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Ground Improvement by Stone Columns: A Review

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Abstract: Stone columns serve to improve the load-bearing capacity of loose soils in an environmentally sustainable as well as cost- effective manner. The review investigates the mechanical performance of encased stone columns compared to traditional ones and highlights the role of geosynthetics in enhancing their ability to bear loads and increase their stiffness. It is also explored the obstacles related to the installation of stone columns, encompassing possible construction complexities, compatibility with the prevailing site conditions, and the impact of groundwater on their effectiveness. Consideration of the stone column in terms of the deformation modulus for settlement analysis might reflect its behavior more accurately and realistically. This review provides a comprehensive assessment of stone column advancements, including current analytical, experimental, and numerical, and a study is carried out of their compressive, uplift, and seismic responses. Based on prior study findings, mathematical analysis, physical simulation, and comprehensive investigation, many aspects that impact the overall effectiveness of this approach have been identified.

Keywords: Stone column; load settlement; analytical approach; experimental approach; geosynthetics.

I. INTRODUCTION

Traditional foundations come with high costs, ecological concerns, and weak soil deposits. To address these issues, stone columns have emerged as a popular method for enhancing subpar soil conditions. However, due to previous observations, the implementation of stone column (Granular pile) structures requires careful research and testing. Embankment foundations situated on poor soil can experience significant vertical and horizontal displacements. To alleviate settlement issues, various enhancement techniques like as granular pile, pre-consolidation with vertical drains, vacuum pre-consolidation, and deep mixed columns have been employed.

This research focuses on the current investigations, evaluation, and modeling of poor soils treated with partial or full penetration, conventional or enclosed granular piles, either individually or in groups. For more in-depth examine on the granular pile, referred to the works of [1],[2],[3],[4], and [5]. Among these techniques, granular piles offer great versatility in geotechnical tasks like densification, reinforcement, and drainage, making them highly adaptable for modifying in situ soil conditions. Stone columns effectively support the overall soil load, rapidly drain excess pore pressures, provide stable and rigid foundations, and can withstand substantial loads. Ground enhancement primarily focuses on improving soil deposits, though it can also be relevant in certain cases for enhancing rock layers. When encountering poor ground conditions at a construction site, geotechnical engineers employ soil improvement techniques to address the issue [6] [7]

Several researchers [8] were the first to propose the idea of load transmission, evaluating the ultimate bearing ability, and predicting the settlement of granular piles. Among the various soil stabilization methods, granular piles stand out as the most adaptable, practical, and profitable. These piles generate shaft resistance along their length, effectively transferring compressive forces to deeper soil layers. The ground improvement method of stone columns has become widely acknowledged for its capacity to improve the load-bearing capabilities and reduce settlement in weak soil deposits. To rise the effectiveness of stone columns when dealing with vertical or lateral loads, modifications such as adding a masonry pedestal at the bottom, and attaching a steel rod at the base are implemented to provide additional pull-out force [9]. Research has been conducted on granular pile anchor models to reduce heaving in expansive soils [10], as well as in situ testing on the pull-out response of granular pile anchors [11] and [12]. Stone columns can be crafted from a variety of stones, such as marble, limestone, granite, and sandstone, each possessing distinct characteristics and looks. The process of constructing these columns involves sculpting and shaping the stone to the desired form and then assembling them using appropriate techniques to ensure their stability and durability. In contemporary construction, stone columns are commonly employed as decorative elements in upscale buildings or historic renovations, contributing an air of sophistication and grandeur. Moreover, they can be utilized to infuse a building's design with a rustic or traditional feel, harmonizing with the surrounding environment. It's worth noting that architectural practices and trends are subject to change over time and may differ across regions, leading to potential evolutions in the utilization and design of stone columns.

According to [13], displacement stone columns are commonly preferred in soft clays. However, implementing the movement system in small-scale laboratory model tests can be challenging. Instead, the replacement technique is used, which has proven to produce granular piles with exceptional consistency. In this technique, with the aid of an auger guide, a thin seamless steel pipe with an outside diameter that matches the granular pile is easily inserted into the middle of the clay bed. The pipe is inserted to the preferred height of the stone column, as depicted in fig. 1. Granular piles constructed with horizontal strips, a specific number of aggregates were placed Between two layers of geogrid, the granular material is compacted inside a hole before introducing the subsequent circular geogrid layer.

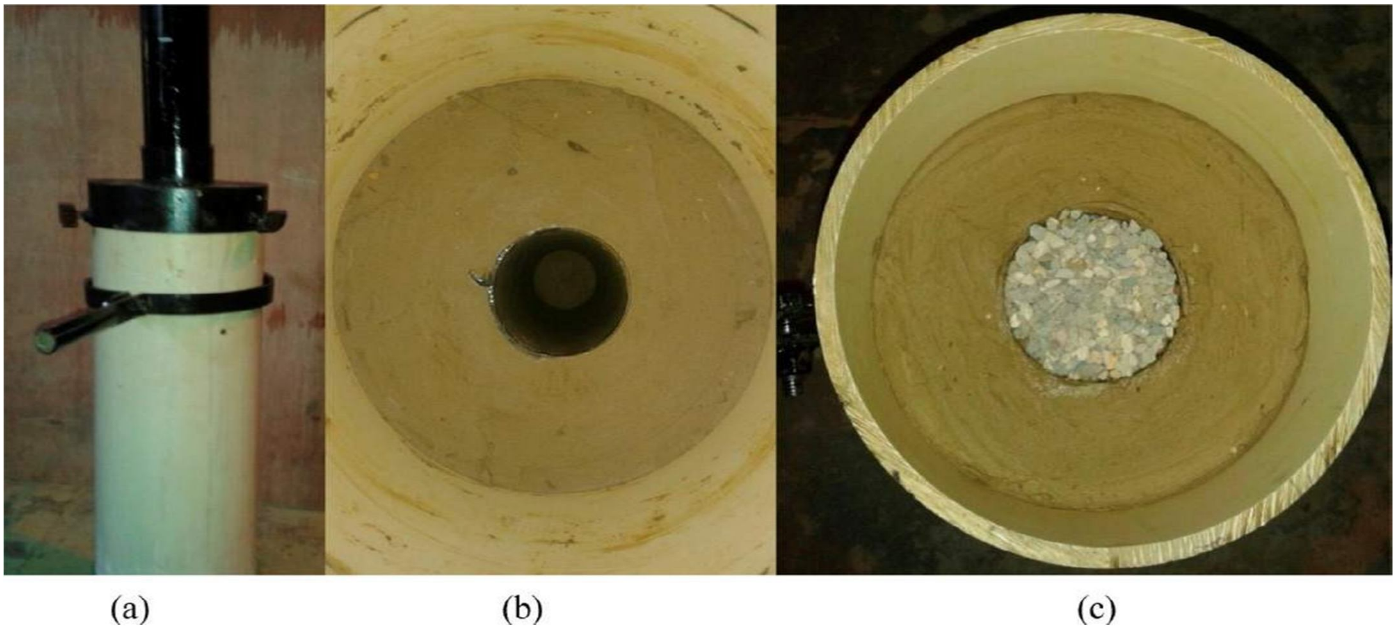


Fig. 1 The construction process of the granular pile involves (a) inserting a steel pipe, (b) creating an excavated hole, and (c) forming the pile within the clay bed, [13]

II. LITERATURE REVIEW

[14] conducted an analysis of stress distribution and movement in a silt loam base reinforced with pile foundations and various mixes. They investigated different depths and the presence or absence of a protective shell. A plate load testing was conducted on a solitary column situated within a large rectangular tank, where they experimented with different aggregate sizes and dimensions to rise load-bearing magnitude and decrease settling in the silty clay substrate.

[15] carried out a numerical three-dimensional analysis of geosynthetic enclosed granular columns at both prototype and model dimensions using FLAC 3D software. They explored the effect of group confinement by stabilizing the ground with granular piles of two dissimilar diameters of 50 mm and 100 mm arranged in three patterns (single, square, and triangular) during a direct shear test. The findings revealed the generation of tensile stresses in both horizontal and vertical directions within the geosynthetic encasement, leading to increased confinement in the granular columns.

[16] compared traditional and geosynthetic columns in a large rectangular tank's clay base under seismic conditions. They conducted a big vibrating table test (1g model test) with excess loads to evaluate the dynamic column performance for embankment supports. The study employed waterproof strain gauges to monitor strain and utilized different non-woven geotextiles for encasement. Gravel-loaded stone columns were found to reduce settlement more effectively during earthquakes than sand-filled ones.

[17] Examined to utilize a layer of soil and cement over stone columns as a measure to alleviate the bulging outcome. The performance of the soil-cement bed and stone columns was investigated using numerical analysis with Plaxis-2D, including both ordinary stone columns (OSCs) and stone columns beneath the soil-cement bed (SCB). By trial and error, they determined the ideal thickness of the bed to minimize settlement at maximum bearing capacity. The study also investigated the impact of stone column groups, through the demonstration, it was established that the bulging behavior of a group of stone columns varies from that

of individual columns, necessitating updates to the current theory for determining composite soil carrying capacity in a group.

[18] proposed an analytical approach that regards the pile as an elastic-plastic material and the soft soils as an elastic material. They conducted the research using a constant dilatancy angle and the Mohr-Coulomb condition. The encasement is assumed to exhibit elastoplastic behavior. The findings from this analytical approach align well with the results obtained from numerical analyses.

[19] conducted axis-symmetric numerical analysis utilizing the Plaxis 2d to the study investigates the behavior of end- bearing stone columns both with and without geogrid encasements. The researchers examined the influence of different axial stiffness and length of encasement on the performance of the reinforced soft clay foundation. The study revealed that as the length of the encasement increases, the load-bearing capacity of the foundation also rises. Furthermore, an increase in the stiffness of the encasement resulted in an improvement in the behavior of the encased granular pile.

[20] suggested an analytical model that takes into account the column as an elastoplastic material with constant dilatancy, the soil as an elastic material, and the geosynthetic encasement as a linear elastic material. By examining the effects of key variables, the study gave researchers a foundation upon which to base predictions about settlement reactions under several stiffnesses, pile configurations, and load levels.

[21] investigated the performance of a column in soft clay and produced a set of three-dimensional finite-element analyses, the results of which were published in the paper. A comparison study was also included in order to replicate the responses of both dense and granular materials inside the encasement.

[22] provide a combined numerical and analytical technique to evaluate how soil that has been reinforced with columns behaves. To examine how soft soil reinforced with stone columns responded to embankment loading, they used the finite difference approach. Using a free strain methodology, the study took both the clogging and arching effects into account. The provided model successfully predicted the dissipation of water pressure and subsequent consolidation settlement over time.

[23] performed numerical simulations to replicate the performance of stone columns, both with and without geogrid encasements, in soft clay. The study detailed the expectations, methodologies, and outcomes of the study. They compared the deformation and bearing ability of the regular stone column to that of the geogrid-encased stone column while exploring different stone column diameters.

[24] performed a finite element analysis using the right material models on a stone column with an encasement. A geogrid element was used to represent the geogrid, and the Mohr-Coulomb model was used to simulate the material of the stone columns. The stress-strain behaviour of the composite encased stone columns was predicted by the finite element analysis, and the outcomes were then compared to experimental data.

[25] used Finite Element Analysis (PLAXIS) to assess the real stress distribution in the stone column and soil. They added a sand pad to the surface for better drainage, and they studied the effect of the thickness of the sand pad on load distribution between the stone column and soil, taking into account both flexible and rigid loading conditions.

[26] explored the essential aspects of utilizing encased stone columns, provided insights into their design and construction, and summarized the most recent research advancements. The study demonstrated that encased stone columns with smaller diameters outperformed larger-diameter stone columns when considering the same encasement.

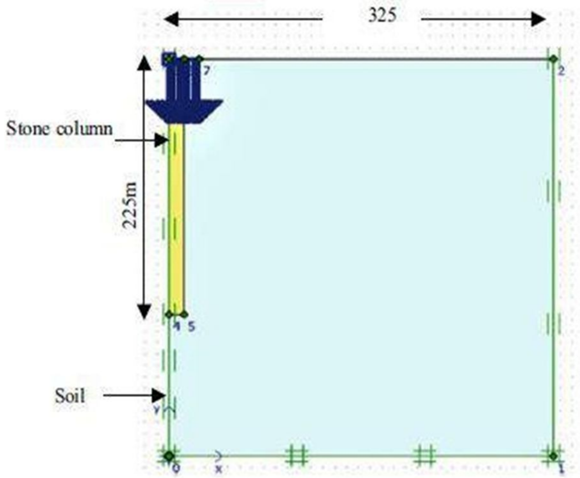
III. GEOSYNTHETIC ENCASED STONE COLUMN

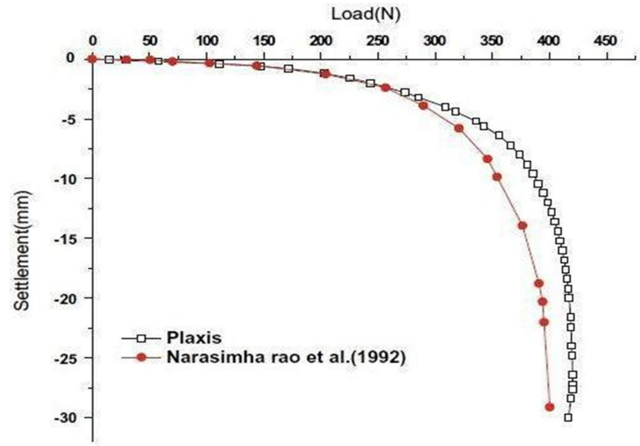
A. *Finite Element Model by Plaxis*

The study, by [27], To replicate real-world conditions, a unit cell model of a stone column with a 1-meter diameter was created within a 15-meter-thick clay layer. The study revealed that the load-carrying capacity of the stone column improved notably up to a length four times its diameter. The immediate soil lacks sufficient lateral confinement in order to prevent lateral bulging this is a successful option that increases compressive capacity by more than twice. In encasement, the greatest hoop stays relatively within such a length that is twice the diameter closest to the top.

As a result, an encasement depth of 25-30 percent of the total length of the stone column from the top is sufficient to fully utilize the maximum capacity of the encased column. Plaxis, a finite element program, examine the impacts of the vertical circumferential encasement. The effect of the casing was explored, and a design-encased stone column numerical technique was developed. The model has been validated by the load-settlement curve acquired as a result of an experimental investigation done by [28]. To impart load, a rigid plate dia. twice of the column was used. Fig. 2(a) displayed an axially symmetric model analysis was performed in Plaxis to simulate the investigation. Fig. 2(b) displayed the computational study's load-settlement curve was quite close to the experimental model. Stone columns serve in the effective transfer of the load to the underlying soil when the load, such as that from a structure, which is put on the ground. There is less settlement or soil deformation as a result of the improved load distribution.

Overall, having stone columns can lessen settlement issues caused on by greater loads.



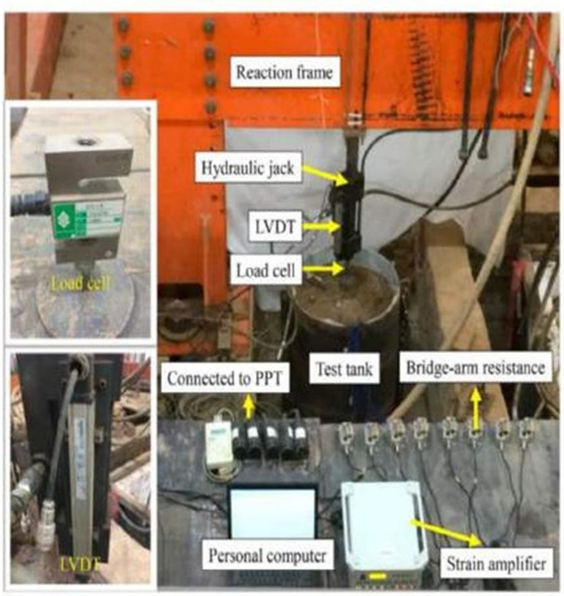


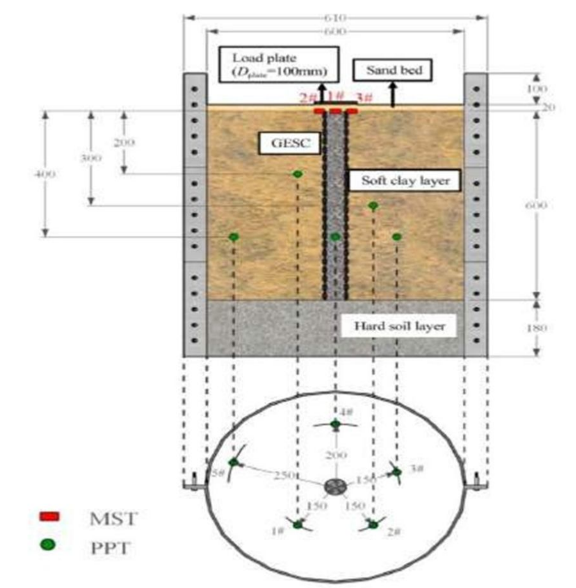
(a) (b)

Fig.2 Plaxis study (a) Model for validation (b) Load-settlement curve [27]

B. Geosynthetic Encased Stone Columns Under Cyclic Loading

An investigation by [29], This study examines how the pile encased in geosynthetic reacts to vertical cyclic loading. In a series of lab tests conducted in a test tank, different loading parameters and column dimensions were changed. The experiments observed various outcomes, including stress distribution at the soil-column interface, plate settlement, pore water pressure and lateral bulging. The study findings showed that, while larger column diameters result in less vertical stress on the pile, loading amplitudes, and loading frequencies, it increases with longer encasement lengths. Fig 3(a) is displayed the test arrangement of the loading system. The loading plate settles more slowly over time and experiences more pore water pressure as the tension on the nearby soil rises. Similar to this, the column bulges out to the side visibly more when there is more strain on it. In order to provide efficient drainage through the geosynthetic encasement serves an important role in preventing clay clogging of the drainage channel through filtering. Fig 3(b) is displayed the test arrangement of the GESC and soil layers, along with the placement of measurement gauges.





(b) (b)

Fig. 3. Test arrangement (a) a photograph showing the loading system (b) the arrangement of the GESC and soil layers, along with the placement of measurement gauges [29]

C. With and without Geosynthetic Encased Stone Columns

The study by [30], to support loads, stone columns depend on the confinement that the adjacent soil offers. However, in extremely loose or soft ground conditions, it’s possible that the lateral constraint is insufficient and that the stone column's development was uncertain. Enveloping individual stone columns with appropriate geosynthetics is an effective method to enhance their performance. The granular piles are made stiffer and stronger due to this geosynthetic encasement, which prevents the stones from experiencing lateral compression into the surrounding clay soil. Additionally, it protects the aggregates' frictional features and the stone column's drainage function. Even though geosynthetic encased stone columns offer numerous benefits, their behavior, and underlying mechanisms are not yet comprehensively understood. These tests were conducted on stone columns that were set up on a controlled clay bed inside of a sizable testing tank. The tests used a variety of geosynthetic materials and involved both single and multiple stone columns, both with and without geosynthetic encasing. The results of the stress tests showed unequivocally that encasing the stone columns significantly increased their ability to support loads. The axial load capacity directly correlated with the modulus of the encasement and the diameter of the stone columns. Fig. 4 displayed the Schematic of geosynthetic encased stone column. The study also looked at how the encasement increased the amount of stress that was placed on the stone columns.

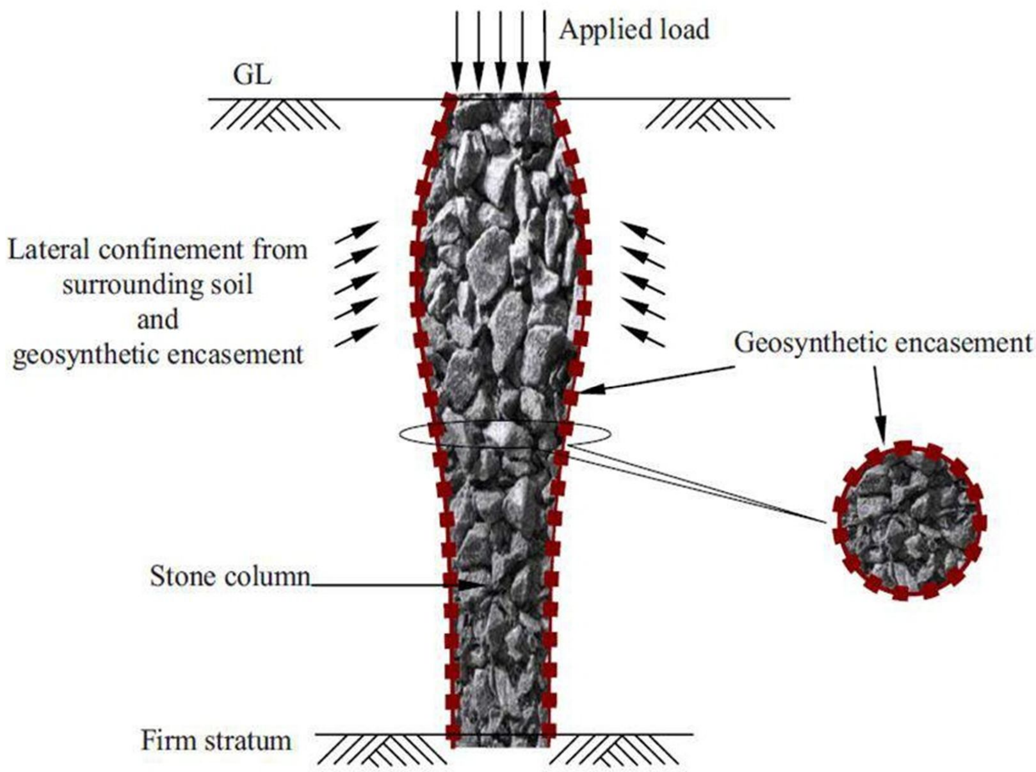


Fig. 4 The Schematic of geosynthetic encased stone column [30]

D. Three-dimensional Finite Element Model

The numerical investigation by [31], The length and stiffness of the encasement, the height of the embankment fill, and the area replacement ratio were some of the influencing factors that were examined in a parametric study using a three-dimensional finite element model. The study showed the column, to reduce settling when the stone column is weighed by an embankment, thorough encasing is necessary. The experiment also showed that increasing encasement stiffness is most effective in situations where there is a significant amount of stress on the soft ground. Design charts are offered for use in preliminary to calculate the extreme settlement and stress concentration ratio based on the study's findings. Under the following circumstances: thicker clay layers, poorer clay consistency, smaller area replacement ratios, and higher embankment loads, the extent of settlement decrease through rise encasement length and stiffness appears to have a more observable effect. Fig. 5 is displayed the cross section of geosynthetic-encased stone column reinforced ground. Fig. 6 is displayed the typical finite element model of width of 55 m.

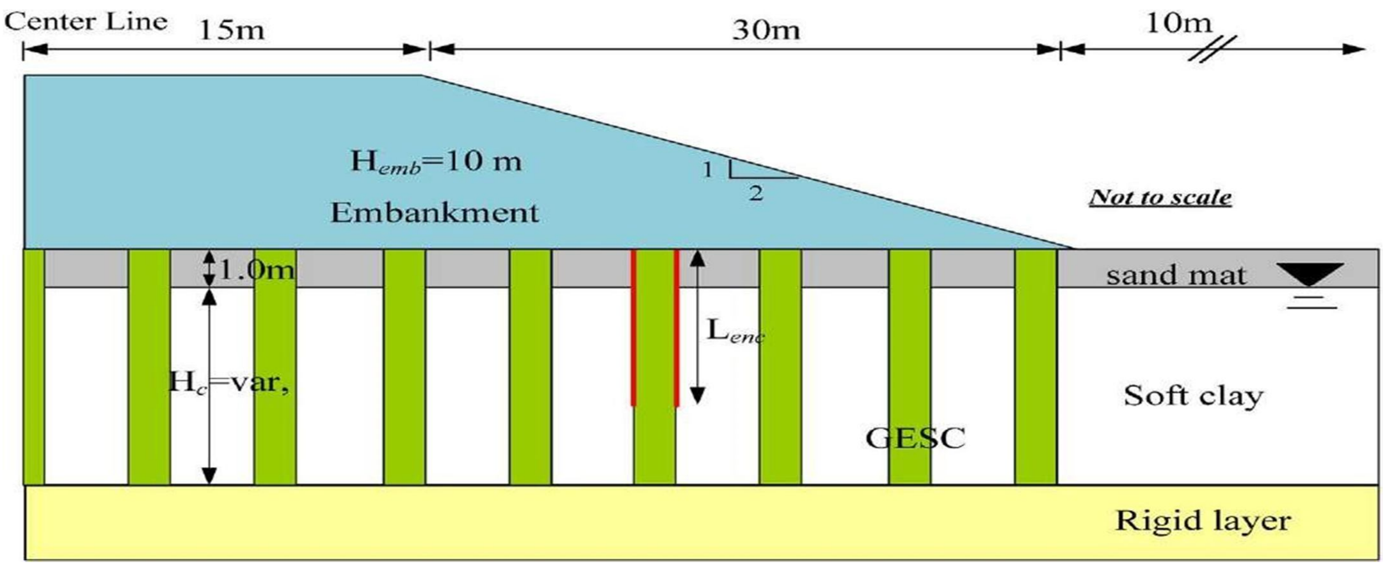


Fig. 5 The cross section of geosynthetic-encased stone column reinforced ground [31]

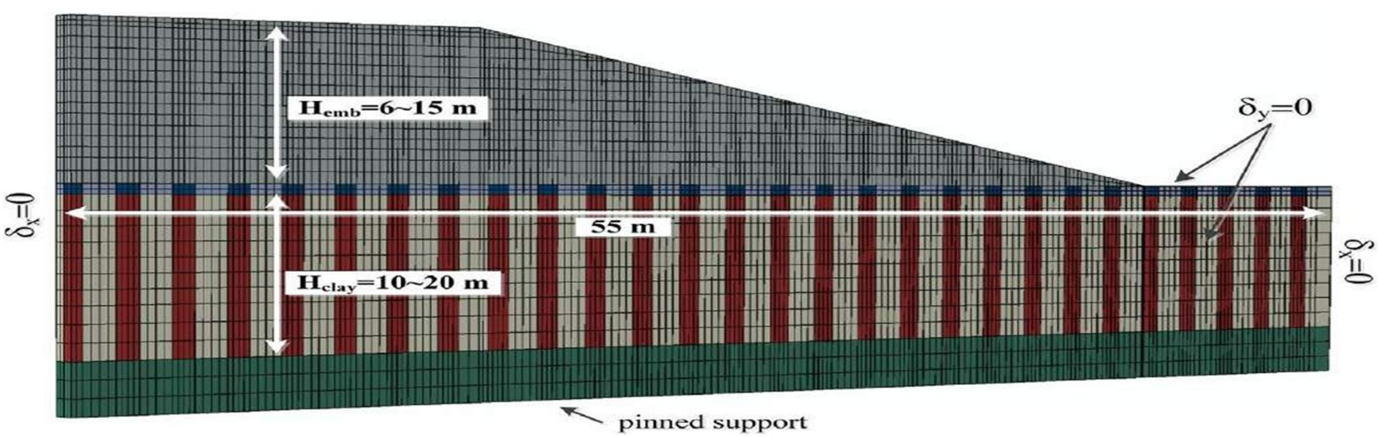


Fig. 6 A typical 3D FE model adopted [31]

IV. CONCLUSIONS

This analysis offers valuable understandings regarding the behavior, design, and uses of stone columns. It serves as a precious reference for geotechnical engineers, researchers, and industry experts aiming to implement this ground improvement method with ability. In regions characterized by soft, collapsible clays, silts, and loose subgrade layers, stone columns offer the most efficient and suitable soil remediation approach. The geosynthetic encasement can augment both the load-bearing capacity and rigidity of the stone column. Encased stone columns exhibit a stiffer and more robust behavior without experiencing substantial strain softening beyond the peak load. In contrast, conventional stone columns demonstrate a softer response with notable strain softening. This review considered the most effective and practical soil improvement technique, especially in areas with abundant sand. In cohesive soil regions, stone columns are commonly constructed using either ramming or geotechnical techniques, which can be either moist or dry. With the extension of the encasement length, a larger proportion of vertical loads is transferred to the column, leading to reduced stress on the surrounding soil. Conversely, an enlargement in column diameter, loading amplitude, and loading frequency are led to reduced stress on the column itself, causing a higher proportion of vertical loads to be borne by the surrounding soil. Compared to other soil improvement methods, stone columns are regarded as a cost-effective approach for ground renovation, resulting in significant cost savings for construction projects. During the process, weak and unsuitable soil elements are replaced with compacted aggregate, forming stiffer and more resistant columns than the poorly maintained native soil. This consolidation effectively penetrates the vulnerable layers, leading to an increase in bearing capacity.

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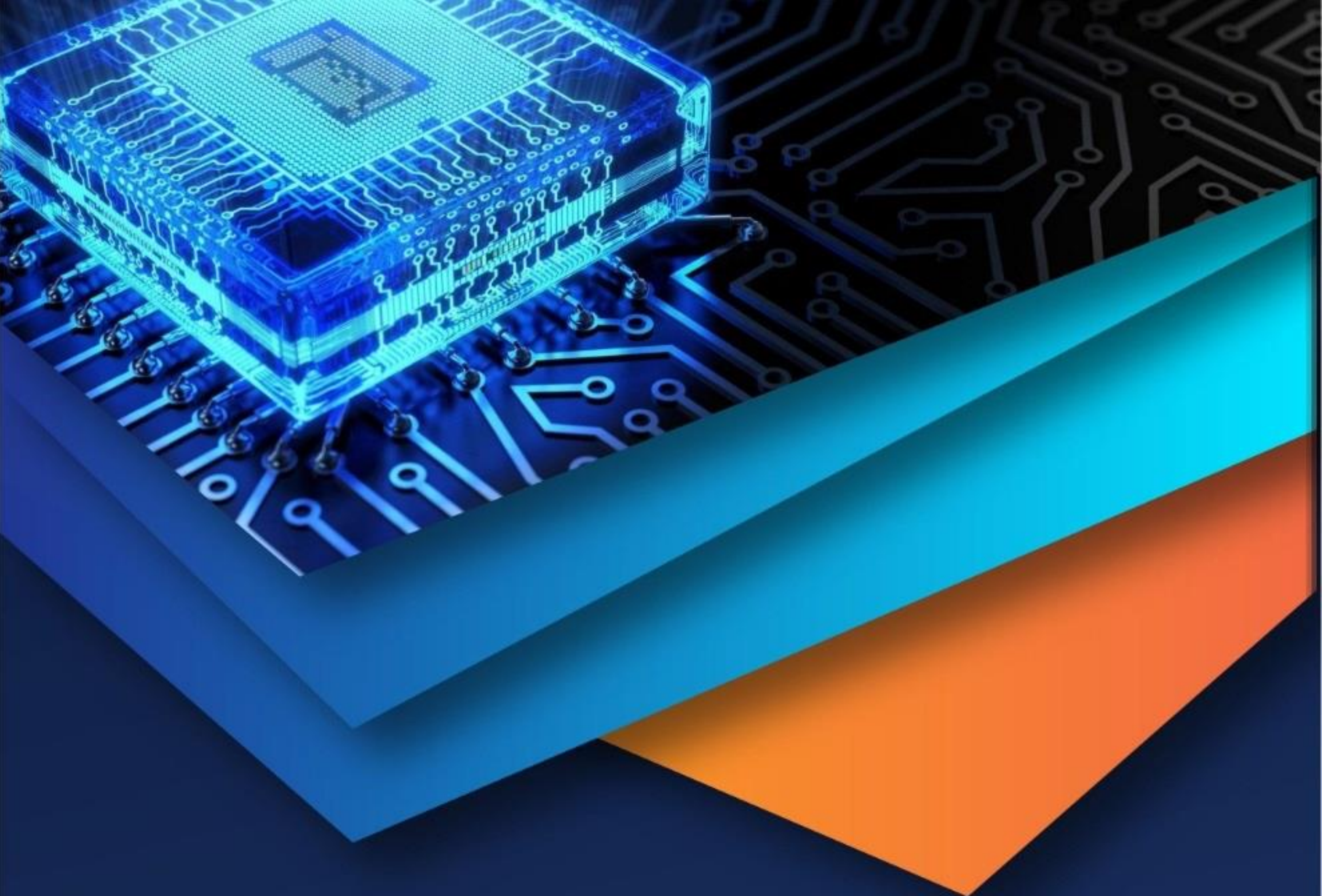

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