Journal of Structural Engineering and Geotechnics,
11(1),57-70,Winter and Spring 2021

3D Analysis of Improved Soft Ground with a Group of Floating of Stone Columns Laid on the Appropriate Bed

Mohammad Javad Shabani[a,*], Mehdi Hatami[b], Seyed Hasan Golmaee[c],Saman Arechi[d]

[a] *Department of Imam Sadiq, Technical and Vocational University, Babol, Iran*

[b] *Geotechnical Engineering, Saroyeh Institute of Higher Education, Sari, Iran*

[c] *Saroyeh Institute of Higher Education, Sari, Iran*

[d] *Geotechnical Engineering, Tabari Institute of Higher Education, Babol, Iran*
Received 19 December 2019, Accepted 19 July 2020

Abstract

One of the proper methods to improve the soft and loose ground is the use of stone columns. High shear strength and low compressibility materials substituted for soft and loose soils with low shear strength and increased compressibility will transfer a significant part of the loads applied to the foundation in the soil and stone columns will improve the soil. The investigation of the previous studies has revealed that most of the numerical analyses are conducted in 2D forms by the equivalence of stone columns or a single cell. Therefore, the numerical analysis of improved soft-ground with stone columns has been investigated using the finite element PLAXIS 3D software. To this end, four layouts of stone column group were used under the foundation with various numbers of columns of 4, 9, 16 and 25. The depth of improvement was considered 6m and 10m for floating and laid on a suitable bed, respectively. The results of decreasing the percentage of a ground settlement for various groups of stone columns and improvement depths of 6m and 10m were in the ranges of 15-49% and 17-63%, respectively. Besides, the shear strain distribution and the amount of stress decreased due to the increase in the number of columns. At the end, a design diagram was presented to examine the reduction of the ground settlement in two improvement modes with an improvement depth of 6 m and 10 m compared with the unimproved ground.

Keywords: Stone Column, Ground Improvement, Numerical Analysis, PLAXIS 3D

1.Introduction

Design engineers usually follow a specific decision-making process to choose and design the optimal type of foundation. In this case, if the shallow foundation is not suitable for the project, before making any decision about the use of deep foundations, an investigation should be conducted on the appropriate methods of the loose soil improvement to compare their advantages and disadvantages of performance, implementation issues, and costs perspectives, and choose the optimal option. The improved ground system by the stone columns is a method to increase the strength of soft and loose soils that can be used to not only increase the soil bearing and toughness capacity but also decrease the total and difference of the ground settlement [1]. The stone columns are used for the high shear strength of the material and the provision of lateral restraint by the surrounding soil.

---

*Corresponding Author: Email Address: javad.shr@gmail.com

Therefore, the stone column applies the load of the structure and transfers it to the resistant layers.

There are different methods for implementing the stone column, and most of them are based on replacement and displacement. In the replacement method, also known as the wet method, the soil is replaced in a distinctive pattern with a stone column that needs to dig ditches using a vibrating rod along with water jets. In the displacement method of the so-called dry method, the soil is displaced by a vibrating rod along with compressed air laterally. When the rod reaches the desired depth, the stone material is poured into the pit and compressed by a vibrating rod. The displacement method is appropriate for low groundwater ground [2, 3]. Soils that are soft are considered to be clay soils with an adhesion of less than 10 kPa. These types of soils display a low amount of shear strength against applied loads. Thus, a great amount of settlement will occur in such soils as a result of the application of overhead loads. Consequently, in order to limit the amount of settlements to a permissible amount, the improvement approach involving the use of stone columns can be practiced.

Many scholars have presented theoretical solutions to estimate the bearing capacity and the ground settlement of the improved bed with stone columns [4-7]. Jalali et al. (2005) investigated a homogenization hypothesis (the improved soil is assumed to be homogeneous with similar properties) estimate load and settlement capacity [8]. Pribe (1995) proposed a method to estimate the settlement of the foundations located in an extensive network of stone columns based on the concept of a unit cell. In the concept of unit cell, the soil around a stone column covered by a single column, the distance between the columns, is considered for analysis. When the columns are loaded simultaneously, the lateral deformations of the soil on the boundary of the unit cell are assumed zero. The soil improvement factor is a function of the surface ratio and the internal friction angle of the materials used in columns. Except near the edges of the loaded surface, the behavior of all the soil-column cells are the same, and therefore, only a single soil-column needs to be analyzed [9]. Poorooshasb and Meyerhof (1997) conducted studied the theory of soil improvement by stone columns. Considering account the linear elastic material, they presented a ratio of the ground settlement with a stone column to a ground settlement without a stone column [10].

Various numerical and laboratory studies have been carried out in order to investigate the effect of stone columns in increasing the bearing capacity, decreasing the settlement, and increasing the stability of the slopes [11-15]. Murugesan and Rajagopal (2006) conducted a numerical study to examine the behavior of geosynthetic covered stone columns. They revealed that the geosynthetic chamber could increase the bearing capacity and stiffness of the stone column. Stone columns are limited, and lateral inflations are reduced by using the chamber [16]. Ambily et al. (2007) examined the behavior of stone columns using laboratory and numerical analysis. The results of the numerical modeling had a good agreement with laboratory results. When a column is loaded solely, the failure caused by blowing up the column at approximately 0.5 times higher than the diameter of the column. Furthermore, the axial bearing capacity of the column decreases with the increase of the distance between the columns [17]. Zahmatkesh and Choobbasti (2010) investigated the effect of diameter, displacement percentage, and soil compaction due to the implementation of stone columns on the settlement of soft clay soil improved by a stone column using a numerical method. Results showed that the settlement reduction ratio increased with an increase of column diameter at a significant percentage of displacement. Also, soil compaction due to the implementation of the stone column has a significant effect on the amount of the settlement coefficient [18]. Deb et al. (2008, 2011) studied on the granular soils armed with geosynthetic laid on the soft soil armed with the stone column. The results showed that the bearing capacity and ground settlement is decreased with the simultaneous implementation of the stone column and the use of geogrid for arming the soil. Furthermore, the blowing up of the diameter is reduced by the implementation of the stone column, and the maximum blowing up is in a deeper location in comparison with a state without implementing the geogrid [19, 20]. Mengfei et al. (2016) examined the improved sand bed with a stone column as a founder under seismic excitations using laboratory modeling. The experimental models were applied under various excitations in this study. The results have shown that soil liquefaction does not occur for the acceleration of input incitement less than 0.2 g, and the rate of settlement is meager. While soil liquefaction was observed in the acceleration of input incitement range of more than 0.2 g in the embankment paw. Also, the increase was observed in the settlement and the water pressure of the drill. [21].

Hoseinpour et al. (2016) studied the impact of ground improvement using a geotextile-armed stone column by constructing an embankment on the soft ground. The results showed that the amount of ground settlement, armed by the stone columns decreased and its bearing capacity has increased by 2.5 times [22]. In a 3D parametric study conducted by Nehab et al. (2017), it was observed that the amount of settlement of improved ground was reduced with the improvement of the mechanical properties of the materials of stone columns [23]. GuhaRay and Roy (2018) analyzed the improved ground with stone columns as a unit cell numerically. The results indicate an increase in bearing capacity by reducing the distance between the columns and increasing the diameter of the columns [24].

According to the previous studies, most of the numerical analyses are carried out in 2D forms with the equivalence of stone columns (surface strain) or as a unit cell (axial strain). Besides, the choice of improvement depth is one of the most significant factors in the designation process. Two improvement depths that are appropriate for floating columns and laid on the bed were chosen in the present study. Therefore, the 3D method of PLAXIS 3D finite element software has been used to analyze the soft ground improvement by the group of stone columns.

2.Modeling

The PLAXIS 3D finite element software was used to model the improved soft ground with a stone column. Figure 1 illustrates an example of a simulated ground. A quarter of the geometry has been modeled due to the symmetry of the model. An element with 15 nodes has been used in PLAXIS 3D to mesh the model. This element is precise that gives a better tension results for complex problems. Also, according to Figure 1, three meshed segments with small, fine, and moderate sizes were used in the models.

In order to simulate the soil behavior, an appropriate model and parameters must be assigned to the structure proportional to the materials. Nonlinear stress-strain behavior of soil can be modeled at different complexity levels of the problem. The number of parameters included in the problem increases directly with the level of failure. There is a need for proper parameters of the materials to simulate precisely. An elastic-plastic model with the Mohr-Coulomb failure criterion was used for modeling soft soils with the stone column. This model requires two fundamental parameters. These parameters include modulus of elasticity (E), the Poisson's Ratio (υ), the Internal Friction Angle of Soil (φ), Soil Adhesion (c), and the Dilation Angle (ψ). The properties of the used materials have been presented in Table 1 [25]. Soil bed contains soft soil with a thickness of 10 m. The dimensions of the stone columns and the distance between these columns are selected based on the practical considerations. The height of the column was 6 and 10 m, and the diameter was 0.8 m. The axial load is 100 kPa that is transferred to the ground through the concrete foundation on the improved ground. Four layout samples of the stone column are shown in Figure 2 that is located below the foundation of 6 × 6 square meters.

The width of the model is considered by the sensitivity analysis conducted in previous studies to reduce the boundary effects with the amount of 8B from the center of the foundation, which B is corresponding to the square foundation dimension [26]. It has been assumed that the soft bed is placed on a hard layer. Therefore, the vertical deformation was prevented on the horizontal boundary. Furthermore, horizontal deformation is also prevented in two vertical boundaries, so that only vertical deformation is allowed. A soft bed is close to a saturated state with the absence of certain free water level. Soft soil acts in an undrained condition to an applied critical load since it is essentially unconsolidated or commonly consolidated. Therefore, undrained adhesion has been used to determine the resistance of soft soil [15]. The stress caused by soil compaction was neglected due to the implementation of a stone column in the current study (the effect on the coefficient of lateral earth pressure).

The ratio of the improved area as the total area of stone column's sections to the total area is called the unimproved area. A considerable improvement is not observed in the soil properties for the less than 10% improved area [18, 27, 28]. Therefore, the percentage of the replacement area applied in this study, has been considered between 10 and 30 percent.

The column compaction process involves forcing the stone laterally into the soft soil. Since the stone becomes tightly interlocked with the surrounding soft soil, no discrete interface zone exists as expected for a pile. Perfect adhesion is assumed at the column–soil interface and interface elements are not used in accordance with standard practice for modeling stone columns [26, 29].

Table 1
Properties of soil material and foundation [25]

Soil type	γ (kN/m^3)	E (kN/m^2)	υ	c (kN/m^2)	φ (°)	ψ (°)
Soft soil	17	2000	0.35	5	21	**0**
Stone column	19	55000	0.3	0	43	**10**
Concrete	24	3e7	0.15	-	-	**-**

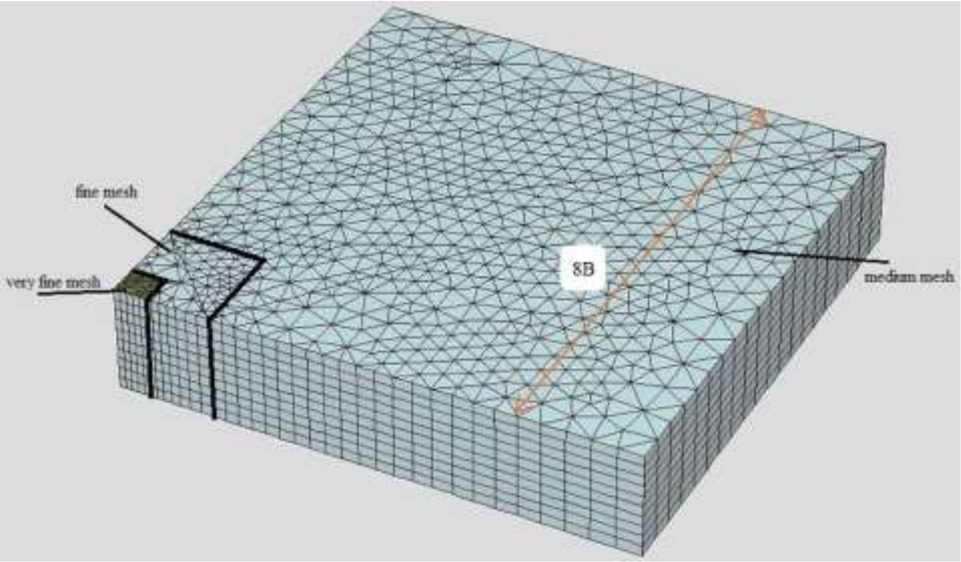

Fig1. Simulation of model geometry

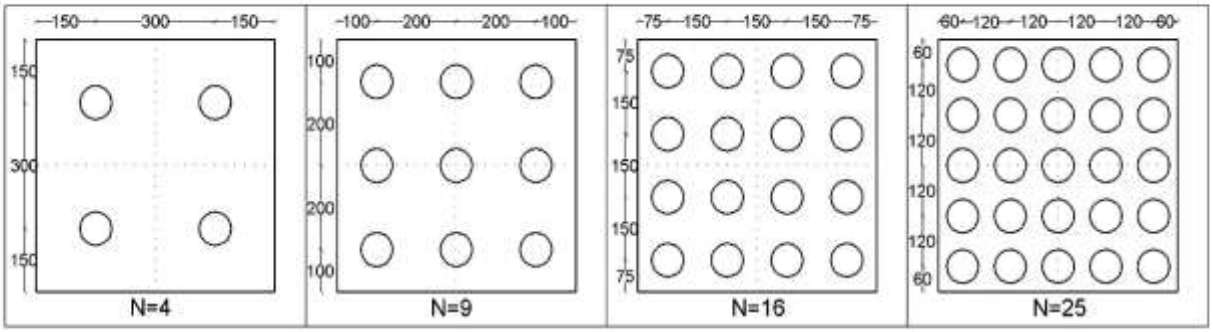

Fig 2. The stone column layouts

3.Verification

In order to verify the software performance, a comparison was initially made between the results of the experimental study conducted by Ambily et al. (2007) and the numerical results obtained in this study [17]. The laboratory model is constructed in a cylindrical chamber on the clay bed with a diameter of 210 mm and a height of 450 mm. A stone column was placed in the center of clay bed with a diameter of 100 mm, and a rigid plate is used to apply load with the same diameter to the cylindrical chamber. A numerical analysis was conducted using PLAXIS 3D software with a fine meshing pattern.

Table2
Soil properties in the verification process [17]

Soil type	γ (kN/m^3)	E (kN/m^2)	c (kN/m^2)	φ (°)	ψ (°)	υ
Clay	15.56	5000	30	0	-	0.42
Stone column	16.62	55000	-	43	10	0.3

Furthermore, an elastoplastic behavioral model was used to model the materials. Table 2 represents the properties of the materials. Figure 3 shows the simulated geometry model. Figure 4 illustrates the load-settlement curve for the numerical analysis and experimental results. The results obtained from the experimental and numerical studies are well matched which proves the fact that the software is appropriate to simulate improved soil with the stone column.

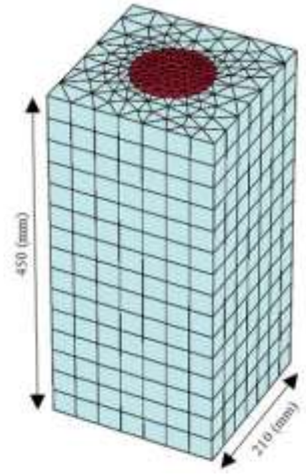

Fig 3. An experimental model simulated in PLAXIS 3D

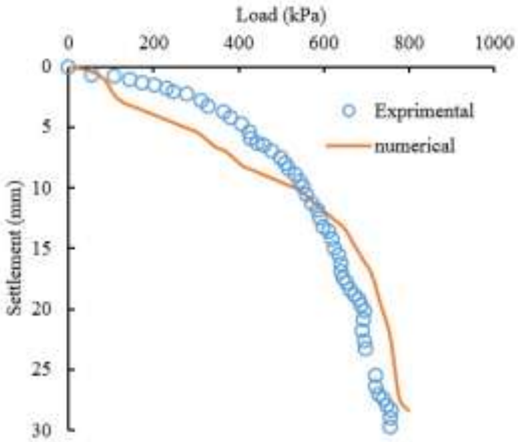

Fig.4. Load settlement curves created to the verification

4.Results

As mentioned in the previous sections, four different layouts of stone columns were used with a diameter of 0.8 m and an improved depth of 6 m and 10 m under the foundation. The results of the numerical analysis are presented below the 100 kPa superimposed load.

4.1.The Effect Of Stone Column On Bearing Capacity And Ground Settlement

The effect of the applied load on the ground settlement under improved and unimproved conditions has been shown in Figure 5. As can be seen, with the increase in the number of stone columns, the amount of settlement has decreased in the constant live load. Therefore, with the replacement of loose soil with appropriate soil that results in the improvement of the mechanical properties of the ground, the ground performance will be improved. According to the mentioned figure, the settlement of improved ground in a range of layouts from N=4 to N=25 has decreased by 15 to 62 percent reduction in comparison to the unimproved ground.

Figure 6 shows the effect of the number of stone columns with a height of 6m on the load of 100 kPa that is applied on the foundation. As expected, the decrease in the number of columns increased the distance between the columns, which would decrease the confinement due to the adjacent of columns and as a result, will increase the amount of the settlement. According to this figure, the enhanced ground settlement has decreased by approximately 15 to 49% by increasing the total number of stone columns. Similarly, in Figure 7, the effect of the number of stone columns at a depth of 10 m on the amount of settlement with the depth of the improved ground has been presented.

As presented, the amount of the settlement is maximum at the depths close to the ground surface and will decrease with increasing depth of the settlement. Also, the amount of the settlement decreases with the increase in the number of stone columns. A similar performance for stone columns with 6 m depth is shown in Figure 8. One of the reasons for the decrease in ground settlement by increasing the depth of the columns is the increased amount of column enclosement. This being the case, by increasing the depth, the overall amount of the coefficient of lateral pressure increases. The result of this is that the columns at deeper depths will be more enclosed compared to those that are at surface depths.

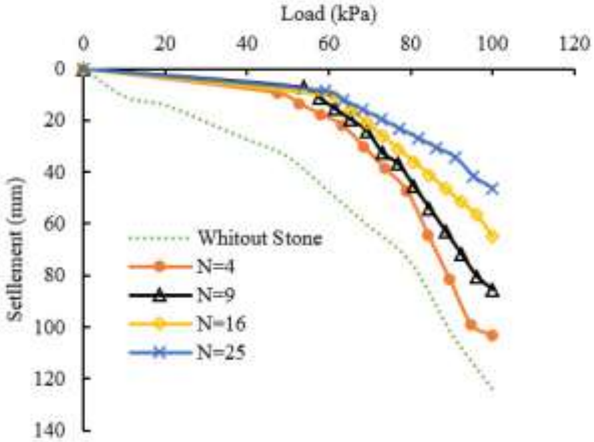

Fig 5. Settlement load for stone column with the length of 10m

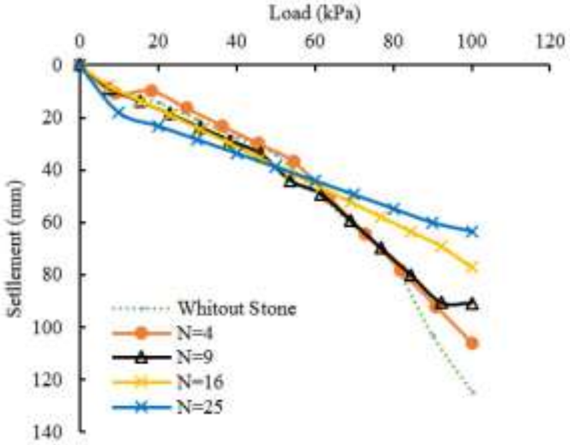

Fig 6. Settlement load for stone column with the length of 6m

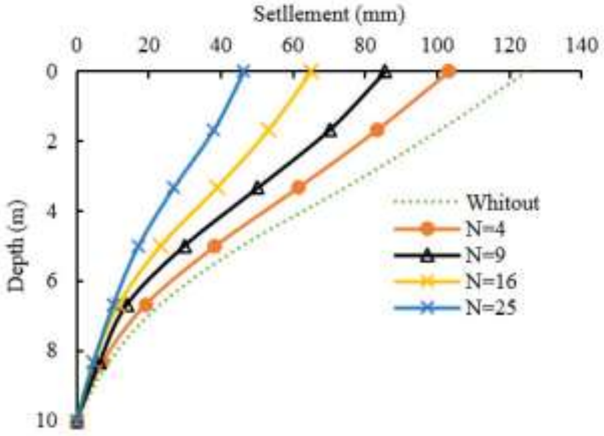

Fig 7. The amount of settlement at the end of loading to the depth of stone column with the depth of 10m

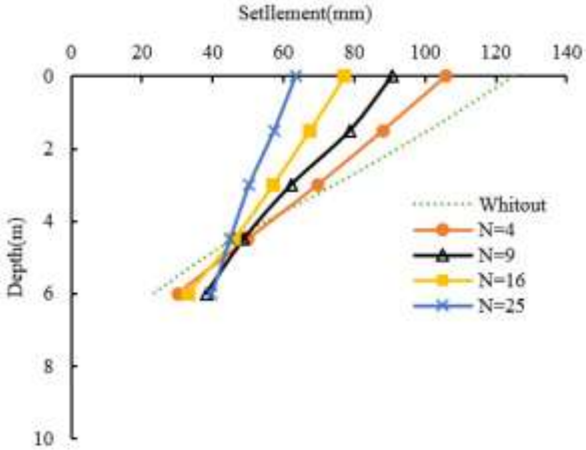

Fig 8. The amount of settlement at the end of loading to the depth of stone column with the depth of 6m

To investigate the amount of the settlement of the improved ground to the settlement of the unimproved ground, the settlement reduction ratio (SRR) has been applied. The SRR is expressed as percentage and is obtained using the following equation.

$$SRR = \frac{S_{WS} - S_S}{S_{WS}} \times 100 \quad (1)$$

S_{WS}: Ground settlement without stone column
S_S: Ground settlement with stone column

The settlement reduction ratio is shown in Figures 9 and 10 for different groups of stone columns at depths of 10m and 6m, respectively. Figure 9 shows that the SRR is constant with an increase in depth up to 8 m and will have a decreasing trend from 8 to 9m. Furthermore, the SRR will increase by increasing the number of stone columns. Hence, for the number of stone columns 9, 14, 16, and 25, the percentage of settlement reduction is 17.3, 31.5, 47.8, and 62.9%, respectively. The group of stone columns with a depth of 6m have similar behavior to the former group, with the difference that the SRR value was constant up to 5m depth for all types of the columns. The SRR value for 9, 14, 16, and 25 numbers of columns are 15.1, 27.3, 38.1and 49.2%, respectively. Comparing the results of Figures 9 and 10 reveals that where the depth of the stone column is 10m and is located on an appropriate bed, the amount of settlement is less than the improved ground with floating stone columns with a depth of 6m.

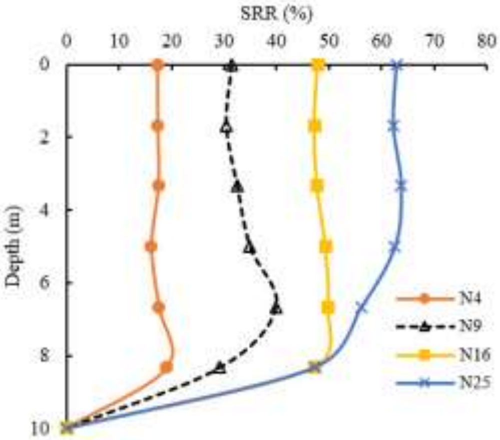

Fig 9. SRR for the improved ground with the 10m columns

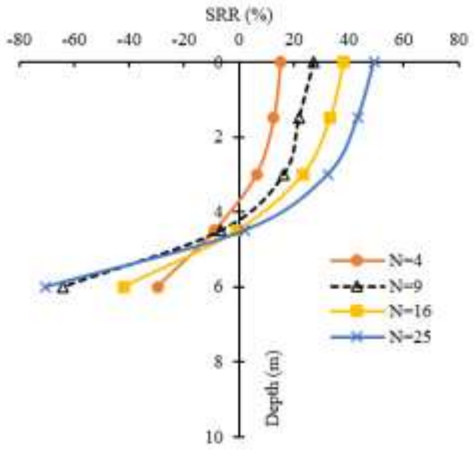

Fig 10. SRR for the improved ground with the 6m columns

4.2.Effect of Stone Columns on Lateral Expansion

The lateral expansion of the stone column is one of the significant parameters that influences the performance of the stone column group. The effect of live load on the lateral expansion has been shown in the group of stone columns with N=9 and N=25 with two different depths in Figures 11 and 12. The lateral expansion in the group of the stone column with N=25 is less than N=9. According to these figures, the maximum lateral expansion in the N = 25 state for the improve depth of 10m and 6m is reduced to 75 and 87 percent, respectively, in comparison to the N=9 state. Additionally, the maximum lateral expansion value for the 10m stone columns was more than the 6m state due to the location of these columns on the harder bed (floating state).

Most of the previous analysis has been determined that the maximum lateral expansion has been taken place in the depth of less than 0.4d, which d represents the diameter of the stone column. Indeed, in some analysis with a depth of 6m, due to the floating of the stone columns, the maximum lateral expansion took place at the end of the columns. In order to reduce the lateral expansion, a 30 cm thick layer of granular soil can be applied on the improved ground.

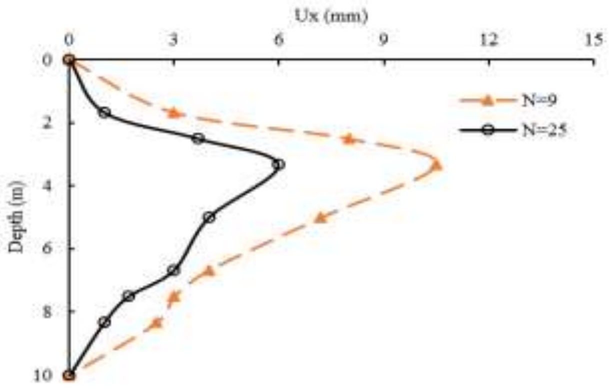

Fig 11. Lateral expansion of 10m stone column in the center of the foundation

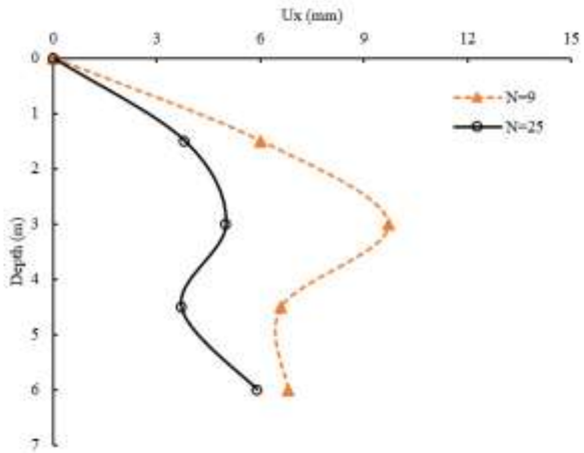

Fig 12. Maximum lateral expansion of the 6m stone column

In order to examine the lateral expansion in the adjacent stone columns, a model with N = 25 is used as it is shown in Figure 13. According to this figure, the stone column located at the corner of the ground has the most lateral expansion due to the lower confinement of that column relative to inner columns. Therefore, the maximum lateral expansion of the corners relative to the central columns has reached more than 3/3 times.

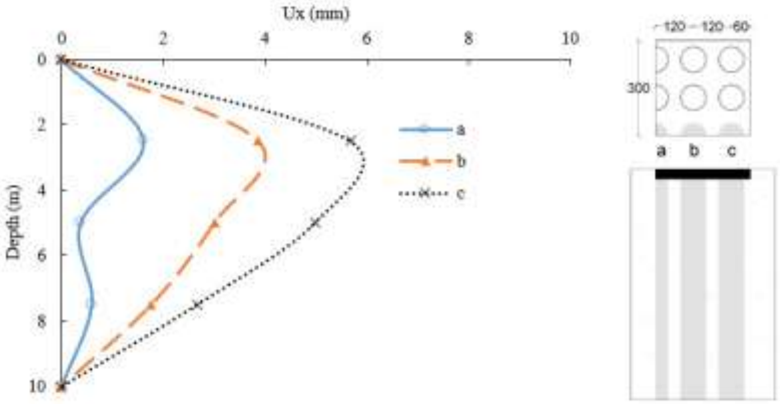

Fig 13. Lateral expansion of 10m stone columns in N=25 state

4.3.The Effect Of Stone Columns On The Tension And Strain Contours

Bearing capacity is among the design factors of columns. Figures 14 and 15 show that the amount of tolerable stress in the improved ground with stone column group is N=9 and N=25, respectively. It is evident that the bearing capacity of the stone columns is higher than the surrounding soil due to the mechanical properties and the hardness of the columns. With the increase in the number of stone columns, the bearing capacity of stone columns decreases such that the maximum bearing capacity decreases from 420 KN to 320 KN as the number of columns decreases from N=25 to N=9.

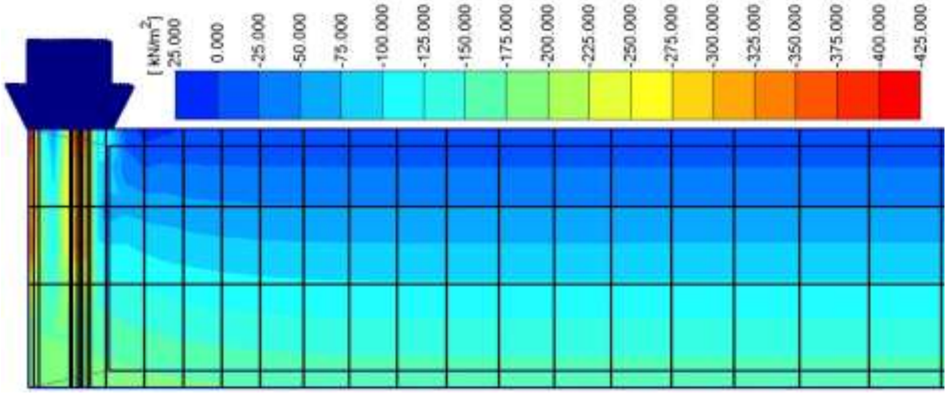

Fig 14. Stress in a group of stone columns with N=9

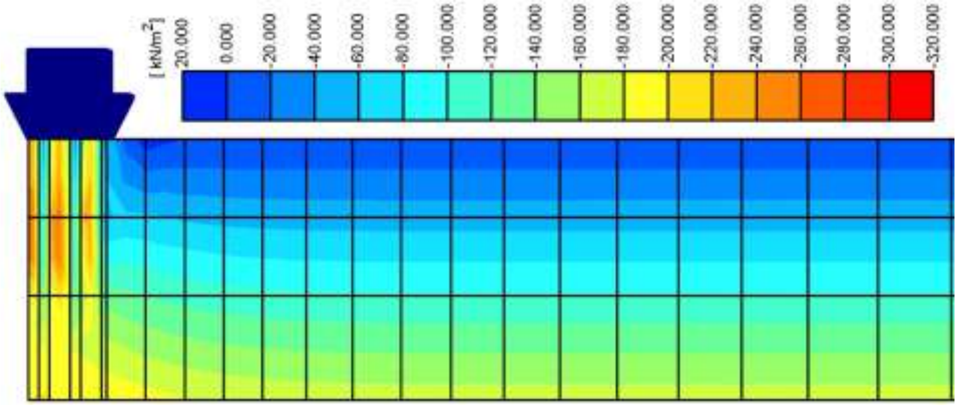

Fig 15. Stress in a group of stone columns with N=25

The sub-foundation failure due to applying the load has been shown in Figure 16. The probable path of failure, which has the highest shear strain, has been specified by the dashed line. The implementation of the stone columns leads to the spread of the shear strain distribution, and accordingly, the range of the shear strain becomes larger. Also, by increasing the number of stone columns, the amount of shear strain decreases.

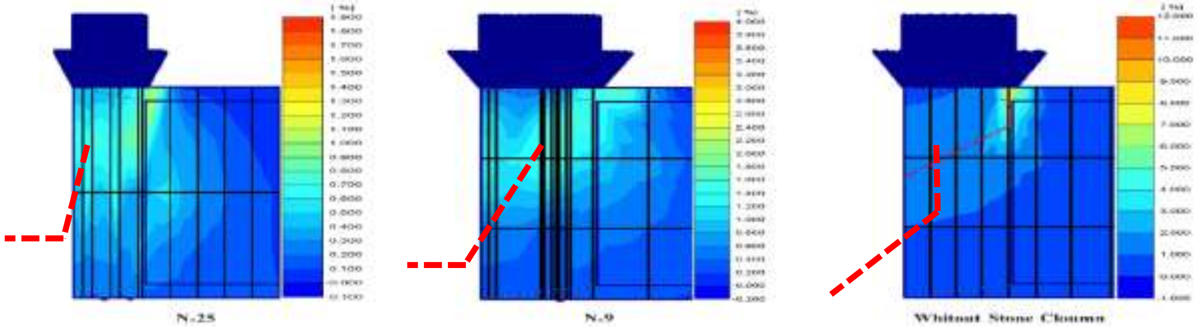

Fig 16. The spread of shear strain with increasing the number of stone columns with 10m depth

4.4.Design Curve

The modified area ratio (AR) is used as a new parameter to provide a design curve of the effect of improved ground on the level of settling. According to the definition, AR is the ratio of the total sum of the columns area to the area of the foundation and expressed in the form of percentage. Accordingly, the effect of the improved area on the settlement reduction ratio (SRR-AR) is shown in Figure 17. According to this figure, the SRR increases with the increase of AR. Likewise, the effect of using a stone column with a depth of 10m was more than 6m that leads to a further decrease in the settlement of the ground surface.

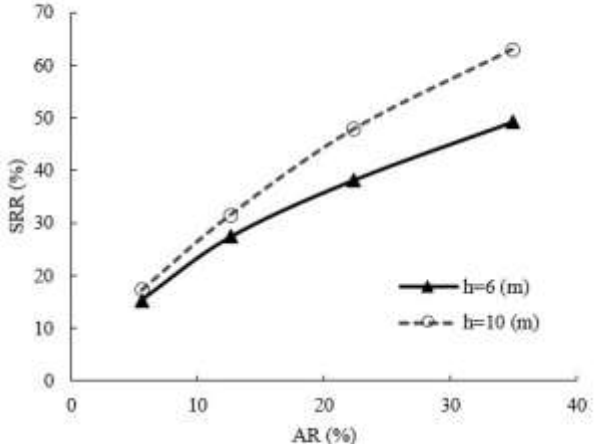

Fig 17. AR-SRR design curve

As mentioned, the settlement caused by loading takes place in the depth of the floating stone columns. The difference between the level of settlement in a surface and the depth of a stone column with a height of 6m is defined as the difference of settlement ratio (DSR). Figure 18 shows the effect of AR on DSR, which the amount of DSR decreased by increasing AR. Thus, by increasing the number of stone columns in the column group, the difference of settlement will decrease between the surface and the depth of the column.

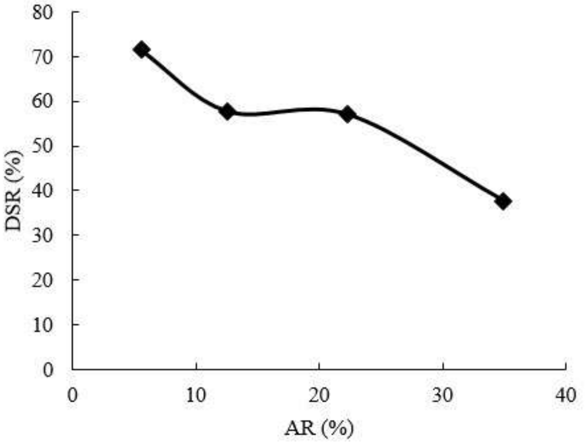

Fig 18. The difference of settlement percentage in a group of stone columns with 6m depth

5.Conclusion

The numerical analysis of the soft ground improvement by stone columns was carried out by PLAXIS 3D. Improvement depth was examined using the 6 and 10m columns in four different layouts. The most important conclusions of this study are as follows:

1. The amount of ground settlement decreases with an increase in the number of stone columns in a specific superimposed load. The results of decreasing the percentage of a ground settlement for various groups of stone columns and improvement depths of 6m and 10m were in the ranges of 15-49% and 17-63%, respectively.
2. The amount of SRR depends on increasing the improvement depth and location of the columns on the appropriate bed. Accordingly, the SRR will have a constant trend of up to 2m and 8m for a depth of 6m and 10m, respectively.
3. The lateral expansion of stone columns differs in two cases of floating and laid-on bed columns. The maximum lateral expansion has been taken place at the end of some floating columns. Generally, in the most studied models, the maximum lateral expansion took place at a depth of 0.4d.
4. Increasing the number of columns resulted in the reduction of the stress from the overburden to the columns so that the stress caused by the increase in the number of stone columns in the N=25 group has been decreased by 30% compared to the N=9 group. Besides, the shear strain created on the ground will be spread more effectively than the unimproved state by the improvement of the ground.

Reference

[1] Ahmed Naseem, A. K., Patil, K. A., (2018). Application of Geo Reinforced Stone-Column Technique for Soft Clay Soil Ground Improvement—A Review, Electronic Journal of Geotechnical

[2] Lee, J.S., Pande, G.N., (1998). Analysis of stone column reinforced foundations, Int J Numer Anal Meth Geomech, 22:1001–1020.

[3] Mokhtari, M., Kalantari, B., (2012). Soft soil stabilization using stone columns—A Review, Electronic Journal of Geotechnical Engineering, 17, pp 1459-1466.

[4] Hughes, J. M. O., Withers, N. J., Greenwood, D. A., (1976). A field trial of reinforcing effect of stone column in soil, Proc., Ground Treatment by Deep Compaction, Institution of Civil Engineers, London 32–44.

[5] Madhav, M. R., Vitkar, P. P., (1978). Strip footing on weak clay stabilized with a granular trench or pile", Can.Geotech. J, 15(4), 605–609.

[6] Aboshi, H., Ichimoto, E., Harada, K., Emoki, M., (1979). The composer—A method to improve the characteristics of soft clays by inclusion of large diameter sand columns, Proc., Int. Conf. on Soil Reinforcement, E.N.P.C., 1, Paris 211–216.

[7] Greenwood, D. A., (1970). Mechanical improvement of soils below ground surfaces, Proc., Ground Engineering Conf., Institution of Civil Engineers, London, 11–22.

[8] Jellali, B., Bouassida, M., De Buhan, P., (2005). A homogenization method for estimating the bearing capacity of soils reinforced by stone columns, Int. J. Numer. Analyt. Meth. Geomech, 29(10), 989–1004.

[9] Priebe, H. J., (1995). The design of vibro replacement, Ground Eng, 28(12), 31–37.

[10] Poorooshasb, H. B., Meyerhof, G. G., (1997). Analysis of behavior of stone columns and lime columns" comput geotech, 20(1):47-70.

[11] McCabe, B. A., McNeill, J. A., Black, J. A., (2007). Ground Improvement Using the Vibro-Stone Column Technique, The Institution of Engineers of Ireland.

[12] Isaac, D. S., (2009). Suitability of Different Materials for Stone Column Construction, M. Tech Thesis, College of engineering Trivandrum.

[13] Halabian, A. M., Naeemifar, I., Hashemolhosseini, S. H., (2012). Numerical analysis of vertically loaded rammed aggregate piers and pier groups, Ground Improvement, pp 167–181.

[14] Sakr, M., Shahin, M., Farouk, A., Khaled Moneim, K., (2017). Numerical Modeling of Stone Columns in Soft Clay for Drained and Undrained Conditions, Electronic Journal of Geotechnical Engineering, (22.06), pp 1907-1924.

[15] Shabani Rameneti, M. J., Rowshanzamir, M. A., (2016). Numerical Investigation of Sand Embankment Stability over Soft Clays Retrofitted with Stone Columns, Sharif Journal of Civil Engineering, 32.2(3.2), pp. 125-132.

[16] Murugesan, s., Rajagopal, k., (2006). Geosynthetic-encased stone columns: Numerical evaluation, Geotextiles and Geomembranes 24, 349–358.

[17] Ambily, A. P., Grandhi, S. R., (2007). Behavior of stone columns based on experimental and FEM analysis, J Geotech Geoenviron Eng ASCE, 133(4):405-415.

[18] Zahmatkesh, A., Choobbasti A. J., (2010). Settlement evaluation of soft clay reinforced with stone columns using the equivalent secant modulus, Arab J Geisci, 5:103-109.

[19] Deb, K., Chandra, S., Basudhar, P. K., (2008). Response of multilayer geosynthetic-reinforced bed resting on soft soil with stone columns, Computers and Geotechnics, 35:323-330.

[20] Deb, K., Samadhiya, N. K., Namdeo, J. B., (2011). Laboratory model studies on unreinforced and geofrid-reinforced sand bed over stone column-improved soft clay, Geotextiles and Geomembranes, 29:190-196.

[21] Mengfei, Q., Xie, Q., Cao, X., Zhao, W., He, J., Jin, J., (2016). Model test of stone columns as liquefaction countermeasure in sandy soils, Frontiers of Structural and Civil Engineering 10, no. 4, 481-487.

[22] Hosseinpour, I., Almeida, M., Riccio, M., (2016). Ground improvement of soft soil by geotextile-encased columns, Proceedings of the Institution of Civil Engineers-Ground Improvement 169, no. 4, 297-305.

[23] Nehab, N., Baba, K., Ouadif, L., Bahi, L., (2017). Numerical Simulations of Ground Improvement Using Stone Columns in Bouregreg Valley, In International Congress and Exhibition, Sustainable Civil Infrastructures: Innovative Infrastructure Geotechnology, (pp. 66-88). Springer, Cham.

[24] GuhaRay, A., Roy, A., (2018). November. Reliability Analysis of Stone Column Improved Soft Soil by Finite Element Approach. In International Congress and Exhibition, Sustainable Civil Infrastructures: Innovative Infrastructure Geotechnology, (pp. 39-50). Springer, Cham.

[25] Shabani, M.J., Farokhzad, F., Mirzaee, S. and Eliasy, M., (2019). Numerical analysis of the performance of geogrid-reinforced stone columns in soft soil. Electronic Journal of Geotechnical Engineering, 24, pp.1233-1249.

[26] Killeen, M. M., McCabe, B. A., (2014). Settlement performance of pad footings on soft clay supported by stone columns: a numerical study, Soils and Foundations, 54(4), pp.760-776.

[27] Hu, W., Wood, D. M., Steward, W., (1997). Ground improvement using stone column foundation: results of model tests, Proc. Int. Conf. on Ground Improvement techniques, Macau 247-256.

[28] Jalili, M., Zare, A. and Shabani, M.J., (2019). Parametric and numerical study on soft ground improvement using stone column reinforced with geogrid. Journal of Engineering Geology, 12(4), pp.571-598.

[29] Castro, J., (2014). Numerical modelling of stone columns beneath a rigid footing. Computers and Geotechnics, 60, pp.77-87.