International Journal of Integrated Engineering, Vol. 10 No. 1 (2018) p. 103-108
© Penerbit UTHM
DOI: https://doi.org/10.30880/ijie.2018.10.01.016

Investigation of the Bearing Capacity of Foundations on Encased Stone Columns Using Finite Element Method

Hassan Kardgar[1*]

[1]Department of Civil Engineering
Rouzbahan University, Sari, IRAN.

Received 27 November 2017; accepted 28 February 2018, available online 01 May 2018

Abstract: Soft cohesive soils containing much silt or clay content with low bearing capacity are not suitable for deep vibratory compaction. To improve the bearing behavior of these types of soils to withstand against heavy building loads, the surrounding soil mass must be reinforced with any stiff physical or chemical admixture. Using stone column technique has been proven to be one of the most appropriate methods of improving soil strength. By employing vertical columns of compacted aggregate through the soils, vertical load carrying capacity and shear resistance in the soil mass will be improved. However, the effect of various parameters on the amount of this enhancement is not fully identified. To that end, the geotechnical finite element program PLAXIS was employed to model the effect of stone column application on the bearing capacity of clay soils. According to the results, as important factors, the influence of the length of the stone columns and the stiffness of their encasement is more significant and need to be considered in the comprehensive analysis and design of the soil-structure system.

Keywords: Stone columns, foundation, geotextile, finite element method, reinforced soil

1. Introduction

Stone columns are increasingly used to improve the ground load bearing, especially in the stabilization of embankments, roads, and reservoirs. The axial capacity of the stone column will be mobilized from the resistance generated against column expansion and increased resistance to lateral deformation. Stone columns are used as an economical and environmentally-friendly way to improve soft soils such as clay, silts, and silty sand. The most important function of stone columns is to increase soil bearing capacity, reduce total soil settlement and increase drainage capacity [1]. This method is based on the replacement of a part of a soft or loose soil with vertical columns consisting of dense aggregates, a soil transformation onto composite materials showing higher shear strength and permeability and lower compressibility. It is commonly expected that the strength and stiffness of stone columns will be achieved by their confining stress caused by surrounding soil. If the soil is strong enough, the stone column will have a uniform diameter with an estimated amount of rock materials, but in case of insufficient confinement from the surrounding soil, the performance of the stone column will be inappropriate. In very soft soils (Cu <15 kPa) [2], the generated confining stress may not be sufficient and although they may be caused by additional containment due to structural loads, but the containment may require radial deformation at the top of the column in poor soils and this point might lead to failure. To develop the required lateral containment for the column and increase the bearing capacity of the soft soil, the column should be covered by a hard and creep-resistant geosynthetics, resulting in geosynthetic-encased column (GEC).

In recent years, geotextile coating has been used to expand the use of stone columns in soft soils. Although this technique has been well established, little research was performed on the use of other coating materials such as geogrid. The idea of covering stone columns was initially presented by van Impe [3]. In spite of the benefits of using encased stone columns, this technique is not widely used, due to the limited understanding of its response and the difficult of installation techniques. To better understand the behavior of engineering structures and avoid the imposed high costs due to large-scale testing of them, experimental, analytical and numerical methods are usually used. In terms of experimental studies, Gniel and Bouazza [4] discussed the results of small-scale testing of stone columns in extremely soft soils with varying encasement length and investigated the effect of increasing the encased length on the reduction of vertical strain. Miranda and da Costa [5] studied the increase in strength of samples encased with geotextiles compared with non-encased ones. In regard to the analytical studies, Pulko et al. [6] developed a design procedure based on analytical closed-form solution for non-encased and encased stone columns, taking into account the encasement stiffness, column arrangements and load levels. Castro et al. [7] compared the stress distribution and the settlement reduction of end-bearing columns from analytical solutions with those from

---

*Corresponding author: hassan.kardgar89@gmail.com

laboratory measurements and numerical simulations, considering plastic strains in the column.

In most geotechnical engineering problems, finite element analysis can be employed as a useful tool to evaluate the performance and predict the bearing behavior of the structure [8-13]. Therefore, the analysis of stone columns by numerical methods such as finite element analysis would give us a good representation of the load carrying behavior of the soil. In this regard, Murugesan and Rajagopal [1] studied the quantitative and qualitative improvement of the stone column load capacity through comprehensive parametric studies with finite element method. Lo et al. [14] showed the potential of using geosynthetic encasement for enhancing the effectiveness of stone columns in very soft clay by employing finite element method.

Based on the mentioned advantages of numerical modeling, the analysis of the effect of stone columns on the bearing capacity of the above shallow foundation was performed in this study. For this purpose, finite element program PLAXIS was used to simulate the soil and foundation was validated against existing literature. In a parametric study, the influence of various diameter, length, and number of stone columns, different stiffness of encasements and varying foundation breadth were investigated.

2. Numerical Model

In this study, the bearing capacity of shallow foundation on geotextile-encased stone columns in different conditions was investigated in two-dimensional space. In general, the arrangement of stone columns is three-dimensional and therefore it is necessary to use the equivalent strip for modeling a row of stone columns in a plane strain state. The width of the equivalent strip is indicated by the following expression:

$$t_e = \frac{\pi . D^2}{4S} \tag{1}$$

where S is center to center distance of stone columns, D is the column diameter and t_e is the width of the equivalent strip.

The Area Replacement Ratio (ARR), defined as the ratio of column cross section area to total treatment area, has also an important effect on the response of stone columns. This ratio is expressed as:

$$ARR = \frac{\pi}{4} . \frac{D^2}{S^2} \tag{2}$$

The area replacement ratio should be between 10% and 30% to have an efficient influence on the results (Hu et al. [15]). Thus, the ratio of 12.5% (corresponding to the ratio of $\frac{S}{D} = 2.5$) was considered as a constant value for this study.

2.1 Finite element simulation

In order to properly model the stone column, finite element tool was employed with the consideration of soil-structure interaction. Fig. (1) shows the finite element mesh used in this study and the foundation on the top of a series of stone columns. Plane strain condition was assumed in the model due to the nature of stone columns. Fifteen-node triangular elements were used in the mesh of the model. The lateral sides of the model were fixed against the horizontal movement and were allowed to have settlement. The bottom of the model was constrained against both vertical and horizontal movements. Only half of the system was modeled due to the symmetry condition. The concentration of finite element mesh near the stone columns is higher than that in farther distances to acquire better accuracy. The connection of the stone columns and the encasement as well as the connection of the encasement and the surrounding soil was modeled by interface elements (as described in Taghavi Ghalesari et al. [16, 17]) with the strength reduction coefficients of 0.7 and 0.8, respectively.

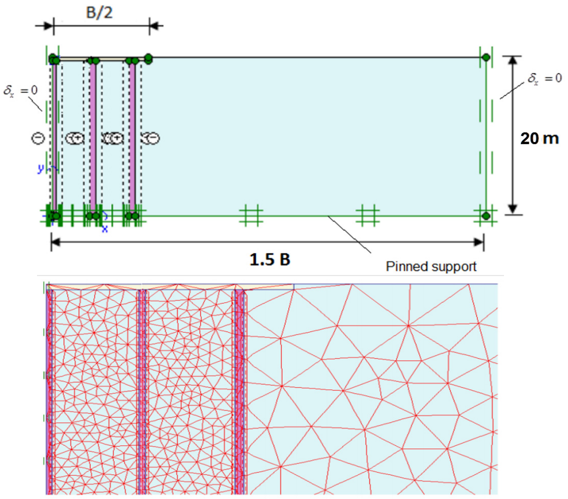

Fig. 1 Finite element mesh and boundary condition.

The depth of the soil was assumed to be 20 m and the width of the model was considered to be dependent on the breadth of the foundation to diminish the effect of the boundary on the response. The width of the foundation for the base model was B=15 m, the vertical applied load was 100 kPa, and the diameter, length and number of stone columns were 1m, 14m and 9, respectively.

After modeling the in-situ condition and generating the corresponding stresses, the staged loading was applied on the model, which means that the excavation, placement of encased stone columns and application of static vertical loading were simulated.

2.2 Verification and validation

Prior to perform any numerical analysis, the described simulation procedure was investigated through a comparison with an existing research by Narasimho et al. [18] on the stone column behavior. The soil mass with a height of 350 mm and a diameter of 650 mm was reinforced with a single stone column with a length of 225 mm and a diameter of 50 mm located in the middle of it and tested with a laboratory model and loaded by a rigid sheet with a diameter of 100 mm to the failure. The clay soil with an elastic modulus of 4 MPa, a Poisson's ratio of 0.45 and an undrained cohesion of 20 kPa, and a stone column with an elastic modulus of 45 MPa, a Poisson's ratio of 0.30 and an internal friction angle of 38° were used. Fig. (2) illustrates the satisfactory agreement between the results of the numerical modeling through the aforementioned procedure and the experimental study conducted by Narasimho et al. [18].

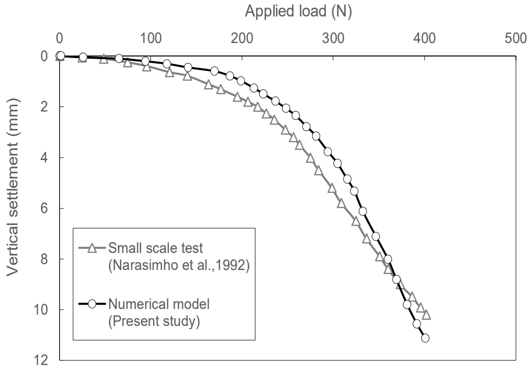

Fig. 2 Comparison of the results from experimental test by Narasimho et al. [18] and the present study.

To validate the accuracy of the proposed modeling procedure, experimental study conducted by Debnath and Dey [19] was modeled. In their study, a group of 12 stone columns (GP soil, $G_s = 2.65$, $\gamma_{d,\max} = 16.64$ kN/m^3, $\gamma_{d,\min} = 14.13$ kN/m^3) with a certain arrangement encased with geotextile (polypropylene, thickness=1.2 mm, E=175 MPa, ν =0.3, Ultimate tensile strength=12 kN/m.) was placed is sand (SP, $G_s = 2.67$, $\gamma_{d,\max} = 17.78$ kN/m^3, $\gamma_{d,\min} = 14.63$ kN/m^3). The loading was applied through a circular plate (200 mm diameter) on the center of the group of stone columns with spacing of 125 mm and diameter of 50 mm with varying length. Fig. (3) shows the results of the FE modeling and the experimental work, which are in reasonable agreement.

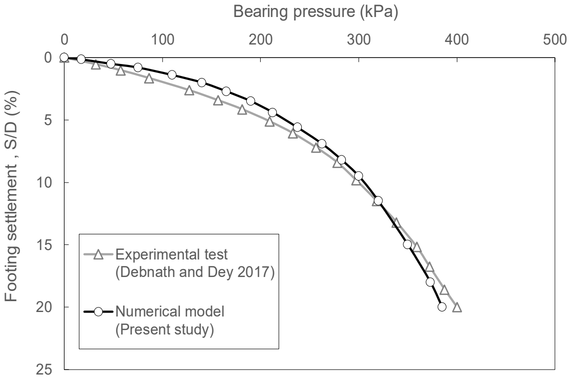

Fig. 3 Comparison of test results [19] and numerical simulation results.

2.3 Materials

Table 1 lists the material used in this study for modeling the soil, foundation and stone columns. To model the soil and stone column, elastic-perfectly plastic Mohr-Coulomb constitutive model with the parameters mentioned in Table 1 was utilized.

Table 1 Material properties used in the numerical model

Parameter	Soft soil	Stone column	Concrete foundation	Geotextile encasement
Elastic modulus, E (MPa)	5	52	25,000	Linear elastic with the Poisson's ratio of 0.30 and axial stiffness of J=2000, 3000 and 4000 kN/m
Poisson's ratio, ν	0.25	0.3	0.2	
Unit weight, γ (kN/m^3)	16	19.5	23.5	
Cohesion, c (kPa)	3	0	-	
Internal friction angle, ϕ (°)	25	44	-	
Dilation angle, ψ (°)	0	11	-	

3. Results and Discussion

To evaluate the effect of using geotextile-encased stone columns (GECs) on the bearing capacity of the overlying shallow foundation, the bearing capacity improvement ratio BCI (bearing capacity of treated-to-untreated soil) was defined as follows:

$$BCI = \frac{q_{GEC}}{q_{OSC}} \tag{3}$$

where q_{GEC} is the bearing capacity of the foundation over geotextile-encased stone columns and q_{OSC} is the bearing capacity of the foundation over ordinary stone columns.

As an indicator of the ultimate bearing capacity of the foundation, the load corresponding to the settlement of 0.1D (D=diameter of stone columns) was considered and compared in different cases, as suggested by Hu and Randolph [20]. The effect of different parameters such as the stiffness of the geotextile encasement ($J = E_{ge} \times t_{ge}$), length (L), diameter (D), number of stone columns (n) and the width of the foundation (B) were investigated in this study.

3.1 Effect of the geotextile stiffness

The stiffness parameter of the geotextile-encased stone column (J) indicates its axial stiffness, which is expressed as $J = E_{ge} \times t_{ge}$ and as observed, it depends on the modulus of elasticity and the thickness of the encasement. In this study, the effect of J values of 2000, 3000, and 4000 kN /m (the usual range of encasement stiffness according to the suggestion of Alexiew et al. [21]) was considered. Fig. (4) shows the effect of stiffness of geotextile encasement on improving the bearing capacity of the foundation on the stone column.

As indicated, by increasing the stiffness (tensile strength) of the geotextile encasement, load bearing capacity ratio linearly increases. This is due to the increase in the confinement of the materials inside the stone column and decreasing the bulging of the columns, which results in an appropriate load transfer from the structure to the underlying stiff layers. The increase in bearing capacity is more pronounced for long stone columns since they are more prone to bulging and need a better confinement.

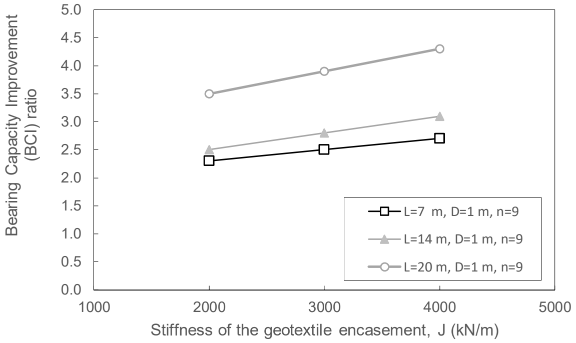

Fig. 4 Variation of the bearing capacity of foundation with the stiffness of the encasement of stone columns.

3.2 Effect of the length of stone columns

As one of the other influencing parameters on the performance of shallow foundations over stone columns, the length of the columns (L) was investigated in this section. Fig. (5) demonstrates the results of the parametric analysis at three lengths of 7, 14 and 20 m.

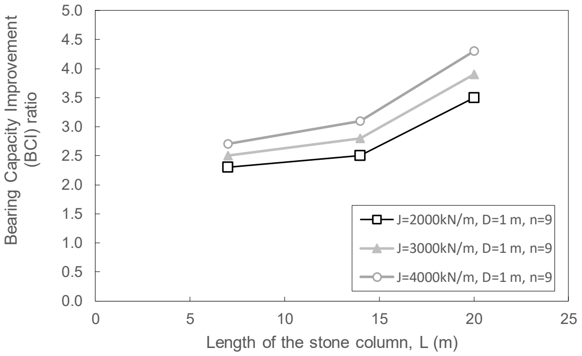

Fig. 5 Change of the bearing capacity ratio with the length of stone columns.

As can be seen, with the increase in the length of the columns, the bearing capacity of the foundation increases. The reason for this is the reinforcement of the underlying soil to further depths with higher strength. In fact, the increase in the length of the ordinary stone column causes the lateral swelling of the column and the subtle increase of the bearing capacity, but in the case of encased stone columns, load carrying capacity is controlled by increasing tensile strength of the encasement and increasing the BCI value. As can be seen in Fig. (5), a significant increase in the bearing capacity ratio and, in fact, a significant improvement in the bearing capacity of the encased stone column with a length of 20 m is due to the decrease in the amount of q_{OSC} in Eq. (3) due to bulging of this tall column. Another reason for this is the increase in the load carrying capacity of the stone column due to the use of the end bearing capacity (the depth considered for the soil is 20 m in accordance with Section 2.1).

3.3 Effect of the diameter of stone columns

Fig. (6) shows the influence of the diameter of stone column (D) on the vertical bearing capacity of the overlying shallow foundation. In this study, three diameters of 0.7, 1 and 1.3 m were considered.

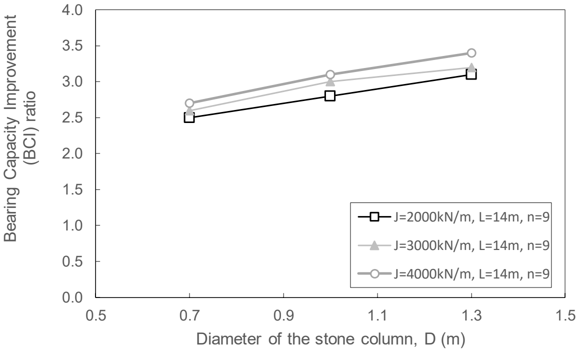

Fig. 6 The effect of diameter of stone columns on the load carrying ratio of the foundation.

As illustrated in Fig. (6), increasing the diameter of the stone columns at constant ratio of S/D, leads to increasing their spacing. Consequently, the overlap of the areas affected by the columns increases and the reinforced soil block is formed, resulting in higher load bearing capacity rather than close columns arrangement.

3.4 Effect of the number of stone columns

The number of stone columns (n) that were built beneath the shallow foundation might affect the bearing behavior of that. For a certain foundation breadth (B) and constant S/D, a limited number of stone columns can be used, which are 4, 9 and 16 in this study. In Fig. (7), the change in the bearing capacity ratio with the number of stone columns has been indicated. As indicated, the bearing capacity of the foundation increases with increasing the number of stone columns. However, the rate of this increase becomes slow when the number of stone columns exceeds 9, which can be considered an approach toward optimum design.

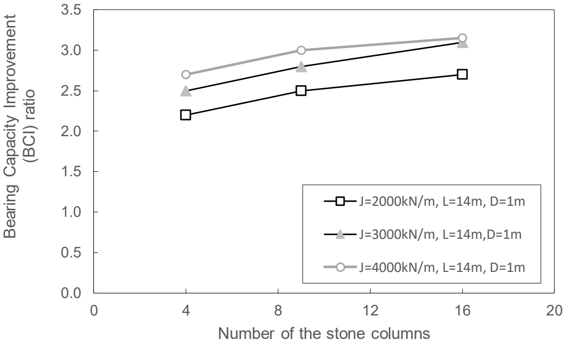

Fig. 7 The variation of bearing capacity improvement ratio with the number of stone columns.

3.5 Effect of the width of the shallow foundation

The effect of using sequences with different widths on 9 stone columns with a length of 14 m, diameter of 1m and the stiffness of 2000 kN/m under a vertical load of 100 kPa were carried out and the results are presented in Fig. (8).

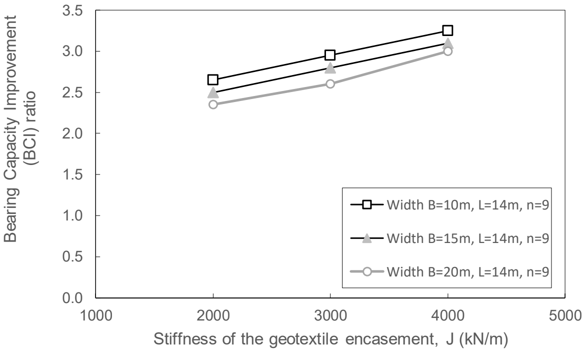

Fig. 8 The influence of width of the shallow foundation over stone columns on the improvement of the bearing capacity

As can be seen in Fig. (8), the use of stone columns under foundations with lower width will have little impact on the load capacity. As the foundation width increases, load capacity will be reduced, and the encasement effect will be more evident. Increasing the width of the foundation will cause part of the applied load to be tolerated by the soil around the columns and as a result of soil stress increase, the tensile stresses of the columns rises, and the lateral encasement reduces and subsequently the load capacity of the foundation decreases.

4. Summary

In this study, the load bearing behavior of shallow foundation constructed on a group of stone columns was investigated through a series of plane strain finite element analyses. The proposed model was validated against the results of a small-scale testing. The parameters considered in the parametric study are geotextile-encasement stiffness, diameter, length and number of stone columns and the width of the foundation. According to the results, even though the foundation breadth and the diameter and number of stone columns cause increasing in the bearing capacity of the foundation, the effect of their length and the encasement stiffness is more pronounced, which can be considered as an important factor in the analysis of shallow foundation on reinforced soils.

References

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

[2] Kempfert, H.G. and Gebreselassie, B. Excavations and foundations in soft soils. Springer Science & Business Media, (2006).

[3] Van Impe, W.F. Soil improvement techniques and their evolution. A.A. Balkema, Rotterdam, Netherlands (1989).

[4] Gniel, J., and Bouazza, A. Improvement of soft soils using geogrid encased stone columns, *Geotextiles and Geomembranes*, (2009), 27(3), 167–175.

[5] Miranda, M., and da Costa, A. Laboratory analysis of encased stone columns, *Geotextiles and Geomembranes*, (2016), 44(3), 269-277.

[6] Pulko, B., Majes, B., Logar, J. Geosynthetic-encased stone columns: Analytical calculation model, *Geotextiles and Geomembranes*, (2010), 29(1), 29-39.

[7] Castro, J., Cimentada, A., da Costa, A., Cañizal, J., Sagaseta, C. Consolidation and deformation around stone columns: Comparison of theoretical and laboratory results, *Computers and Geotechnics*, (2013) 49, 326-337.

[8] Modarresi, M., Rasouli, H., Taghavi Ghalesari, A., Baziar, M.H. Experimental and numerical study of

pile-to-pile interaction factor in sandy soil, *Procedia Engineering*, (2016), 161, 1030-1036.

[9] Taghavi Ghalesari A, and Janalizadeh Choobbasti A. Numerical analysis of settlement and bearing behaviour of piled raft in Babol clay. *European Journal of Environmental and Civil Engineering*, (2016). http://dx.doi.org/10.1080/19648189.2016.1229230.

[10] Tirado, C., Rios-Gomes, K. Y., Fathi, A., Mazari. M., Nazarian, S. Simulation of light weight deflectometer measurements considering nonlinear behavior of geomaterials. Transportation Research Record: *Journal of the Transportation Research Board*, (2017), No. 2641, 58–65, http://dx.doi.org/10.3141/2641-08.

[11] Fathi, A., Tirado, C., Gholamy, A., Lemus, L., Mazari, M., and Nazarian, S. Consideration of depth of influence in implementation of intelligent compaction in earthwork quality management. Transportation Research Board, (2018) Annual Meeting, Washington, DC.

[12] Barari, A., Ibsen, L. B., Taghavi Ghalesari, A., Larsen, K.A. Embedment effects on vertical bearing capacity of offshore bucket foundations on cohesionless soil, *International Journal of Geomechanics*, (2017), 17 (4), 04016110, https://doi.org/10.1061/(ASCE)GM.1943-5622.0000782.

[13] Rashidi M, and Haeri M. Evaluation of behaviors of earth and rockfill dams during construction and initial impounding using instrumentation data and numerical modeling. *Journal of Rock Mechanics and Geotechnical Engineering*, (2017), 9 (4), 709-725.

[14] Lo, S.R., Zhang, R., Mak, J. Geosynthetic-encased stone columns in soft clay: A numerical study, *Geotextiles and Geomembranes*, (2010), 28(3), 292–302.

[15] Hu, W., Wood, D.M., Stewart, W. Ground improvement using stone column foundation: results of model tests. *Proc. Int. Conf. on Ground Improvement techniques*, Macau 1977, pp. 247-256.

[16] Taghavi Ghalesari, A., Barari, A., Fardad Amini, P., Ibsen, L. B. The settlement behavior of piled raft interaction in undrained soil, ASCE GSP 232*, Proc. Second International Conference on Geotechnical and Earthquake Engineering*, Chengdu, China 2013, https://doi.org/10.1061/9780784413128.071.

[17] Taghavi Ghalesari, A., Barari, A., Fardad Amini, P., Ibsen, L. B. Development of optimum design from static response of pile–raft interaction. *Journal of Marine Science and Technology*, (2015), 20, 331–343. https://doi.org/10.1007/s00773-014-0286-x.

[18] Narasimho, R.S., Madhiyan, M., Prasad, Y.V.S.N. Influence of bearing area on the behavior of stone column, *Proc. Indian Geotech. Conf.*, Calcutta, India 1992, pp. 235-237.

[19] Debnath, P., and Dey, A. K. Bearing capacity of geogrid reinforced sand over encased stone columns in soft clay. *Geotextiles and Geomembranes*, (2017), 45(6), 653-664.

[20] Hu, Y., and Randolph, M. Bearing capacity of foundations on normally consolidated clay, *Soils and foundations*, (2002), 42(5), 71-77.

[21] Alexiew, D., Brokemper, D., Steve, L. Geotextile Encased Columns (GEC): Load capacity, geotextile selection and pre-design graphs, *Geofrontiers* 2005, GSP 131 Contemporary issues in foundation engineering, 1-14.