Numerical Simulation of Behaviour of Partially Penetrating Stone Columns

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ABSTRACT
With the sharp decrease in good construction sites, the society is focusing its attention towards using the problematic soils, such as marine clays, by improving the strength and stiffness characteristics in-situ. Of the various ground improvement techniques available, stone columns (or Granular Piles) are finding wider application, due to their ease of construction, and use of locally available construction material. Stone columns installed in soft soils have low lateral confinement and undergo excessive bulging to derive their strength. It has been observed from the research carried out on various experimental and numerical studies that the stone columns when subjected to loading undergo bulging up to a depth of 4 times the diameter of stone columns to generate their strength. It is also evident that top portion of the stone columns contribute much to the additional load carrying capacity. In general, the stone columns extend to the full depth of the soft soil layer. However, recent laboratory investigations revealed that stone columns with partial penetration would behave similar to full penetration columns, and hence, the partial penetrating stone columns may provide a better solution, saving both time and material. Hence, efficacy of the partially penetrating stone columns is studied in this paper using one of the widely used geotechnical software packages, PLAXIS, to establish the behaviour of single stone columns with varying depths, as a percentage of the depth of clay layer, into which the columns are inserted. The model is validated using the available experimental results from the literature. The study offers very promising results, and it can be concluded that use of partially penetrating stone columns up to a depth of 1.75 D behave in the same manner as that of a fully penetrating stone columns, which lead to considerable saving in time and natural stone aggregate used for improving the ground.

RÉSUMÉ
Avec la forte baisse des chantiers de construction bon, la société concentre son attention vers l'utilisation des sols problématiques, telles que les argiles marines, en améliorant les caractéristiques de résistance et la rigidité in-situ. Parmi les différentes techniques d'amélioration au sol disponible, colonnes de pierre (ou empilements granulaires) trouvent une application plus large, en raison de leur facilité de construction, et l'utilisation de matériaux de construction disponibles localement. colonnes de pierre installé dans les sols mous ont une faible confinement latéral et subissent bombement excessif de tirer leur force. Il a été observé à partir des recherches menées sur diverses études expérimentales et numériques que les colonnes de pierre lorsqu'elle est soumise à un chargement subir renflement jusqu'à une profondeur de 4 fois le diamètre des colonnes de pierre pour générer leur force. Il est également évident que la partie supérieure des colonnes de pierre contribuent beaucoup à la charge supplémentaire la capacité de charge. En général, les colonnes de pierre s'étendent sur toute la profondeur de la couche de sol mou. Toutefois, des enquêtes récentes en laboratoire ont révélé que les colonnes en pierre avec pénétration partielle se comporteraient semblables à des colonnes à pleine pénétration et, par conséquent, les colonnes en pierre de pénétration partielle peut fournir une meilleure solution, d'économiser du temps et du matériel. Par conséquent, l'efficacité des colonnes de pierre pénétrant partiellement est étudiée dans le présent document en utilisant l'un des paquets de logiciels largement utilisés en géotechnique, PLAXIS, à établir à la fois le comportement de colonnes en pierre unique avec des profondeurs variables, en pourcentage de la profondeur de la couche d'argile, en. L'analyse numérique est effectuée à l'aide à 15 nœuds éléments triangulaires sur un modèle de révolution pour simuler l'argile marine et pénétrant partiellement colonne de pierre. Le modèle est validé en utilisant les résultats expérimentaux disponibles dans la littérature. L'étude offre des résultats très prometteurs, et il peut être conclu que l'utilisation de la partie pénétrante colonnes de pierre jusqu'à une profondeur de 1,75 D se comportent de la même manière que celle d'une des colonnes en pierre entièrement pénétrante, qui conduisent à des économies considérables en temps et en pierre naturelle

1 INTRODUCTION

With the onslaught of urban and infrastructure growth globally, good construction sites seldom come across, as they have been already utilised. Most of the available sites experience presence of weak soil deposits within the influence zones, wherein the designers are challenged by the presence of either loose sand or soft clay layers of considerable thickness. The soft clay deposits are characterised by very low bearing capacity and high compressibility, which require longer duration to consolidate, and the structures constructed on these deposits settle continuously, if these soils are not treated properly.

These sites, if to be put to utilisation, have to be re-engineered to improve their inherited properties. Out of several techniques available, stone columns (also known as granular column or granular pile) have been widely used as an effective ground improvement technique to enhance the inherent in-situ properties of soft clay. The use of stone columns has been successful to increase the bearing capacity and to reduce the settlement of foundation of structures, like, storage tanks, embankments, raft foundations, etc. Stone columns have also been used to improve slope stability of embankments on soft ground.

Stone columns when subjected to compressive loads fail in different modes, such as bulging (Hughes and Withers 1974; Hughes et al. 1976), general shear failure (Madhav and Vitkar 1978), and sliding (Aboshi et al. 1979). Researchers have developed theoretical solutions for estimating bearing capacity and settlement of foundations strengthened by stone columns (Greenwood 1970; Hughes et al. 1976; Madhav and Vitkar 1978; Aboshi et al. 1979). Priebe (1995) proposed a method to estimate the settlement of foundation resting on the infinite grid of stone columns based on unit cell concept. In this concept, the soil around a stone column for area represented by a single column, depending on column spacing, is considered for the analysis. By using model tank dimensions, which are obtained based on the unit cell concept, and loading the stone column alone, it is assumed that lateral deformations in soil at the boundary of unit cell are zero.

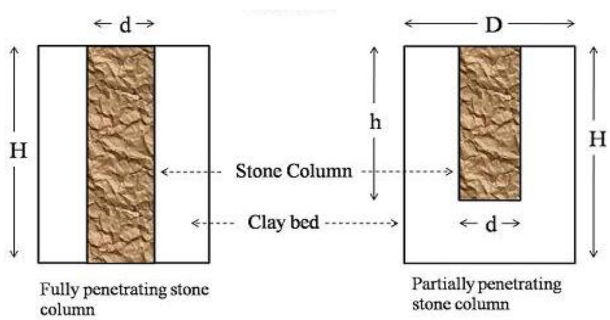

Figure1. Stone column–Fully and Partially penetrating

The unit cell concept introduced by Barksdale and Bachus (1983) is very popular among researchers, to simulate actual behavior of stone column improved ground, using 1-g physical and numerical modelling. Some of the notable work using this concept are reported in Goughnour (1983), Han and Gabr (2002), Murugesan and Rajagopal (2006, 2007), Ambily and Gandhi (2007). Balaam et al. (1978), Murugesan and Rajgopal (2006, 2007), and Ambily and Gandhi (2007) carried out finite-element analyses of soft clay model bed treated with granular piles and reported significantly improved load-settlement response, compared to the unreinforced ground. Generally, the penetration length of stone columns/prefabricated vertical drains/sand drains is kept equal to the total thickness of clay layer, which is to be consolidated or improved. However, previous studies, though limited, revealed that a reduced penetration length, say 80-90% of clay bed thickness, proved sufficient, without significantly affecting either the time for settlement in case of PVDs or load settlement behavior of stone column improved ground. This way, the time of construction, project cost, and use of natural resources can be reduced. More research is being focused in this direction in the case of PVDs (Geng et al. 2011), than in case of stone columns. Keeping in mind the wide usage of stone columns in India for various infrastructure projects, efficacy of partially penetrating stone columns, on the load-settlement baheviour, is taken as the objective of the present study. The analysis is restricted to the case, where the bottom layer (soil below the clay layer) is considered as an impervious boundary. In this study, finite element based numerical analysis is used, the results of which are validated with the available experimental results from the published literature.

2 FINITE ELEMENT ANALYSIS

The analysis was carried out with the help of finite element package PLAXIS (Plaxis BV, The Netherlands). Numerical analysis is initially conducted on a fully penetrating stone column model of Ambily and Gandhi (2004), wherein the model clay bed exhibited an average undrained cohesion (c_u) of 12 kPa. The cylindrical unit cell dimensions were kept as: diameter 420 mm and height 450 mm. A stone column of diameter 100 mm and depth 450 mm was installed at the centre of unit cell. Properties of clay and stones used in the experimental program were given in Table 1.

Table 1. Properties of Geo materials used for validation of Plaxis (Ambily & Gandhi 2004)

Material	Clay	Stones
Young's modulus, E (kPa)	2000	48000
Poisson's ratio (v)	0.45	0.30
Undrained cohesion, c_u (kPa)	12	-
Bulk unit weight, γ_{bulk} (kN/m^3)	18.20	-
Dry unit weight, γ_{dry} (kN/m^3)	-	16.0
Friction angle, ϕ (deg)	-	43
Dilation angle, Ψ (deg)	-	10

Axisymmetric analysis with 15 noded triangular elements were used in the analysis, along with Mohr-Coulomb failure criterion to model elastoplastic behavior of clay and stones, and drained behavior was assumed for both clay bed and stone columns. The vertical and horizontal displacements were restrained at the base and only horizontal displacements were restrained along the wall of the unit cell. The zone of interface between stone column and clay is a zone with very high difference in magnitudes in young's modulus of the order of ten times or more. Also the shear strength properties of this zone depend on the method of installation of stone column. The above two properties of the interface are very difficult to quantify, and also during the loading stage the stone column undergoes bulging and induce lateral displacement of clay in the radial direction, where the shearing phenomenon along the interface is nearly absent. Hence, to make the analysis simple, the interface element is not considered in the analysis.

Fig. 2 shows the deformed mesh of the validated stone column model. The bulging of the column is noticed up to a depth of 3d from the top surface, where "d" is the diameter of the stone column. The heaving of clay adjacent to the loading area, can also be seen in the figure. Fig. 3 shows a comparison of the observed load-settlement response of the present study with that of

Ambily and Gandhi (2004), and it is noted that the results obtained from the present model compare well with experimental findings.

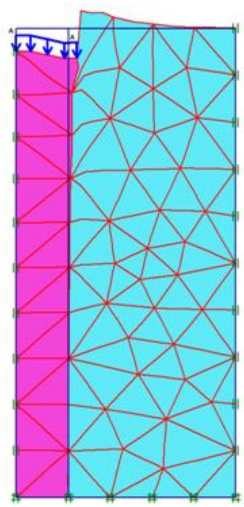

Figure 2. Deformed mesh of validated model

3 ANALYSIS OF MODEL STONE COLUMN

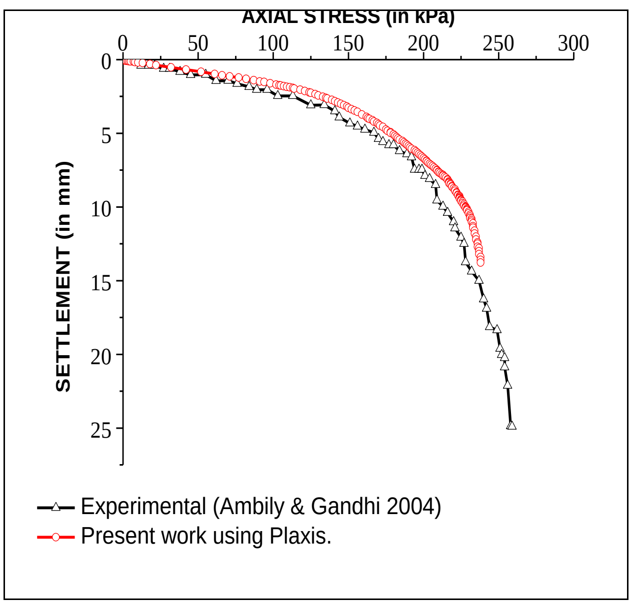

Figure 3. Validation of numerical results (Cu =12kPa; s/d = 4)

This validated model is further analyzed to study the effect of partial penetration of stone column on the load-settlement response, considering different ratios of height of stone column (h) to the thickness of clay bed (H=450 mm). The parameter h/H is varied as 1.0, 0.89, 0.78, 0.67, 0.61, and 0.55, and the results are presented in Figure 4.

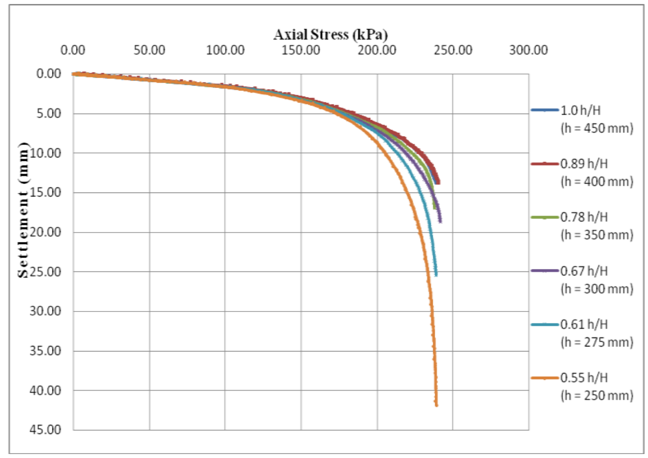

Figure 4. Load settlement behaviour of fully and partially penetrating stone columns

From Fig. 4, it can be seen that partial penetration of stone columns has nearly no or very minimal effect on the load-settlement response, for h/H ratios above 0.55. The axial stress corresponding to 10 mm settlement level (i.e. 10% of stone column diameter) for the case of h/H=0.61 is 213 kPa, whereas for 1.0 h/H it corresponds to 228 kPa, which shows a variation of just 7%. This decrease in strength for 0.61h/H stone column can be partially recovered at a later stage by removal of pore water pressure due to continuing consolidation process and simultaneously building up of the shear strength of the clay. This partial increase in strength with time has not been considered in the present analysis. The variation of ultimate axial load for various h/H ratios is shown in Fig. 5. Similarly, the variation of axial stress corresponding to settlement levels of 10 mm and 13 mm, with h/H ratio is shown in Fig. 6.

For values of h/H less than 0.55, it was observed that the finite element mesh had failed prematurely, and there was a drastic reduction in axial stress associated with extremely high settlements. This behavior may be due to very low shear strength of clay. However, for clay beds with better shear strength values, a still lower h/H may be obtained, without much sacrificing on the load carrying capacity.

In this study, the load is applied on stone column alone. By doing so, the column of aggregates share majority of the applied load, as modulus of elasticity of aggregates very high compared to that of soft soil, and clay being very soft takes negligible load at any load stage, until any excess pore water pressure is released. Though there is a significant increase in the settlement for the 0.61 h/H case, the increase in settlement up to 0.67 h/H is only marginal. For the case 1.0 h/H and 0.89 h/H the settlement is nearly same for the same ultimate axial stress.

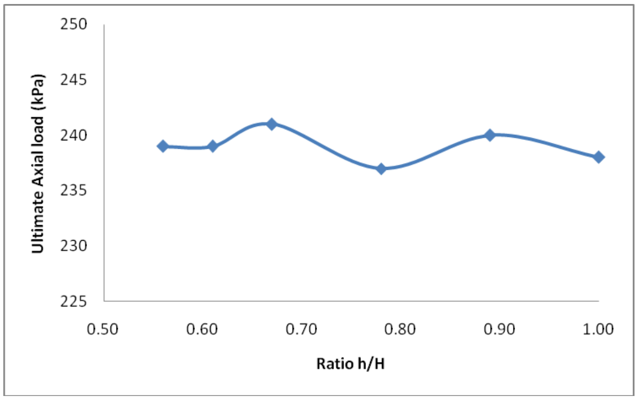

Figure 5. Effect of partial penetration of stone column on the ultimate axial stress

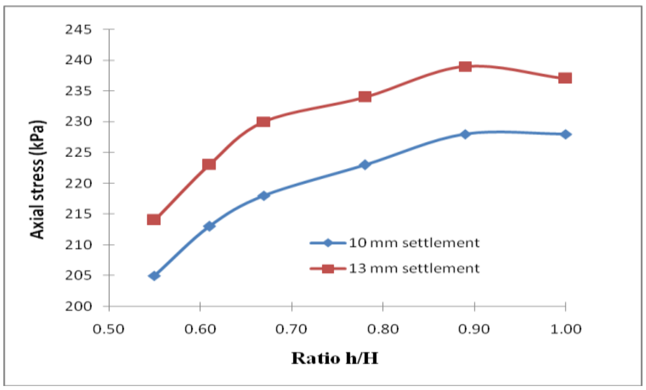

Figure 6. Axial stress for 10 mm & 13 mm settlement

The lateral deformation of the stone column is observed to increase with the decrease in the depth of stone column, from h/H=1.0 to 0.56, as shown in Figure 7. The maximum lateral deformation is 4.97 mm at 1.0 h/H and 21.09 mm for 0.56 h/H. This is because as depth of stone column decreases the quantity of aggregates in stone column decreases due to which the aggregates in stone columns with shallow depths are subjected to greater stresses as compared with that 1.0 h/H. This results in higher radial displacement of stone columns with and formation of bigger bulbs, for lower h/H ratios. For 10 mm settlement level, the reduction in axial stress for 0.56 h/H is 10%, compared to full penetration stone columns, and this reduction is quite less for stone columns with higher h/H ratios. However, further studies involving varying sizes of single stone columns, group stone columns, and loading applied to not only to stone columns, but to surrounding soil as well, and studies to overcome size effects due to use of small-scale models are warranted to fully realize the beneficial use of partially penetrating stone columns.

4. LIMITATIONS

This paper reports the behaviour of single stone column and the behaviour of group of stone columns will be

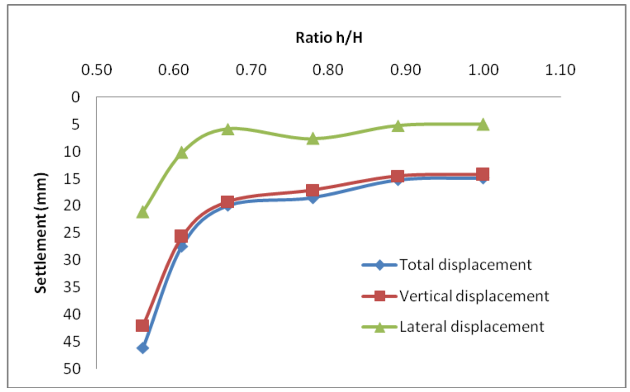

Figure 7. Effect of partial penetration on the Horizontal, Vertical and Total displacements of reinforced soil bed

different since there is marked difference in the bulging patterns of single and group of stone columns, which affect their behaviour.

5. CONCLUSIONS

Effect of partially penetrating stone columns on the load-settlement response of reinforced soft soil is studied using a numerical code, and following conclusions can be made from the present study.

1. The phenomenon of bulging of stone columns is observed up to a depth of 3.0 times the diameter of the stone column from the soil surface.
2. The bulging of stone columns increases with the decrease in the ratio h/H. And the bulging nearly doubles when the depth ratio h/H decrease from 0.67 to 0.61 and with further decrease of h/H, the bulging increases by 4 times.
3. The settlement of ground with partial penetrating stone columns with h/H=0.67, is less than 20 mm which is 20% of the column.
4. Corresponding to 10 mm settlement level, the axial carrying capacity of the ground is only reduced by 7% when stone columns are partially penetrated to a depth of 0.61h/H, compared to fully penetrating stone columns.

NOTATIONS

D = diameter of unit cell;
E = Young's modulus of elasticity;
H = depth of clay bed;
c_u = undrained shear strength of clay;
d = diameter of stone column;
h = height of stone column;
s = centre to centre spacing of stone columns;
γ = unit weight of soil;
ν = Poisson's ratio;
φ = angle of internal friction;
ψ = dilation angle;

REFERENCES

Aboshi, H., Ichimoto, E., Harada, K., and Emoki, M. (1979). “The composer—A method to improve the characteristics of soft clays by inclusion of large diameter sand columns.” *Proceedings, International Conference on Soil Reinforcement.*, E.N.P.C., 1, Paris 211–216.

Ambily, A.P. and Gandhi, S.R. (2004) “Experimental and theoretical evaluation of stone column in soft clay” *Proceedings of International Conference on Geotechnical and Geoenvironmental Engineering,* Mumbai, India pp 201-206.

Ambily, A.P. and Gandhi, S.R. (2007) “Behavior of stone columns based on experimental and FEM analysis.” *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 133(4), p 405-415.

Balaam, N. P., Poulos, H. G., and Brown, P. T. (1978). “Settlement analysis of soft clays reinforced with granular piles.” *Proc., 5th Asian Conference on Soil Engineering*, Bangkok, Thailand, 81–92.

Barksdale, R. D. & Bachus, R. C. (1983). Design and Construction of Stone Columns. Report No. FHWA/RD-83/026, *Office of Engineering and Highway Operations Research and Development*, Federal Highway Administration, Washington, DC, USA.

Geng, X., Indraratna, B. & Rujikiatkamjorn, C.(2011). Effectiveness of partially penetrating vertical drains under a combined surcharge and vacuum preloading, *Canadian Geotechnical Journal*, 2011, 48(6), 970-983.

Goughnour, R. R. (1983). “Settlement of vertically loaded stone columns in soft ground.” *Proceedings, 8th European Conference on Soil Mechanics, and Foundations Engineering*, Helsinki, Finland, 1, 235–240.

Greenwood, D. A. (1970). “Mechanical improvement of soils below ground surfaces.” *Proceedings, Ground Engineering Conference, Institution of Civil Engineers*, London, 11–22.

Han, J. & Gabr, M. A. (2002). “Numerical analysis of Geosynthetic reinforced and pile-supported earth platforms over soft soil.” *Journal of Geotechnical and Geoenvironmental Engineering*, 128, No. 1, 44–53.

Hughes, J. M. O., and Withers, N. J. (1974). “Reinforcing of soft cohesive soils with stone columns.” *Ground Engineering.*, 7(3), 42–49.

Hughes, J. M. O., Withers, N. J., and Greenwood, D. A. (1976). “A field trial of reinforcing effect of stone column in soil.” *Proceedings, Ground Treatment by Deep Compaction*, Institution of Civil Engineers, London, 32–44.

Madhav, M. R., and Vitkar, P. P. (1978). “Strip footing on weak clay stabilized with a granular trench or pile.” *Canadian Geotechnical Journal*, 15(4), 605–609.

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.

Priebe, H. J. (1995). “The design of vibro replacement.” *Ground Engineering.*, 28(12), 31–37.