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Structural Analysis of Geosynthetics Encased Columns for Load Bearing and Settlement Properties

Shubham Kumar, Deepak Mathur*

Civil Enginerring department, KITE, Jaipur (India)

A B S T R A C T

Present research study presents an intricate examination of the optimal design and functioning of Geosynthetics Encased Columns (GEC) in the context of load-bearing and settlement properties, focusing on a specific case study in Rajasthan, India. The research is segmented into three comprehensive investigations, incorporating various scenarios, materials, and configurations. The study explores settlement and load variations for sand samples. Analyzing two trials, the research depicts a systematic relationship between applied loads (0 to 5 kN) and resultant settlements. This part of the study adds a foundational understanding of the load-settlement relationship and sets the stage for more complex analyses. In the present research delves into the effects of incorporating a single stone column within the GEC system, employing four distinct types of stones: Hybrid of all, Granite, Marble, and Crusher. The behavior of each stone type under various loads was meticulously recorded, revealing unique trends and susceptibilities for each material. These findings underline the importance of material selection in the design process and its consequential impact on load-bearing capabilities.

Keywords: stone column, Rajasthan sand, load analysis, settlement, stone types

1. Introduction

Weak soils, such as loose sands or soft clays, typically have a lower bearing capacity than stronger soils. This means that they are not able to support the same amount of weight or load as a stronger soil. This can be a major problem in areas where buildings or other structures are being constructed, as the weak soil may not be able to support the weight of the structure without settling or even failing. Additionally, weak soils can lead to problems such as differential settlement, which can cause damage to the structure or create safety hazards. Furthermore, weak soils can also lead to issues with stability, particularly in areas with steep slopes or high water tables. In these situations, the weak soil may not be able to resist the forces of erosion or the weight of water, leading to landslides or other stability problems.

In order to address these issues, it is often necessary to improve the bearing capacity and stability of the weak soil. One way to do this is by using stone columns. This technique involves installing vertical columns of crushed stone or gravel into the soil using a vibrating probe. The vibration compacts the surrounding soil, creating a denser and more stable soil mass. This can significantly increase the bearing capacity and stability of the soil, making it suitable for supporting structures and improving the stability of slopes and other areas. Overall, weak soils require bearing capacity improvement because they are not able to support the same amount of weight or load as a stronger soil. This can lead to issues with settlement, stability and safety. Improving the bearing capacity and stability of weak soils can be done using various methods like stone columns, which can help ensure that structures can be built safely and that stability issues can be prevented.

Stone columns, also known as vibro-replacement or vibro-compaction, are a method of soil improvement used to increase the bearing capacity and stability of loose or weak soils. The technique involves installing vertical columns of crushed stone or gravel into the soil using a vibrating probe. The vibration compacts the surrounding soil, creating a denser and more stable soil mass. One of the main benefits of using stone columns is that they can significantly improve the load-bearing capacity of weak or loose soils. This is especially useful in areas where the soil is not suitable for traditional foundation systems, such as shallow soils or areas with high water tables.

Another advantage of stone columns is that they can be used to improve the settlement characteristics of a soil. By increasing the density of the soil and reducing the compressibility, stone columns can reduce the amount of settlement that occurs under load. This can be especially important in areas where settlement can cause damage to buildings or other structures. In addition, stone columns can also be used to improve the drainage characteristics of a soil. By creating a network of vertical drainage paths through the soil, stone columns can improve the ability of the soil to drain water and reduce the potential for settlement due to excess water.

The process of installing stone columns involves drilling a hole into the soil using a vibrating probe, and then filling the hole with crushed stone or gravel. The probe is then withdrawn, leaving the stone column in place. The vibration caused by the probe compacts the surrounding soil, creating a denser and more stable soil mass. Overall, stone columns are a useful method of soil improvement for increasing the bearing capacity and stability of weak or loose soils. They can also be used to improve the settlement and drainage characteristics of a soil, making them a versatile option for a wide range of applications. The prime aim of the present study is to explore, design, and optimize the applicability and real-world effectiveness of geosynthetics encased columns, utilizing three unique local stones and a novel hybrid combination of these, for targeting load-bearing and land settlement remedies. The research work dissects through a geotechnical and environmental calculus of Rajasthan's depository and cartography, to improve understanding of the processed variants of the geomaterial couched structural behavior under stipulated stressors,

2. Literature Review

Experimental studies were conducted to investigate the behavior of stone columns under varying conditions, such as spacing, shear strength of the underlying soft clay, and moisture content. The results of these studies revealed that bulging of the columns occurred in the upper portion, with the amount of bulging being approximately half to one times the diameter of the column. Additionally, the settlement behavior of the columns was found to be linear, which improved the stiffness of the ground. These findings were supported by previous research by Ambily & Gandhi (2004) and Ali et al. (2010). Furthermore, the stiffness obtained from the model tests was found to be consistent with the results obtained from finite element analysis for load-settlement ratios of 2 and 3. However, for a load-settlement ratio of 4, the improvement was only marginal. In addition, the studies also examined the effects of encasement, the length-to-diameter ratio, and the diameter of the column on the bearing capacity of floating and fully penetrated single piles, as well as unencased and encased columns with geotextile. It was found that stone columns with lengths more than six times their diameter showed bulging effects.

Lu and Li, 2023 [1] focus on addressing the limitations of the existing models for consolidating stone column composite foundations, specifically in the context of time-dependent loading and boundary effects. A new analytical model has been developed to capture these dynamic attributes, with solutions presented for two distinct conditions: permeable top and bottom surfaces (PTPB) and permeable top with an impermeable bottom surface (PTIB). To ascertain the validity of the proposed solutions, a comparative analysis with previous solutions was conducted. The extensive computations made using the new solutions provided significant insights into the consolidation behaviors of stone column composite foundations under variable time constraints. The research found that interface parameters significantly influence the excess pore water pressure (EPWP) distribution. Furthermore, the study revealed that the permeability of the foundation's surfaces has a reduced impact on the average consolidation rate in longer-term projects. The proposed model was successfully applied to real-world engineering, showing alignment with actual measured data. This research advances the understanding of stone column composite foundations and offers a more nuanced approach to considering time-dependent factors in the consolidation process.

Bouziane et al, 2022 [2] explores the impact of stone column reinforcement on soil through a laboratory-scaled experimental model. Using cylindrical samples of soil, the study assesses how various materials and configurations of stone columns affect axial deformation during vertical loading tests. The soil samples were created using poly-dispersed glass beads (GB) with grain sizes under 50 mm. Two types of reinforcing materials were studied: crushed sand (CS) and coarser GB (0.7–1.0 mm). By comparing different configurations (triangular or square) and spacings between columns, the study revealed significant differences in reinforcement efficiency. The findings provide valuable insights into how medium-density granular soils can be improved through vibrocompaction, making the research beneficial for practical applications in soil stabilization and reinforcement.

Geramian et al, 2022 [3] focuses on the study of the installation effects of groups of stone columns in cohesive soils using three-dimensional (3D) finite element analyses. Utilizing the Coupled Eulerian Lagrangian formulation, the installation is modeled as the insertion of rigid cylindrical elements with conical tips into a homogeneous soil layer. The study considers three different scenarios: the installation of a single column (as a reference), two columns, and a group of nine columns. Through this investigation, the paper uncovers the way in which the installation of multiple stone columns alters the neighboring soil. The results reveal that installing several columns at common spacings causes an overlap of effects, leading to an accumulation of horizontal stresses and pore pressures over a more expansive area. Moreover, the study emphasizes that the installation sequence has a noticeable impact, particularly around the last column installed, where radial stresses are found to be lower. The findings of this research provide valuable insights into the complex interactions during the installation of stone columns, which could have significant implications for construction and engineering practices.

Ramadan et al, 2022 [4] investigates a solution to the bulging problem encountered in the design of stone columns in very soft soils. Since the confinement provided by surrounding soft soil may not suffice to develop the needed load-carrying capacity, the study explores the use of geosynthetics for additional confinement to prevent stones from squeezing into the surrounding clay. It also looks into the added benefits of a sand bed over the stone columns, which can increase load capacity and reduce settlement. The sand bed further aids in uniform load distribution from the foundation. Through a series of numerical model tests using FLAC3D, the study compares the performance of unreinforced sand beds (USB) and geogrid-reinforced sand beds (GRSB) situated over vertically encased stone columns (ESC) in soft clay. In the analyses, geosynthetics are modeled as an elasto-plastic material. The findings highlight the efficacy of employing geosynthetics and sand beds to enhance the performance of stone columns, offering valuable insights for foundation design in challenging soil conditions.

Gu et al, 2022 [5] delves into the performance of floating stone columns reinforced with geogrid encasements, providing a comprehensive analysis of various behaviors such as load-displacement, bulging deformation, load transfer mechanism, and radial stress. Through model tests, the research unveils that geogrid encasement significantly elevates the bearing capacity of floating stone columns, with longer encasements leading to increased stiffness at considerable settlements. Additionally, the study reveals that the encasement alters the bulging deformation pattern, allowing more vertical pressure to transfer from the top to the bottom of the column. This leads to the development of high radial stress, which efficiently confines the column. The research emphasizes that the bearing capacities of these encased stone columns are governed by bulging deformation rather than penetration failure. The conclusions drawn from the study affirm that floating-encased stone columns are a promising solution for field construction, particularly in areas with extensive soft soils, enhancing our understanding of geotechnical engineering techniques.

Rezaei et al, 2022 [6] examines the innovative use of steel slag as granular columns for enhancing ground stability in geotechnical projects. Granular columns, typically used to increase bearing capacity and reduce settlement, have been explored with steel slag, an industrial waste product. This utilization offers an eco-friendly and cost-effective approach to managing solid waste. While previous research has focused on bearing capacity and settlement with or without geosynthetic encasement, this study specifically probes the lateral load capacity of steel slag granular column-soil composites. Using a series of large direct shear tests, the paper compares the performance of steel slag columns to ordinary stone columns with various configurations including different materials, column diameters, numbers of columns, arrangements, and encasement. The findings demonstrate that steel slag columns enhance the lateral load-bearing capability of the soil, underscoring the value of steel slag as a sustainable material for ground improvement. This research contributes to the ongoing efforts in sustainable engineering practices by integrating waste materials into construction techniques.

Miranda et al, 2021 [7] focuses on determining the critical length of encased stone columns in soft soils, where further extension of the column length offers minimal improvement, rendering additional construction inefficient. Encased stone columns, typically formed by gravel wrapped with geotextile, have specific lengths beyond which they become ineffective. The paper utilizes both two-dimensional axisymmetric and full three-dimensional finite element analyses to estimate common values of this critical length. Considering a uniform soft soil layer with linear elastic perfectly plastic behavior for simplicity, the research identifies the critical column length to be around 1.3 to 2.5 times the footing diameter for encased stone columns, and slightly less for ordinary stone columns (around 1.1 to 1.9). Furthermore, the critical length of encasement is found to be marginally lower than that of the column. The findings suggest a general value for the critical column length, which is 2 to 2.5 times the footing diameter for ordinary and encased stone columns respectively. These results provide valuable insights for the design phase of construction projects, aiding in the efficient utilization of resources without the need for extensive parametric analyses.

Alkhorshid et al, 2021 [8] explores the challenges posed by soft clays due to their high compressibility and low shear strength, and examines solutions to stabilize and reduce settlements in such terrains. The research focuses on geosynthetic-reinforced granular columns, a widely-used method to mitigate these problems, specifically under embankments on soft clays. The study investigates both encased and layered granular columns, utilizing numerical evaluations to understand the effects of geosynthetic stiffness and column length on embankment settlements. Findings indicate that these parameters significantly influence the performance of the columns. Additionally, the paper reveals that granular columns have a critical role in reducing excess pore water pressures, thus speeding up the consolidation settlements of embankments on soft clays. The study's outcomes not only highlight the efficacy of using geosynthetic-reinforced granular columns but also offer insights into optimizing their design and implementation for specific geotechnical problems, contributing valuable knowledge to the field of soil stabilization and foundation improvement.

Ghorbani et al, 2021 [9] presents a comprehensive investigation into the impact of stone columns and basal geosynthetic reinforcement on the deformation and stability of an embankment constructed on soft soil. Utilizing two-dimensional numerical analysis via Plaxis 2D finite element code, the study transformed columns into equivalent walls, allowing for the simulation of a complete embankment over a group of columns. The findings indicate that the integration of stone columns substantially minimized the total deformations of the underlying soil, although the effect was less pronounced when a high-stiffness geogrid was placed beneath the embankment. Notably, the length of the stone columns was identified as the most significant factor in controlling embankment deformations; an increase in column length from 0.25Hs to 0.75Hs resulted in a dramatic reduction in both vertical and horizontal deformations. Additionally, the utilization of a high-stiffness basal geogrid significantly enhanced the stability of the embankment, elevating the safety factor at the construction's conclusion from 1.25 to approximately 1.9. Overall, the study offers valuable insights and quantitative data on optimizing the use of stone columns and geosynthetic reinforcement for embankment construction over soft ground, contributing to safer and more effective geotechnical engineering practices.

Dar et al, 2021 [10] intricate analysis of the behavior of geosynthetic encased stone columns (GESC) under vertical stresses, employing a three-dimensional (3D) numerical model developed in PLAXIS3D. The study begins by validating the numerical models with existing experimental data from the literature on GESC. Following validation, the paper embarks on a detailed investigation, focusing on a range of parameters to understand their influence on load-settlement behavior in the condition where only the column is loaded. The examined parameters encompass the diameter of GESCs, spacing to diameter (S/D) ratio, stone column installation pattern, geosynthetic encasement stiffness, length of encasement, length of floating column, cohesion of soil, and the friction angle of stone column infill. The findings reveal several key insights.

3. Research Methodology

The present study involves the use of three different materials to investigate the behavior of reinforced soil systems. The first material used in this study is a soil sample, which serves as the base material for the reinforced soil system. The soil sample was collected from the study site and characterized using standard laboratory tests to determine its geotechnical properties such as grain size distribution, plasticity, and shear strength parameters.

The second material used in this study is aggregates for stone column construction. Stone columns are a popular method for improving the load-bearing capacity of weak soil deposits. The aggregates used in this study were carefully selected to meet the design requirements of the stone columns. They were tested for their physical and mechanical properties, including gradation, density, and compressive strength. The stone columns were constructed using the wet top feed method and the performance of the reinforced soil system was evaluated through laboratory tests. The third material used in this study is a polymeric geotextile for encasement. Geotextiles are synthetic materials used to improve the stability, filtration, and drainage of soil structures. In this study, a polymeric geotextile was used to encase the stone columns to provide additional confinement and lateral support to the soil. The geotextile was characterized for its physical and mechanical properties, including tensile strength, thickness, and permeability.

The experimental testing involved a series of laboratory tests to evaluate the behavior of the reinforced soil system under various loading conditions. The tests included unconfined compression tests on the soil sample, triaxial compression tests on the stone columns, and direct shear tests on the geotextile. The results of the laboratory tests were used to validate the performance of the reinforced soil system and provide insights into the contribution of each material to the overall behavior of the system. Finally, the use of three different materials in this study - soil sample, aggregates for stone column, and polymeric geotextile for encasement - allowed for a comprehensive evaluation of the behavior of reinforced soil systems. The findings of this study could be beneficial in the design and construction of soil improvement techniques in areas with similar geotechnical conditions. Additionally, the use of polymeric geotextiles as encasement for stone columns could potentially enhance their performance and improve the load-bearing capacity of the reinforced soil system.

Stone Aggregates Selection

The proper selection of crushed stone size range is a critical factor in the construction of stone columns. Ali et al. advise that stone aggregates should be within the size range of 5 mm to 40 mm to maintain the appropriate d/D ratio for prototypes of stone columns. This is because the ratio of the diameter of the stone column (d) to the size of the stone aggregate (D) is a critical parameter for determining the performance of stone columns. Typically, crushed stones with a size range of 20-60 mm are used to construct stone columns with diameters between 0.3-1 m, resulting in a d/D ratio between 12-40 [Ali et al. And D.Muir et al]. This ratio is widely used in practical applications, as it provides the necessary strength and stability for the structure. In the present study, stone aggregates between 1-10 mm in size (Figure 3.3) were selected for constructing stone columns, resulting in a d/D ratio ranging from 5-25. This range is suitable for practical applications and can be used for a variety of construction purposes. It is important to note that the appropriate size range of crushed stones will depend on several factors such as the soil conditions, column diameter, and the intended use of the structure. Therefore, careful consideration of these factors is necessary to ensure the optimal selection of crushed stone size range for constructing stone columns.

Figure 1 Crushed Stone for present study a. marble b. granite c. kota-stone

All samples of the crushed stones was collected from the local region of the stones and then size distribution was carried out for all three type of stones.

Experimental test setup

To conduct laboratory experiments on stone columns, a test setup must be designed to simulate real-world soil conditions. The setup requires a container to hold the soft soil in which the stone columns will be constructed. The stone columns should be constructed to the desired dimensions and using the required type of stone. If geogrid encased stone columns are to be tested, the geogrid must be wrapped around the stone columns according to the predetermined specifications. A load frame is required to apply vertical and horizontal loads to the stone columns, and displacement sensors should be placed on the top and bottom of the stone columns to measure deformation under load. A data acquisition system (DAQ) is required to collect and record the data from the load frame and displacement sensors accurately. In addition to this, laboratory testing equipment such as a triaxial testing apparatus and consolidation apparatus may be required depending on the testing requirements. The experimental test setup should be calibrated before conducting experiments to ensure that all instruments and equipment are functioning correctly, and the testing procedure should be designed carefully to ensure accurate and reliable test results. The following experiments steps and instruments required for the present investigation.

4. Result and discussion

Single Stone Column experiment results

The load-settlement behavior of single stone columns is an important area of study in geotechnical engineering. A single stone column is a type of ground improvement technique used to increase the load-bearing capacity of weak soils. It involves the installation of a vertical column made of crushed stone or other types of aggregate material into the soil to create a more stable foundation. The behavior of a single stone column under load is influenced by several factors, including the diameter and height of the column, the type and properties of the soil, and the placement and compaction of the stone material. Load testing is an essential part of evaluating the performance of a single stone column, as it allows for the measurement of the column's load-carrying capacity and its corresponding settlement.

During load testing, a single stone column is subjected to a series of incremental loads until it reaches its maximum load-carrying capacity. The corresponding settlement is then measured and plotted against the applied load, resulting in a load-settlement curve. The load-settlement behavior of a single stone column is typically nonlinear, with a rapid increase in settlement occurring at the beginning of the loading process, followed by a more gradual increase in settlement as the load increases. The load-settlement behavior of a single stone column is influenced by several factors, including the diameter and height of the column, the type and properties of the soil, and the placement and compaction of the stone material. Load testing is an essential part of evaluating the performance of a single stone column, as it allows for the measurement of the column's load-carrying capacity and its corresponding settlement.

The load-settlement behavior of a single stone column can be improved by reinforcing the column with a geosynthetic material. The geosynthetic material provides additional lateral confinement to the column, which can increase its load-carrying capacity and reduce its settlement. Reinforced single stone columns have been shown to be effective in stabilizing weak soils and increasing their load-bearing capacity. The load-settlement behavior of a single stone column is an important area of study in geotechnical engineering. Load testing is essential in evaluating the performance of a single stone column and provides valuable information on its load-carrying capacity and corresponding settlement.

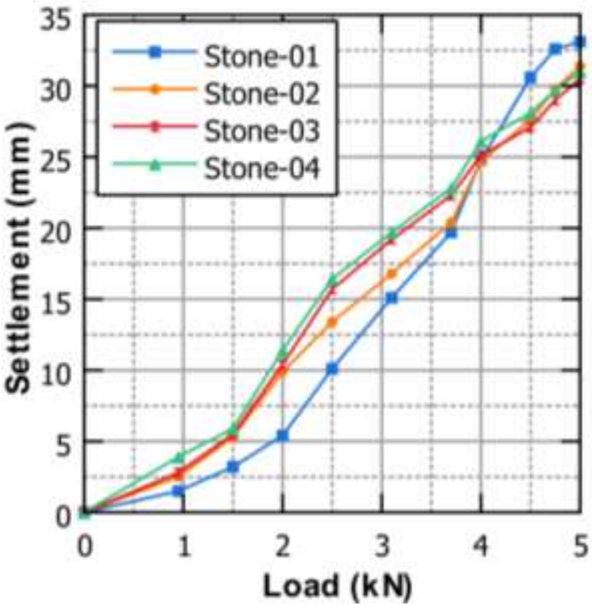

Figure 2 Load and settlement for normal sand bed with stone column (Four different Stone Samples)

Table 1

Settlement and load variation for sand sample used in present study having single stone column

Load	Stone-01	Stone-02	Stone-03	Stone-04
	Hybrid of all	Granite	marble	Crusher
kN	mm	mm	mm	mm
0.00	0.00	0.00	0.00	0.00
0.95	1.5	2.5	2.8	3.9
1.50	3.2	5.3	5.5	5.9
2.00	5.4	9.9	10.4	11.4
2.50	10.1	13.4	15.7	16.4
3.10	15.1	16.8	19.2	19.7
3.70	19.7	20.4	22.3	22.8
4.00	24.8	24.7	25.1	26.1
4.50	30.6	27.6	27.1	28.1
4.75	32.6	29.8	29.0	29.7

Load	Stone-01	Stone-02	Stone-03	Stone-04
	Hybrid of all	Granite	marble	Crusher
kN	mm	mm	mm	mm
5.00	33.1	31.4	30.50	31.0

Settlement study for three stone column design conditions

The study was conducted through a series of laboratory tests using model sand specimens. The settlement and bearing capacity of the sand specimens were measured under different loading conditions, including static, cyclic, and repeated loading. The results of the study showed that all three design conditions of stone columns improved the stability of the sand bed and reduced the settlement. However, the most effective design condition was found to be the use of stone columns with geogrid reinforcement. This design condition provided the greatest improvement in soil stiffness, bearing capacity, and reduction in settlement.

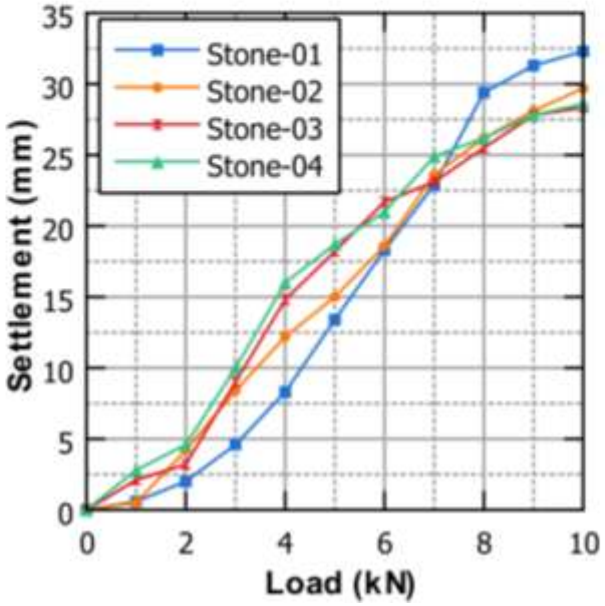

Figure 5.3 Load and settlement for normal sand bed with three stone column (Four different Stone Samples)

5. Conclusion

The contribution of this research to the field of civil engineering and construction is a testament to the importance of interdisciplinary research and the application of both traditional experimental methods and modern simulation techniques. As we continue to explore and innovate, this study serves as a foundation upon which future researchers and practitioners can build, optimize, and expand. The journey towards efficient, sustainable, and resilient infrastructure is long, but this research marks a significant milestone on that path.

The research embarked on a comprehensive investigation into the optimal design of geosynthetics encased columns for load-bearing and settlement properties in the context of Rajasthan. Through a systematic series of experimental trials and FEA simulations, the study revealed:

Without Stone Columns: The inherent lack of strength and support in the sand sample used, resulting in increased settlement as the load increased.

Single Stone Column: A significant reduction in settlement with the introduction of a single stone column, with varying effectiveness among different materials.

Three and Four Stone Columns: A pattern of diminishing returns on investment as more columns were introduced, indicating a need for strategic planning rather than simple multiplication of columns.

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