STUDY OF THE BEHAVIOUR OF STONE COLUMN IN LAYERED SOFT SOIL USING PLAXIS 2D

A DISSERTATION

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GEOTECHNICAL ENGINEERING

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MAY, 2023

CANDIDATE'S DECLARATION

I, Sadaf Mir (2K21/GTE/15) of M. Tech (Geotechnical Engineering), hereby declare that the Project Dissertation entitled “STUDY OF THE BEHAVIOUR OF STONE COLUMN IN LAYERED SOFT SOIL USING PLAXIS 2D”, which is submitted by me to the Department of Civil Engineering, Delhi Technological University, Delhi is submitted in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

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CERTIFICATE

I hereby certify that the Project Dissertation entitled “STUDY OF THE BEHAVIOUR OF STONE COLUMN IN LAYERED SOFT SOIL USING PLAXIS 2D”, which is submitted by Sadaf Mir (2K21/GTE/15) of M. Tech (Geotechnical Engineering), Delhi Technological University, Delhi submitted in partial fulfillment of the requirement for the award of Master of Technology, is a record of the project work carried out by the student under my supervision. To the best of my knowledge, this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: Delhi
Date:

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ABSTRACT

The study presents the results of numerical analysis conducted in unit cell configuration to investigate the behavior of stone columns in stratified soils. Specifically, the study focuses on the behavior of stone columns when the upper layer consists of weak soil, while the underlying layer is a relatively stronger firm clay. The thickness of the top weak layer is varied to understand its impact on the performance of the stone columns. Two types of loading conditions were employed in the simulations. In the first condition, the entire area of the unit cell area was loaded to estimate the stiffness of the improved ground. In the second condition, only the stone column was loaded to determine the limiting axial capacity. The simulations were run using a column with a diameter of 88 mm surrounded by layered soil, maintaining an area ratio of 22% (ratio of the area occupied by stone columns to the total area). The study included the influence of the depth of the top weak layer thickness on various aspects, including stiffness, load bearing capacity, and bulging behavior of the stone columns. The findings indicate that the thickness of the top weak layer has a significant influence on the behavior of stone columns. The stiffness, load bearing capacity, and bulging behavior are all affected by the depth of the top weak layer thickness. These results have practical significance in understanding and optimizing the performance of stone columns as an effective and economical ground improvement technique, particularly in soft grounds with layered soil profiles.

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS, ABBREVIATIONS

E	Young's modulus
μ	Poisson's ratio
c_u	Undrained Cohesion
φ	Friction Angle
ψ	Dilatancy Angle
γ_{dry}	Dry Unit Weight
γ_{bulk}	Unit Weight

Contents

CHAPTER 1

INTRODUCTION

1.1 General

The rising expenses associated with traditional foundations and multiple environmental limitations strongly promote the on-site enhancement of unstable soil deposits. Among the large no. of methods available to improve ground conditions in situ, the utilization of stone columns or granular piles for ground reinforcement proves to be highly adaptable and economically advantageous. Stone columns effectively serve the dual purpose of enhancing soil strength and deformation properties, thereby providing reinforcement and facilitating drainage within the soft soil. Stone columns have several beneficial effects on soil behavior. Firstly, they increase the unit weight of the surrounding soil by compacting it during construction, thereby enhancing its overall density. Additionally, stone columns effectively dissipate excess pore pressures that may be generated, promoting rapid drainage. These columns act as robust and rigid elements, enabling them to withstand higher shear stresses. The versatility of stone columns is evident in their application across a wide range of soil types, including loose sands and soft compressible clays. They have been successfully employed in challenging foundation sites worldwide to achieve multiple objectives. Stone columns are utilized to achieve various objectives such as increasing soil bearing capacity, reducing settlements, enhancing consolidation, improving slope stability, and strengthening resistance to liquefaction. They find applications in supporting embankments, raft foundations, liquid storage tanks, and low-rise buildings.

The primary source of a stone column's ability to support weight is the lateral restricting pressure that the soils in the vicinity create. The passive resistance that the surrounding soil offers affects how well the columns operate when they are under load. Usually, the top portion of the column experiences greatest column bulging because of the lowest overburden forces. However, the axial load capacity of stone columns may be constrained by inadequate lateral confinement when they are installed in very soft soils or layered soils with a soft layer existing at the top. This can result in excessive bulging. In reality, the majority of naturally occurring soils contain separate layers or show variety. Therefore, footings are frequently placed on uneven or multi-layered soil profiles. It is very important from a practical standpoint to look at how stone columns behave when they are functioning in stratified soils, especially when the top layer has very low bearing capacity. However, there aren't many experimental studies that look at how well stone columns operate in stratified soils in the literature that is currently available. The goal of the current study is to better understand how stone columns behave in layered soil deposits, especially when a thin, soft clay layer is placed on top of a thicker, more robust soil layer. The study involves a series of simulations run on Plaxis 2D.

The study aims to assess how the depth of the top soft and firm clay layers, along with the area replacement ratio, affect both the overall axial capacity of the upgraded layered soil system and the individual stone column. It is important to note that the analysis does not consider the coupled modeling of time-dependent soil behavior, as the focus is on long-term settlement. Therefore, a drained behavior assumption is made throughout the analysis. Additionally, this analysis does not include a model of the stone column's production process.

The study examines the effects of different area replacement ratios on the bulging of the stone column, the overall stiffness of the improved ground, and the axial capacity limit of the stone column. This study employs the concept of a unit cell to isolate and analyze the behavior of a single stone column within a two-layered soil system. By separating the single column from the larger group of stone columns, the study focuses on understanding its specific behavior and response within the given soil layers.

1.2 Introduction to Finite Element Analysis

The finite element method (FEM) is a numerical approach used to solve complex physical problems by approximating the solutions of partial differential equations (PDEs). Analytical solutions are often not possible for most geometries and scenarios, so we rely on discretization methods and numerical techniques.

The FEM breaks down the problem domain into smaller, finite elements. Each element is described by simpler equations, allowing us to analyze their behavior. By combining these element equations, we form a system of algebraic equations that can be solved numerically to obtain an approximate solution to the original PDEs.

The FEM offers several advantages, such as handling complex geometries and incorporating various boundary conditions and material properties. It also allows for localized refinement to improve accuracy in specific regions.

However, it's crucial to understand that the solutions obtained through FEM are approximations. The accuracy depends on factors like element size, approximation order, and convergence of the numerical method. Nevertheless, with appropriate refinement and convergence criteria, the FEM provides reliable and accurate solutions for a wide range of engineering and scientific problems.

1.3 Different Ways to Model in Plaxis 2D

PLAXIS 2D supports two main conditions for modelling geotechnical projects.

1.3.1 Plane Strain

In practical terms, the concept of plane strain assumes that you are working with a cross-section that extends infinitely in the out-of-plane direction.

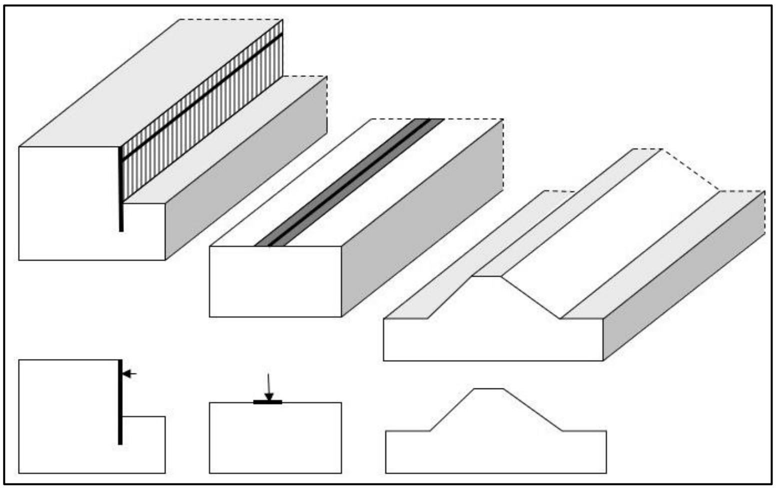


Figure 1 Plain Strain Modelling (Source: https://communities.bentley.com)

1.3.2 Axisymmetric

In the context of axisymmetric conditions, the modeling assumption is that you are considering a slice or sector of a structure or system that spans 1 radian (or a fraction of a complete circle). This means that the model is extending in a circular manner around a central axis.

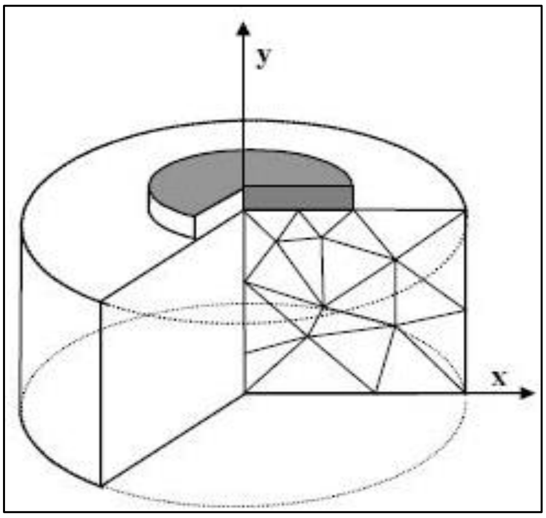


Figure 2 Axisymmetric Modelling (Source: https://communities.bentley.com)

1.4 Motivation of Present Study and Problem Statement

The Central University of Kashmir (cukashmir), formerly known as the Central University of Jammu and Kashmir, is a central university situated in the Ganderbal district of Jammu and Kashmir, India. Its approximate geographic coordinates are 34° 14′ 0.56″ N and 74° 43′ 35.14″ E. The institution was founded in March 2009 under the "The Central Universities Act, 2009" passed by the Government of India. It commenced its operations in May 2009.

Currently, the university functions across four campuses in the Ganderbal district. The Science Campus in Nunar, the Science and Arts Campus at the Old Hospital Building in Ganderbal, and the Main Campus at Tulmulla are a few among these.

Tulmulla's Main Campus sprawls across an expansive landmass exceeding 500 acres, with ongoing construction work on various buildings.The university administration has often attributed the construction delays to the perceived "poor land and soil quality" at Tulmulla.

The foundation work has finally been completed only this year after reinforcing it with stone columns. In this age of advancement, this delay shouldn’t have happened. After going through the reports of geo-technological testing that was done over the years, it is seen that the top soil at the site is soft and marshy with a firmer layer underneath. As the soil is unpredictable even at extremely short distances from a test location, a complete study of the behaviour will get easier with the use of modelling softwares.

From the experimental data collected from the testing agencies and also from NIT Srinagar, representative soil parameters for the stratified ground are chosen to simulate the condition and study the behaviour of stone column in this site. Proper analysis using FEM can aid the designers to better understand the problems and estimate the reduction in settlements after installation of the stone column.

Figure 3 Picture showing the problematic soil of the study area

1.5 Various Stages Involved in the Study

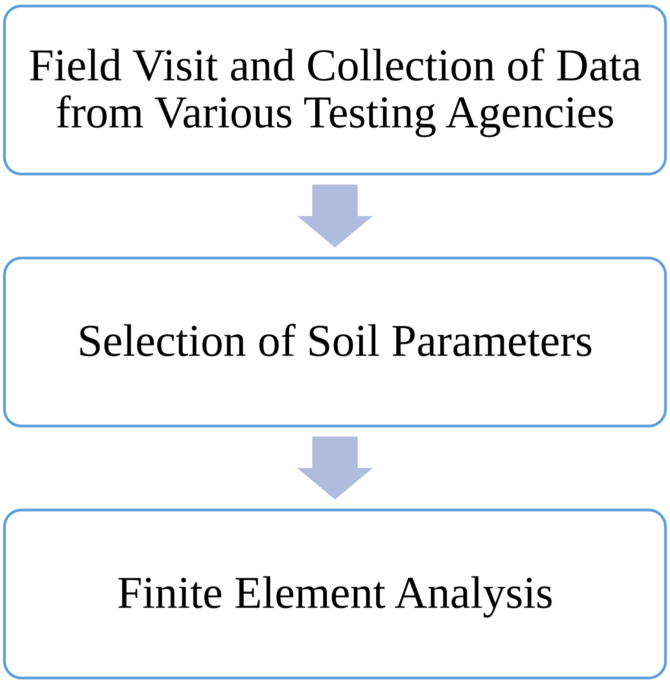


Figure 4 Stages involved in the Study

1.6 Objectives of the Study

1. To select the geotechnical parameters of the site.
2. To model a stone column in the stratified soil and analyse it numerically.
3. To study the behaviour of stone column in layered soils with weak soft clay at the top having varied thickness and firm clay underneath it.

1.7 Organisation of the Thesis

Chapter 2 discusses the literature review relevant to the present work and research gaps found. Chapter 3 discusses the methodology, materials and boundary conditions. Chapter 4 is about validation and convergence. Chapter 5 discusses the results. Chapter 6 enlists the conclusions made.

CHAPTER 2

2.1 LITERATURE REVIEW

Balaam and Brooker [1], Proposed solutions have been presented to address the challenges posed by large-scale foundations with stiffness and settling issues, which are supported by soil that has been reinforced using granular piles. The settlement of the foundation was resolved through an analytical approach utilizing the principles of elasticity theory. Formulas were derived to facilitate the calculation of moment and shear distributions across the foundation. The two common pile layouts (square and triangular) that are employed in practice have been thoroughly examined. Each pile of soil in these layouts has a square or a hexagonal plan. Through the application of finite element analysis to assess settlement, coupled with the development of formulas for moments and shears within square and hexagonal domains of influence, the feasibility of considering this area as an equivalent circular region has been investigated. The findings indicate that by assuming a similar circular area, the discrepancies in stress distribution (and consequently settlement) are negligible, suggesting a reasonable level of accuracy.

Ambily and Gandhi [2], conducted comprehensive experimental investigation to study the behavior of both individual and grouped columns. Various parameters, such as column spacing, shear strength of the soft soil layer, and the condition of loading, were carefully adjusted during the experiments. In the laboratory, column with a diameter 100mm confined by soft clay of different densities was subjected to testing. To evaluate the stiffness of the composite ground, tests were conducted on either the complete equivalent area loading or only a single column loaded. In the group experiments, pressure cells were installed on the loading plate to accurately measure the stress on both the column and the confining clay. Finite-element calculations using triangular elements of 15 nodes were performed using the PLAXIS program. The analysis carried out was drained, applying the Mohr-Coulomb criterion for the soft clay, stones, and sand. Results obtained from the finite element method (FEM) exhibited good agreement when compared to the experimental data. It was observed that column spacing greater than three times the column diameter did not significantly improve the situation.

McCabe et al. [3], conducted a comprehensive study where they thoroughly examined and evaluated the field characteristics of stone columns in soft clays and silts. They utilized both published and unpublished data to analyze the behavior of these columns under different load conditions, including large-scale scenarios like embankments and small-scale scenarios like footings. Their research aimed to provide a thorough understanding of performance of stone columns in various soil types and loading conditions. The study demonstrates the reliability of a well-established analytical technique and establishes a clear differentiation between preferred dry bottom-feed system performance and other methods of construction of the column. This distinction is made possible through the creation of a new database comprising settlement improvement elements. Based on the results, it can be predicted that construction of stone columns will result in a permanent increase in undrained shear strengths, provided that adequate construction standards are followed. While higher-precision measurements are necessary for enhanced confidence, it is observed that the installation process leads to an augmentation of lateral effective stresses in the vicinity of the column. The existing literature lacks comprehensive and reliable information regarding certain facets of stone column behavior in soft cohesive soils. Specifically, there is a scarcity of data regarding the stress distribution that is present between the soil and stone, the prolonged alterations in lateral effective stress caused by construction of column, and the effects on prolonged creep settlements. Moreover, most of available data pertains to heavily loaded sites rather than strip or pad footings. To further our understanding of the factors influencing stone column behavior, there is a pressing need for high-quality instrumented field tests that can provide valuable insights into these variables.

Black et al. [4], conducted experiments using triaxial specimens measuring 400 mm in height and 300 mm in diameter. This study explored several variables, including the ratio of column length to diameter, the area replacement ratio, and the configuration of single or multiple columns. This research yielded several important conclusions. Settlement can be effectively managed by modifying the design, either by using shorter columns with higher area replacement ratios or longer columns with reduced area replacement ratios. The ideal range for area replacement ratio, in order to regulate settlement, was found to be between 30 and 40 percent. The performance of tiny column groups during loading was significantly impacted by the interaction between nearby columns and the footing. It was observed that both shorter columns with greater replacement ratios and longer columns with lesser area replacement ratios effectively managed settlement. Furthermore, it was shown that the interaction between the structure and the soil was vital in limiting excessive column deformations. When compared to isolated columns, it was discovered that the small-group configuration's block mechanism and higher localised stress within the confined soil were harmful to settlement. These findings have the potential to greatly enhance current design practices; however, further model and field trials, as well as parametric numerical evaluations, are needed to validate these results.

Shivashankar et al. [5], carried out a series of laboratory plate load tests to examine response of stone columns in layered soils. These soils comprised a weaker soft clay layer overlaying a stronger silty soil layer. The tests were conducted using unit-cell tanks. The thickness of the top layer was varied to examine its influence on the effectiveness of the stone columns. Two loading scenarios were employed during the tests: loading the entire unit-cell tank to evaluate stiffness of the composite ground, and loading only the stone column to assess its limiting axial capacity. The laboratory testing focused on a column of 90 mm diameter having an area ratio of 15%. The results of the study showed that the stiffness, load-carrying ability, and bulging behaviour of the stone columns are all considerably influenced by the thickness of the weak top layer.

Das and Pal [6], conducted a study focusing on the utilization of stone columns to enhance the load-carrying capacity of naturally consolidated sandy silt soil containing clay. The study involved subjecting single, unencased stone columns to compression testing loads in the sandy silt soil with clay, where the soil composition consisted of approximately 37.29% sand, 33.00% silt, and 29.71% clay. The study also examined the behaviour of both unencased and geotextile-encased stone columns in layered soil situations. For unencased stone columns, the load-carrying capacity increased as the diameter of the stone column expanded. However, for both unencased and encased layered soil columns, the load-carrying capacity decreased as diameter of the stone column increased. The stone column diameter was found to have an impact on its ability to support weight in both unencased and encased layered soil conditions.

Ng and Tan [7], introduced a practical and effective method called the Equivalent Column Method (ECM) to predict the consolidation behavior of improved ground with stone columns. The ECM utilizes a homogenization technique to simulate the behavior of composite ground by determining equivalent material properties. While existing homogenization procedures based on elasto-plastic behavior of composition materials can be challenging for practical engineers, modifications are required in terms of finite element constitutive models. This novel technique provides equivalent stiffness for the materials that are composite in nature and also ensures similar permeability. The approach involves analyzing a unit cell model in a 2D axi-symmetrical configuration. By comparing the results with those obtained using a common general composite stiffness for the enhanced ground, the settlement is quantified, and a correction factor has been determined. Design charts are provided to summarize the correlations between important parameters such as the area replacement ratio, friction angle and load intensity of the material of column. Furthermore, a design chart is developed to estimate the equivalent permeability for different permeability ratios through a series of soft tests with varying area replacement ratios. ECM exhibits good agreement with existing design methodologies and field observations. In addition to its capability to accurately predict consolidation time, the proposed method offers the advantage of ease of application, simplifying the modeling setup in finite element programs, particularly for embankments and large-scale tank problems. Ng and Tan's study focuses on the distribution of stress mechanism within a unit cell under embankment loading. The main aspects examined in this research include the deformation mode, arching stress, stress concentration ratio, and plastic straining within the unit cell. Software tool PLAXIS was utilized for finite element analysis to investigate these characteristics. Both two-dimensional (2D) axi-symmetrical models and representative three-dimensional models were simulated to study the cell unit. The analysis specifically considered the drained loading condition, where the gradual construction of the embankment was assumed without the build-up of excess pore pressure. This study explored how the ratio of stress concentration changed with exceeding embankment height. It was observed that bulging occurred near the column top, followed by the development of shear bands moving down the column. The stone column within the unit cell typically carried around four to five times greater loads compared to the adjacent soils along the depth of the column. Comparing the results obtained from the 2D and 3D models, it was found that for most cases, they showed similar settlement performance and failure mechanisms. The outcomes from both types of models were consistent, supporting the validity of the findings regarding settlement behavior and failure mechanisms.

Mohanty and Samanta [8], conducted a study that summarizes the findings from small-scale laboratory investigations and numerical calculations on the influence of soil stratification on response of stone column and stone column improved ground. Two different layering systems were considered: soft clay on top of stiff clay and vice versa. The laboratory experiments involved 88 mm diameter stone columns installed in a two-layered stratified soil system. The behavior of one column within an unlimited group of stone columns was analyzed using unit cell concept. Both the whole unit cell and only the stone column region have been subjected to loading to compare the stress-settlement responses of overall improved composite ground and the stone column alone. Laboratory tests were conducted to study the effect of the stiffness and softness of the top clay layer on the axial tension of the entire enhanced composite ground and the individual stone column. Additionally, a comprehensive parametric analysis was carried out using the Plaxis finite element program. For the soil and stone columns under drained conditions, the elastic-perfectly plastic Mohr-Coulomb failure criterion was used in the numerical analyses. The numerical analysis aimed to simulate the behavior of the stone columns and evaluate the stress and settlement responses. Overall, this study provides useful insights into the behavior of stone columns and stone column improved ground under different soil layering conditions through a combination of laboratory experiments and numerical analysis using Plaxis finite element program. According to the study's findings, the stone column's limiting axial stress is affected by the extent of the top clay stratum only up to a specific diameter. Limiting axial stress for both stacking techniques is constant beyond that diameter. Furthermore, it was discovered that for both layering techniques, the top layer affects the limiting axial stress of the entire enhanced ground up to a depth that is four times the diameter of the stone column. Additionally, as the depth of the top soft clay layer grows, the stiffness improvement measured is the higher quality ground rises until it achieves its highest level. But regardless of the extent that the top stiff clay layer is, this element is constant. The study also discovered that for both layering systems, the vertical extent of bulging grows up to double the diameter of the stone column as the amount of thickness of top soft clay stratum increases. These outcomes give important new understanding of how stone pillars behave and how soil layering affects how well they operate, especially in terms of vertical stress, stiffness enhancement, and expanding features.

Ng and Tan [9], suggested a novel mechanical approach to take into account the yielding effect within the plastic zone and introduced the concept of optimal length. Currently, the available methods for evaluating the performance of settling of a footing on a finite number of columns of stone have generally been based on mainly empirical or approximate techniques based on elastic theory. The proposed strategy can be applied to both homogeneous and non-homogeneous ground conditions. The accuracy of settlement generated by this method were compared to the results obtained from finite element simulations and field measurements. This comparison demonstrated good agreement in terms of the displacement profile and the load settling response. This innovative approach offers a more accurate and reliable method for assessing settlement performance when using a finite number of stone columns. By considering the yielding effect and incorporating the concept of optimal length, the proposed method improves upon existing empirical and approximate techniques. The validation through comparison with finite element simulations and field measurements further supports the effectiveness of this approach in predicting settlement behavior.

Madun et al. **[10]**, introduced a methodology to optimize settlement and bearing capacity of soft clay by optimizing column diameters and lengths using the response surface methodology (RSM) program. The study involved load testing using numerical modeling with Plaxis 2D on a loading plate with a diameter of 66 mm. The results depicted that enhancing both the diameter and length of a stone column resulted in an increase in its load-bearing capacity and decrease in settlement. Specifically, longer column lengths were found to reduce soil settling, while increasing the column diameter was associated with increased load-bearing capacity.To further enhance the design, the researchers proposed altering the ideal stone column design separately for the diameter and length factors. By optimizing these parameters individually, it was possible to achieve improved load-bearing capacity and minimize settlement, thereby enhancing the production of the columns of stone in soft clay conditions.The utilization of the response surface methodology (RSM) program provided a systematic approach to optimize the effects of column diameters and lengths on load-bearing capacity and settlement. By considering these factors and their respective impacts on soft clay behavior, more efficient and effective stone column designs can be achieved, leading to improved performance in terms of load-bearing capacity and settlement reduction.

Gaber et al. [11], conducted a study comparing the performance of a stone column modeled as a unit cell using plain strain modelling with the help of the finite element program PLAXIS-2D-V8.2. The study concentrated on measuring the soft soil's undrained cohesiveness, the friction angle of the stone column material, and the diameter and center-to-centre spacing of the stone columns. This parametric study's major focus was on settlement improvement factor and excess pore water pressure, two crucial design factors for stone columns. The researchers aimed to compare the improvement in settlement and excess pore water pressure results obtained from the two modeling approaches. The primary conclusion of the study was that the settlement was significantly improved in the planar strain model compared to the unit cell model. In contrast to the unit cell model, where settlement improvement factor did not surpass 1.53, the planar strain model's ranged from 2.2 to 3.2. These results were contrasted with theoretical justifications frequently employed in research on the behaviour of stone columns. Furthermore, the study noted that the excess pore water pressure had a smaller peak value in the unit cell model compared to the model employing plain strain conditions. This indicates that the planar strain model exhibited higher excess pore water pressure, suggesting a potentially larger influence on the overall soil behavior. Overall, the study demonstrates how the unit cell and planar strain models for stone columns differ in terms of settlement improvement and surplus pore water pressure. These findings contribute to the understanding of the behavior of stone columns and provide insights for their design and analysis.

Ng [12], examined the load carrying capacity of a single stone column in a study employing three-dimensional numerical analysis. The study focused on identifying failure modes and examining the influence of key factors like the modular ratio, undrained soil shear strength, and column friction angle. Based on the numerical analysis, the study identified two main failure mechanisms for the single stone column: bulging and a combination of bulging and punching. These failure modes occur depending on various factors and conditions. The final bearing capacity was found to be most significantly influenced by the column’s friction angle and the soil's undrained shear strength. These parameters played a crucial role in determining the failure modes and overall performance of stone column. The study also highlighted that a single stone column with the same length could exhibit different failure modes, including bulging, punching, or a combination of both. The specific failure mode observed depended largely on the angle of friction value of the column, while modular ratio and surrounding soil’s shear strength had comparatively lesser effects. Overall, this study highlights the significance of variables like friction angle, undrained shear strength, and modular ratio in affecting single stone column behaviour, bearing capacity, and failure mechanisms. The findings contribute to the understanding of stone column behavior and can assist in the design and analysis of such systems.

Nayak et al. [13], conducted tests to study the behaviour of stone columns with various thicknesses of clayey silt soil (lithomargic clay) present at the bottom and lateritic soil present at the top. The lateritic layers had thicknesses ranging from 1D to 5D (D denoting the diameter of the stone column). This study focused on comparing different configurations, including standard stone columns, geogrid-encased columns, and geogrid-encased columns with an additional horizontal reinforcement layer known as the basal layer. Laboratory experiments were carried out on untreated soils and a layered mixture of lithomargic clay and lateritic soil. Using a unit cell configuration, the tests were carried out on a floating stone column with a diameter of 60 mm. The findings demonstrated that the buildup of lateritic soil layers had a negative impact on the stone column's load carrying capacity and bulging characteristics. The presence of encasement, such as geogrid wrapping, improved the load capacity and reduced the bulging in the stone column. The addition of a second horizontal reinforcing layer, known as the "basal layer," also had a substantial effect on the stone column's ability to support its weight. To model and analyze these experiments, the PLAXIS 2D software suite was utilized. This allowed for a numerical assessment of the behavior of the stone columns under different configurations and soil layering conditions. Overall, the study shed light on how soil layering, encasing, and extra reinforcement affect stone column load capacity and bulging behaviour. The findings contribute to the understanding of stone column performance and can aid in the design and optimization of such systems in similar soil conditions.

Hamzh et al. **[14]**, undertook a study focused on the design of stone columns with irregular diameters in order to enhance the carrying capacity of soft soil. The goal was to offer design advice that could decrease the amount of stone needed to build the stone column while boosting the soil's carrying capability. Using two-dimensional Finite Element analysis with PLAXIS 2D, determination of the bearing capacity of regular and irregular shaped stone columns in soft soil. A Mohr-Coulomb constitutive soil model was used in the numerical analysis. In the study, stone columns of non-uniform geometry were modeled with two different diameters and lengths. With tested diameter ratios of d_2:d_1 of 1:2, 1:4, and 1:5, the upper diameter was consistently bigger than the bottom half diameter. Ten-meter-long columns with nine distinct length-to-width ratios (l_1:l_2) were used. The study intended to find the best column design by contrasting uniform and non-uniform column shapes. The results showed that the non-uniform stone column with a top and bottom diameter ratio of 1:5 exhibited the highest bearing capacity. Additionally, the most cost-effective shape for the stone column, which utilized the least amount of volume, was achieved with l_1:l_2 = 3:7 and d_2:d_1 = 1:2. The study's findings offer insightful information for designing stone columns with uneven diameters to optimize their bearing capacity and cost-effectiveness in soft soil conditions. These insights can aid in the efficient utilization of construction materials and enhance the performance of stone column foundations.

Naseer et al. [15], presented a research to study the impact of floating columns on clayey soil with silty deposits. The research focused on the impact of sand columns on soils with varying shear strengths and column slenderness ratios. The study also examined the influence of column spacing on the group effect. Small-scale laboratory models were utilized to conduct the experiments, and the results were compared with numerical analyses. The numerical analysis was executed using the finite element program PLAXIS 2D, employing a 15-node triangular mesh. The undrained analysis was conducted for soft clay, while the drained analysis was carried out for sand columns, utilizing Mohr-Coulomb's criterion. The study showed that the ultimate loading capacity of soft soils can be greatly increased by the presence of sand columns. It was seen that the critical length for floating columns is between 4 and 5.5 times their diameter. Beyond this critical length, bulging occurs and a decrease in loading capacity occur. The influence of column spacing within the group was also investigated. The findings showed that the effectiveness of the group decreases with increased spacing between the sand columns. Axial capacity of the columns diminishes as the distance between the columns rises. The behaviour of floating columns is studied when they have been installed in clayey soil with silty deposits. The findings highlight the potential benefits of using sand columns to enhance the load-bearing capacity of soft soils. Additionally, this study emphasizes the importance of considering the critical length of floating columns and the spacing between columns in optimizing their performance.

Farah and Nalbantoglu [16], did a study to examine the behavior of both encased and unencased floating stone columns on soft soils. While previous research has extensively investigated stone columns constructed on base of different layers of soil, behavior of stone columns on a single-layered soil base has received less attention. In this work, laboratory pilot tests at small scale were carried out to examine how homogeneous soft soil and layered soil with loose sand on top of the soft soil behaved. The goal was to assess how stone columns affected the axial strength of the soft soil. In all cases where stone columns were implemented, the bearing capacity of the soft soil was found to increase. To measure the impact of stone columns on the soft soil's ability to support loads, the study coined the term "bearing improvement ratio" (BIR). The BIR was approximately 3.3-fold for stone columns that are not encased in single-layered soft soil and increased to 3.4-fold when stone columns are encased with geotextiles in the same soil deposit. BIR for stone columns that are encased in layered soils further increased to 4.0-fold when geotextile reinforcement was added, compared to approximately 2.0-fold without reinforcement. The use of geotextiles helped distribute the induced stresses over a wider area, thereby increasing the bearing capacity of the soft soil. This study also examined the bulging behavior of the stone columns. Non-encased stone columns in homogeneous soft soil exhibited the greatest bulging at a depth 1.5 times their original diameter from ground level, while encased stone columns in homogeneous soft soil experienced the greatest bulging at a depth 3.0 times their original diameter from the top. Overall, this study's findings add to our understanding of how stone columns behave on soft soils. The results highlight the potential of stone columns, both encased and unencased, to enhance the bearing capacity of single-layered soft soil and layered soils. The addition of geotextiles in encased stone columns was found to enhance the bearing capacity further.

Saxena and Roy [17], conducted a non-linear analysis of a single stone column buried in a semi-infinite sandy soil medium. This research aimed to identify the significant factors influencing stone column bulging failure and settlement characteristics. Based on their settlement patterns, 2 different natural aggregates -crushed pebble gravels and pebble gravels—were assessed for their appropriateness as components for stone columns. The study utilized 2D numerical modeling and the PLAXIS program. With the increasing demand for ground improvement using stone columns, various types of natural aggregates were incorporated into the stone columns. On comparing the load-settlement response of pebble gravels and crushed pebble gravels, the relative settlement and deformation were found to be less pronounced for case of the crushed pebble gravels. This indicates that crushed pebble gravel is a more effective material for the stone columns in soft soils. The research also revealed that an enhancement in the angle of internal friction led to a reduced tendency of the stone columns to settle under load. Furthermore, the settlement of the stone column decreased as undrained cohesiveness of the surrounding clay increased. Additionally, the stone column settlement decreased as the slenderness ratio (L/D ratio) increased, and beyond an L/D ratio of four, there was no substantial change observed in the load-settlement curve of the stone column. This study emphasizes the applicability of crushed pebble gravels as an efficient material for stone columns in soft soils and offers insightful information about how stone columns behave in sandy soil overall. The findings emphasize the influence of factors such as internal friction angle, undrained cohesiveness, and slenderness ratio on the settlement characteristics of stone columns.

Kiruthika et al. [18], conducted a study using 3D finite element analysis in order to verify the effectiveness of a representative unit cell with homogeneous and multi-layered soil profiles. Settlement, stress concentration ratio and horizontal deformation, were the main performance metrics in this study. The findings of the study demonstrated that the arrangement of the layers of soft soil and their relative stiffness levels significantly influenced the stress concentration ratio and the level of bulging in multi-layered stratification profiles. In homogeneous soil profiles, bulging, which refers to horizontal deformation at the column edge, occurred more frequently in the range of 2.5 times d to 4.5 times d near the ground surface. Vertical deformations of the stone column in both homogeneous and multilayered soil profiles matched those of the confining soil, indicating strain compatibility. For multilayered soil profiles, the maximum vertical deformation observed in the unit cell was 314 mm. These findings provide insights into the stone column behaviour in both homogeneous and multi-layered soil profiles, particularly regarding settlement, horizontal deformation, and stress concentration ratio. Understanding these aspects is crucial for designing effective ground improvement strategies using stone columns.

2.2 Research Gaps

After going through a detailed research literature available on the numerical analysis of stone columns, the following research gaps are observed:

- There is not enough understanding of the performance of stone column in stratified soft soil.
- Not enough studies to validate the application of numerical modeling techniques in stratified layers for analysis purposes.
- Less practical use of numerical analysis in the field due to less research data available.

CHAPTER 3
MATERIALS AND METHODS

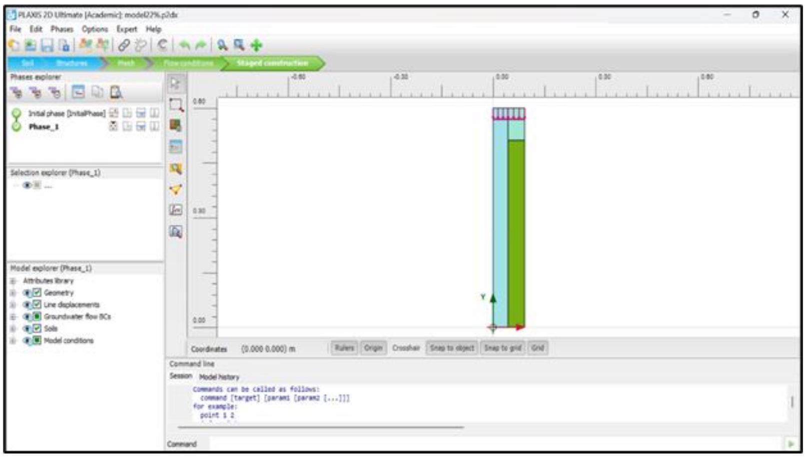
3.1 Numerical Modelling

The analysis approach used in studying the behavior of soft clay, firm clay, and stones is under axisymmetric conditions. The Mohr-Coulomb criterion, which is commonly used to model the elasto-plastic behavior of soils, was employed in the simulations. The assumption of drained behavior means that excess pore water pressure dissipation was considered in the analysis. Sufficient time was allowed for the stress concentration and settlement to stabilize after the load application. The initial vertical stress resulting from the gravitational load was taken into account in the analysis. However, the stress induced during the installation of the column, which is dependent on the construction method, was not considered in these analyses.

The input parameters, including E (Young's modulus), μ (Poisson's ratio), c_u (undrained cohesion), ψ (dilatancy angle), φ (friction angle), and γ_{dry} (dry unit weight), are provided in Table 1. To simulate the behavior of the system, a basic finite element mesh was created using axi-symmetric modeling. The mesh consisted of fifteen-noded triangular elements, which were employed to create proper meshing of the system. To accurately represent the system's behavior, appropriate boundary conditions were applied. Specifically, radial deformation along the sample periphery, which corresponds to the interface between the stratified clay and the unit cell’s cylindrical surface, was constrained, while settlement was allowed. Across the bottom of the tank, radial deformation as well as settlement were not allowed, indicating a fixed boundary condition at that location. These boundary conditions were selected to ensure the model captures the realistic behavior of the system during the analysis.

At the junction, interface elements are not utilized between the stone column and soft soil due to the predominant radial bulging deformation with minimal shear involved in the column. The interface zone between the stone column and stratified soil is characterized by varying shear strength properties that can be influenced by the method of installation. Owing to the uncertainty associated with these properties, the decision was made to refrain from incorporating interface elements in the analysis.

Consistency was maintained in the soil model dimensions throughout the simulations, with a size of 600mm × 600mm. The single column featured a diameter of 88mm, spanning the entire length of the specimen. This configuration was crucial in achieving an L/D ratio exceeding 4.5, ensuring the development of the complete limiting axial stress on the column [4].



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Commands can be called as follows:
  command [target] [param1 [param2 [...]]]
for example:
  point 1 2
```

Figure 5 Plaxis Interface with a Model having 1D Soft Clay over Firm Clay

Table 1 Properties of Materials Used in the Study

	Materials		
Properties	Soft Clay [20]	Firm Clay [20]	Stone [8]
E (kPa)	1500	5000	50,000
μ	0.4	0.35	0.3
c_u (kPa)	15	25	0
φ°	0	15	42
ψ°	0	0	12
γ_{dry} (kN/m^3)	17.8	19	16.2
γ_{bulk} (kN/m^3)	13.2	14.47	16.2

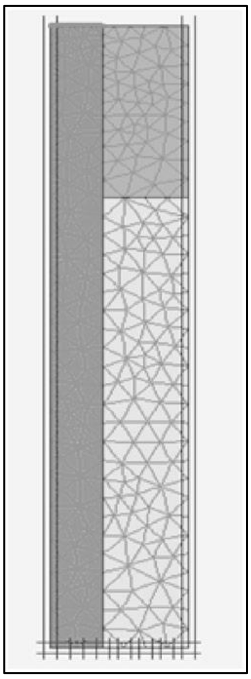

Figure 6 Boundary Conditions – At Bottom, Radial and Vertical Deformation = 0 and at lateral periphery, only Radial Deformation = 0

3.2 Codal Provision [19]

The specifications and calculations in this study adhere to the guidelines outlined in IS 15284(Part 1):2003 [19]. A triangular pattern of arrangement of the stone columns has been decided to be followed at the site, with each column having a diameter of 88mm. To achieve area replacement ratio of 22%, spacing between columns needs to be maintained at 176.2mm. This has been calculated using

$$a_s = 0.907\ (D/S)^2 \qquad (1)$$

where the constant 0.907 is a function of the arrangement, which is triangular for this case [19].

The formula for the calculation of equivalent diameter is

$$d_e = 1.03S \qquad (2)$$

with d_e = equivalent diameter of single column and S = spacing between columns [19].

Based on the given equation, the calculation results in an equivalent diameter of 185mm for a single column, considering the specified area replacement ratio.

Figure 7 Markings for Triangular Arrangement of Stone Columns at the Site

Figure 8 Installing the Stone Columns

CHAPTER 4
VALIDATION AND CONVERGENCE

4.1 Validation

Validation was done using a model by Naseer et al. [15]. In a cylindrical tank with a diameter of 300mm, one column measuring 37mm in diameter and 150mm in length was tested. To achieve a settlement of 30mm, a continuous load is applied at a rate of 0.025 MN/min. In this instance, the load was applied to the entire sample. In the illustration, a schematic diagram is shown. The author and the current modelling results agree nicely.

Table 2 Material Properties used by Naseer et al. [15]

Parameters	Soft Soil	Sand
E (kPa)	4610	25000
μ	0.4	0.3
c_u (kPa)	54	0
$\varphi°$	0	30
$\psi°$	0	1
γ_{dry} (kN/m^3)	14.4	15.5
γ_{bulk} (kN/m^3)	18.87	15.5

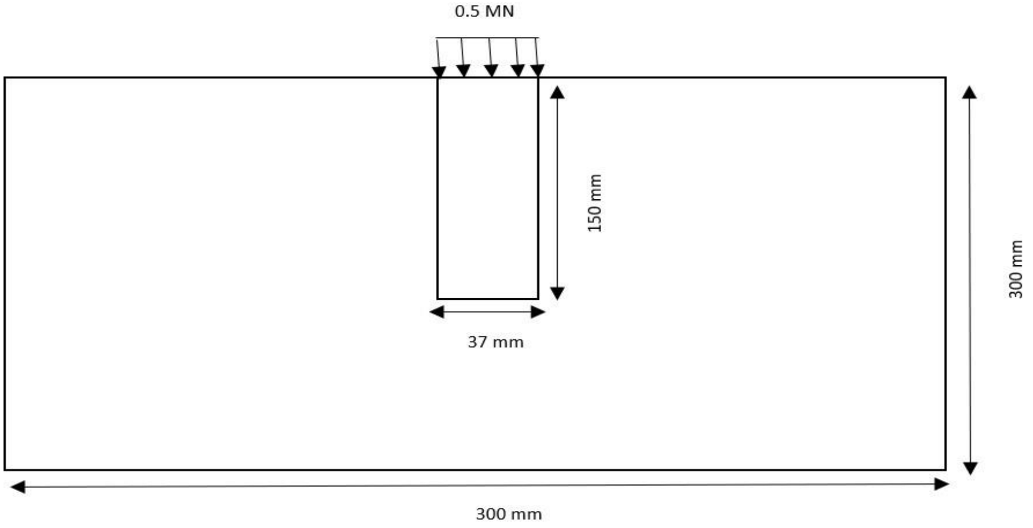

Figure 7 Test Set-Up

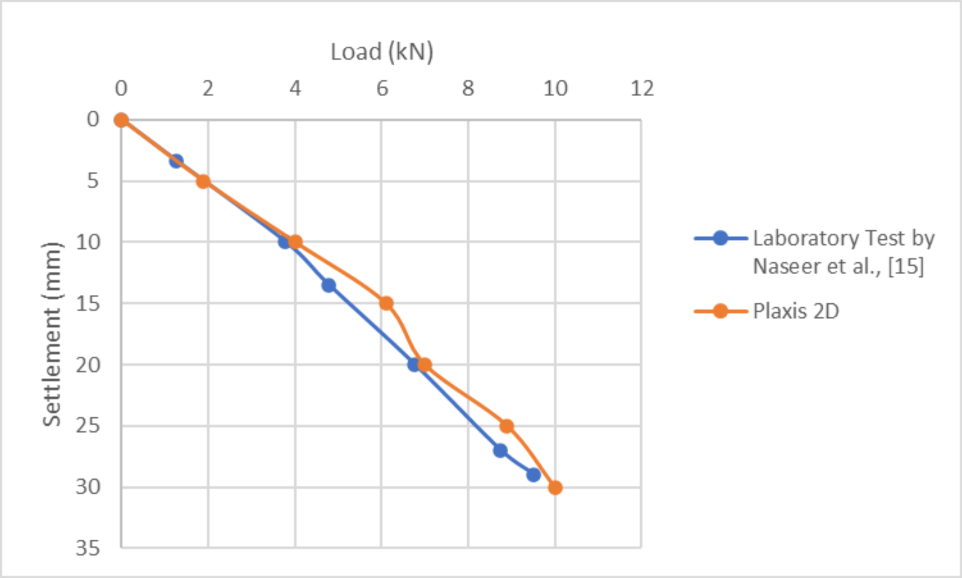

Figure 9 Validation

4.2 Convergence

The convergence analysis of mesh indicates that the increase in the number of elements above 250 has no substantial effect on the settlement response of analyzed geometry. Therefore, for all the numerical calculations, a range of 250-300 elements with an average element size of 7×10^{-3} m or smaller has been utilized.

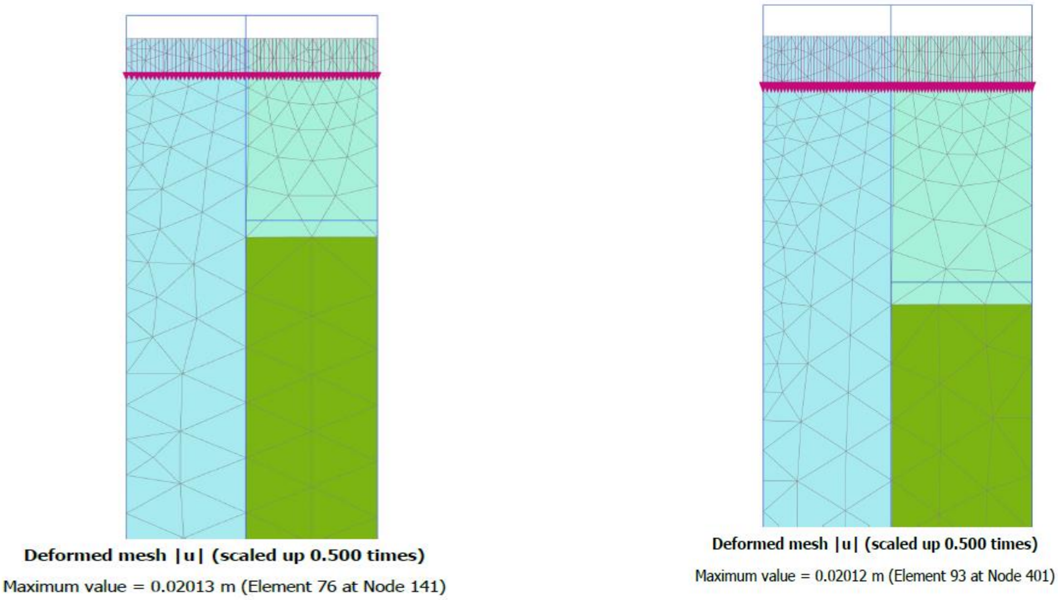

Figure 10 Small variations in deformation calculation seen in changing the setting from fine to very fine. Thus fine mesh is used in the analysis without much error.

CHAPTER 5
RESULTS AND DISCUSSION

5.1 Behaviour of Ground Before Treatment

The figure 11 depicts the settlement behavior of untreated ground under applied loads, considering various soft top layer thicknesses ranging from (1 to 4)D. The ability of untreated ground to support loads declines as the top soft soil layer gets thicker. The ability of untreated ground to support loads declines as the top soft soil layer gets thicker. The calculations are given in table. Specifically, for a 20 mm settlement, the load carrying capacity reduction is 21%, 35%, 44%, and 50% for layer thicknesses of ranging from 0D (i.e., no soft layer) to 4D respectively, compared to the load carrying capacity of the firmer soil (bottom layer soil) alone. The load carrying capacity ratio (LCR) is used in the table to quantify how much the top soft layer reduces the untreated ground's ability to support loads. The load bearing capacity ratio, or LCR, is the comparison of the layered ground's capacity to that of the homogenous ground (silty soil). The table demonstrates that with the increase in depth of the top soft layer, the LCR decreases.

Table 3 Load Intensity Calculations for Untreated Layered Ground

	Homogeneous Soft Clay		1D Soft Layer		2D Soft Layer		3D Soft Layer		4D Soft Layer		Homogeneous Stiff Clay	
Settlement (mm)	Load kN/rad	Load Intensity (kPa)	Load kN/rad	Load Intensity (kPa)	Load kN/rad	Load Intensity (kPa)	Load kN/rad	Load Intensity (kPa)	Load kN/rad	Load Intensity (kPa)	Load kN/rad	Load Intensity (kPa)
0	0	0	0	0	0	0	0	0	0	0	0	0
10	0.229	53.52812272	0.462	107.9912345	0.395	92.33016801	0.344	80.409057771	0.304	71.05916728	0.572	133.7034332
20	0.436	101.9138057	0.894	208.9700511	0.742	173.4404675	0.639	149.3644996	0.565	132.0672023	1.144	267.4068663

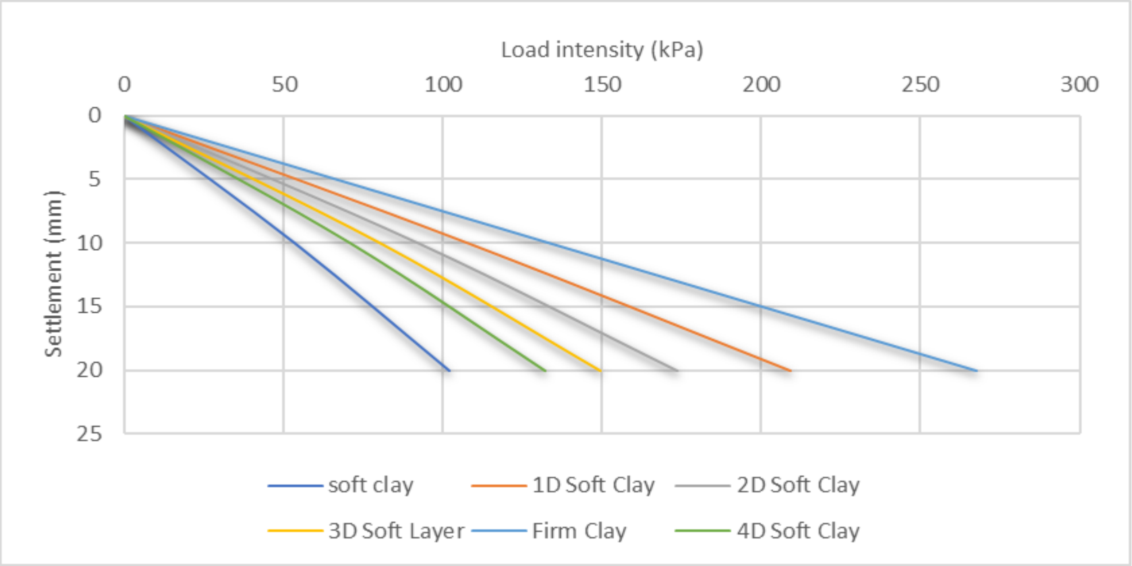

Figure 11 Load settlement curve for untreated ground for entire unit cell loading

Table 4 LCR Values for Untreated Ground

Top Soil Thickness	LCR
0D	1
1D	0.78
2D	0.65
3D	0.56
4D	0.5

5.2 Behavior of Treated Ground with Stone Column

The presence of the soft clay layer at the top has a significant impact on the limiting axial stress of the improved layered composite soil. Table shows the calculations for the limiting axial stress after stone column installation. These simulations aimed to assess the effectiveness of treating the ground with stone columns by evaluating improvements in stiffness and reductions in settlement compared to untreated ground. To accurately reflect field circumstances, the unit cell's whole surface area was loaded. This aids in figuring out the effectiveness of the treated ground and how well placement of the stone columns increased load-bearing capacity and reduced settling.

Table 5 Load Intensity Calculations For Different Thicknesses of Top Soft Layer For Stone Column Treated Ground

	Stiff		1D		2D		3D		4D		Soft	
Settlement (mm)	Load (kN/rad)	Intensity (kPa)	Load (kN/rad)	Intensity (kPa)	Load (kN/rad)	Intensity (kPa)	Load (kN/rad)	Intensity (kPa)	Load (kN/rad)	Intensity (kPa)	Load (kN/rad)	Intensity (kPa)
0	0	0	0	0	0	0	0	0	0	0	0	0
5	0.594	138.8458729	0.49	114.5361578	0.46	107.52374	0.404	94.43389335	0.329	76.90284879	0.289	67.55295836
10	1.066	249.17458	0.96	224.3973703	0.876	204.7626004	0.748	174.8429511	0.643	150.2994887	0.543	126.9247626
15	1.606	375.3981008	1.447	338.2322863	1.272	297.3265157	1.128	263.6669102	0.996	232.8122717	0.794	185.5953251

Figure 12 illustrates the load-settlement response of improved ground for an 88mm dia stone column using various top layer thicknesses and an area ratio of 22%.

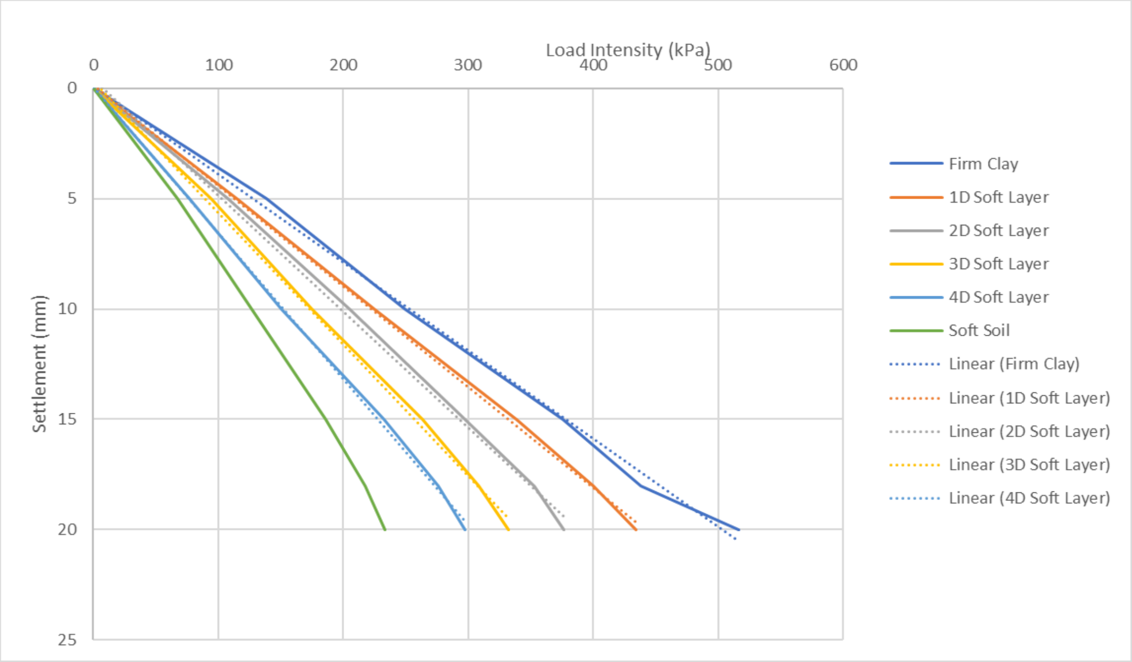

Figure 12 Load Vs Settlement Curve of Composite Ground for loading of entire unit cell

5.2.1 Stiffness Factor Comparison

The stiffness of the improved ground was evaluated by calculating the stiffness factor (β), which takes into account the layer thickness and represents the ratio of the load intensity applied to the treated ground in relation to the untreated ground. This calculation allowed for the assessment and comparison of the improvement seen in stiffness between the treated and untreated ground under the same settlement conditions.

Layer Thickness (t/D)	Load Intensity of Treated Ground (kPa)	Load Intensity of Untreated Groud (kPa)	Stiffness Ratio
0	516.3477	267.40687	1.930944
1	434.3024	208.97005	2.0783
2	376.5668	173.44047	2.171159
3	332.6224	149.3645	2.226917
4	297.3265	132.0672	2.251327
8	297.3265	132.0672	2.251327

Table 6 Calculations for Stiffness Ratio

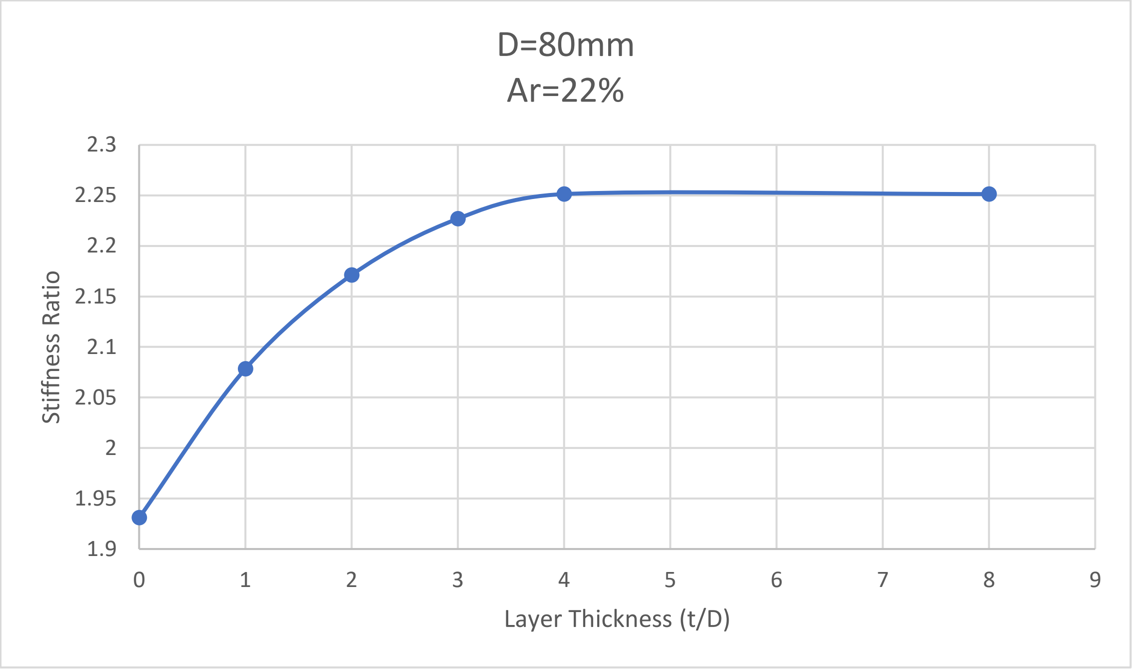

Figure 13 Variation of Stiffness Ratio with Different Soft Layer Thicknesses

In the presence of a top soft clay layer, the overall stress in the unit cell is distributed between the stone column and the confining soil. With increasing thickness of the top soft clay layer, the role of the bottom firm clay layer in bearing axial stress diminishes. This leads to a decrease in the limiting axial stress of the composite stratified soil. In other words, the presence of the soft clay layer at the top affects the distribution of stress within the unit cell and ultimately influences the overall load-bearing capacity of the enhanced soil system. In other words, as the depth of the top soft clay layer increases, the treated soil's capacity to support loads falls because the bottom stiff clay layer's role in distributing axial stress is reduced. An intriguing finding is that stiffness increases as the thickness of soft layer increases.

Similar simulations were run on layered soils but with stiff layer of soil on top and soft underneath it to study its behavior. After doing the same limiting axial stress calculations, stiffness ratio was again calculated and compared. As the depth of the firm clay layer at the top increases, there is a corresponding increase in the limiting axial stress, indicating improvement in the load-bearing capacity and stiffness of the enhanced soil system.

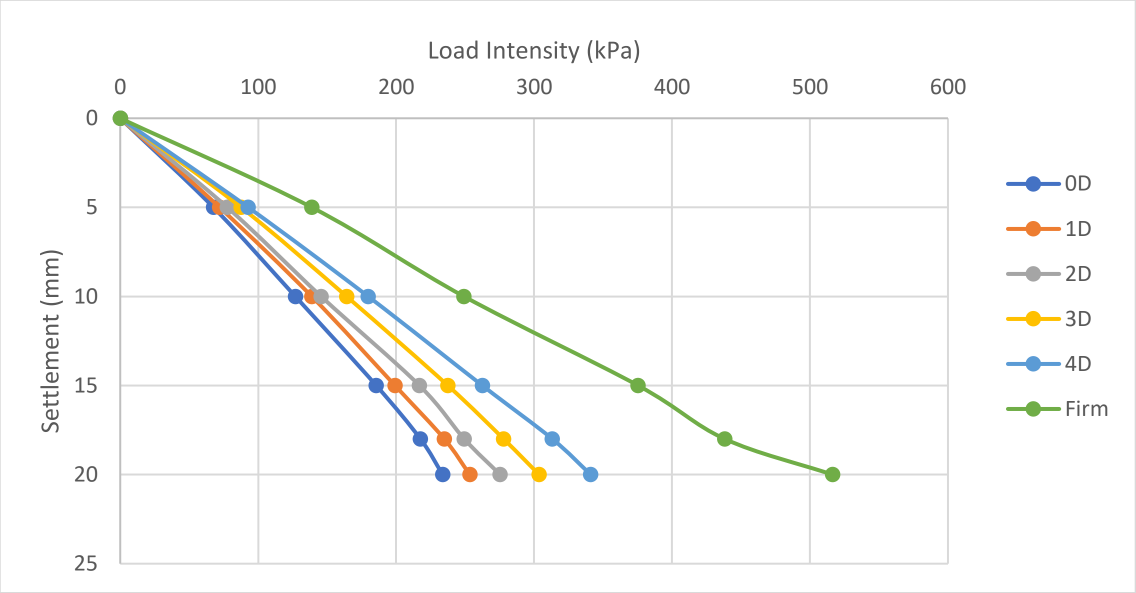

Figure 14 Effect of a top firm clay layer on limiting axial stress on treated ground

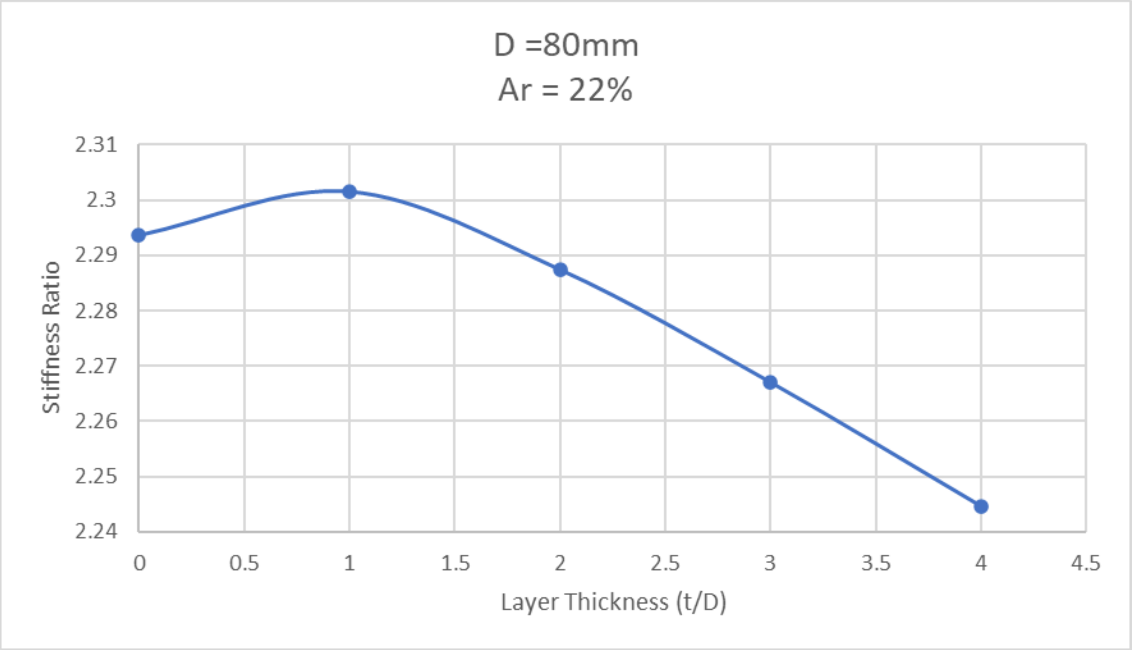

Figure 15 Effect of top firm layer on stiffness ratio

When a top, firm layer is added to soft soil, the improvement percentage rises. The data show that after then, the percent improvement in load carrying capability diminishes. However, due to the strong lateral constraint offered, the total limiting axial capacity rises with the thickness of the solid layer.

5.2.2 Settlement reduction ratio comparison

Table 7 gives the calculations for the settlement reduction ratio for different thicknesses of the top soft clay layer.

Table 7 Calculations for Settlement Ratio

	0D			1D			2D			3D			4D		
Load Intensity (kPa)	Treated	Untreated	Settlement Reduction Ratio	Treated	Untreated	Settlement Reduction Ratio	Treated	Untreated	Settlement Reduction Ratio	Treated	Untreated	Settlement Reduction Ratio	Treated	Untreated	Settlement Reduction Ratio
50	1.8799	3.73999878	0.502647223	2.1258	4.6769	0.454531848	2.2273	5.5586	0.400694419	2.2928	6.4465	0.355665865	1.8799	7.3211	0.256778353
100	3.8799	7.47999878	0.518703293	4.4058	9.4619	0.465635866	4.8573	11.3186	0.42914318	4.9228	13.1265	0.375027616	3.8799	14.8761	0.260814326
150	5.8799	11.2199988	0.524055316	6.6858	14.2469	0.469281037	7.4873	17.0786	0.438402445	7.5528	19.8065	0.381329362	5.8799	22.4311	0.262131594
200	7.8799	14.9599988	0.526731327	8.9658	19.0319	0.47109327	10.117	22.8386	0.442991252	10.183	26.4865	0.384452457	7.8799	29.9861	0.26278509
250	9.8799	18.6999988	0.528336933	11.246	23.8169	0.472177319	12.747	28.5986	0.445731609	12.813	33.1665	0.386317519	9.8799	37.5411	0.26317556
300	11.88	22.4399988	0.529407337	13.526	28.6019	0.472898654	15.377	34.3586	0.44755316	15.443	39.8465	0.387557251	11.88	45.0961	0.263435197
350	13.88	26.1799988	0.530171912	15.806	33.3869	0.473413225	18.007	40.1186	0.448851655	18.073	46.5265	0.388440996	13.88	52.6511	0.263620323

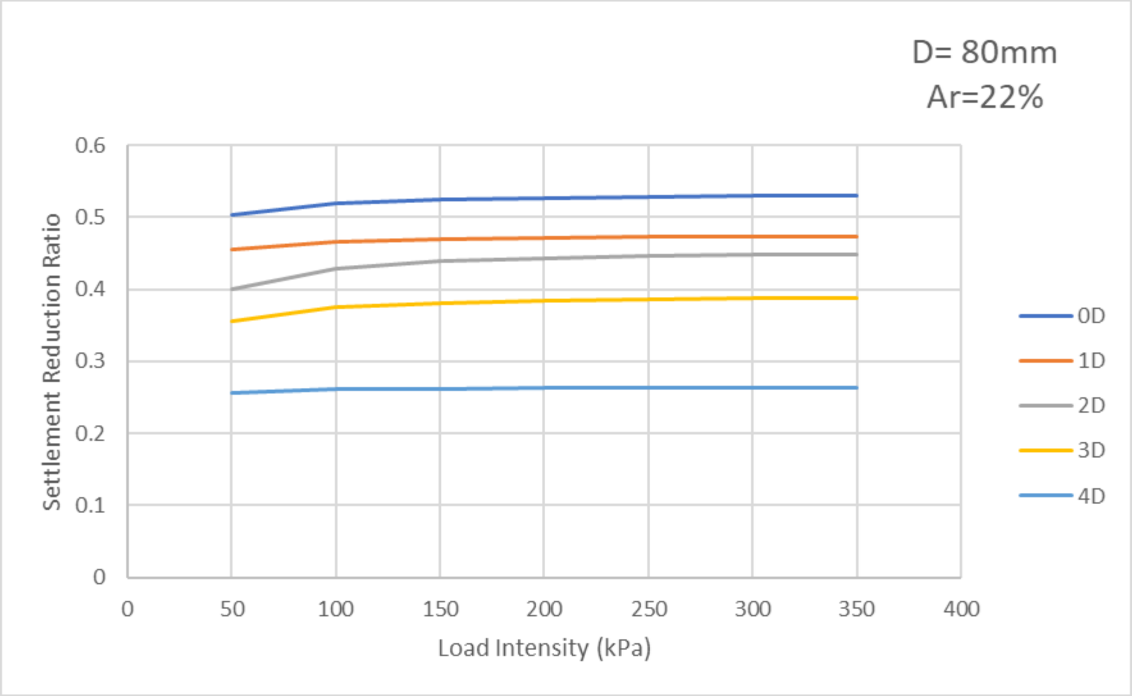

Figure 16 Shows top soft clay layer's impact on the settlement reduction ratio

The graph demonstrates that firm clay has the largest settlement reduction ratio. Hence, with an increase in the depth of the soft clay layer, performance of the column deteriorates. Because of inadequate lateral confinement, stone columns in soil beds bulge. To enhance its performance, adequate reinforcement is therefore required.

5.3 Effect of the area replacement ratio

To investigate the impact of the area replacement ratio on the limiting axial stress of the enhanced layered soil, isolated column tests were conducted using columns of different diameters. The diameters used were 88mm, 92mm, 100mm, and 70mm, corresponding to area replacement ratios of 22%, 25%, 30%, and 15%, respectively.

The results of the study indicate that for a fixed top soil layer depth, the limiting axial stress of the total composite ground exhibits an increasing trend as the area replacement ratio of the installed stone column rises. This is because as the area replacement ratio rises, the size of the stone column within a given unit cell enlarges. The upgraded unit cell's total composite stiffness and load carrying capacity increase as area replacement ratio rises because the stone column is more rigid than the soil it is surrounded by.

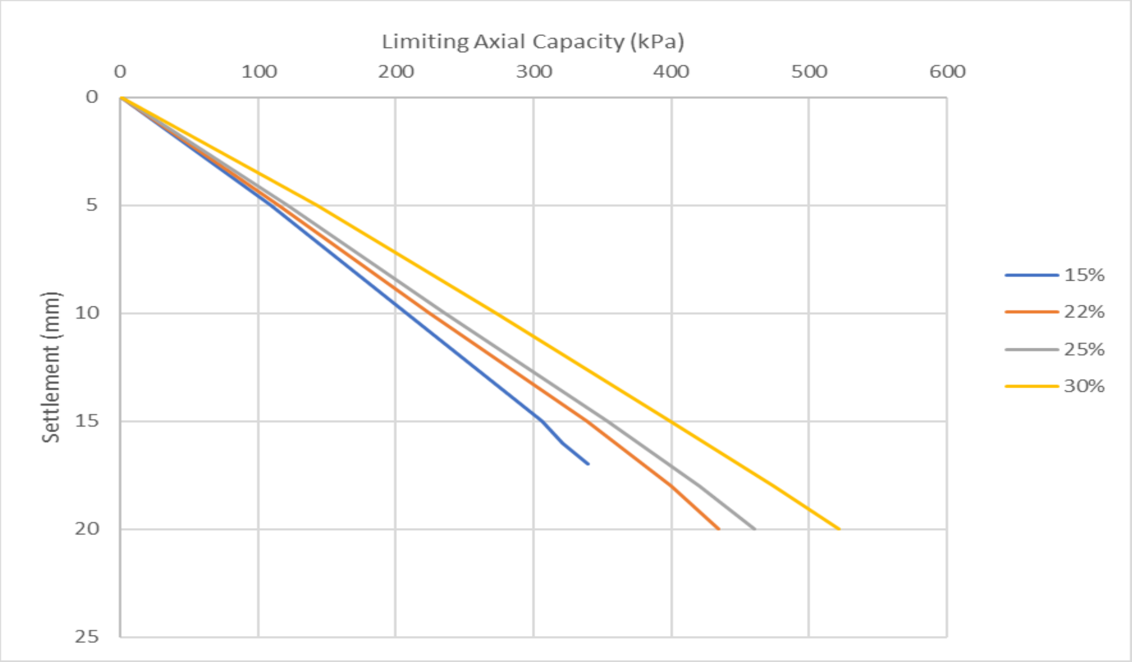

Figure 17 Settlement when unit cell is loaded with increasing area replacement ratio

5.4 Behaviour of Treated Layered Soil if Column Alone is Loaded

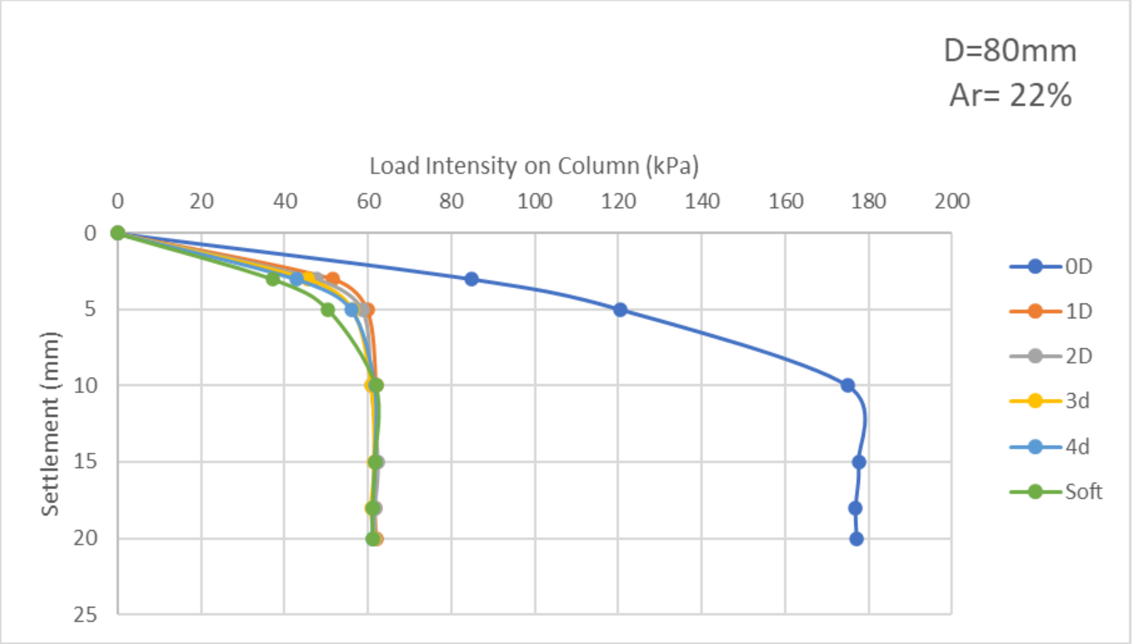

Figure 18 The effect of the thickness of the soft clay layer on the load settlement behavior when the column alone is loaded

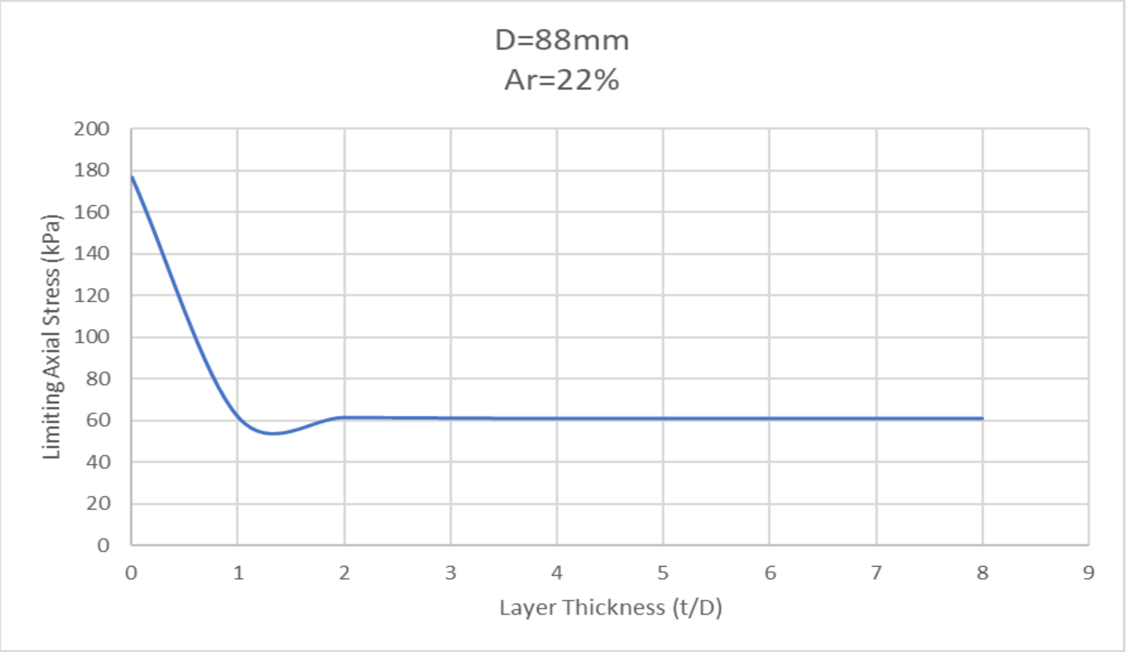

Figure 19 Graph between limiting axial stress and the thickness of the top soft clay layer

The findings demonstrate that even for 1D thickness, the top soft layer has a considerable impact when a column is loaded alone. After that, due to severe bulging, the column fails at almost the same limiting axial stress.

5.5 Bulging Behaviour of Columns

When the entire region was loaded, there was hardly any bulging, which suggests that some of the imposed weight was shared by the nearby soil. The passive resistance is offered to the lateral bulging of column due to surcharge loading that occurs when the entire area is loaded. As a result, the presence of the soft clay layer at the top leads to reduced bulging compared to the case where only the column is subjected to loading. In contrast, when only the area of column is loaded, it can lead to failure, and significant bulging is observed. The presence of load-sharing and the additional lateral support that is given by the confining soil in the case of entire area loading helps to mitigate bulging and improve the stability of the stone column.

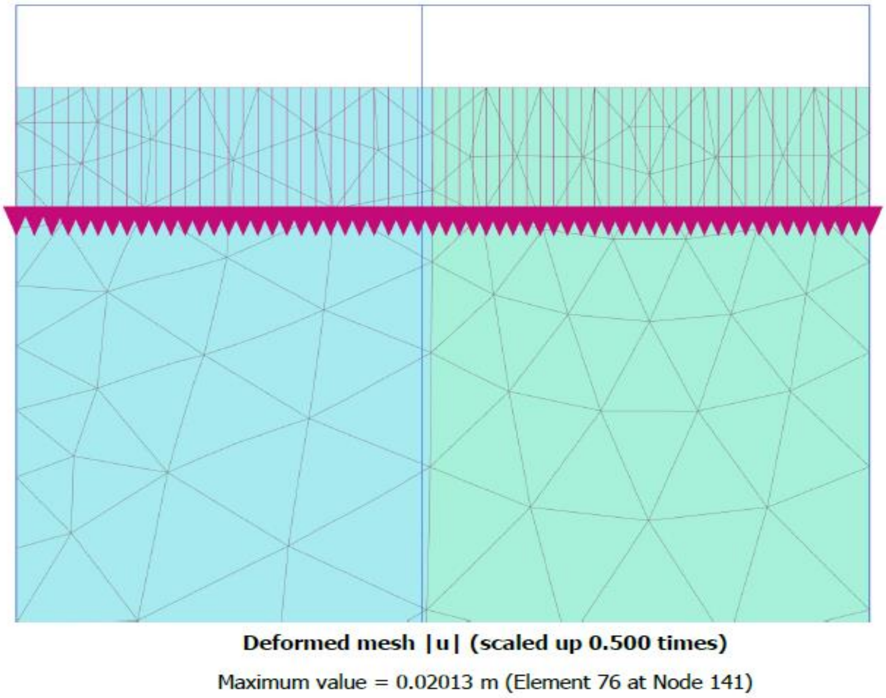

Figure 20 Bulging Behaviour when Whole Unit Cell is Loaded

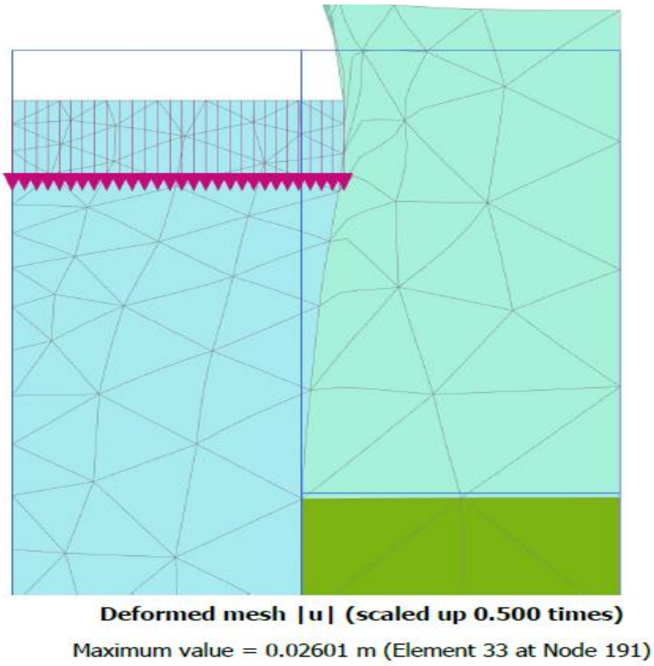

Figure 21 Bulging Behaviour when Only Column is Loaded

CHAPTER 6

6.1 CONCLUSIONS

Based on the numerical analysis, the following findings are made:

1. Because the graph is almost linear, the determination of the stiffness of composite ground becomes possible by evaluating the load settlement behaviour of a unit cell with the entire region loaded.
2. With increase in the area replacement ratio, the limiting axial stress of the composite ground also increases. For the enhanced ground to have the desired limiting axial capacity, a decision must be made regarding an economical diameter.
3. When a whole area is loaded, the stiffness and load-bearing capability of layered ground treated with stone columns decreases as the thickness of the top weak layer rises. The improvement in limiting axial capacity ranges from 62.5% for 1D depth of weak layer at the top to 75% for 4D depth.
4. The stiffness improvement factor varies only very slightly with the changing shear strength of the confining clay. The values range from 1.94 to 2.25 in present study.
5. For firm clay, the settlement reduction ratio is maximum (>0.5). Therefore, with the increase in the depth of the soft clay layer, the performance of the stone column falls. Due to inadequate lateral confinement, stone columns in soil beds bulge. To enhance its performance, adequate reinforcement is therefore required.
6. The settlement reduction ratio ranged from 0.25 to 0.55, indicating a settlement improvement of at least 40%.
7. Bulging failure occurs when the column area is subjected to load in isolation, with the largest bulging deformation observed at a depth approximately equal to half times the diameter of the stone column.
8. The weak layer at the top has a substantial impact on the amount of axial stress that a stone column can withstand in layered ground when loading is applied only on the column region. In comparison to a stone column in hard clay, the limiting axial stress is decreased by more than 50%, even for 1D layer thickness.
9. The maximum bulging occurs at a depth equivalent to the column's diameter from the top in the case of homogeneous soil beds. It is found that the stone column's overall length that underwent bulging was two to three times greater than its diameter.

10. In layered soils, bulging of the stone column was primarily concentrated in the weak layer at the top. When the thickness of the top layer reached 2 times the column diameter or greater, significant bulging was observed.

6.2 FUTURE SCOPE OF STUDY

The findings in the paper have the potential to improve current design practices for ground improvement using stone columns. However, additional research through model and field experiments, along with numerical evaluations, is needed to validate these conclusions and enhance their applicability.

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