

Numerical analysis of settlement behavior and bearing capacity of stone columns enclosed with geotextiles in soft soil

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Abstract: Soft soils are always considered one of the main challenges in the implementation of civil engineering projects due to their low shear strength and high settlement. Improving these soils through stone columns is a common method that has been proven to be effective in improving the geotechnical properties of the soil. However, conventional stone columns do not have sufficient resistance to lateral expansion and buckling, which limits their bearing capacity. Enclosing columns with geotextiles is a new approach to solving this problem that has attracted much attention in recent years. In this study, in order to investigate the effect of enclosing stone columns on settlement behavior and bearing capacity, two-dimensional and three-dimensional numerical modeling was performed using PLAXIS software. In the two-dimensional model, the behavior of a single column under confined and unconfined conditions was analyzed, and in the three-dimensional model, the group performance of columns under a loading plate was investigated. In both cases, the geometric parameters of the columns included diameters of 0.6, 0.8, 1, and 1.2 meters and heights of 3, 4, 5, and 6 meters. Also, geotextiles were used to enclose the stone columns in three vertical, horizontal, and combined vertical-horizontal positions with different sizes. The modeling results were evaluated based on indicators such as total settlement, initial stiffness, bearing capacity, and settlement reduction ratio. The analysis results showed that enclosing the columns with geotextiles significantly reduced settlement and increased soil bearing capacity. In two-dimensional models, the settlement reduction ratio (SSR) was obtained in the range of 30 to 50 percent and the bearing improvement factor (BIF) was about 35 to 60 percent. The initial stiffness of the enclosed columns (K_{init}) was calculated to be about twice that of the unenclosed case. In three-dimensional models, the settlement reduction rate was between 40 and 50 percent and the improvement in bearing capacity was about 55 percent. Also, comparison of group arrangements showed that triangular arrangement performed better than square arrangement due to better soil coverage.

Keywords: Stone columns, 'Geotextile', 'Soft soils', 'Land improvement', 'PLAXIS2D & 3D'

1. Introduction

Soft clay soils are considered to be the most unsuitable substrates for the construction of civil structures due to their low shear strength, high compressibility, and high sensitivity to stress changes. The low undrained strength and low deformation modulus in these soils cause significant settlements and reduce the stability of structures under typical loadings. Stone columns, as one of the common methods of soil improvement, increase the stiffness of the bed, improve the bearing capacity and accelerate the consolidation process by replacing part of the soft soil with granular materials. However, the performance of conventional stone columns in very soft soils is limited due to the insufficient lateral resistance of the surrounding soil. In such conditions, the stone column under load undergoes lateral expansion and the phenomenon of bulge occurs, especially in the upper areas of the column, which leads to a decrease in the bearing capacity and an increase in the overall settlement of the system. In order to overcome this limitation, enclosing stone columns using geosynthetic materials, especially geotextiles, has been proposed as an efficient solution. Previous experimental and numerical studies have reported beneficial effects of geosynthetic reinforcement, including the works of Bazzazian Bonab et al. (2020), Thakur et al. (2020, 2021), Katakia and Parmar (2023), and Negahdar and Fatholouloumi (2022). Despite the studies conducted, a review of the research literature shows that there are still gaps in this field. A significant part of previous research has been limited to the study of individual stone columns and the effect of column interaction in group arrangements has received less attention. In addition, in many studies, the analyses have been conducted solely based on 2D modeling and the difference between the results of 2D and 3D analyses has not been quantitatively investigated. In the present study, a coherent numerical framework based on

PLAXIS software has been developed that allows simultaneous investigation of the effect of column diameter and height, type of geotextile confinement (vertical, horizontal, and combined), and group arrangement of columns in 2D and 3D environments. Also, the performance difference of 2D and 3D models in terms of settlement, bearing capacity, and initial stiffness has been quantitatively evaluated, and based on the results, a practical perspective has been presented for selecting the most appropriate arrangement and type of confinement in soft soil improvement design.

2. Methodology

The model geometry in the 2D modeling phase was considered as a soil domain with dimensions of 12×12 meters for a single column, and in the 3D modeling phase, for group stone columns, it was considered as a soil domain with dimensions of 60×60 meters and a plate with dimensions of 12×12 meters under which the columns are placed. The dimensions of the geometry intended for design were also implemented in such a way that it was at least 5 times the largest horizontal dimension in width and at least 5 times the largest vertical member dimension in length. The soil height was also defined as 5 times the height of the columns in each case in both modeling. Also, in both modeling modes, stone columns with four different diameters were used, including 0.6, 0.8, 1, and 1.2 meters. The column heights were also considered as 3, 4, 5, and 6 meters, respectively. In this research, the Mohr-Coulomb soil behavior model was used in both modeling phases. The dimensions of the 3D model domain in the finite element software have been chosen in such a way that the effects of stress and strain caused by the columns do not reach the domain boundary. The soil was classified as CL and the column aggregate as GW. The soft soil had a cohesion of approximately 1 kPa, an internal friction angle of 1° , a saturated unit weight of 19.1 kN/m^3 , a dry unit weight of 22.78 kN/m^3 , a Young's modulus of $10,000 \text{ kN/m}^2$, and a Poisson's ratio of 0.35. The stone column material had a cohesion of 15 kPa, an internal friction angle of 42° , a saturated unit weight of 23.25 kN/m^3 , a Young's modulus of $55,000 \text{ kN/m}^2$, and a Poisson's ratio of 0.30. The geotextile was a woven polypropylene material. Its reported properties included a yield tensile strength of 45 kN/m , an areal mass of 200 g/m^2 , an axial stiffness (EA) of $75,000 \text{ kN/m}$, and an elastic modulus of $150,000 \text{ kN/m}^2$. Three reinforcement configurations were examined. In the horizontal configuration, geotextile layers were placed at different elevations within the stone column. In the vertical configuration, the geotextile formed full, semi-full, or spaced encasement around the column. The combined configuration incorporated both horizontal layers and lateral encasement. Interface elements were introduced between the stone column and surrounding soil to account for possible sliding and separation. The reported soil-geotextile interface parameters were an interface friction angle of 38.73° and cohesion of 15 kN/m^2 , while the soil-soil interface parameters were 30° and 1.6 kN/m^2 , respectively. The upper soil surface was treated as free, while horizontal displacement was restrained at the lateral boundaries. The base of the model was fixed in both horizontal and vertical directions. Uniform distributed loading was applied at the ground surface or loading plate. Mesh sensitivity was also investigated using very coarse, medium, and very fine meshes. The final modeling strategy was selected according to the observed convergence of settlement and bearing-capacity results, with local refinement around the columns.

3. Result and Discussion

The two-dimensional analyses showed that geotextile encasement substantially improved the load-settlement response of individual stone columns. For a 0.6 m diameter column under a reference load of 40 kN, settlement decreased from about 60 mm for the uncased case to approximately 33 mm for the encased case, corresponding to an SSR of about 40%. The initial stiffness approximately doubled, while the bearing capacity at a settlement of 50 mm increased by about 35–45%. For a 0.8 m diameter and 5 m high column, the final settlement decreased from approximately 90–95 mm to 45–50 mm after encasement, representing a reduction of about 45–50%. Increasing column diameter generally reduced final settlement in both encased and uncased cases, with the improvement being more pronounced when geotextile was present. A larger diameter increases the contact area between the column and surrounding soil and enhances soil-column interaction. In the encased condition, the additional lateral confinement allows a greater proportion of the applied load to be carried without excessive lateral deformation. Increasing column height also improved performance, particularly for floating columns; however, the benefit became less pronounced after the critical deformation zone had been adequately covered. The numerical results indicate that the most significant lateral deformation and bulging occur in the upper third of the column. The configuration of the geotextile had a clear influence on performance. Among the investigated configurations, the combined horizontal-vertical arrangement produced the greatest improvement. Vertical encasement increases radial resistance and limits bulging,

whereas horizontal layers contribute to a more uniform stress distribution and local stiffness. The combined system activates both mechanisms simultaneously and therefore provides the highest equivalent stiffness. For the investigated diameters, the SSR ranged approximately from 40 to 50%, while the bearing improvement factor indicated about 40–60% higher bearing capacity for encased columns. The vertical stress contours further showed that encasement produces a more uniform stress distribution along the column and reduces stress concentration near the upper portion. The three-dimensional analyses demonstrated that column interaction is an important component of the response of improved ground. In unencased groups, overlapping stress and deformation zones increased overall settlement, whereas geotextile encasement reduced this effect by providing additional lateral confinement to the individual columns. Settlement reduction in the three-dimensional cases was approximately 30–55%. For the larger diameters, particularly 1.0 and 1.2 m, the effect of geotextile became more pronounced because the reinforcement could mobilize greater circumferential tensile resistance. Increasing diameter from 0.6 to 1.2 m resulted in settlement reduction of up to about 55% and bearing- capacity improvement of up to about 60% . The three-dimensional models generally predicted lower settlements than the corresponding twodimensional representations, with the reported difference being about 15–20% on average. This indicates that three-dimensional modeling is more suitable for capturing the spatial interaction of column groups, stress concentration, and local deformation. Increasing the D/H ratio improved performance up to approximately $D/H = 5$, after which the influence of additional height became limited. The maximum bulging of unencased columns occurred at approximately 0.3–0.4 of the column height below the ground surface, while geotextile encasement reduced bulging by about 40% and produced a more uniform deformation pattern. A comparison of group arrangements showed that triangular arrangement performed better than square arrangement. The triangular layout provides more uniform coverage of the loaded area, increases the overlap of influence zones, and reduces the extent of weak soil between columns. The study reported an improvement of approximately 10–15% for the triangular arrangement compared with the square arrangement in terms of settlement and stress distribution. Mesh sensitivity analyses also confirmed acceptable numerical stability for the adopted strategy; for the group models, the difference between medium and very fine meshes was small, whereas the single-column analysis was more sensitive and required finer mesh refinement, particularly at higher loads. Validation against the studies of Bazzazian Bonab et al. (2020) and Thakur et al. (2020) showed acceptable agreement in load–settlement behavior and in the reported settlement reduction and bearing-capacity improvement. Bazzazian Bonab et al. reported approximately 40–60% settlement reduction and 25–45% bearing-capacity improvement, while Thakur et al. reported about 30% settlement reduction and 30–40% bearing-capacity improvement. The present study yielded approximately 40–53% settlement reduction and 35–60% bearing-capacity improvement in twodimensional analyses, and approximately 30–55% and 37–60%, respectively, in three-dimensional analyses. The differences in absolute values can be attributed to differences in geometry, D/H ratio, column spacing, boundary conditions, material properties, and modeling assumptions.

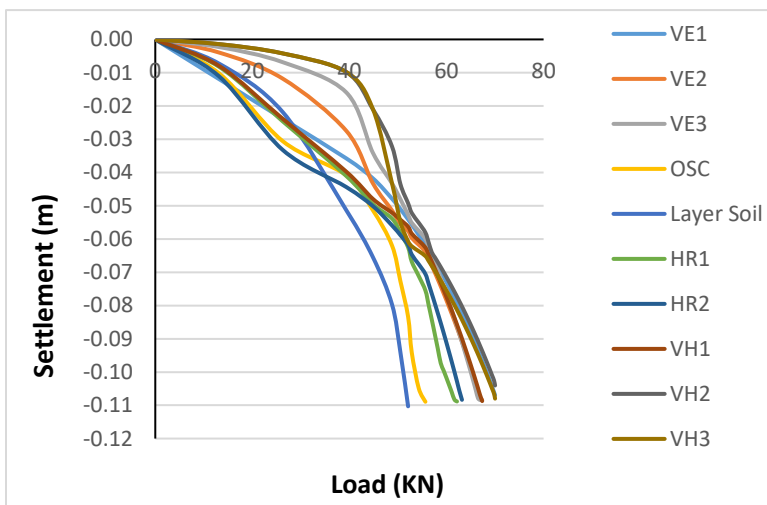


Fig2) Load-settlement diagram of a stone column with a diameter of 0.6 and a height of 3 with a square arrangement

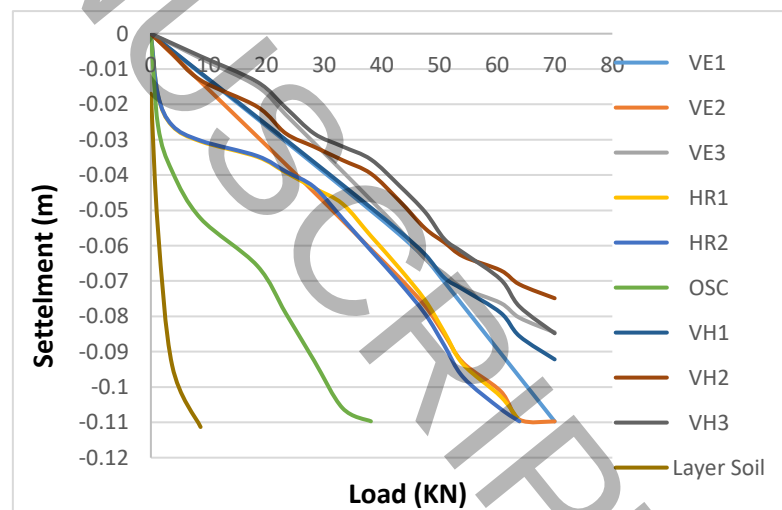


Fig1) Load-settlement diagram of a single stone column with a diameter of 0.6m and a height of 3m

Table 5) Validation of research results with previous studies

Increased carrying capacity	Settlement Reduction	Model or method used	Type of research	Researchers	Number
25-45%	40-60%	Physical model	Laboratory	Bazzazian Bonab et al. (2020)	1
30-40%	30%	Physical Model + PLAXIS 2D & 3D	Laboratory + Numerical	Thakur et al. (2020)	2
35-60% (2D) 37-60% (3D)	40-53% (2D) 30-55% (3D)	PLAXIS 2D & 3D	Numerical	Current research (2025)	3

4. Conclusion

The results of numerical analyses showed that enclosing stone columns with geotextiles plays an effective role in increasing the bearing capacity and reducing the settlement of the soil-column system. This performance improvement is mainly due to providing lateral confinement and increasing the resistance to lateral expansion of the stone column. A comparison of confined and unconfined stone columns showed that in unconfined columns, the concentration of lateral deformations and the occurrence of the bulge phenomenon mainly occur in the upper region of the column, while the use of geotextiles effectively controls these deformations and distributes the stress more evenly along the column. Enclosing stone columns with geotextiles reduces the final settlement of soft soil by about 45 to 50 percent. The bearing capacity of confined columns increases by an average of 50 percent compared to unconfined columns.

5. Reference

- [1] Bazzazian Bonab, S., Lajevardi, S. H., Saba, H. R., Ghalandarzadeh, A., & Mirhosseini, S. M. (2020). Experimental studies on single reinforced stone columns with various positions of geotextile. *Innovative Infrastructure Solutions*, 5(3). <https://doi.org/10.1007/s41062-020-00349-0> (In Persian)
- [2] Thakur, A., Rawat, S., & Gupta, A. K. (2020). Experimental and numerical modelling of group of geosynthetic-encased stone columns. *Innovative Infrastructure Solutions*, 6(1). <https://doi.org/10.1007/s41062-020-00379-8>
- [3] Katakiya, M., P Parmar, Samirsinh. (2023). Experimental Study of Bearing Capacity in Single and Group Stone Columns With and Without Encasement. *Journal of Advances in Geotechnical Engineering*, 6(1). <https://doi.org/10.5281/zenodo.7736100>
- [4] Negahdar, A., Fatholouloumi, Nader. (2022). The Experimental and Numerical Studies of Encased Stone Column Individually, in Group and Nucleated on Improvement of Loose Sandy Soil. *Journal of Structural and Construction Engineering*. <https://doi.org/10.22065/jsce.2022.337866.2789> (In Persian)