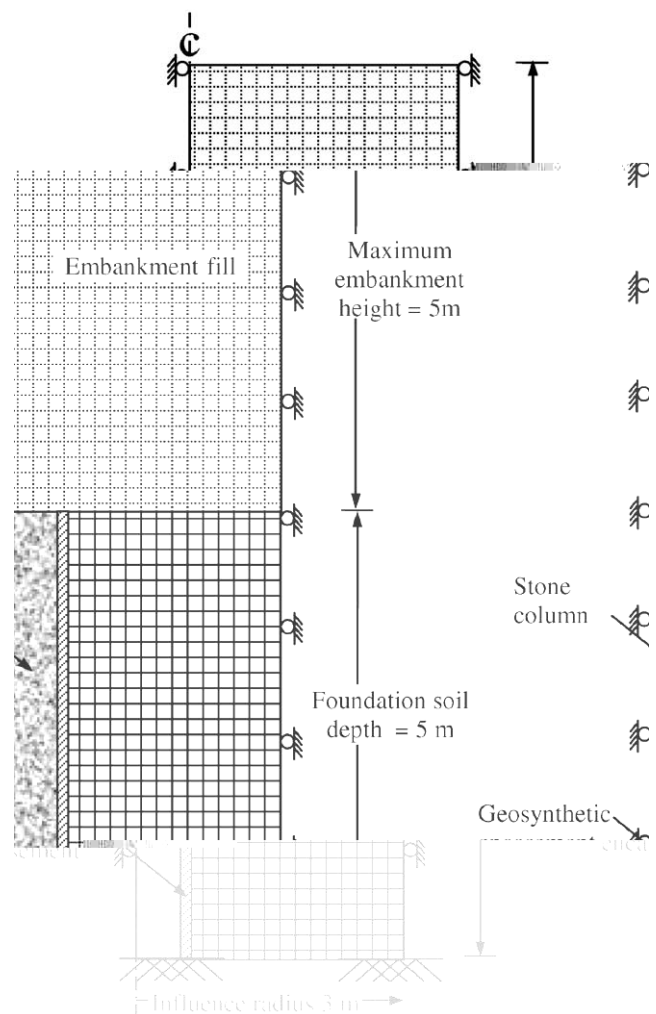


Fig. 17. Schematic finite element mesh with embankment loading.

The stress transfer into the stone column was examined in order to study the influence of encasement on the stiffness of the column. A quantity termed as stress intensity factor (SIF) is defined as the ratio between the average vertical stress in the stone column and the vertical stress corresponding to the height of the soil fill (γz).

The SIF values at different heights of embankment constructed over 1 m diameter ordinary and encased stone columns are shown in Fig. 18. It can be observed that SIF increases as the encasement stiffness or the embankment height increases. As the encasement stiffness increases, the overall stiffness of the encased stone column increases and hence higher stresses are transferred to it from the embankment. Han and Gabr (2002) reported higher SIF values for embankment piles with higher stiffness values. The results from the current investigations are in close agreement with their observations. The higher SIF at larger heights of the embankment indicates that higher percentage of embankment load is transferred into the relatively stronger or stiffer column as the embankment height increases. This is because at some height of the embank-

ment, the foundation soil may not be able to support any more imposed loads. At that stage, all further imposed loads are transferred into the relatively stronger column. Fig. 19 shows the comparison between the SIF values developed in two different diameters of encased columns. It may be noted that the SIF values are higher for smaller diameter encased column. This could be attributed to higher stiffness of smaller diameter column owing to relatively larger confining pressures generated as compared to larger diameter encased columns as discussed earlier.

5. Summary and conclusions

In this paper, we have studied the performance of stone columns encased with geosynthetic reinforcement. The results from the parametric studies are presented to quantify the effect of confinement and the mechanism for improvement in load capacity due to encasement. Based on the results obtained from this study, the following conclusions are made:

1. The load capacity and stiffness of the stone column can be increased by all-round encasement by geosynthetic. By geosynthetic encasement, it is found that the stone columns are confined and the lateral bulging is minimised.
2. The elastic modulus of the geosynthetic encasement plays an important role in enhancing the capacity and stiffness of the encased columns. The confining pressures generated in the stone columns are higher for stiffer encasements.
3. The hoop tension forces developed in the encasement are significant within a depth equal to approximately twice the diameter of the stone column. The pattern of variation of hoop tension forces closely follows that of the lateral bulging of the column.
4. The performance of encased stone columns of smaller diameters is superior to that of larger diameter stone columns because of mobilisation of higher confining stresses in larger stone column. The higher confining stresses in the column leads to higher stiffness of smaller diameter encased columns.
5. The confinement at the top portion of the stone column (where predominant bulging occurs) is sufficient for the improved performance of the stone column. It is adequate to encase the stone column up to a depth equal to two times the diameter of stone column to substantially increase its load carrying capacity.
6. The load capacity of encased columns is not as sensitive to the shear strength of the surrounding soils as compared to OSCs. This is especially true for higher stiffness values of the encasement.
7. The magnitude of loads transferred into the encased stone columns from the embankments can be increased by using stiffer encasement.

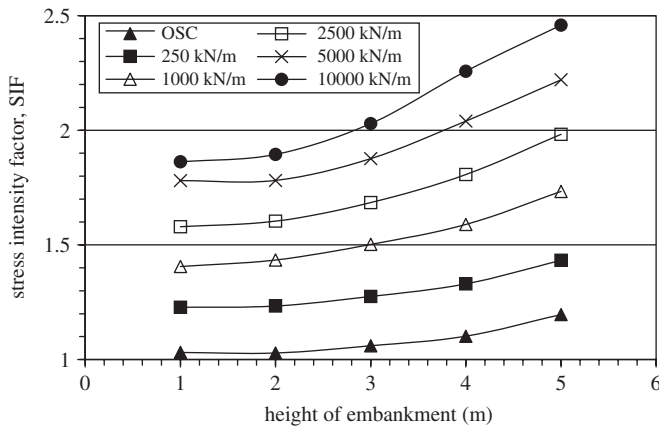


Fig. 18. Variation in SIF with height of embankment (for 1 m diameter stone column with various values of encasement stiffness).

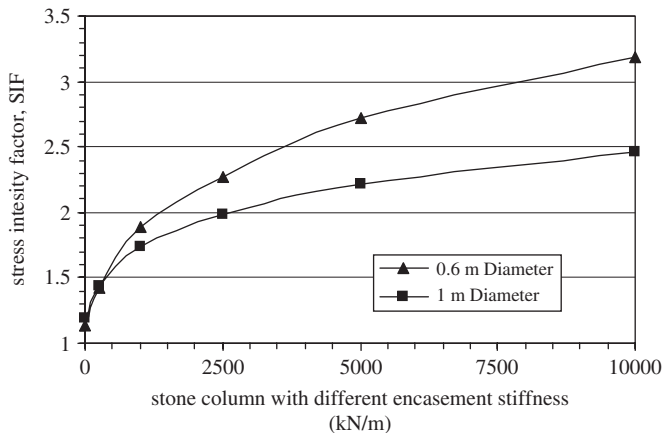


Fig. 19. Influence of encasement stiffness on stress concentration of stone columns of 1 and 0.6 m diameter (5 m high embankment).

Acknowledgements

The authors are thankful to the anonymous reviewers for their meticulous review and several suggestions for improving the presentation in the paper.

References

- Ayadat, T., Hanna, A.M., 2005. Encapsulated stone columns as a soil improvement technique for collapsible soil. *Ground Improvement* 9 (4), 137–147.
- Barron, R.A., 1948. Consolidation of soil using vertical drain wells. *Geotechnique* 31, 718–742.
- Bathurst, R.J., Karpurapu, R., 1993. Large scale model triaxial compression testing of geocell-reinforced granular soils. *ASTM Geotechnical Testing Journal* 16 (3), 296–303.
- Bergado, D.T., Singh, N., Sim, S.H., Panichayatum, B., Sampaco, C.L., Balasubramaniam, A.S., 1990. Improvement of soft Bangkok clay using vertical geotextile band drains compared with granular piles. *Geotextiles and Geomembranes* 9 (3), 203–231.
- Duncan, J.M., Chang, C.Y., 1970. Non linear analysis of stress and strain in soils. *Journal of Soil Mechanics and Foundations Divisions* 96 (5), 1629–1652.
- Duncan, J.M., Byrne, P., Wong, K.S., Mabry, P., 1980. Strength, stress–strain and Bulk modulus parameters for finite element analyses of stresses and movements in soil masses. *Geotechnical Engineering Report No. UCB/GT/80-01*, submitted to the University of California, Berkeley.
- Greenwood, D.A., 1970. Mechanical improvement of soils below ground surface. In: *Ground Engineering Proceedings Conference Organised by the Institution of Civil Engineers*, London, June 1970, pp. 11–22.
- Han, J., Gabr, M.A., 2002. Numerical analysis of geosynthetic-reinforced and pile-supported earth platforms over soft soil. *ASCE Journal of Geotechnical and Geoenvironmental Engineering* 128 (1), 44–53.
- Hughes, J.M.O., Withers, N.J., Greenwood, D.A., 1975. Field trial of the reinforcing effect of a stone column in soil. *Geotechnique* 25 (1), 31–44.
- Indraratna, B., Bamunawita, C., Khabbaz, H., 2004. Numerical modeling of vacuum preloading and field applications. *Canadian Geotechnical Journal* 41 (6), 1098–1110.
- Katti, R.K., Katti, A.R., Naik, S., 1993. *Monograph to Analysis of Stone Columns with and without Geosynthetic Encasement*. CBIP Publication, New Delhi.
- Latha, G.M., Rajagopal, K., Krishnaswamy, N.R., 2006. Experimental and theoretical investigations on geocell-supported embankments. *International Journal of Geomechanics*, ASCE 6 (1), 30–35.
- Malarvizhi, S.N., Ilamparuthi, K., 2004. Load versus settlement of clay bed stabilized with stone and reinforced stone columns. In: *Proceedings of GeoAsia–2004*, Seoul, Korea, pp. 322–329.
- Raithel, M., Kempfert, H.G., 2000. Calculation models for dam foundations with geotextile coated sand columns. In: *Proceedings of the International Conference on Geotechnical & Geological Engineering, GeoEngg–2000*, Melbourne.
- Raithel, M., Kempfert, H.-G., Kirchner, A., 2002. Geotextile-encased columns (GEC) for foundation of a dike on very soft soils. In: *Proceedings of the Seventh International Conference on Geosynthetics*, Nice, France, pp. 1025–1028.
- Rajagopal, K., Bathurst, R.J., 1993. *User's Manual for Geotechnical Finite Element Modelling (GEOFEM)*, vols. 1–3. Department of Civil Engineering, Royal Military College, Kingston, Ont., Canada.
- Rajagopal, K., Krishnaswamy, N.R., Latha, G.M., 1999. Behaviour of sand confined with single and multiple geocells. *Geotextiles and Geomembranes* 17 (3), 171–184.
- Rajasekaran, G., Rao, S.N., 2002. Compressibility behaviour of lime-treated marine clay. *Ocean Engineering* 29 (5), 545–559.
- Rampello, S., Callisto, L., 2003. Predicted and observed performance of an oil tank founded on soil-cement columns in clayey soils. *Soils and Foundations* 43 (4), 229–241.
- Sharma, J.S., 1998. A study on the behaviour of geogrid reinforced stone column. In: *Proceedings of the Sixth International Conference on Geosynthetics*, Atlanta, pp. 877–882.
- Sharma, S.R., Phanikumar, B.R., Nagendra, G., 2004. Compressive load response of granular piles reinforced with geogrids. *Canadian Geotechnical Journal* 41 (1), 187–192.
- Shen, S.L., Chai, J.C., Hong, Z.S., Cai, F.X., 2005. Analysis of field performance of embankments on soft clay deposit with and without PVD-improvement. *Geotextiles and Geomembranes* 23 (6), 463–485.