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3D Numerical Analysis of Stone Columns Reinforced with Horizontal and Vertical Geosynthetic Materials

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***Abstract*—**Improvement and reinforcement of soils with poor strength and engineering properties for constructing low height structures or structures such as liquid storage tanks, bridge columns, and heavy structures have necessitated applying particular techniques. Stone columns are among the well-known methods applied in such soils. This method provides an economically justified way for improving engineering properties of soft clay and loose sandy soils. Stone column implementation in these soils increases their bearing capacity and reduces the settlement of foundation build on them. In the present study, the finite difference based FLAC3D software was used to investigate the performance and effect of soil reinforcement through stone columns without lining and those with geosynthetic lining with different levels of stiffness in horizontal and vertical modes in clayey soils. The results showed that soil improvement using stone columns with lining in vertical and horizontal modes results in improvement of bearing capacity and foundation settlement.

***Keywords*—**Bearing capacity, FLAC3D, geosynthetic, settlement, stone column.

I. Introduction

THE increasing population and the development of urban areas and suitable land shortage in the suburbs are now causing engineers to improve weak soils for the construction of light and heavy structures. In urban areas and areas close to sensitive structures, the use of methods such as dynamic and explosive compaction is not suitable due to excessive and annoying vibration and noise. Therefore, under such conditions, the use of stone column elements is recommended as a suitable alternative for most of these methods [1]. Stone columns were first used in France in 1830 and since 1950 they widely have been used in all countries [2]. For the first time, Americans used the stone column limitedly in 1972 in several projects. The main idea of this method is to reduce the exerting forces on the soft soil of the place without major changes in soil structure. The use of stone columns results in a reduction in soil settlement and an increase in bearing capacity and shear strength of soil [3]. This method is performed by digging wells with a certain diameter, depth, and distance from each other and filling them with sand or gravel or pebbles and compressing them into vertical columns. Aggregates are poured into wells layer by layer and are compressed by special vibrating devices [3]. Stone columns are used in fine-grained silt, clay, and loose sandy soils mostly [3]. Among the most important limitation of the use of stone columns, one can name their failure under the influence of loads and lack of adequate encasement by the soil surrounding the stone column. In these cases, additional encasement is provided by a geosynthetic. For the first time in 1989, Van Imp introduced the idea of encasing stone columns by wrapping with a geotextile [5]. The use of geogrids as a reinforcing element greatly increases the bearing capacity and reduces soil settlement [6], [7]. Encasing stone columns not only prevents the side scattering in soft soils during constructing stone column, but also results in a decrease in wasting stone and consequently increases the construction speed [8]. Based on laboratory tests, Shivashankar et al. demonstrated that when the stone column was implemented in loose soil with different thickness, the lateral buckling occurs almost in the upper part of the loose soil and causes the failure of the stone pillar [10]. Morogsan and Rajagapul examined the effect of geosynthetic-reinforced stone columns in clay soil numerically and reported an increase in bearing capacity and a decrease in lateral expansion of stone column. They also showed that vertical reinforcement of stone columns by wrapping geotextile to a depth twice the diameter of the stone column from the top of the soil was enough to increase the bearing capacity [11]. Ghazavi and Nazarafshar conducted laboratory tests on the single stone column and a group of stone columns in form of physical model, as well as their numerical study under the conditions of encasement with the elements of geosynthetic reinforcement. The results demonstrated an increase in bearing capacity of the single and group of the stone column under encasement condition by elements of geosynthetic reinforcement [4]. Makarchian and Hamidi tested the combined reinforcement of stone columns by geosynthetic in laboratory scale. They showed that combined reinforcement of stone columns by geosynthetic resulted in an improvement in stone column strength against lateral deformation and an increase in bearing capacity [12]. Mohapatra et al. investigated the effect of geotextile-encased granular columns on lateral bearing capacity using a direct shear test. Besides, they evaluated the effect of three types of cover, two different diameters, and columns arrangement. Finally, they showed that geosynthetic led to an increase in shear strength of stone column [9].

Although various studies have been carried out on the performance of geosynthetic-reinforced stone columns, further research is needed to predict the performance and the beneficial effects of this method on soil improvement. In the present study, it is aimed to investigate the stone column with

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vertical and horizontal coverings in clay soils using the FLAC3D software.

II. Methods of Stone Column Reinforcement

The research in the field of geosynthetic reinforcements usually is conducted by two following methods:

- Geosynthetic reinforcements of stone columns using horizontal layers placed in the upper part of the column to reduce bulging
- Geosynthetic reinforcements of stone columns using environmental encasement through geotextile covering

A. Stone Columns Reinforcement Using Horizontal Layers

The stone columns tend to expand laterally during loading. The magnitude and position of this radial expansion, in addition to the physical characteristics of the column and the surrounding soil, depend on whether the columns act individually or in the group. Although radial expansion can be attributed to the lateral encasement of an adjacent column, excessive expansion can lead to a column failure. The conducted experiments on the single columns show that bulging usually occurs in the upper part of the column, where the lateral encasement is low. Accordingly, research was carried out on geosynthetic materials located in the horizontal layers in the bulging part of the stone column, which was created to increase the resistance to lateral deformation. This resistance is provided by interfacing and interlocking between the stone column and reinforcement materials. This concept is shown in Fig. 1 [13].

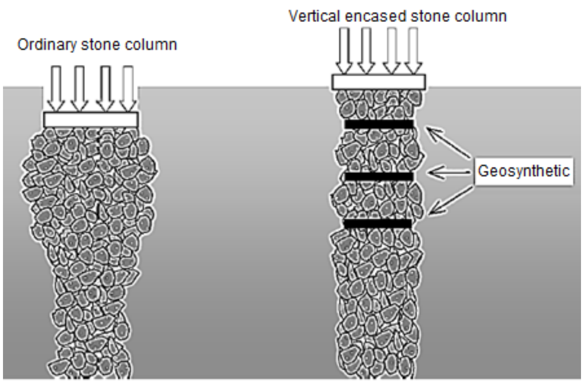

Fig. 1 Horizontal reinforcement of stone column [13]

Cai and Li examined some tests in the large triaxial cells (with a diameter of 300 mm) using horizontal reinforcement. They showed that the optimal number of reinforcement layers is about four, which higher than four results in a slight increase in column capacity. Also, the optimal space between the reinforcement layers is half of the stone column diameter [14]. According to this research, four layers of horizontal geotextile with 25 cm spacing were used for stone columns with 50 cm diameter and 50 cm spacing for a 100 cm diameter stone column.

B. Geotextile Encased Columns (GECs)

The Geosynthetic-Enclosed Columns (GEC) are an innovation, which was developed for use on sites with very loose soils, with the undrained shear strength of less than 5 kPa. Today, GEC is a more economical and useful solution for keeping structures with moderate and lightweight loading [13]. The presence of encasement for stone columns increases the stiffness of the column and reduces the masses of the soil settlement.

III. Specifications of Materials

For an accurate simulation of stone column-reinforced soil system, proper selection of material specifications is necessary for numerical modeling. The analyses were carried out on clay in different regions of Hormozgan province with a high groundwater level (3 m under ground level). It was assumed that all materials are drained and that the criterion of Mohr-Coulomb and the elastoplastic behavior are established for all materials. Specifications of materials are presented in Table I. Moreover, the properties of geosynthetic used in this work are shown in Table II.

TABLE I
Properties of Soil & Stone Column

Parameters	E (MPa)	**ν**	C (Pa)	**φ** (°)	**γ** (kN/m^3)
Clay	3	0.4	0	25	18.5
Stone column	55	0.3	0	43	19

TABLE II
Properties of Geotextile [4]

Parameters	Geotextile
Yarn material	Polypropylene
Ultimate tensile strength (kN/m)	14
Strain at ultimate strength (%)	40
Secant stiffness at ultimate strain (J) (kN/m)	35
Thickness (mm)	1.8
Mass (g/m^2)	180

IV. Numerical Modeling

In the present study, the FLAC3D software was used to perform a numerical analysis. This software is based on a finite difference numerical method for the 3D analysis of deformation and stability in geotechnical engineering. Therefore, the results of solid and rocky environments are approved. First, an initial meshing model from the environment was created using mesh creator commands, and then suitable boundary conditions, the geotechnical profile of geological layers, and in situ stresses were imported to the model by related commands. Next, the model was analyzed to achieve an initial equilibrium. Finally, loading condition was stimulated on the stone column and reanalyzed to reach considered results.

In the software, the model was created with dimensions of 13.5 × 7.5 × 13 m^3 and the accuracy of the modeling and analysis was increased by distributing fine zones around sensitive areas and coarse zones distant from sensitive areas. In this study, the Mohr-Coulomb model was selected to represent soil behavior because of the higher accuracy, prevalent application, ease of use, and ease of obtaining required parameters. Then, the boundary conditions and in-situ stress were applied to the model, and the model was implemented under large strain. Once the model reached an equilibrium state, the displacement and the velocity of the nodes were set to zero to simulate the natural conditions of the soil in the nature. The constructed geometry model is shown in Fig. 2.

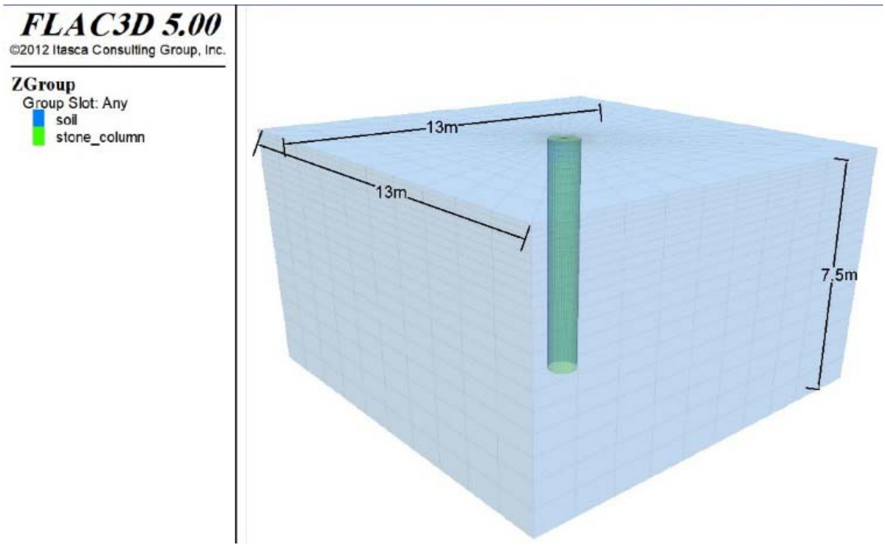

Fig. 2 Geometry of created model

At first, unreinforced clay was modeled and then standard stone columns with diameters of 50 and 100 cm were modeled in clay with the characteristics of Table I. In this study, the loading was applied vertically on a stone column. The results are shown in Fig. 3.

In Fig. 4, a contour plot of uncovered stone column settlement is shown.

Stone column with vertical and combined (vertical and horizontal) cover was analyzed using the geotextile shown in Table I. The results of a stone column with a diameter of 50 and 100 cm are shown in Fig. 5. Fig. 6 presents the percentage of decrease in settlement of reinforced stone column compared to unreinforced stone column. Fig. 7 shows the amount bearing capacity of stone column in 25 mm of settlement.

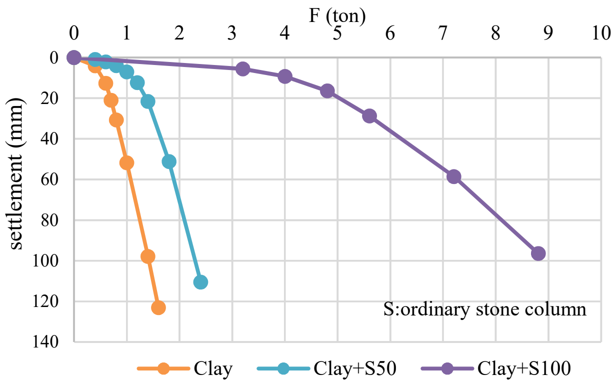

Fig. 3 Load-settlement diagram of clay and clay with stone column with a diameter of 50 and 100 cm

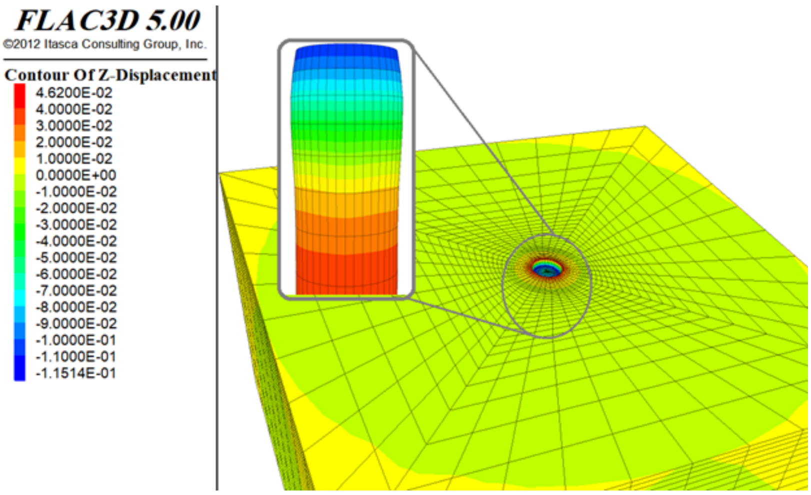

Fig. 4 Bulging deformation in uncovered stone column

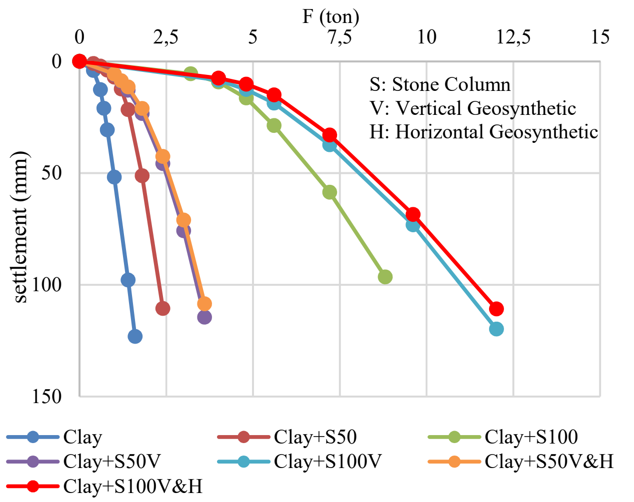

Fig. 5 Results of load-settlement of stone column with a diameter of 50 and 100 cm in different

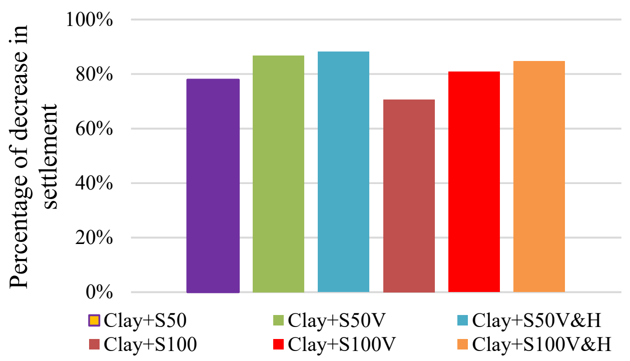

Fig. 6 Effect of Geosynthetic reinforcement on reducing of stone column settlement

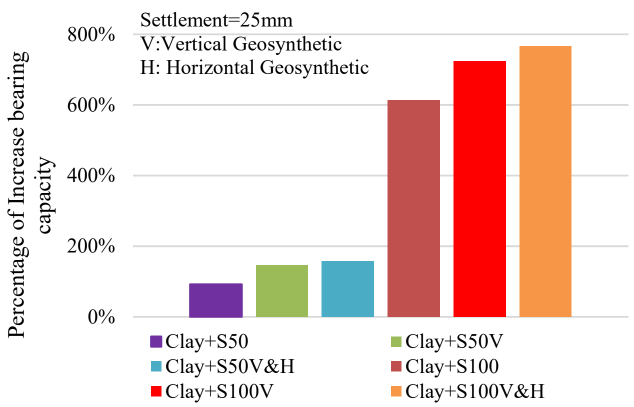

Fig. 7 Bearing capacity increase of stone column due to geosynthetic reinforcement on 25 mm of settlement

V. Discussion and Results

The obtained result from Fig. 5 shows that presence of stone column in clay has a significant effect on improvement of its strength properties. Besides, an increase in the diameter of the uncovered stone column from 50 cm to 100 cm results in an increase in bearing capacity. Fig. 4 showed that failure in uncovered stone column occurred due to the bulging deformations above the stone column. This bulging failure controls the bearing capacity. For this reason, geotextile was used to control this form of failure. The existence of horizontal geotextile layers alone on the stone column causes a little increase in bearing capacity, as well as a reduction in the settlement. Accordingly, in the best condition, a maximum reduction in the settlement was about 10 mm. The cause can be attributed to the low cross-section of the stone column and the absence of the geotextile bending stiffness. As seen in Fig. 5, in both Clay+S50V&H and Clay+S100V&H models by increasing the cross-section of the stone column the effect of horizontal geotextile was increased.

The vertical reinforcement of the stone column plays an important role in increasing the bearing capacity due to the encasement of the upper part of the stone column and prevention of its bulging failure. The results also showed that an increase in the diameter of the stone column from 50 to 100 cm is more effective in increasing the bearing capacity than the construction of a 50 cm diameter stone column. This issue indicates that the large diameter plays more important role than reinforcement. It can be seen in Fig. 6 that due to the same problem of bulging failure, which occurs in stone columns with smaller diameter earlier than the stone column with a larger diameter, the effect of enforcement in a stone column with a 50cm diameter, is greater than a stone column with 100cm diameter. Fig. 7 shows the increasing bearing capacity in 25mm of settlement. As it is clear from the results, the stone column with a combined covering and a diameter of 100 cm increase about 7.5 times the bearing capacity compared to clay without a stone column, which indicates the good performance of this kind of refinement in clay soils.

VI. Conclusion

Loading on clay soil with a stone column with 50 and 100 cm diameters and without horizontal and vertical covering were analyzed by FLAC3D. The results showed that reinforcement of horizontal layers in stone column alone has no effective role in decreasing settlement and increasing bearing capacity. It is best to use reinforcement with vertical geotextiles. Moreover, the results showed that an increase in diameter of the stone column is more effective than reinforcement.

References

[1] Kempfert, G. H. and Gebreselassie, B. (2006), “Excavation and Foundation in Soft Soils”, Springer-Verlag Berlin Heidelberg.
[2] Etezad, M., Hanna, A. M. and Ayadat, T., "Numerical model for group of stone Columns ", Proc. 73rd Annual Meeting of ICOLD, Tehran, Iran 2005; paper No. 097-OT.
[3] Barksdale, R. D., and Bachus, R. C. (1225), “Design and Construction of Stone Columns”, Federal Highway Administration, Vol. 1, Report No. FHWA/RD-25/022, National Technical Information Service, Springfield, Virginia, USA.
[4] Ghazavi, M., and Afshar, J. N. (2015), “Bearing capacity of geosynthetic encased stone columns,” Geotextiles and Geomembranes, Vol. 52, pp. 22-52.
[5] Van Impe, W. F., 1989. Soil Improvement Techniques and Their Evolution. Balkema, Rotterdam, the Netherlands.
[6] Gniel, J., Bouazza, A., 2008. Improvement of soft soils using geogrid

encased stone columns. Geotextiles and Geomembrances 27(3), 167e175.
[7] Arvizhi, Mal, and il Amparuthi. “Comparative study on the behavior of encased stone column and conventional stone column. “Soil and foundation 47, NO.5 (2007):873-885.
[8] Ayadat, T., Hanna, A.M., 2005. Encapsulated stone columns as a soil improvement technique for collapsible soil. Ground improvement 9(4), 137-147.
[9] Mohapatra, S. R, Rajagopal, K, Sharma, J. (2016), ‘’ Direct shear tests on geosynthetic-encased granular columns”, Geotextiles and Geomembranes, Vol.44. pp. 396-405.
[10] Shivashankar, R. and Dheerendra Babu, M. R. S. and Nayak, S. and Rajathkumar, V. (2011), “Experimental Studies on Behaviour of sone column in Layered Soils” Geotechnical and Geological Engineering. 29, pp 749-757.
[11] Murugesan, S., and Rajagopal, K. (2002), “Geosynthetic-encased stone columns: numerical evaluation, ”Geotextiles and Geomembranes, Vol. 24, pp. 542-512.
[12] Makarchian, M, Hamidi, A, (2016), ‘‘Laboratory study of the bearing capacity compound encased stone column (Horizontal and Vertical) with Geosynthetic’’. 9th National Congress on Civil Engineering, Ferdowsi University of Mashhad, Iran.
[13] Jamali Moghadam, M. Hajiyan niya, A. MOyedi, H. Nazem, R. (2016), ‘‘Investigate the behavior of encased stone columns with using geogrid’’ International conference of Civil Architecture & Urban Planning Elites, Shahid Beheshti University Tehran, Iran.
[14] Cai, F., Li, G.X., 1994. Granular piles reinforced with geosynthetics. In: Proceedings of the Fifth International Conference on Geotextiles, Geomembranes and Related Products, Singapore, vol. 1, pp. 347e350.