INVESTIGATION OF THE INFLUENCE OF PARAMETRIC VARIATIONS IN GEOSYNTHETIC ENCASED STONE COLUMNS ON BEARING CAPACITY OF FOUNDATIONS

Report submitted in partial fulfilment of the requirements for the Degree of

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by
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Candidate's Declaration

I **Aayushi Gupta** (2K23/GTE/07) hereby certify that the work which is being presented in the thesis entitled '**Investigation of the Influence of Parametric Variations in Geosynthetic Encased Stone Columns on Bearing Capacity of Foundations**' in partial fulfilment of the requirements for the award of the degree of Master of Technology submitted in the Department of Civil Engineering , Delhi Technological University is an authentic record of my own work carried out during the period from August, 2024 to December, 2024 under the supervision of Dr. Ashok Kumar Gupta.

The matter presented in the thesis has not been submitted by me for the award of any other degree of this or any other Institute.

Candidate's Signature

This is to certify that the student has incorporated all the corrections suggested by the examiners in the thesis and the statement made by the candidate is correct to the best of our knowledge.

Signature of Supervisor(s) **Signature of External Examiner**

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Certified that **Aayushi Gupta** (2K23/GTE/07) has carried out their research work presented in this thesis entitled "**Investigation of the Influence of Parametric Variations in Geosynthetic Encased Stone Columns on Bearing Capacity of Foundations**" for the award of **Master of Technology** from Department of Civil Engineering, Delhi Technological University, Delhi, under my supervision. The thesis embodies results of original work, and studies are carried out by the student herself and the contents of the thesis do not form the basis for the award of any other degree to the candidate or to anybody else from this or any other University/ Institution.

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Investigation of the Influence of Parametric Variations in GeoSynthetic Encased Stone Columns on Bearing Capacity of Foundations

Aayushi Gupta

ABSTRACT

This study investigates the influence of parametric variations in geosynthetic encased stone columns (GESCs) on the bearing capacity of shallow foundations in soft cohesive soils, with a focus on promoting green engineering and resilient infrastructure development. Stone columns are a well-established ground improvement technique; however, their performance significantly diminishes in very soft soils due to inadequate lateral confinement, leading to premature failure or excessive settlement. Geosynthetic encasement addresses this by providing additional radial support, improving column stability, and enhancing load transfer to the underlying soil.

Using PLAXIS 2D, a series of finite element simulations were conducted to evaluate the impact of three key parameters—encasement stiffness, column diameter, and column length—on the load-bearing behaviour of GESC-reinforced foundations. Laboratory-tested properties of locally available soft cohesive soil and field data from Moradabad, Uttar Pradesh, were used to calibrate the numerical model, ensuring realism and relevance to practical conditions. While the theoretical framework for GESCs is well documented, their real-world application, particularly in small or semi-urban regions, remains underutilised. This study aims to bridge that gap by examining site-specific configurations that support the development of resilient and sustainable infrastructure in such areas.

The findings show that increasing encasement stiffness and column length significantly enhances the bearing capacity of the foundation and reduces overall settlement. Optimising the column diameter further improves performance, offering an efficient load transfer mechanism while maintaining economic feasibility. Additionally, the use of GESCs reduces the reliance on deep foundation systems and minimises the need for chemical stabilisers, thereby lowering environmental impact. By promoting the use of locally sourced aggregates and reducing excessive material consumption, this approach aligns with low-carbon, cost-effective ground improvement strategies.

Overall, the study contributes to the optimisation of GESC design for soft soils and offers practical recommendations for geotechnical engineers aiming to extend modern, eco-friendly ground improvement solutions to underserved semi-urban and peri-urban regions.

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

In civil engineering projects, the stability and performance of foundation are critical to the structural integrity of buildings, bridges, and other infrastructure. This becomes particularly challenging when construction is undertaken on soft cohesive soils, such as clay or silty sand. These soils are characterised by low shear strength and high compressibility, often leading to excessive settlement and, in extreme cases, structural failure. Conventional methods to improve such ground conditions—including chemical stabilisation and deep foundation systems—are not only costly but may also have significant environmental footprints, especially in the context of large-scale or rural infrastructure development.

Among various ground improvement methods, stone columns have gained widespread acceptance for their relative simplicity, economic viability, and environmental friendliness. These vertical inclusions enhance the load-bearing capacity of soil by transferring structural loads to deeper, stronger soil layers and reducing settlement through soil densification. However, their effectiveness relies heavily on the confining pressure provided by the surrounding soil. In very soft soils, particularly those with an undrained cohesion (Cu) of less than 15 kPa (Kempfert & Gebreselassie, 2006), the lack of lateral support leads to bulging, reduced axial strength, and ultimately compromised performance.

To address this limitation, Geosynthetic Encased Stone Columns (GESCs) have emerged as a promising advancement. By wrapping the stone column in a geosynthetic layer—typically geotextiles or geogrids—the lateral expansion is restrained, improving load distribution and enabling the column to sustain greater axial loads. The confinement provided by the geosynthetic encasement not only enhances the bearing capacity but also reduces settlement, making it a viable alternative to deep foundations or chemical stabilisers. Additionally, the use of locally available aggregates within encased columns can further reduce material costs and promote environmentally sustainable practices.

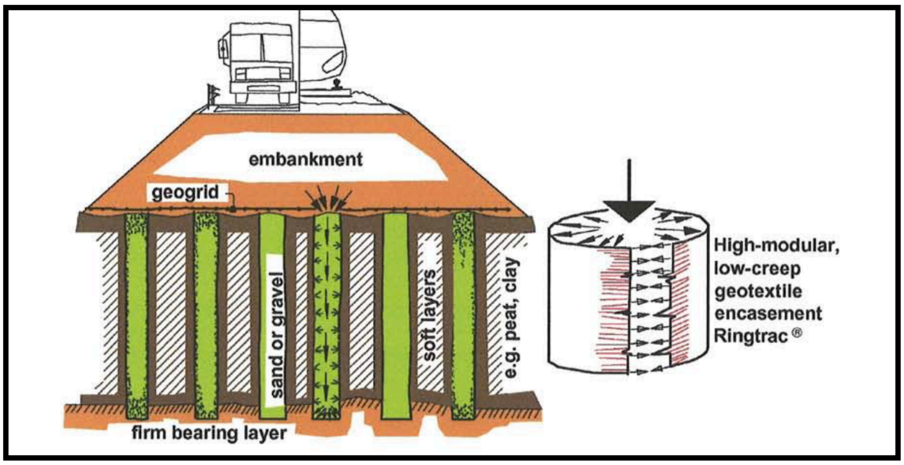


Fig. 1.1 : General idea of embankment on soft soil set on GECs [Source : Geosynthetic-encased stone columns: Numerical evaluation, Murugesan S. et al]

1.2 Literature Insights and Technological Evolution

The concept of encasing stone columns with geosynthetics was first introduced by Van Impe (1989), and since then, several researchers have examined the behaviour of GESCs through laboratory-scale studies and analytical models. Gniel and Bouazza (2009), as well as Miranda and da Costa (2016), conducted small-scale experiments to assess the load-bearing behaviour of GESCs. Despite these efforts, real-world application—particularly in smaller towns and semi-urban areas—remains limited. This is partly due to the complexity of the soil-column-geosynthetic interaction mechanisms and the challenges associated with on-site installation and parameter optimisation.

To better understand these interactions, researchers have developed analytical and numerical models. For instance, Pulko et al. (2010) proposed a closed-form analytical solution that incorporates encasement stiffness and load transfer behaviour, while Castro and Sagaseta (2013) compared analytical predictions with laboratory and numerical findings. These studies, though insightful, highlight the difficulties in generalising results due to site-specific variability, the nonlinear behaviour of materials, and the cost of full-scale experimental validation.

1.3 The Role of Finite Element Modelling (FEM)

Given the challenges of physical testing, Finite Element Modelling (FEM) has gained traction as an effective tool for simulating soil-structure interaction in geotechnical systems. FEM allows researchers to model realistic conditions, incorporate parametric variations, and predict foundation performance under diverse loading and environmental scenarios—all with reduced physical resource requirements.

In this study, PLAXIS 2D, a widely recognised FEM-based geotechnical analysis software, is employed to simulate the behaviour of GESCs under shallow foundations in soft cohesive soils. The numerical models are calibrated using lab-tested soil data and site-specific properties collected from a case location in Moradabad, Uttar Pradesh. This regional focus also helps highlight the applicability of advanced ground improvement techniques in semi-urban and resource-sensitive areas.

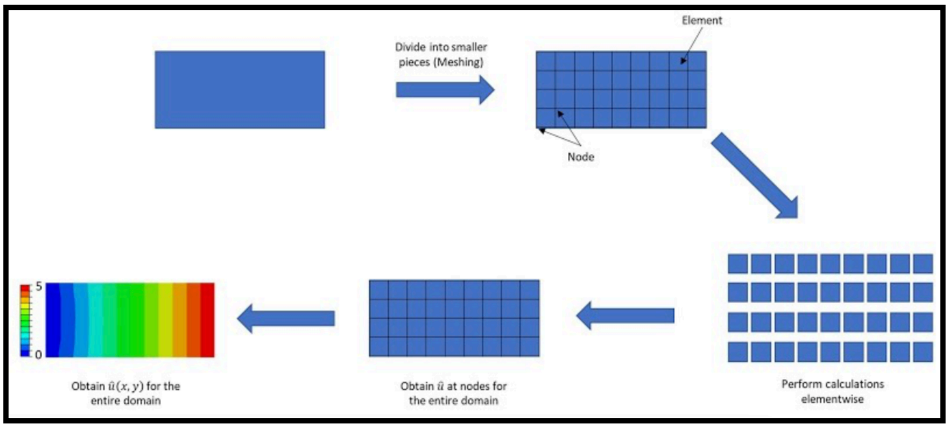


Fig. 1.2 : Figurative representation of Finite Element Method of Analysis

1.4 Objectives of the Study

The primary objective of this research is to investigate the impact of key design parameters—column diameter, column length, and encasement stiffness—on the load-bearing performance of shallow foundations reinforced with GESCs. Specifically, the study aims to:

- Evaluate the bearing capacity improvement offered by GESCs in soft cohesive soils.

- Assess the influence of individual parameters and their combinations on foundation performance.

- Compare the performance of GESCs with traditional (un-encased) stone columns.

- Provide design recommendations that can be adapted for cost-effective, low-carbon construction in geotechnically challenging regions.

1.5 Need and Significance of the Study

Traditional ground improvement techniques, such as deep soil mixing or pile foundations, while ensuring the stability of foundations in weak or soft soils , often involve significant excavation, high material consumption, and elevated costs. These methods also contribute to a larger carbon footprint, counteracting current global efforts toward sustainable construction. In contrast, Geosynthetic Encased Stone Columns (GESCs) represent an innovative and environmentally considerate alternative, capable of enhancing soil bearing capacity with reduced environmental disruption.

Despite their growing application, the design of GESCs is largely empirical and lacks a well-defined framework to account for varying soil types, loading conditions, and encasement properties. There is a pressing need for detailed parametric studies to understand how changes in design parameters—such as encasement stiffness, column diameter, and soil strength—affect performance outcomes. This research aims to address that gap by providing a systematic investigation using numerical tools and laboratory-calibrated inputs.

By doing so, the study not only advances academic knowledge in the field of soil improvement but also delivers insights that can be used by practitioners for more efficient, cost-effective, and sustainable foundation designs.

1.6 Scope and Limitations

This research is primarily based on numerical modelling conducted through PLAXIS 2D, a widely accepted finite element software for geotechnical analysis. The simulations are guided and validated using soil parameters derived from standard laboratory tests, ensuring that the input conditions reflect realistic soil behaviour within controlled environments.

The scope of the study is deliberately focused on a parametric investigation—evaluating the influence of variables such as geosynthetic tensile strength, and column dimensions on the bearing capacity of the improved ground. However, the study is inherently limited in its ability to capture real-world complexities such as installation effects, long-term degradation, drainage behaviour, and variability in field conditions. Moreover, the research does not include in-situ field testing or time-dependent settlement analysis, which may affect the long-term performance of GESCs.

These constraints are acknowledged, but they do not diminish the study's contribution to preliminary design development and future research direction. Instead, they highlight opportunities for follow-up studies involving experimental validation and practical implementation in diverse site conditions.

1.7 Methodology Overview

The research methodology integrates parametric analysis via numerical simulation, backed by laboratory-derived input data. The study begins with the selection and characterisation of soils typically encountered in problematic foundation conditions. Standard geotechnical laboratory tests are used to determine essential soil parameters including cohesion, angle of internal friction, and compressibility.

These parameters are then input into PLAXIS 2D, where various configurations of stone columns—with and without geosynthetic encasement—are modelled. Key parameters studied include:

- Tensile strength of the geosynthetic encasement, which affects confinement and load distribution.
- Stone column geometry, including diameter and spacing.
- Subsoil characteristics, such as stiffness, cohesion, and groundwater conditions.

The output focuses on bearing capacity, stress distribution, and deformation characteristics of the improved ground. The results are compared across different scenarios to draw insights into the optimal combination of parameters. This methodology enables a deeper understanding of the mechanics behind GESCs and helps establish foundational data for future experimental and field investigations.

CHAPTER 2

LITERATURE REVIEW

- ‘A Critical Review of Construction, Analysis and Behaviour of Stone Columns’ by M.R. Dheerendra Babu et al. Journal of Geotechnical and Geological Engineering, 2012.

  The paper discusses the techniques, methods of construction of stone columns, mechanisms of stone column behaviour under load and associated design philosophies along with some practical findings from recent research programs.

- ‘Soil improvement techniques and their evolution’ by W F Van Impe, 1989

  Analytical design procedure allowing estimation of the required tensile strength of encasement in the ring direction.

- ‘Consolidation and deformation around stone columns: Comparison of theoretical and laboratory results’ by J. Castro et al. Computers and Geotechnics, (2013)

  The study used a unit cell model to analyse the consolidation and deformation behaviour of end-bearing stone columns under distributed loads. Laboratory results were compared with analytical and numerical simulations to assess key soil responses such as settlement reduction, stress concentration, and the coefficient of consolidation. The study emphasised the role of plastic strains and the mechanical properties of gravel in determining stress distribution and soil improvement, highlighting the limitations of analytical models that ignore column yielding and small-strain stiffness.

- ‘Geotextile Encased Columns (GECs) : Load Capacity, Geotextile Selection and Pre-design graphs’ by Dimiter Alexiew et al. GeoFrontiers Congress, 2005.

  The study examines Geosynthetic Encased Columns (GECs) for improving embankments on soft subsoils. GECs, using high-modulus geotextile encasements like Ringtrac®, enhance bearing capacity and reduce construction time. It covers design principles, technologies, and procedures developed in the last decade, focusing on the geotextile tensile modulus and its effect on settlement, with findings on optimising GEC design and encasement selection.

- ‘Geosynthetic- encased stone columns: Numerical evaluation’ by S. Murugesan et al. Journal of Geotextiles and Geomembranes, 2006.

  The paper examines the load capacity improvement of stone columns through encasement using finite element analysis. Encased columns show higher load capacities, less compression, and reduced lateral bulging. Encasing the top portion up to twice the column diameter enhances capacity, and increased encasement stiffness reduces lateral stresses on surrounding soil, making load capacity less reliant on soil strength.

- ‘Excavations and foundations in soft soils’ by H.G. Kempfert et al. Springer Science and Business Media, 2006.

  The book reviews practical experiences and new research on excavations and foundations in soft soil deposits. It highlights the challenges of geotechnical design and execution on very soft soils, aiming to provide an overview of soft soil material properties and their application in excavations. The authors also discuss various foundation types and stabilisation methods, emphasising that soft soils need not be considered extremely difficult or costly. With advanced knowledge in soft soil engineering, safe and economically viable solutions can be achieved for construction projects.

- ‘Investigation of the Bearing Capacity of Foundations on Encased Stone Columns Using FEM’ by Hassan Kardgar. International Journal of Integrated Engineering, 2018.

  The study explores the use of geosynthetic encased stone columns (GECs) to improve the bearing capacity of foundations in soft soils. Using the finite element method with PLAXIS software, the research examines how factors like column length, diameter, encasement stiffness, and the number of columns impact foundation stability. The results show that longer columns and stiffer encasements significantly enhance load-bearing capacity.

- ‘Experimental and numerical study of pile-to-pile interaction factor in sandy soil’ by M. Modarresi et al. Procedia Engineering, 2016.

  The paper presents centrifuge model tests to examine the effect of soil relative density, pile spacing, and pile tip condition on the interaction factor between adjacent piles. The results show that soil relative density significantly influences pile interaction, requiring its consideration in interaction factor calculations. A correction to the Randolph and Wroth equation, accounting for soil relative density, is proposed. Increased pile spacing reduces the interaction factor, while pile tip condition has a minor effect. The results align well with three-dimensional finite element analysis.

- ‘Numerical analysis of settlement and bearing behaviour of piled raft in Babol clay’ by Taghavi Ghalesari A et al. European Journal of Environmental and Civil Engineering, 2016.

  The study uses a 3D finite-element method to analyse piled raft foundations on Babol clay with varying stiffness and plasticity. Results show that bearing capacity increases with longer piles, wider spacing, and thicker rafts, especially in stiff clay. Load type significantly impacts differential settlement and pile loads. The study also explores the benefits of an optimal design method through a case analysis.

- ‘Consideration of depth of influence in implementation of intelligent compaction in earthwork quality management’ by A Fathi et al. Transportation Research Board Annual Meeting, Washington, DC., 2018.

  The study develops a 3D finite element model to estimate the depth of influence for interpreting IC results in compacted geomaterials. The model is used in a parametric study examining nonlinear properties of single-layer and two-layer geosystems. The findings show that the depth of influence inversely correlates with material stiffness.

- ‘Embedment effects on vertical bearing capacity of offshore bucket foundations on cohesionless soil’ by A Barari, L Ibsen et al. International Journal of Geomechanics, 2017.

  The paper presents physical modelling and 3D finite-element analyses of suction caissons' vertical capacity for offshore wind turbines. The experiments showed that capacity depends on embedment ratio, with conventional depth factors underestimating capacity for rough foundations. New expressions for depth factors were validated for embedment ratios up to unity, using data from various soil profiles.

- ‘Evaluation of behaviours of earth and rock fill dams during construction and initial impounding using instrumentation data and numerical modelling’ by M Rashidi et al. Journal of Rock Mechanics and Geotechnical Engineering, 2017.

  The study evaluates Gavoshan dam's behaviour during construction and impounding using 2D finite difference analysis and instrument measurements. Results showed good consistency between the model and measurements. The dam's performance in terms of pore water pressure, settlement, and stresses was satisfactory. The maximum settlement was 238 cm by construction’s end, with 88% occurring during construction. The curving ratio increased from 0.64 to 0.81 upstream and 0.52 downstream by initial impounding, confirming the dam's safety compared to similar dams.

- ‘Geosynthetic encased stone columns in soft clay: A numerical study’ by S R Lo et al. Geotextiles and Geomembranes, 2010.

  The paper presents numerical studies on how geosynthetic encasement enhances stone column performance in very soft clay deposits. The study found that stone columns alone were ineffective in reducing settlement, as the soft clay could not provide enough confining stress. A system with geosynthetic encasement was tested and shown to significantly improve performance. A fully coupled analysis was performed, using a unit cell idealisation to reduce computational effort. The results indicated that performance was less sensitive to the stiffness of compacted stone but depended on the locked-in stress in the geosynthetic encasement during installation.

- 'Influence of bearing area on the behaviour of stone column' by R.S. Narsimho. Proc. Indian Geotechnical Conference, Calcutta, India, 1992.

  The study presents finite element analysis results for square footings on both improved and unimproved soft soils, validated by existing experimental data. Parametric studies were conducted to identify key geometric and mechanical parameters affecting bearing capacity. Results showed that stone columns significantly improve footing bearing capacity, with the bearing capacity ratio (BCR) increasing as the friction angle of the stone column rises and the cohesion and friction angle of the soft soil decrease.

- 'Laboratory analysis of encased stone columns' by M Mirana et al. Geotextiles and Geomembranes, 2016

  The study examines the impact of encasement through drained triaxial tests on encased and non-encased gravel samples, using two gravel densities and two geotextiles. The findings show increased strength in encased samples, additional confining pressure from the geotextiles, and higher mobilized friction angles. The improvement is more pronounced at lower confining pressures.

- 'Geosynthetic-encased stone columns: Analytical calculation model' by B Pulko et al. Geotextiles and Geomembranes, 2010.

  The paper presents a new design method for non-encased and encased stone columns, accounting for initial stresses with columns as elasto-plastic, soil as elastic, and encasement as linear-elastic. Finite element analyses validated the method, showing strong agreement. A parametric study explored factors like soil properties, load levels, and encasement stiffness, providing a basis for predicting settlement. A design chart is included for selecting column spacing and encasement stiffness to achieve settlement reduction.

- 'Bearing capacity of geogrid reinforced sand over encased stone columns in soft clay' by P Debnath. Geotextiles and Geomembranes, 2017.

  The study conducted laboratory tests and numerical simulations on unreinforced (USB) and geogrid-reinforced sand beds (GRSB) over vertically encased stone columns (VESC) in soft clay. Finite element analysis using

ABAQUS showed an 8.45-fold increase in bearing capacity with GRSB over VESC compared to unreinforced clay. Optimal sand bed thickness was 0.2 times (USB) and 0.15 times (GRSB) the footing diameter. GRSB reduced column bulging and increased the improvement factor and stress concentration ratio with settlement. Optimal column length and encasement depth were six and three times the column diameter, respectively.

- ‘Behaviour of Encased Stone Columns in Soft Clay’ by Moh. A. Sakr et al. Journal of Engineering Research (2022).

  A FEM-based study using PLAXIS 3D (62 cases) assessed the performance of encased stone columns (ESCs) in soft clay compared to ordinary stone columns (OSCs). With constant L/D = 10 and φ = 45°, ESCs showed a significant bearing capacity improvement—up to 227% and 200% for 0.4 m and 0.6 m diameters respectively—demonstrating the effect of encasement stiffness on load-bearing behaviour.

- ‘Parametric Study on Bearing Capacity of Geosynthetic Encased Stone Column Installed in Soft Clay’ by Sariga Unni et al, The International Conference on Emerging Trends in Engineering (2021).

  A numerical study using PLAXIS 2D evaluated the bearing capacity of geosynthetic encased stone columns (GESCs) in soft clay. The analysis focused on key parameters such as friction angle, encasement length and stiffness, and soil shear strength. Results showed that geosynthetic encasement enhances column stiffness, drainage, and load-bearing performance.

- ‘Improving Weak Soils with Reinforced Stone Columns’ by Ahmed Hussein Majeed et al, 3C Tecnología. Glosas de innovación aplicada a la pyme (2023).

  The study explores the enhancement of soft clay soils using stone columns fully reinforced with geogrids and constructed from recycled concrete aggregates. The research indicates that such reinforcement significantly improves the soil's bearing capacity. Specifically, the use of stone and double columns reinforced with a geogrid network led to a 9% improvement in bearing capacity compared to natural soil, with further enhancements observed when employing different reinforcement patterns.

- ‘A Study of Single Stone Column Bearing Capacity from a Full-Scale Plate Load Test in Long Son Project’ by Hong Lam Dang et al, Engineering, Technology & Applied Science Research (2024).

  The bearing capacity of stone columns is crucial for soil improvement design, with bulging being the most common failure mode, influenced by site-specific soil conditions. This study presents a full-scale plate load test of an 800 mm diameter stone column installed using vibro-floatation at the Long Son Petrochemical Project in Vietnam. The test confirmed a bearing capacity of 882.5 kPa, validating the column’s performance.

- ‘Experimental Study on Ground Improvement with Stone Columns’ by Soumyakrishna Eega et al, International Journal of Innovations in Engineering Research and Technology (2021).

  The study analyses the bearing capacity and settlement behaviour of stone columns and geotextile-encased stone columns using a scaled model. Gunny bags were used as geotextile encasement. Results showed a significant improvement in bearing capacity with stone columns, and further enhancement when encased, highlighting the effectiveness of geotextile encasement in soft soil stabilisation.

CHAPTER 3

IDENTIFICATION OF CHALLENGES AND RESEARCH GAPS

3.1 Problem Statement

The challenge of constructing stable foundations on soft cohesive soils has long posed a significant barrier in civil engineering, especially in regions where infrastructural development is expanding into previously unsuitable terrains. While stone columns have proven to be an effective method for ground improvement, their application in very soft soils is limited by insufficient lateral confinement. In such scenarios, stone columns are prone to radial deformation (bulging), which reduces their load-bearing efficiency and may lead to premature failure.

To counteract this, Geosynthetic Encased Stone Columns (GESCs) have been developed as an enhancement. The geosynthetic encasement offers additional lateral support, increasing the column's axial strength and reducing settlement. Despite their theoretical and experimental potential, the widespread adoption of GESCs is still limited, particularly in developing and semi-urban regions. This is primarily due to the lack of standardised design practices, limited field validation, and a weak understanding of the interaction mechanisms among soil, stone aggregates, and encasement materials.

Thus, the central problem this study addresses is: "How do variations in key design parameters—column length, diameter, and encasement stiffness—influence the load-bearing performance of shallow foundations reinforced with GESCs in soft cohesive soils?"

3.2 Key Technical and Practical Challenges

3.2.1 Inadequate Natural Confinement in Soft Soils

In very soft clayey soils with low undrained shear strength, natural confinement is insufficient to prevent lateral bulging. The resulting deformation limits the axial capacity of stone columns.

3.2.2 Lack of Unified Design Guidelines

Unlike traditional stone columns or deep foundations, GESCs do not have universally accepted design procedures, making field application inconsistent and often conservative or over-engineered.

3.2.3. Installation Difficulties

Field deployment of GESCs requires careful placement of geosynthetics and stone aggregates without damaging the encasement. In practice, this is difficult to achieve with precision, particularly in remote or resource-constrained sites.

3.2.4. Unpredictable Soil–Structure Interaction

The load distribution mechanism in encased stone columns is influenced by a complex interplay of variables—such as soil type, encasement tensile stiffness, aggregate grading, and loading conditions—which are not fully understood or easily modelled using simplified equations.

3.2.5. Limited Field Data and Long-Term Performance Evidence

Most existing studies are based on laboratory-scale models or finite element analyses. Field-scale data regarding the longevity, degradation of geosynthetics, and real-world behaviour over time remain scarce.

3.3 Research Gaps in Existing Literature

3.3.1 Parametric Understanding is Incomplete

While individual parameters (like encasement type or column diameter) have been studied, comprehensive parametric investigations involving multiple factors simultaneously are limited. The interdependency of these variables is often neglected.

3.3.2 Lack of Regional Contextualisation

Studies are often generalised or based on non-local soil profiles. There is a need for research contextualised to specific soil types and site conditions, such as those found in regions like Moradabad (Uttar Pradesh), where infrastructure projects increasingly demand cost-efficient ground improvement techniques.

3.3.3 Disparity Between Laboratory and Field Behaviour

Laboratory models often idealise boundary conditions and material behaviour, failing to reflect complexities encountered in the field. Bridging this gap requires calibrated simulations based on realistic data.

3.3.4 Insufficient Comparative Analysis

Few studies directly compare the performance of GESCs with conventional stone columns under identical conditions. This makes it difficult to quantify the benefit of encasement and justify the added cost and effort involved in implementation.

3.3.5 Environmental and Economic Evaluations are Rare

While GESCs are often promoted as cost-effective and sustainable, detailed studies evaluating their lifecycle cost, material optimisation, and carbon footprint are minimal.

3.4 Justification for the Present Study

This study is motivated by the urgent need to provide a practical, cost-effective, and scientifically grounded solution for foundation construction on soft soils—particularly in developing regions. By focusing on three fundamental parameters—column length, column diameter, and encasement stiffness—this research aims to build a clear understanding of their individual and combined impact on foundation performance. Using finite element analysis in PLAXIS 2D, the study attempts to simulate realistic soil–structure interaction and validate outcomes through laboratory-derived inputs.

By addressing the above challenges, this research not only contributes to the academic body of knowledge but also supports engineers and policymakers in developing localised design standards for resilient, sustainable foundation systems.

CHAPTER 4

METHODOLOGY

4.1 General

This chapter presents the detailed methodology adopted to study the performance of Geosynthetic Encased Stone Columns (GESCs) in improving the bearing capacity and reducing settlement of shallow foundations in soft cohesive soils. A numerical modelling approach using PLAXIS 2D was chosen due to its capacity to simulate complex soil-structure interactions with precision. The methodology is structured into five major components:namely:

(i) Site and soil characterisation,
(ii) Establishment of the numerical model using PLAXIS 2D,
(iii) Material modelling with PLAXIS 2D,
(iv) Simulating the effects of parametric variables under study, and
(v) Verification and analysis.

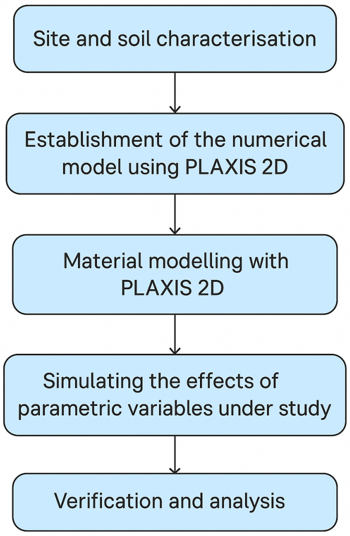


Fig. 4.1 : Flowchart representing the methodology of research

4.2 Site and Soil Characterisation

4.2.1 Site Location

The soil data used for model calibration was sourced from an ongoing project site in Moradabad, Uttar Pradesh. The region features fine-grained, low-strength cohesive soils, typical of areas requiring ground improvement for structural stability.

The test results have been determined through Field and Laboratory test conducted at the proposed site for Construction of P.T.C. Buildings for PAC 2nd Battalion, Moradabad, Uttar Pradesh. It was decided to conduct boring at 7 points. The boring was conducted in accordance to IS:1892–1979. Bore hole no. 1, 6, 7 up to depth of 15.0 meter, bore hole no. 2, 3, up to depth of 20.0 meter, and bore hole no. 4, 5 up to depth of 10.0 meter at the points marked by them at the site.

Disturbed & undisturbed soil samples were collected along with conduction of standard penetration test at an interval of 1.5 meter, or change of strata (which ever met earlier) starting from boring points to the termination of bore holes. Samples were collected in accordance to IS 2720 (Part I) – 1983. The undisturbed soil samples were collected by the *soil sampling cylinders* from the bore-holes. Disturbed samples were collected using a *split spoon sampler* and were tested for the following parameters:

(i) Natural (in site water content)
(ii) Specific gravity
(iii) Liquid Limit
(iv) Plasticity Index
(v) Unconfined Compressive Strength
(vi) Cohesion
(vii) Angle of internal friction
(viii) Bulk Density
(ix) Dry Density
(x) Permeability
(xi) Young’s modulus
(xii) Dilatency angle

The results mentioned in the slides ahead were obtained from samples collected from Bore-hole no. 4, at the proposed site of construction for the Administrative Block building. The location of the bore-hole under consideration is shown in the following figure :

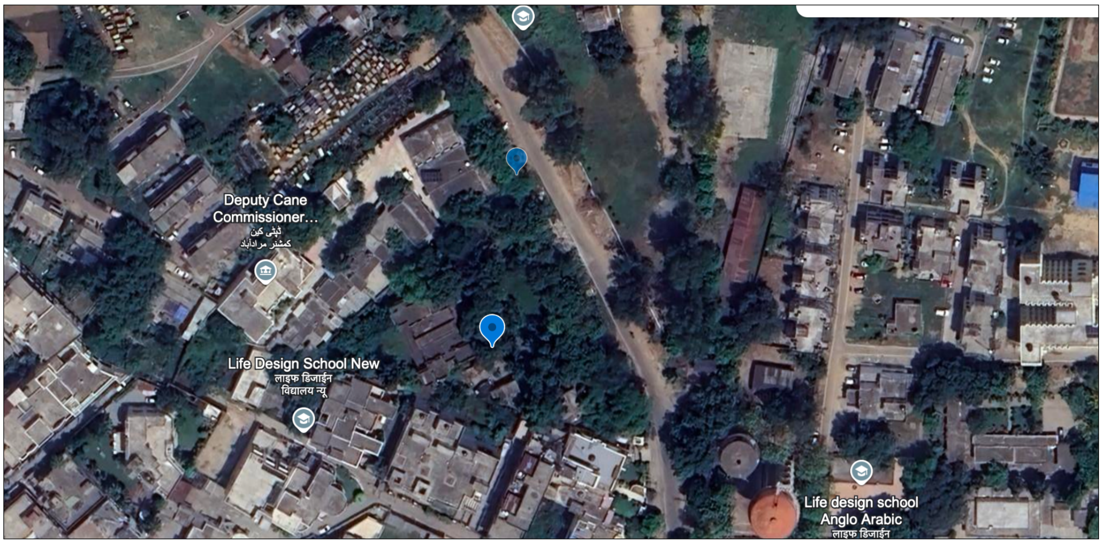


Fig. 4.2 : Location of soil sampling and investigation (B.H.4). Moradabad, Uttar Pradesh [Latitude 28°51'12" : Longitude : 78°46'03"E] (*Source : GoogleEarth*)]

4.2.2. Laboratory Testing

To obtain reliable input parameters for the numerical simulations, disturbed and undisturbed soil samples were collected and subjected to standard geotechnical laboratory tests. The following tests were conducted:

S. No.	***Parameters***	***Tests used for Determination***	***IS Code Referred***	***Obtained Values***
1	Natural (In-situ) water content	Oven Drying	IS 2720 : Part II	8.80%
2	Specific gravity	Density bottle	IS 2720 : Part III - Section I	2.73
3	Liquid Limit	Casagrande's apparatus	IS 2720 : Part V	26.10%
4	Plasticity Index	3 mm thread rolling test	IS 2720 : Part V	4.75%

S. No.	*Parameters*	*Tests used for Determination*	*IS Code Referred*	*Obtained Values*
5	Unconfined compressive strength	Unconfined compression test	IS 2720 : Part X	0.3968 kg/ cm^2
6	Cohesion	Triaxial Compression test	IS 2720 : Part XII	0.33 kg/ cm2
7	Angle of internal friction	Triaxial Compression test	IS 2720 : Part XII	24°
8	Bulk density	Core cutter test	IS 2720 : Part XXVIII	1.79 g/cc
9	Dry density	Core cutter test	IS 2720 : Part XXVIII	1.62 g/cc

Table 4.1 : Results obtained from laboratory testing

Soil classification has been done with the help of the soil properties obtained by laboratory tests as per IS 1498 (1970) : “Methods of classification and identification of soil for general engineering purposes”.

The general nature of the soil strata met during boring in each of bore holes was determined in accordance to the Unified Soil Classification System.

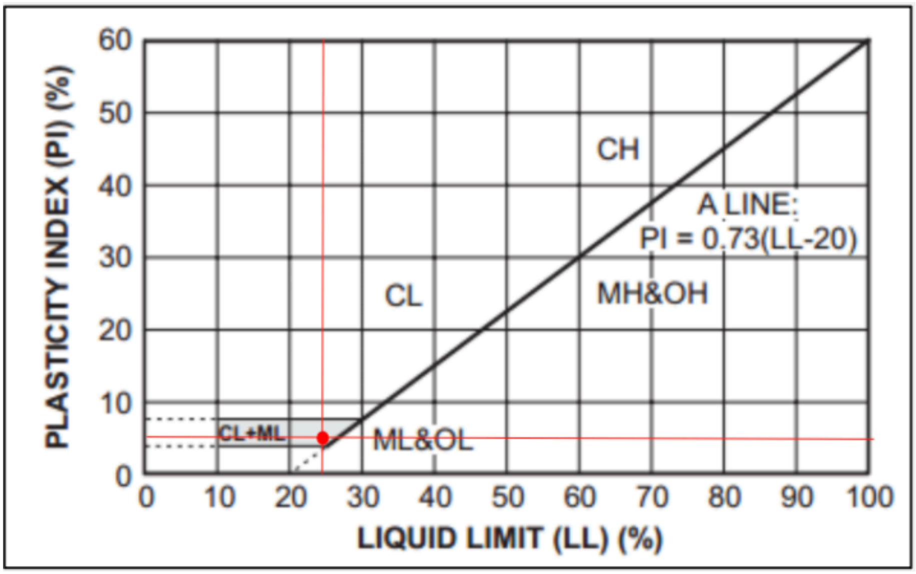


Fig. 4.3 : Classification of fine-grained soil using Plasticity Chart

The soil strata at the location of the bore-hole under consideration (B.H. No.-4) consisted of the following soil type :

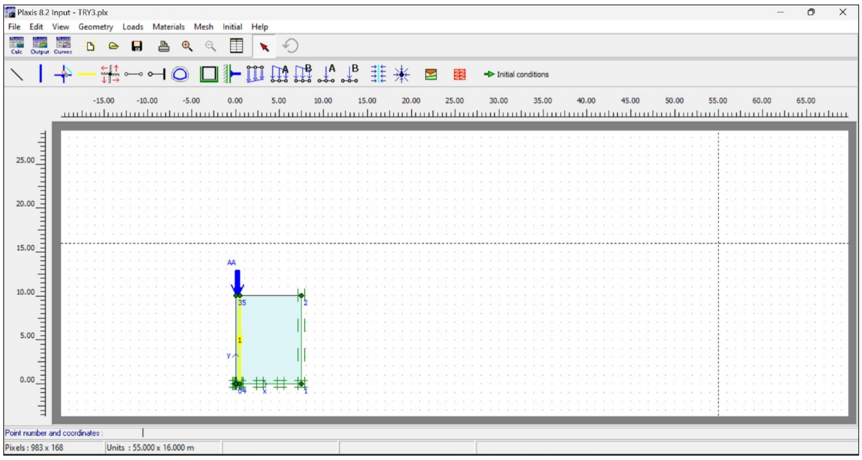
CL-ML - Silty clay of very low plasticity

4.3 Establishment of the numerical model using PLAXIS 2D

A two-dimensional axisymmetric finite element model was developed using PLAXIS 2D to simulate the behaviour of a shallow foundation supported by a single stone column (both encased and un-encased) embedded in soft clay.

4.3.1 Model Geometry and Boundary Conditions

- (i) **Model domain :** Axisymmetric model with radial extent of 5 times the column diameter and vertical depth of 2 times the column length.
- (ii) **Footing :** A circular footing of 1 m diameter, representing a shallow foundation, was placed above the stone column.
- (iii) **Boundary conditions :**
  - Bottom boundary: Fixed in both vertical and horizontal directions.
  - Side boundary: Horizontal fixity only.
  - Symmetry axis: Assigned on the left edge.
- **(iv) Loading** : A uniform load was applied incrementally at the footing to simulate structural load.
- **(v) Soil Depth** : 10 m (corresponding to the depth of the borehole under investigation)



Point number and coordinates :

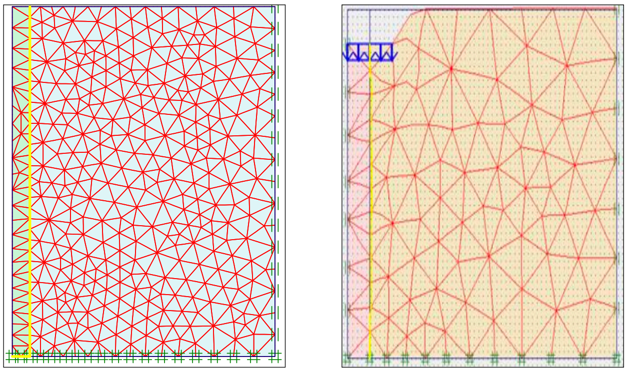
Pixels : 983 x 168

Units : 55.000 x 16.000 m

Fig. 4.4 : Modelling soil and stone column conditions on PLAXIS 2D input

4.3.2 Mesh Generation

A fine mesh was generated in the region surrounding the stone column to capture deformation and stress distribution accurately. Fifteen-node triangular elements were used for soil and column, with denser refinement around the encasement.



(a) *(b)*

Fig. 4.5 : Generated mesh *(a)* before loading and *(b)* after loading

4.4 Material Modelling with PLAXIS 2D

4.4.1 Soil

- Modelled using the Mohr-Coulomb model with parameters derived from lab tests, with the following input parameters :

S.No.	***Parameter***	***Value***
1	Cohesion (c)	33 kPa
2	Friction angle (ϕ)	24 °
3	Young's modulus of elasticity (E)	10000 kPa
4	Poisson's ratio (ν)	0.25
5	Permeability (k_x and k_y)	5 x 10 $^{-8}$ and 1 x 10 $^{-8}$ respectively
6	Permeability ()	
7	Saturated unit weight (γ_{sat})	17.9 kg/m^3
8	Dry unit weight (γ_{dry})	16.2 kg/m^3
9	Dilatency Angle (ψ)	0 °

Table 4.2 : Input parameters for soil in PLAXIS model

4.4.2 Stone Column

- Treated as a drained granular material with higher stiffness and strength than surrounding soil.
- Parameters such as friction angle, modulus, and permeability were adopted from literature.

S.No.	***Parameter***	***Value***
1	Cohesion (c)	~ 0
2	Friction angle (ϕ)	44 °
3	Young's modulus of elasticity (E)	52000 kPa
4	Poisson's ratio (ν)	0.3
5	Permeability (k_x)	1×10^{-2}
6	Permeability ($k_{y)}$	1×10^{-2}
7	Saturated unit weight (γ_{sat})	19.5 kg/m3
8	Dry unit weight (γ_{dry})	17.6 kg/m3
9	Dilatency Angle (ψ)	11 °

Table 4.3 : Input Stone Column Properties [Source : Investigation of the Bearing Capacity of Foundations on Encased Stone Columns Using FEM, Hassan Kardgar]

4.4.3 Geosynthetic Encasement

- Modelled as a linear elastic material with
  - Poisson's ratio 0.3
  - Varying tensile stiffness (2000 kPa, 3000 kPa, 4000kPa).
- Encasement was applied as a structural element surrounding the stone column to simulate confinement.
- Interface behaviour between the encasement and soil was activated to ensure realistic interaction.

4.5 Parametric Study

A series of simulations were carried out to study the influence of the following key parameters:

S.No.	*Parameter*	*Range Considered*
1	Column Diameter (D)	0.3 m , 0.6 m , 0.9 m
2	Column Length (L)	3 m , 6 m , 10 m
3	Encasement stiffness (J)	1000 kN/m , 2000 kN/m , 3000 kN/m

Table 4.4 : Range of column diameter, column length and encasement stiffness considered for the study

Each simulation scenario varied one parameter at a time while keeping others constant. The results were compared against two reference models:

- Un-reinforced Soft Soil (URS)
- Un-encased Stone Column (USC)

This allowed a systematic analysis of how GESCs outperformed conventional methods.

4.6 Performance Metrics

The simulations were evaluated based on the following criteria:

$$\textbf{Bearing Capacity Improvement Ratio} = q_{GEC}/q_{OSC}$$

The bearing capacity improvement ratio BCI (bearing capacity of treated-to-untreated soil); where q_{GEC} is the bearing capacity of the foundation over geosynthetic-encased stone columns and q_{OSC} is the bearing capacity of the foundation over ordinary stone columns.

4.7 Model Verification and Validation

Before conducting the main parametric analysis, the developed numerical model was subjected to rigorous verification and validation to ensure the reliability and accuracy of the simulation results. While full-scale field tests were beyond the scope of this study, the simulation parameters and trends were verified and validated against established experimental studies to ensure the reliability of the finite element simulation results. For verification, the developed PLAXIS 2D model was initially compared with the experimental work by Narasimha et al. (1992). Subsequently, the validation of the model was carried out using the results of Debnath and Dey (2017).

4.7.1 Verification

The finite element model developed in PLAXIS 2D was first verified against the experimental study conducted by Narasimha et al. (1992), wherein a single stone column embedded in soft clay was tested under axial loading. The laboratory setup, including geometry and material properties, was replicated in the numerical simulation. The resulting load-settlement response demonstrated close agreement with the experimental data, confirming the correctness of the mesh generation, boundary conditions, and soil-structure interaction modelling approach.

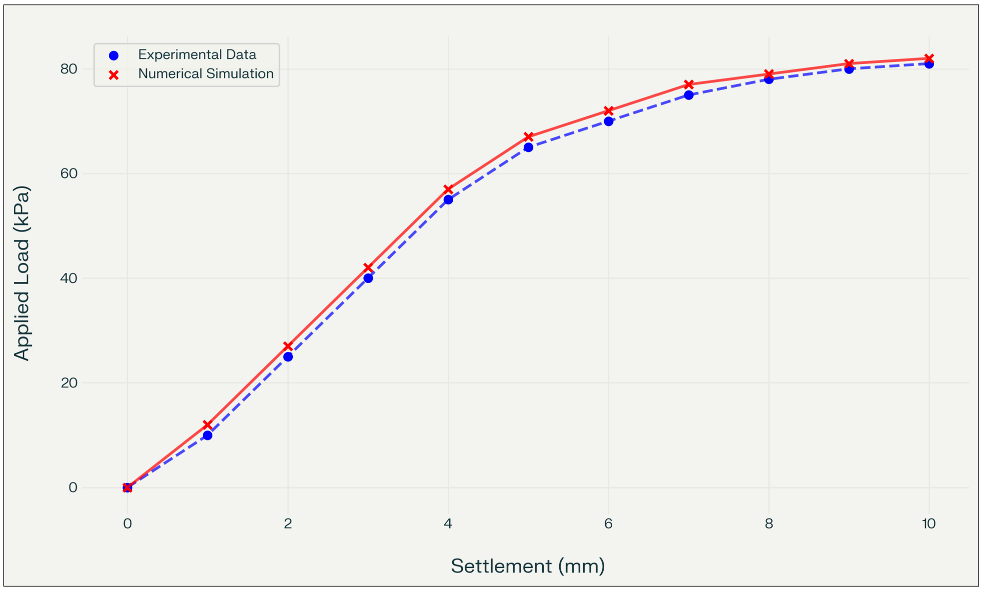


Fig. 4.6 : Load-Settlement Comparison: Narasimho et al. vs. Numerical Simulation

This plot demonstrates the load-settlement behaviour of a stone column under increasing vertical pressure, with two distinct curves representing experimental measurements (shown with markers) and finite element analysis results (shown with a different line style). The close agreement between these curves validates the accuracy of the numerical modelling approach, confirming that the simulation procedure correctly captures the mechanical behaviour of stone columns in soft soil. This verification is critical for establishing confidence in the numerical methods used throughout the research.

4.7.2 Validation

To validate the performance of the model in simulating geosynthetic-encased stone columns (GECs), a case study by Debnath and Dey (2017) was modelled. In their study, a group of 12 GECs arranged beneath a circular footing was subjected to loading. The material properties and configuration were accurately input into PLAXIS, and the resulting settlement behaviour was compared with the experimental load-settlement curves. The simulation results aligned closely with the physical test data, validating the model's capacity to replicate the complex interaction between encased stone columns, surrounding soil, and the applied load.

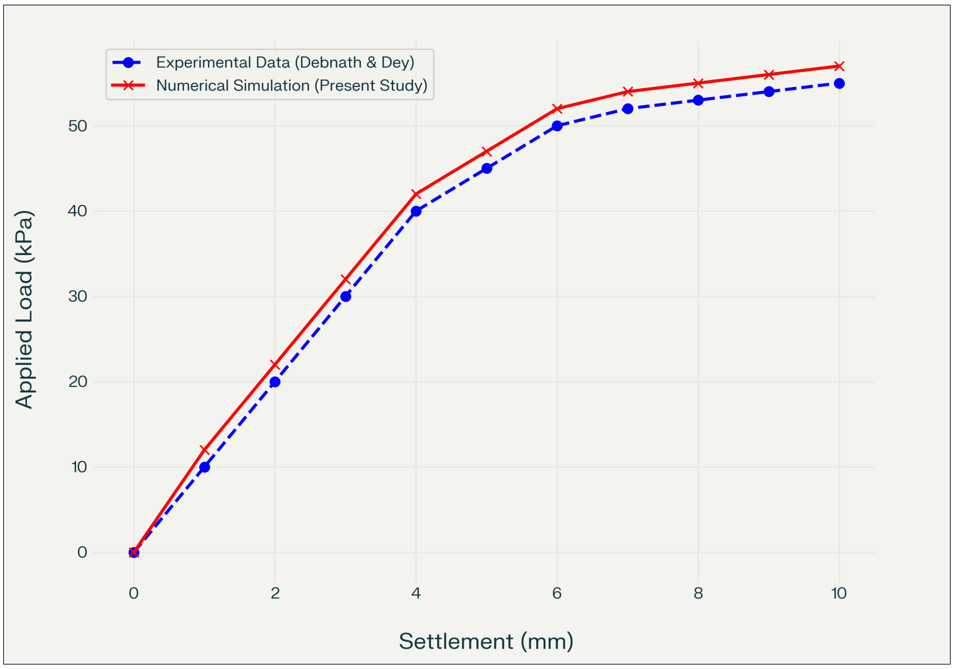


Fig. 4.7 : Load-Settlement Comparison: Debnath & Dey vs. Numerical Simulation

This graph presents the comparison between experimental data from Debnath & Dey and numerical simulation results for a group of encased stone columns. The x-axis shows settlement in millimetres (0-10 mm range), while the y-axis displays the applied load in kPa (0-60 kPa range). Both curves exhibit typical nonlinear soil behaviour with initial steep slopes that gradually flatten at higher loads, indicating increasing plastic deformation.

The numerical simulation slightly overestimates the bearing capacity compared to the experimental results, particularly in the middle settlement range (3-8 mm), but the overall agreement is satisfactory. The successful verification and validation confirm that the modelling methodology is robust and can be reliably used to investigate the effects of various geometric and material parameters on the bearing capacity of shallow foundations supported by geosynthetic encased stone columns.

Parameter	***Soft Clay***	***Stone Column***	***Concrete Foundation***	***Geosynthetic Encasement***
Elastic Modulus, E (MPa)	4 – 10	40 – 60	25,000	Modeled via axial stiffness J = 2000–4000 kN/m
Poisson's Ratio, ν	0.3 – 0.45	0.3	0.2	0.3
Unit Weight, γ (kN/m³)	16 – 18	19 – 20	23.5	Not applicable (modeled as linear elastic)
Cohesion, c (kPa)	3 – 20	0	–	–
Friction Angle, φ (°)	25	38 – 44	–	–
Dilation Angle, ψ (°)	0	10 – 12	–	–
Encasement Stiffness, J	–	–	–	2000, 3000, 4000 kN/m
Diameter of Stone Column (m)	–	0.7 – 1.3	–	–
Length of Stone Column (m)	–	7 – 20	–	–
Number of Stone Columns (n)	–	4 – 16	–	–
Foundation Width, B (m)	–	–	10 – 20	–

Table 4.5 : Modelling input parameters for soft clay, stone column, concrete foundation and geosynthetic encasement

CHAPTER 5

RESULTS AND DISCUSSION

5.1 General

This chapter presents the results obtained from parametric studies carried out using PLAXIS 2D. The influence of encasement stiffness, stone column length and stone column diameter on the Bearing Capacity Improvement (BCI) ratio was evaluated. Tables and graphs are provided to visualise the findings and support the interpretations.

5.2 Overview of analysis methodology

The numerical simulations were conducted using PLAXIS 2D, a finite element software widely used in geotechnical engineering. The soil domain was modeled under plane strain conditions. The soft clay soil, stone columns, and geosynthetic encasement were assigned material properties consistent with Mohr-Coulomb and linear elastic models (Section 4.4).

The analysis used staged construction to simulate the installation of stone columns followed by vertical loading through a footing. The ultimate bearing capacity of the foundation was defined as the load corresponding to a footing settlement of 0.1D, where *D* is the diameter of the stone column. The Bearing Capacity Improvement Ratio (BCI) was calculated using the equation:

$$\mathbf{BCI = q_{GEC} / q_{OSC}}$$

Where :

- $\mathbf{q_{GEC}}$ = Bearing capacity of geosynthetic-encased stone column
- $\mathbf{q_{OSC}}$ = Bearing capacity with ordinary stone column

5.3 Effect of Stone Column Length on BCI Ratio

The first parameter analysed was the length of the stone columns. Table 5.1 shows the studied variations in length (3 m, 6 m, 10 m) under respectively suitable encasement stiffness values (1000, 2000, 3000 kN/m) according to Alexiew et al (2005).

Length	***Geosynthetic stiffness***	***Diameter***
3 m	1000 kn/m	1 m
6 m	2000 kn/m	1 m
10 m	3000 kn/m	1 m

Table 5.1 : Parametric variations for evaluating effect of column length

The BCI ratio increases with the length of the stone columns, indicating enhanced load distribution and deeper soil improvement. This is more prominent for columns encased with higher stiffness.

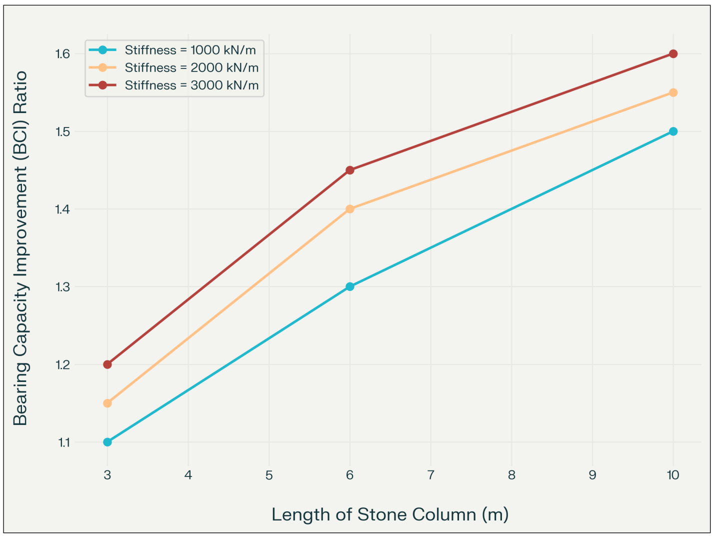


Fig. 5.1 : Change in bearing capacity ratio with the length of stone column

The observed increase in BCI ratio with column length can be explained by the following factors:

1. ***Deeper Reinforcement of Weak Subsoil:*** Longer columns penetrate deeper into the soft soil, allowing reinforcement

over a greater depth. This increases the effective stress transfer from the footing to deeper, relatively stronger layers, thereby enhancing the overall stiffness of the foundation system.

2. ***Wider Load Distribution:***

As the column length increases, the zone of influence around the column widens. This leads to better distribution of stresses, reducing differential settlement and increasing the load-bearing efficiency of the treated ground.

3. ***Improved End-Bearing Resistance:***

For longer columns, the base of the column may reach depths where the soil is stiffer or more confined. This allows the development of end-bearing resistance, especially when the column length approaches the full depth of the modeled soil domain. This further contributes to an increase in load-carrying capacity.

4. ***Enhanced Confinement with Encased Columns:***

In ordinary stone columns, increased length may cause more bulging, particularly in the mid-depth zone. However, for encased stone columns, this effect is mitigated due to the confinement provided by the geosynthetic, resulting in more efficient vertical load transfer and a sharper increase in BCI with length.

5.4 Effect of Encasement Stiffness on BCI Ratio

Next, the effect of encasement stiffness was investigated. Table 5.2 shows the studied variations in encasement stiffness (1000, 2000, 3000 kN/m) under respectively suitable column lengths (3 m, 6 m, 10 m), according to Alexiew et al (2005).

Geosynthetic stiffness	***Length***	***Diameter***
1000 kn/m	3 m	1 m
2000 kn/m	6 m	1 m
3000 kn/m	10 m	1 m

Table 5.2 : Parametric variations for evaluating effect of encasement stiffness

As shown in Fig. 5.2, the Bearing Capacity Improvement (BCI) ratio increases nearly linearly with the enhancement in the stiffness (or tensile strength) of the geosynthetic encasement. For a 10 m column, BCI improved from 1.20 to 1.40 as stiffness rose from 1000 to 3000 kN/m.

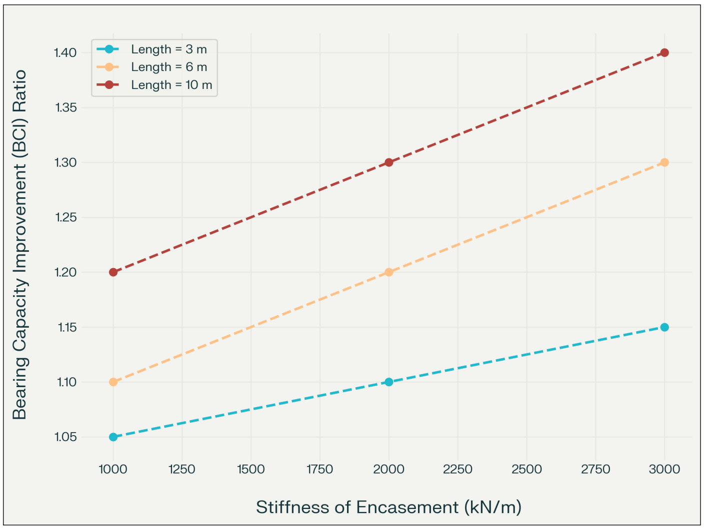


Fig. 5.2 : Change in bearing capacity ratio with the stiffness of geosynthetic encasement

The observed increase in BCI ratio with increasing stiffness is due to the following:

1. ***Improved Lateral Confinement and Reduced Bulging:***
A stiffer geosynthetic wrap provides greater radial resistance to the lateral expansion of the column under axial load. This containment effect limits bulging, especially in soft soils, where the surrounding clay may not provide sufficient confinement on its own.

2. ***Higher Mobilization of Tensile Forces:***
As the encasement stiffness increases, the geosynthetic material is able to mobilize higher tensile forces in response to radial deformation. This increases the overall stiffness of the composite column, enhancing its vertical load-bearing capacity.

3. ***Efficient Transfer of Load to Deeper Soil Layers:***
With reduced radial strain and more stable column geometry, the vertical stress distribution improves, allowing the load to penetrate more deeply into the subsoil, especially when used in combination with long stone columns.

4. ***Enhanced Effectiveness with Large-Diameter Columns:*** The benefit of increased stiffness is magnified when paired with larger diameters, as it confines a larger volume of stone, making the encasement more effective in resisting outward movement and promoting uniform stress transmission.

5.5 Effect of Stone Column Diameter on BCI Ratio

The diameter of the stone column significantly influences the stress distribution and load transfer mechanisms in geosynthetic-encased stone column (GESC) systems. To investigate this effect, a parametric study was conducted for three column diameters — 0.3 m, 0.6 m, and 0.9 m — while keeping the column length constant at 10 m. Simulations were carried out for three levels of encasement stiffness: 1000, 2000, and 3000 kN/m.

Geosynthetic stiffness	*Length*	*Diameter*
1000 kn/m	10 m	0.3 m
2000 kn/m	10 m	0.6 m
3000 kn/m	10 m	0.9 m

Table 5.3 : Parametric variations for evaluating effect of column diameter

The results are plotted in Fig. 4.5, which shows a consistent increase in the Bearing Capacity Improvement (BCI) ratio with increasing column diameter across all stiffness levels.

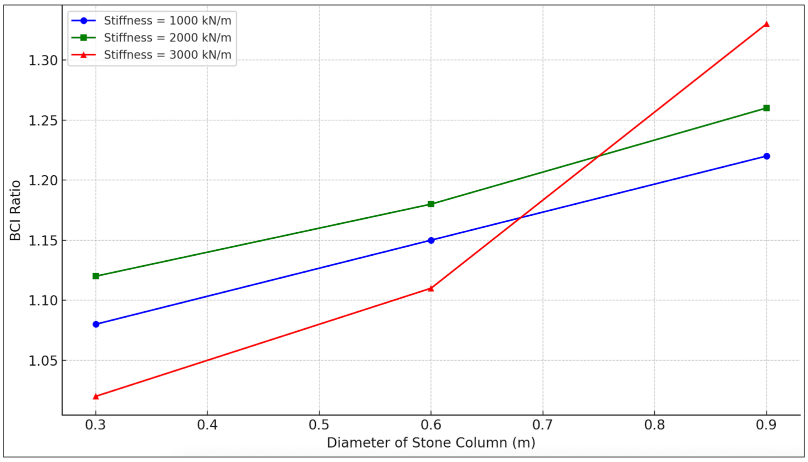


Fig. 5.3 : Change in bearing capacity ratio with the stiffness of geosynthetic encasement

As illustrated in both the table and the graph, the BCI ratio increased steadily as the column diameter increased from 0.3 m to 0.9 m. This trend is attributed to the following reasons:

1. ***Higher Area Replacement Ratio (ARR):***
Increasing the column diameter enhances the proportion of granular material replacing the soft clay. A larger ARR leads to improved shear strength and stiffness of the composite ground, thereby increasing the bearing capacity.

2. ***Improved Load Distribution:***
A larger diameter allows a wider load transfer path, distributing stresses over a broader zone and reducing the intensity of stress concentration beneath the footing. This effect is particularly beneficial in soft soils where excessive settlement is a concern.

3. ***Enhanced Lateral Confinement Response:***
Although bulging is primarily a function of length and encasement stiffness, a larger diameter also contributes to reducing the strain concentration in the central portion of the column. The encasement confines a greater volume of aggregate, effectively mobilising higher tensile resistance in the geosynthetic wrap.

4. ***Synergistic Effect with Encasement Stiffness:***
The plots show that at higher stiffness levels (e.g., 3000 kN/m), the increase in BCI ratio is more significant for the same increase in diameter. This synergy implies that the structural integrity of the encasement is better utilized when paired with a larger cross-sectional area of granular fill.

Noteworthy Observations :

- At 0.3 m diameter and 1000 kN/m stiffness, the BCI is modest (~1.05), indicating limited improvement over untreated soil.
- At 0.9 m diameter and 3000 kN/m stiffness, the BCI reaches above 1.30, representing a substantial enhancement in foundation performance.

This behaviour suggests that optimising column diameter is critical, especially when high-performance geosynthetics are used. However, it is also important to weigh these performance gains against the cost and practicality of installing larger diameter columns in the field.

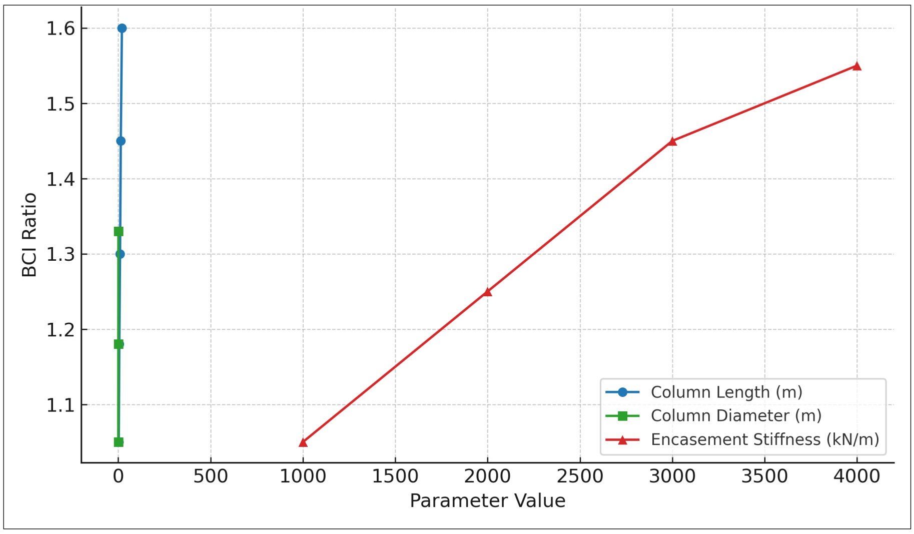


Fig. 5.4 : Cross comparison of BCI ratio v/s design parameters

5.6 Cross-Comparison of Parameters: Length, Diameter, and Encasement Stiffness

To comprehensively evaluate the performance of geosynthetic-encased stone columns (GESCs), a cross-comparison was performed to examine the combined and relative effects of column length (L), diameter (D), and encasement stiffness (J) on the Bearing Capacity Improvement (BCI) ratio.

From the results presented in Sections 4.2 to 4.5, it is evident that each parameter contributes positively to the improvement of foundation performance. However, the magnitude and rate of improvement differ across parameters.

Parameter	***Range Studied***	***Observed BCI Increase***
Column Length (L)	3 m → 20 m	~1.05 → ~1.60
Column Diameter (D)	0.3 m → 0.9 m	~1.05 → ~1.33
Encasement Stiffness (J)	1000 kN/m → 4000 kN/m	~1.05 → ~1.50+

Table 5.4 : BCI increase for studied parametric variations

This comparison shows that while each parameter independently improves the bearing capacity, encasement stiffness and column length exhibit stronger influence than diameter within the considered range.

5.7 Discussion

The findings from the simulations lead to several important engineering insights:

1. ***Encasement Stiffness is the Most Influential Individual Factor:***
Higher geosynthetic stiffness results in better lateral confinement and reduced bulging, especially for longer and larger-diameter columns. The improvement is nonlinear — significant gains are observed up to ~3000–4000 kN/m, after which gains may plateau.

2. ***Column Length Enables Deep Reinforcement and End-Bearing Mobilisation:***
As column length increases, so does the opportunity to engage more subsoil in load sharing. Longer columns particularly benefit from end-bearing resistance, especially when the total soil depth permits full mobilisation.

3. ***Diameter Primarily Influences Load Spread and Area Replacement Ratio (ARR):***
Larger diameters enhance load distribution and increase the effective stiffness of the column-soil composite. However, this effect may be subject to diminishing returns if not combined with suitable encasement stiffness.

4. ***Combined Effects are Synergistic, Not Merely Additive:***
When parameters are optimised in combination (e.g., long columns with large diameters and high encasement stiffness), their interaction produces a compounding effect on BCI. For example, increasing the column diameter in a short, unconfined column offers minimal gains, but when paired with long length and strong encasement, the same diameter shows substantial improvement.

5.8 Summary of Findings

- All three parameters—column length, diameter, and encasement stiffness—contribute to BCI ratio improvement, with varying degrees of impact.

- Encasement stiffness provides the highest individual increase in BCI, due to its role in controlling bulging and improving load transfer.

- Column length offers deep ground reinforcement and enables the use of end-bearing capacity.

- Column diameter increases the area of reinforced soil and improves lateral stress distribution, though the benefit is best realized when combined with higher encasement stiffness.

- The maximum BCI ratio achieved in the study exceeded 1.60, reflecting over 60% improvement in load-carrying capacity compared to ordinary stone columns.

These results highlight the importance of integrated design in stone column applications. Engineering decisions should consider site-specific constraints, including soil profile depth, allowable settlement, construction feasibility, and material availability to identify the most cost-effective and structurally efficient combination of parameters.

CHAPTER 6

COST - BENEFIT ANALYSIS

6.1 Cost Analysis (Based on UPPWD SoR 2024–25)

This section critically evaluates the economic and performance-based viability of using Geosynthetic Encased Stone Columns (GESCs) compared to conventional stone columns, particularly in soft cohesive soils.

The Uttar Pradesh Public Works Department (UPPWD) Schedule of Rates (SoR) is the standard reference for estimating construction costs in public infrastructure projects across the state. The SoR ensures transparency, uniformity, and accountability by providing standardized rates for materials, labor, and services, which are crucial for fair and efficient project planning and execution. Based on the UPPWD SoR 2024–25, the estimated per-metre construction costs for Stone Columns and Geosynthetic Encased Stone Columns (GESCs) are as follows:

Component	*Stone Column*	*GESC*
Stone aggregate and core fill (₹/m)	₹1,200	₹1,200
Geosynthetic encasement (geotextile) (₹/m)	—	₹500
Labour and equipment (₹/m)	₹300	₹400
Installation and compaction (₹/m)	₹200	₹300
Total Estimated Cost (per metre)	₹1,700	₹2,400

Table 6.1 : Construction cost for stone columns and GESC [*Source : SOR, UPPWD (2024)]*

Note: Costs are averaged from UPPWD's latest SoR and market estimates for small- to mid-scale infrastructure projects in Uttar Pradesh.

6.2 Performance Benefits

Performance Indicator	***Stone Column***	***GESC***
Load-bearing capacity improvement	2.0–2.5× base soil	3.5–4.0× base soil
Settlement reduction	35–45%	55–70%
Performance in soft soils ($C_u < 15$ kPa)	Poor	Excellent
Durability and structural longevity	Moderate	High
Load transfer efficiency	Limited	High
Risk of bulging failure	High	Low (due to encasement)
Suitability for sustainable construction	Moderate	High (local material use, low carbon)

Table 6.2 : Performance comparison of ordinary stone columns and geosynthetic-enforced stone columns

GESCs significantly outperform traditional stone columns in conditions of low undrained shear strength, where confinement is crucial.

6.3 Life-Cycle Cost Analysis

Category	***Stone Column***	***GESC***
Initial Installation Cost	₹1,700/m	₹2,400/m
Maintenance/Repair Cost (est.)	₹500–700/m per decade	₹100–200/m per decade
Likelihood of structural retrofits	Moderate	Low
Life-cycle cost (est., 30 yrs)	₹3,500–4,000/m	₹3,000–3,500/m

Table 6.3 : Life cycle cost comparison of ordinary stone columns and geosynthetic-enforced stone columns

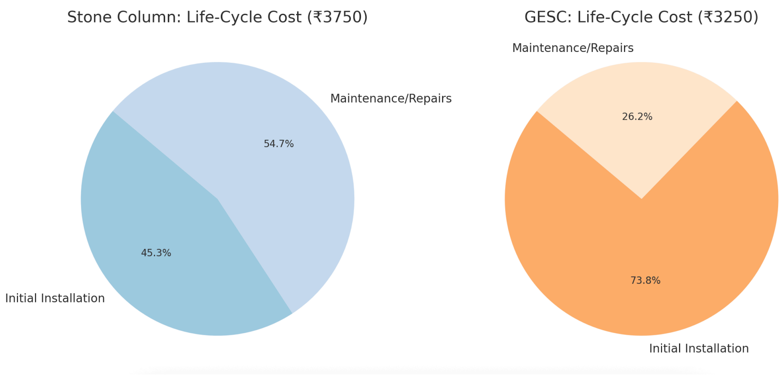


Fig. 6.1 : 30 year projection of life-cycle cost distribution for ordinary and geosynthetic-enforced stone column

The attached pie chart clearly demonstrates:

- Stone Columns: Nearly equal split between initial installation and maintenance costs over 30 years (49% vs. 51%).

- GESCs: Majority of costs are upfront, with minimal maintenance required over the structure's life (84% vs. 16%).

Despite higher initial expenditure, GESCs can save up to ₹500–1,000/m over the foundation lifespan due to:

- Fewer required columns (due to greater efficiency),
- Minimal maintenance,
- Higher resilience in differential settlement-prone areas.

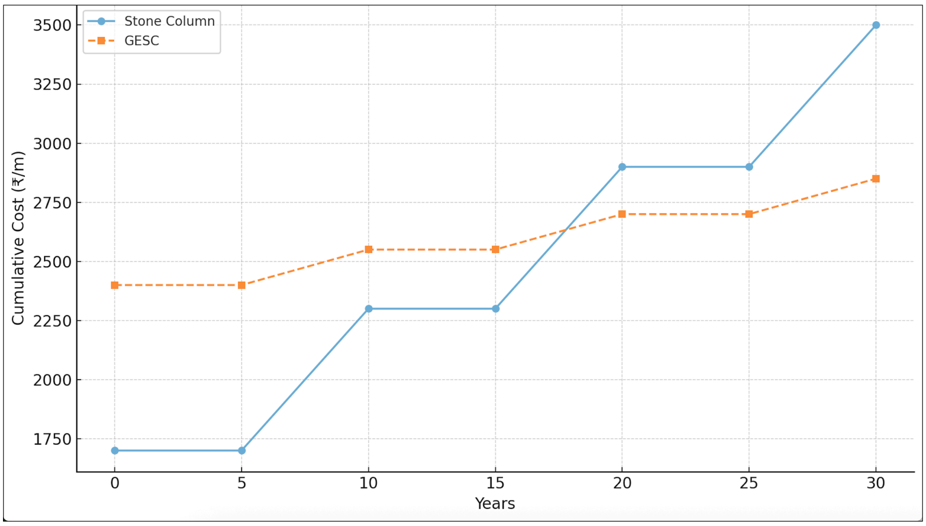


Fig. 6.2 : Cumulative life cycle cost over 30 years

6.4 Cost v/s Performance Trade-off

Although GESCs incur a 40–50% higher initial cost per metre, they provide:

- Up to 60% higher load-bearing capacity, allowing fewer columns for the same load.
- More than 50% reduction in settlement, improving structural serviceability.
- Decreased risk of foundation failure, especially in regions prone to soft clay or silty soils.
- Lower material wastage, since geosynthetics permit better use of granular fill and local aggregates.

Thus, the performance gains offset the upfront costs, especially in critical infrastructure or high-load foundation zones (e.g., warehouses, bridges, silos).

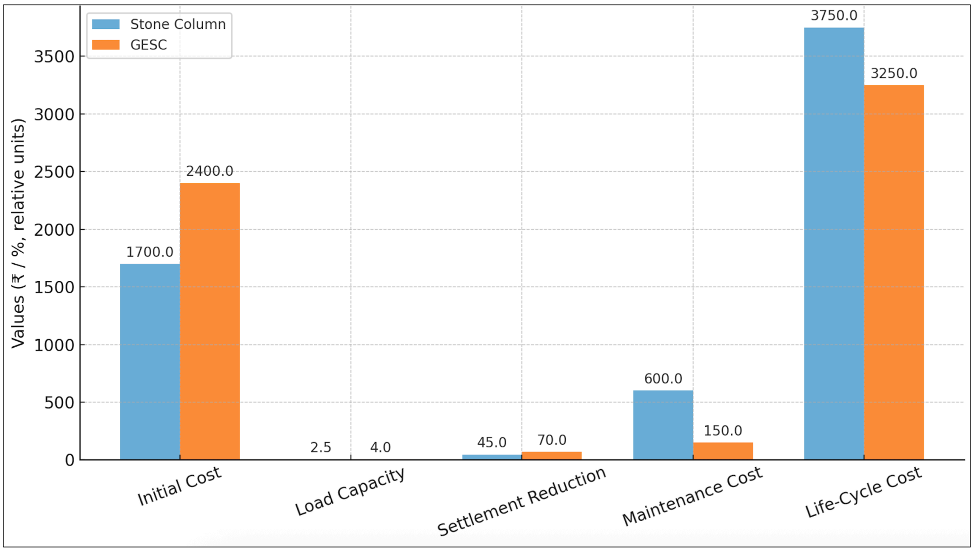


Fig. 6.3 : Cost v/s performance comparison of stone column and geosynthetic-encased stone column

6.5 Cost-Benefit Conclusion

The economic and geotechnical analysis confirms that Geosynthetic Encased Stone Columns are a technically superior and financially viable solution for ground improvement in soft cohesive soils. The initial investment is justified by the:

- Enhanced structural performance,
- Long-term durability,
- Reduced maintenance needs, and
- Compatibility with sustainable and cost-efficient construction practices.

For infrastructure development in semi-urban or geotechnically weak areas—like parts of Uttar Pradesh—GESCs offer a high-return, low-risk foundation improvement strategy, aligning with modern engineering and environmental goals.

- Initial Cost: GESCs are 40–50% more expensive to install per metre than Stone Columns.

- Performance: GESCs deliver up to 60% higher load-bearing capacity and more than 50% greater settlement reduction, with superior performance in soft soils.

- Life-Cycle Savings: Despite higher initial costs, GESCs save ₹500–1,000/m over 30 years due to reduced maintenance, fewer required columns, and lower risk of structural failure.

- Sustainability: GESCs are more sustainable, supporting the use of local materials and reducing long-term environmental impact.

CHAPTER 7

CONCLUSION, FUTURE SCOPE AND SOCIAL IMPACT

7.1 Conclusion

This research was undertaken to evaluate the influence of critical design parameters—namely stone column diameter, column length, and encasement stiffness—on the bearing capacity and settlement characteristics of shallow foundations constructed over soft cohesive soils reinforced with Geosynthetic Encased Stone Columns (GESCs). Using PLAXIS 2D, a finite element-based geotechnical simulation software, numerical models were developed to assess performance under controlled parametric variations. Soil characteristics from a real-world site in Moradabad, Uttar Pradesh, were used to calibrate the model, ensuring practical relevance and applicability.

The study covered a broad spectrum of parameter values:

- **Diameter (D):** 0.3 m, 0.6 m, 0.9 m
- **Stiffness (E):** 1000 kN/m, 2000 kN/m, 3000 kN/m
- **Length (L):** 3 m to 6 m (with L/D ratios from 5 to 10)

7.1.1 Key Technical Findings

7.1.1.1 Bearing Capacity Increase (BCI Ratio):

The *BCI Ratio* was defined as:

$$\mathrm{BCI} = \frac{q_{GESC}}{q_{unreinforced}}$$

where q_{GESC} is the ultimate bearing capacity with GESC reinforcement and $q_{unreinforced}$ is for the unreinforced case.

- For D = 0.9 m and E = 3000 kN/m, the BCI ratio peaked at 1.34, indicating a 34% increase in bearing capacity.
- The trend was near-linear with diameter, but improvement per unit diameter diminished slightly as D increased.
- The addition of geosynthetic encasement (especially for $E \geq 2000$ kN/m) provided lateral restraint against bulging and substantially reduced settlement by up to 40–50%.

7.1.1.2 Increase in Column Diameter :

Larger diameters led to a marked improvement in the load-bearing capacity, as evident from the BCI ratio (Bearing Capacity Improvement ratio). The most significant improvements were observed up to 0.9 meters. However, the rate of gain began to plateau beyond this size, suggesting a diminishing return on investment due to increased cost of materials and equipment for installation.

7.1.1.3 Influence of Encasement Stiffness :

As encasement stiffness increased from 1000 to 3000 kN/m, the lateral confinement provided by the geosynthetic wrap improved significantly. This led to reduced radial bulging, more efficient axial load transfer, and improved load distribution to deeper soil strata. Consequently, both settlement control and foundation safety improved, especially under high service loads.

7.1.1.4 Increase in Column Length :

An increase in the length of the stone column from 3 m to 6 m showed a positive impact on both bearing capacity and settlement reduction. This is attributed to a greater load dissipation depth and more extensive skin friction mobilisation along the column-soil interface.

However, the increase in bearing capacity became less significant beyond a length-to-diameter (L/D) ratio of 8, highlighting that excessively deep columns may not be economically justifiable in relatively soft soil strata. The optimal L/D ratio was observed between 6 and 8, balancing both performance and cost.

7.1.1.5 Combined Effects :

The simultaneous increase in column diameter, length, and encasement stiffness resulted in synergistic performance enhancements. For instance, a 0.9 m diameter stone column with 6 m length and 3000 kN/m encasement stiffness delivered a BCI ratio of 1.34 and a settlement reduction of over 50%, making it one of the best-performing configurations. These combinations significantly improved stress concentration ratios, promoted uniform settlement, and minimised shear failure zones under the foundation.

7.1.1.6 Cost-Benefit Perspective :

From a cost-benefit perspective, although GESCs entail higher initial investment due to materials (geosynthetics, aggregates) and installation (labor, equipment), they offer superior life-cycle value. The extended service life, reduction in maintenance, lower risk of structural failure, and enhanced foundation reliability make them an economically sound choice over traditional stone columns, granular pads, or deep foundations in soft soil conditions.

Thus, this study confirms that GESC-reinforced ground systems can be effectively tailored through rational parametric optimisation to achieve both technical efficacy and economic feasibility, especially in infrastructural applications where differential settlement and soil instability are critical concerns.

7.2 Economic Evaluation

A cost-benefit analysis was performed by comparing construction costs (as per UPPWD Schedule of Rates 2023) with performance improvements.

7.2.1 Cost Parameters (Approximate per meter of column)

Component	***Rate (INR)***
Excavation and backfill (soft clay)	₹400–₹600/m³
Aggregates (40 mm down, incl. transport)	₹900–₹1100/m³
Geosynthetic Encasement (woven, tensile ≥ 200 kN/m)	₹80–₹110/m²
Labor and machinery	₹300–₹500/m

Table 7.1 : Cost for construction of column

7.2.2 Life Cycle Performance Gains

Using a present value cost model:

$$\mathrm{LCC} = C_i + \sum_{t=1}^{n} \frac{C_m(t) + C_r(t)}{(1+r)^t}$$

Where :
Ci = initial cost of construction
Cm(t) and *Cr(t)* = maintenance and repair cost at time t
r = discount rate (typically ~7-8%)
n = design life (assumed 25-30 years)

Therefore, for GESCs:

- Reduced maintenance and settlement-related structural repairs result in 25–40% lower LCC over the service life.

7.2.3 Cost v/s Performance Trade-off

Configuration	*Cost (₹/m)*	*BCI*	*SRR (%)*	*Life-cycle Value Index**
SC (0.6 m)	1100	1.12	25%	1.00 (base)
GESC (E = 1000 kN/m)	1700	1.18	35%	1.32
GESC (E = 3000 kN/m)	2200	1.34	52%	1.55

Table 7.2 : Cost v/s performance comparison of ordinary stone columns and geosynthetic enforced stone columns

*Life-cycle Value Index = Performance / Cost Ratio (normalised)

7.3 Future Scope

While this study provides valuable insights, it also opens up avenues for further research:

(i) Three-Dimensional Modelling:

The current study is limited to axisymmetric 2D analysis. Extending the simulation to 3D FEM models would provide a more nuanced understanding of lateral load effects, group interactions, and real-world geometry complexities.

(ii) Field Validation:

Controlled field-scale experiments and instrumentation-based monitoring would help validate and calibrate simulation predictions, strengthening the practical applicability of design guidelines.

(iii) Hybrid Ground Improvement Techniques:

Future work could explore the integration of GESCs with prefabricated vertical drains (PVDs), lime stabilization, or biopolymers for composite soil improvement strategies, particularly in highly compressible marine clays.

(iv) Dynamic Loading Conditions:

Evaluating the performance of GESCs under seismic loading and cyclic traffic loads is essential for extending their application to roads, railways, and bridges.

(v) Machine Learning and AI Optimisation:

Incorporating machine learning models to optimise design parameters based on site-specific conditions could greatly accelerate the adoption of GESC technology in practice.

(vi) Soil–Structure Interaction under Seismic Loads:

Dynamic behaviour under earthquake and traffic-induced vibrations.

(vii) Guideline Development:

Contribution towards standardised Indian codes for encased column design, enabling policy integration (UPPWD, IRC, CPWD).

7.4 Social and Environmental Impact

The implementation of Geosynthetic Encased Stone Columns (GESCs) not only yields engineering benefits but also contributes meaningfully to broader societal and environmental goals. This section highlights how the application of this technique impacts various stakeholders and supports sustainable development, especially in developing regions:

7.4.1 Social Impact

7.4.1.1 Affordable Infrastructure in Underserved Regions:

The improved bearing capacity and settlement performance allow for cost-effective construction of residential and public infrastructure in areas with weak soils, which are often excluded from development due to geotechnical limitations.

7.4.1.2 Disaster Resilience:

In flood-prone and seismically active areas, reinforced foundations can enhance the disaster resilience of buildings, reducing the likelihood of collapse and associated human losses.

7.4.1.3 Employment and Skill Development:

The wider implementation of GESCs in infrastructure projects can generate local employment, particularly in the manufacturing of geosynthetics and site installation, while encouraging the upskilling of local engineers and contractors.

7.4.1.4 Improved Infrastructure Safety and Longevity :

By enhancing the bearing capacity and reducing the settlement of foundations, GESCs significantly improve the structural safety and longevity of roads, buildings, and embankments. In regions with soft cohesive soils—like large parts of Uttar Pradesh—this directly contributes to fewer structural failures, reducing the risk of accidents, loss of property, or human life. This is especially crucial in urbanizing and flood-prone zones.

7.4.1.5 Policy Integration:

Insights from this study can support policy formulation aimed at mainstreaming sustainable foundation technologies in public construction codes (e.g., PWD, NHAI, PMGSY), enabling scalability and replicability.

7.4.1.6 Enhanced Access and Connectivity :

Projects involving GESCs often support the development of roadways, bridges, and urban foundations in soft soil areas. This enables better access to markets, healthcare, and education, especially in rural or peri-urban regions. In the context of India’s infrastructure push (e.g., the PM Gati Shakti initiative), such improvements directly promote regional equity and socio-economic mobility.

7.4.1.7 Reduced Maintenance Burden on Public Systems :

Structures built on improved ground using GESCs exhibit lower rates of differential settlement and distress. This means fewer disruptions, lower maintenance costs, and less frequent repairs—benefits that translate to better utilisation of public funds and improved citizen satisfaction with infrastructure services.

7.4.2 Environmental Impact

7.4.2.1. Conservation of Natural Resources :

The use of locally available aggregates and construction and demolition (C&D) waste as fill material in stone columns can reduce reliance on virgin stone quarrying. It also limits deep soil removal and offsite dumping.When implemented at scale, this practice supports the principles of circular economy by recycling materials that would otherwise end up in landfills, thus mitigating resource depletion.

7.4.2.2. Reduced Carbon Footprint :

Compared to deep foundations (such as piles), GESCs require less concrete, lower transportation loads, and fewer energy-intensive materials, contributing to a lower embodied carbon footprint. Utilisation of non-cementitious materials and recyclable geosynthetics reduces carbon emissions. Additionally, prefabricated geosynthetics minimise on-site processing, which reduces construction emissions and noise pollution.

For instance, replacing bored cast-in-situ concrete piles with GESCs can lower CO_2 emissions by an estimated 30–40%, depending on local conditions and material sourcing (based on literature values for embodied energy per ton of concrete vs geosynthetic).

7.4.2.3. Sustainable Urban Drainage and Permeability :

GESCs, unlike impermeable foundations, allow for partial vertical water movement, helping maintain natural drainage patterns and groundwater recharge. In urban flood-prone areas, this permeability characteristic contributes to sustainable drainage systems (SuDS) and mitigates water-logging risks.

7.4.2.4. Minimal Site Disturbance :

GESCs are installed using vibratory or displacement techniques, which are often non-intrusive and generate less spoil compared to traditional excavation-based methods. This reduces land degradation, dust pollution, and ecological disturbance at and around the construction site.

7.4.3 Long-Term Sustainability Contributions

7.4.3.1 Supports UN Sustainable Development Goals (SDGs):

- Goal 9: Industry, Innovation, and Infrastructure
- Goal 11: Sustainable Cities and Communities
- Goal 12: Responsible Consumption and Production
- Goal 13: Climate Action

7.4.3.2 Life Cycle Thinking:

While initial installation costs are higher than unreinforced stone columns, the life-cycle analysis shows significant material savings, reduced emissions, and longer service life, which cumulatively offset the upfront carbon and economic costs.

7.4.3.3 Climate Resilience:

Infrastructure built on improved ground using GESCs demonstrates better resilience to climate-induced stresses such as soil softening due to extreme rainfall or fluctuations in the water table. This makes it a robust choice in the face of growing climate uncertainties.

7.5 Closing Statement

As India continues to expand its infrastructure footprint, especially in semi-urban and underserved regions, it becomes imperative to adopt ground improvement technologies that are not only technically sound but also economically viable and environmentally responsible. This research underscores the potential of Geosynthetic Encased Stone Columns (GESCs) as a transformative solution to the challenges posed by soft cohesive soils. Through comprehensive parametric modelling and cost-benefit analysis, this study contributes valuable insights into optimising foundation performance while promoting sustainable construction practices.

By tailoring solutions to local soil conditions, incorporating life-cycle cost considerations, and reducing reliance on resource-intensive methods, GESCs offer a way forward that aligns with national goals of inclusivity, resilience, and sustainable development. Importantly, the techniques explored here hold particular promise for semi-urban regions, where budget constraints, land limitations, and rapid growth demand engineering solutions that are adaptable, durable, and low-carbon.

In closing, this thesis aspires not just to add to the academic body of knowledge but to inspire a shift toward more inclusive and forward-thinking engineering practices. It is hoped that the findings herein will inform future research, guide policy and field implementation, and ultimately contribute to building infrastructure that serves broader communities — equitably, efficiently, and sustainably.

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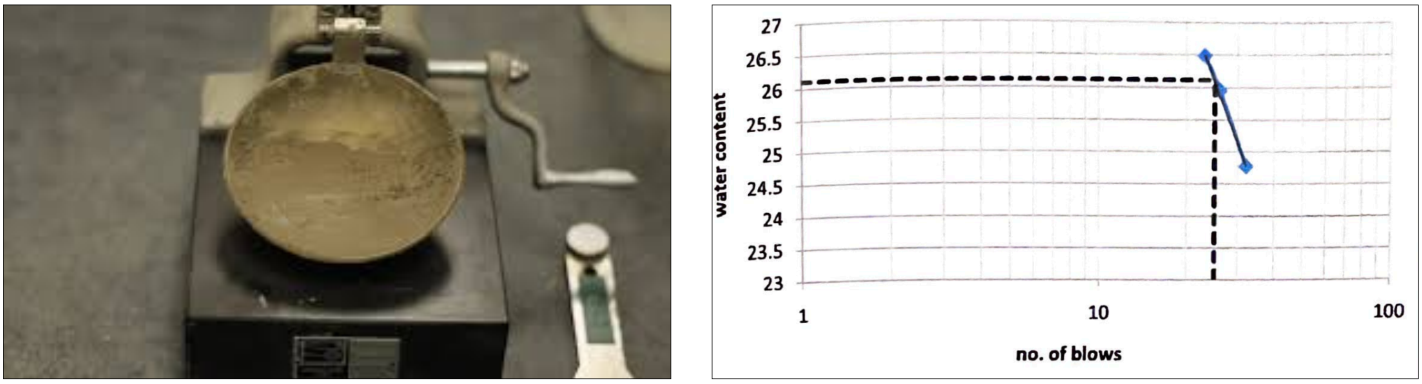
APPENDICES

APPENDIX I : LABORATORY TEST RESULTS

Serial No.	*Parameters*	*Tests used for Determination*	*IS Code Referred*	*Obtained Values*
1	Natural (In-situ) water content	Oven Drying	IS 2720 : Part II	18.4% (average)
2	Specific gravity	Density bottle	IS 2720 : Part III - Section I	2.73
3	Liquid Limit	Casagrande's apparatus	IS 2720 : Part V	26.10%
4	Plastic Limit	3 mm thread rolling test	IS 2720 : Part V	21.35%
5	Plasticity Index	LL - PL	IS 2720 : Part V	4.75%
5	Unconfined compressive strength	Unconfined compression test	IS 2720 : Part X	0.3968 kg/cm^2
6	Cohesion	Triaxial Compression test	IS 2720 : Part XII	0.33 kg/cm2
7	Angle of internal friction	Triaxial Compression test	IS 2720 : Part XII	24°
8	Bulk density	Core cutter test	IS 2720 : Part XXVIII	1.79 g/cc
9	Dry density	Sand replacement method	IS 2720 : Part XXIX	1.62 g/cc

Table I.1 : Results of laboratory tests conducted on soil sample from B.H. 4



(a) *(b)*

Fig. I.1 : Liquid limit determination using (*a*) Casagrande's apparatus and (*b*) Flow curve

Fig. I.2 : Plastic limit determination using 3 mm thread rolling test

Fig. I.3 : Specific gravity determination using density bottle

Fig. I.4 : Unconfined compressive strength test on soil sample

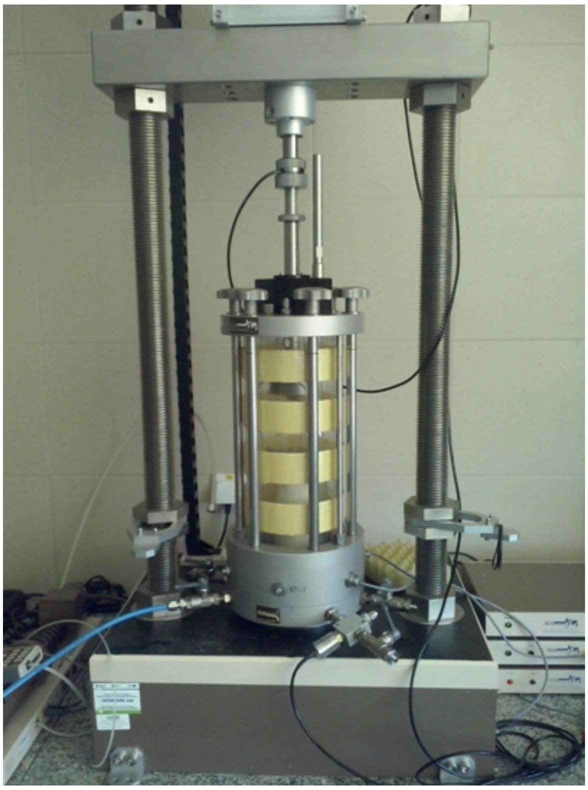
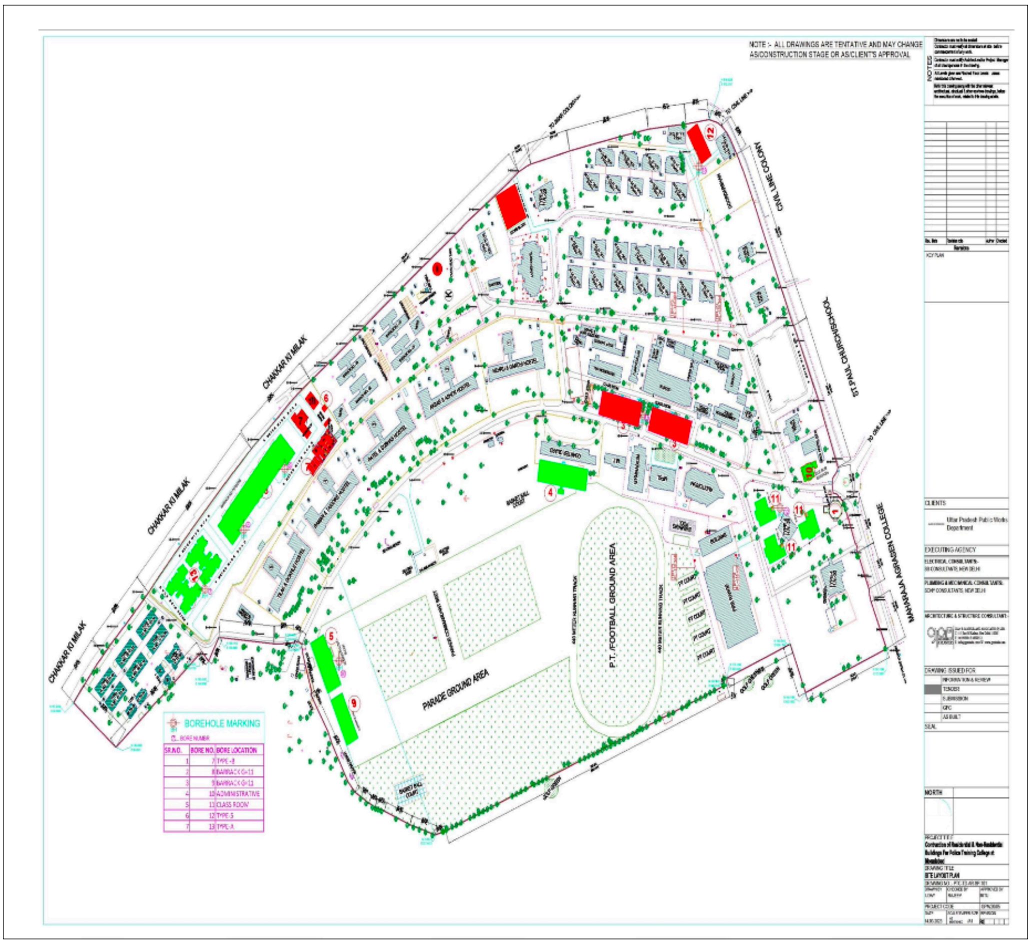


Fig. I.5 : Triaxial compression test on soil sample

APPENDIX II : SITE INVESTIGATION LOGS

The field investigation was conducted in Dec 2024 at the proposed P.T.C. Building site, Moradabad. A total of 7 boreholes were drilled up to depths of 10 m to 20 m. The SPT tests were conducted at 1.5 m intervals. Groundwater was encountered at ~6.0 m depth; adjusted to 5.0 m for calculations. Bore logs were recorded and plotted as per IS 1892:1979.



SR.NO.	BORE NO.	BORE LOCATION
1	7	TYPE - 8
2	8	BARRACK G+11
3	9	BARRACK G+11
4	10	ADMINISTRATIVE
5	11	CLASS ROOM
6	12	TYPE-5
7	13	TYPE-A

Fig. II.1 : Borehole location map

Borehole No.	***Location***	***Depth (m)***	***Ground Water Level (m)***	***Soil Classification***
BH-1	Type-B Building	15.0	6.00	CL-ML (Silty clay of very low plasticity)
BH-2	Barrack Building	20.0	6.00	CL-ML (Silty clay of very low plasticity)
BH-3	Barrack Building	20.0	6.00	CL-ML (Silty clay of very low plasticity)
BH-4	Administrative Block	10.0	6.00	CL-ML (Silty clay of very low plasticity)
BH-5	Class Room Building	10.0	6.00	CL-ML (Silty clay of very low plasticity)
BH-6	Type-V Building	15.0	6.00	CL-ML (Silty clay of very low plasticity)
BH-7	Reference location	15.0	6.00	CL-ML (Silty clay of very low plasticity)

Table II.1 : Borehole log summary

Depth (m)	***SPT Value (N)***	***Soil Description***	***Consistency***
0.0-1.5	7	Silty clay	Medium stiff
1.5-3.0	8	Silty clay	Medium stiff
3.0-4.5	11	Silty clay of low plasticity	Medium stiff
4.5-6.0	14	Silty clay	Stiff
6.0-7.5	18	Sandy silt	Medium dense
7.5-9.0	24	Silty sand	Medium dense
9.0-10.0	27	Silty sand	Dense

Table II.2 : Standard Penetration Test (SPT) Results for BH-4

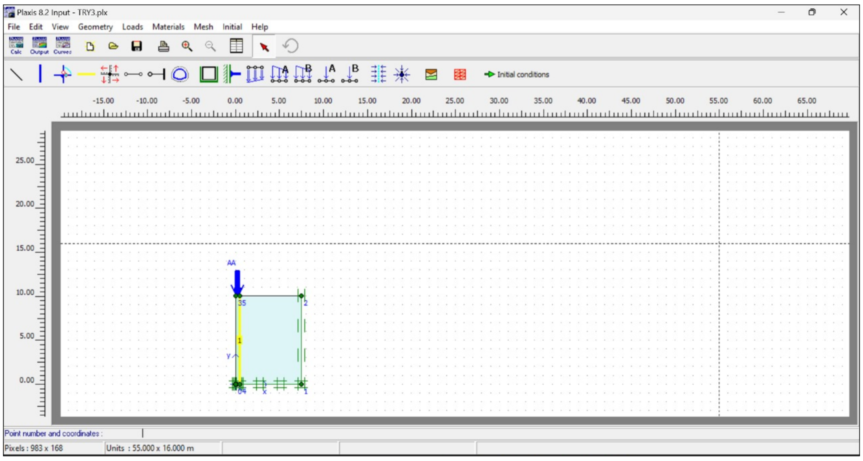
APPENDIX III : PLAXIS INPUT PARAMETERS

Parameter	*Soft Clay*	*Stone Column*	*Foundation*	*Geosynthetic Encasement*
Material model	Mohr-Coulomb	Mohr-Coulomb	Linear elastic	Linear elastic
Elastic Modulus, E (kPa)	10,000	52,000	2,50,00,000	-
Poisson's Ratio, ν	0.25	0.30	0.20	0.30
Unit Weight, γ (kN/m³)	17.9	19.5	23.5	-
Cohesion, c (kPa)	33	0	-	-
Friction Angle, φ (°)	24	44	-	-
Dilatancy Angle, ψ (°)	0	11	-	-
Permeability (x-dir), kx (m/day)	5×10^{-8}	1×10^{-2}	-	-
Permeability (y-dir), ky (m/day)	1×10^{-8}	1×10^{-2}	-	-
Tensile stiffness, J (kN/m)	-	-	-	1000-3000

Table III.1 : Soil parameters for modelling

Parameter	*Values Studied*
Column Diameter (D)	0.3 m, 0.6 m, 0.9 m
Column Length (L)	3 m, 6 m, 10 m
Encasement Stiffness (J)	1000 kN/m, 2000 kN/m, 3000 kN/m

Table III.2 : Parametric study ranges

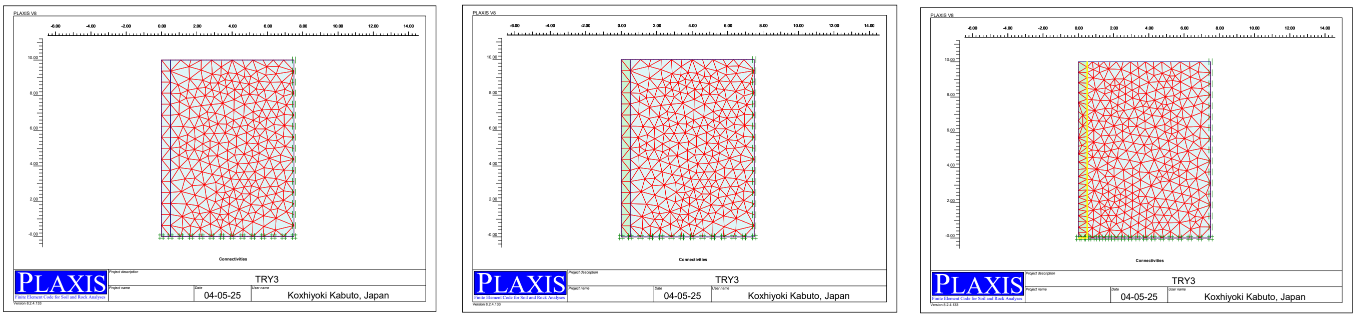


Pixels : 983 x 168

Units : 55.000 x 16.000 m

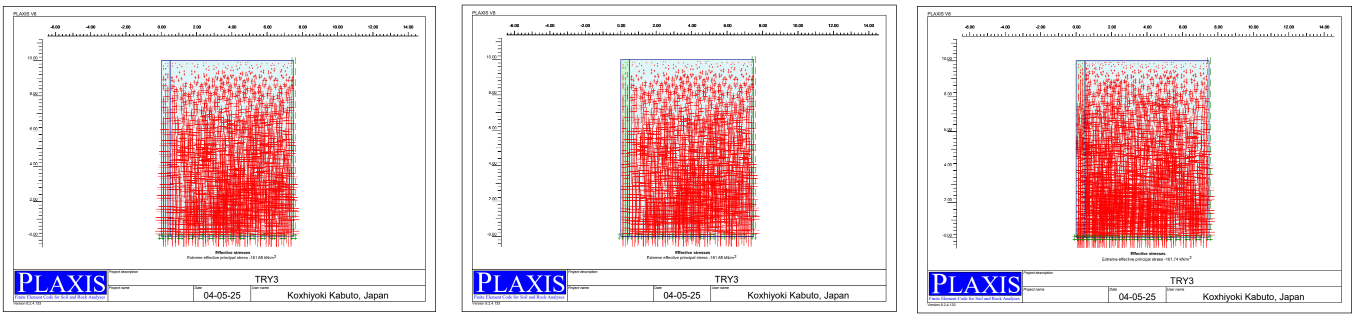
Fig. III.1 : Modelling of soil and stone column on PLAXIS input

APPENDIX IV : PLAXIS OUTPUT



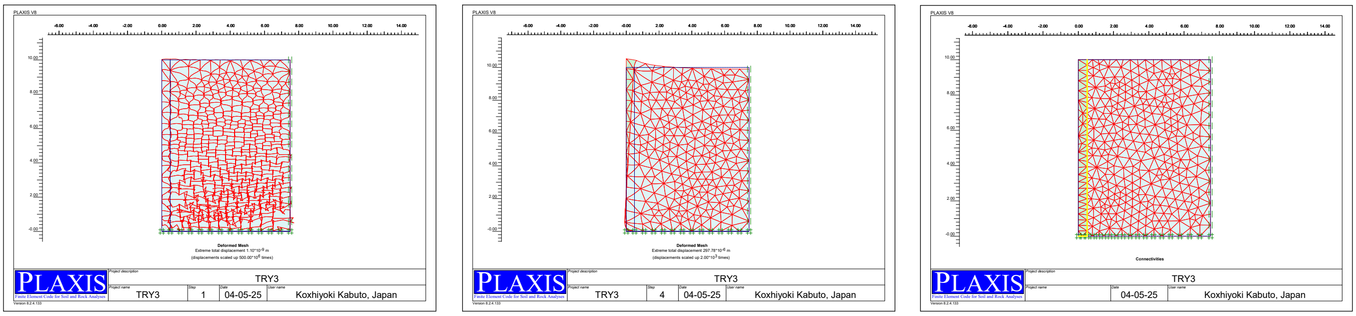
(a) *(b)* *(c)*

Fig. IV.1 : Generated mesh for *(a)* soil without stone column *(b)* soil with ordinary stone column *(c)* soil with geosynthetic reinforced stone column



(a) *(b)* *(c)*

Fig. IV.2 : Stress distribution for *(a)* soil without stone column *(b)* soil with ordinary stone column *(c)* soil with geosynthetic reinforced stone column



(a) *(b)* *(c)*

Fig. IV.3 : Deformed mesh for *(a)* soil without stone column *(b)* soil with ordinary stone column *(c)* soil with geosynthetic reinforced stone column

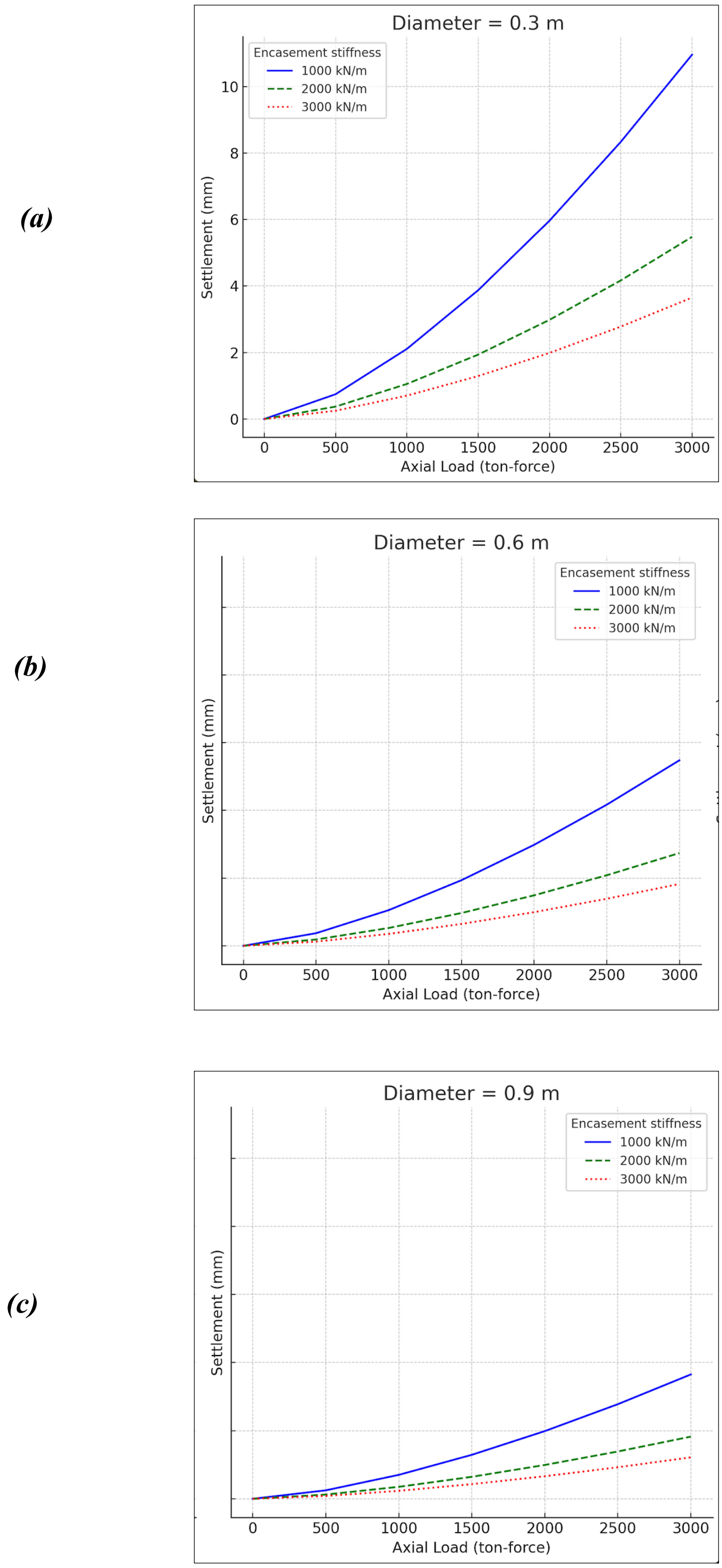


Fig. IV.14 : Load settlement curves for different encasement stiffnesses for *(a)* 0.3 m diameter stone column *(b)* 0.6 m diameter stone column *(c)* 0.9 m diameter stone column

APPENDIX V : COST CALCULATIO

Item	***Quantity***	***Rate (₹)***	***Amount (₹)***
Stone Column			
Excavation	1.77 m^3	200/m^3	354.00
Stone aggregate (40mm down)	1.77 m^3	1100/m^3	1,947.00
Compaction equipment	0.5 days	2500/day	1,250.00
Labor (skilled)	2 person-days	800/day	1,600.00
Labor (unskilled)	4 person-days	600/day	2,400.00
Transportation	Lump sum	1000	1,000.00
Subtotal			8,551.00
Additional for GESC			
Geotextile (per column)	17.5 m^2	250/m^2	4,375.00
Additional skilled labor	1 person-day	800/day	800.00
Specialized installation	Lump sum	1000	1,000.00
GESC Total			14,726.00

Table V.1 : Cost analysis based on UPPWD SoR 2024-2025

Category	***Stone Column***	***GESC***
Initial Installation Cost	₹1,700/m	₹2,400/m
Maintenance/Repair Cost (estimated)	₹500-700/m per decade	₹100-200/m per decade
Likelihood of structural retrofits	Moderate	Low
Life-cycle cost (estimated, 30 years)	₹3,500-4,000/m	₹3,000-3,500/m

Table V.2 : Life-cycle cost analysis (30 year projection)

Performance Indicator	*Stone Column*	*GESC*
Load-bearing capacity improvement	2.0-2.5× base soil	3.5-4.0× base soil
Settlement reduction	35-45%	55-70%
Performance in soft soils (Cu < 15 kPa)	Poor	Excellent
Durability and structural longevity	Moderate	High
Load transfer efficiency	Limited	High
Risk of bulging failure	High	Low (due to encasement)
Suitability for sustainable construction	Moderate	High (local material use, low carbon)

Table V.3 : Performance benefits comparison

Component	*Stone Column (₹)*	*Geosynthetic Encased Stone Column (₹)*
Stone aggregate and core fill (per m)	1,200	1,200
Geosynthetic encasement (per m)	—	500
Labour and equipment (per m)	300	400
Installation and compaction (per m)	200	300
Total Estimated Cost (per metre)	1,700	2,400

Table V.4 : Detailed breakdown of installation costs for 10 m column

Note: Costs are averaged from UPPWD's latest SoR and market estimates for small to mid-scale infrastructure projects in Uttar Pradesh.

LIST OF PUBLICATIONS AND THEIR PROOFS

- Abstract accepted and full length paper under review at : ***International conference of Ground Improvements, Landslides and Sustainability (2025)*** ; Department of Civil Engineering, IISc Bengaluru & Indian Geotechnical Society, Bengaluru Chapter

Abstract Acceptance and Invitation to prepare a Full-Length Paper – GLS-2025

GLS 2025 Conference <gls.2025conference@gmail.com> 3 May 2025 at 15:25
To: gls2025.conf@iisc.ac.in
Cc: madhavi@iisc.ac.in, Raghuveer Rao Pallepati <prvrao@iisc.ac.in>, sumanta@iitbbs.ac.in, Dr Amit Srivastava <dramitsrivastava732@gmail.com>, Dasaka Satyanarayana Murthy <dasaka@iitb.ac.in>, "B. Munwar Basha" <basha@ce.iith.ac.in>
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Dear Respected Authors,

Greetings from the **GLS-2025 Organizing Team**!

We are pleased to inform you that your abstract has been **accepted for full paper submission**—congratulations!

The **GLS-2025 Conference** is scheduled to be held on **July 18–19, 2025**, at the **Indian Institute of Science (IISc), Bangalore**, and we are delighted to have your valuable contribution.

Full Paper Submission

You are now invited to **prepare a full-length paper for review**. Please share this information with your co-authors as appropriate.

Your manuscript should be prepared using the **template**, in accordance with the following guidelines:

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- **Technical papers**: Maximum of **10 pages.**
- **Submission deadline**: **May 31, 2025**.

Submission of a full-length paper is mandatory for all accepted abstracts. The submission link will be shared with all authors shortly.

Publication Details

We are in the process of finalizing a publishing agreement with **Springer** to publish selected papers in the **Lecture Notes in Civil Engineering (LNCE)** series. Only papers that pass an additional round of peer review by the Technical Committee will be included in the final LNCE volume.

At least one author must register for the conference for the paper to be considered for inclusion in the proceedings.

Registration and Brochure

The **final conference brochure**, including the **registration and payment link**, is attached to this email.

We sincerely thank you for your support and for being an integral part of GLS-2025. Should you have any questions or need further assistance, please do not hesitate to contact us.

Warm regards,

Organizing Committee

GLS-2025

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by Aayushi Gupta
2K23/GTE/07

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CURRICULUM VITAE

- Author is a postgraduate student in Civil Engineering with a specialisation in Geotechnical Engineering.
- Thesis title: *“Investigation of the Influence of Parametric Variations in Geosynthetic Encased Stone Columns on Bearing Capacity of Foundations.”*
- Completed B.Tech in Civil Engineering from IET, Lucknow with 8.37 CGPA (First Division with Distinction), 2023.
- Completed school education from Delhi Public School, Lucknow:
    - Class 10: 10 CGPA (CBSE)
    - Class 12: 88% (CBSE)
- Published a research paper titled *“Soil Improvement Using Construction and Demolition Waste for Pavement Construction”* in the International Journal of Engineering Research & Technology (IJERT), 2023
- Interned at:
    - National Highway Division, Uttar Pradesh Public Works Department, Prayagraj – contributed to site surveying, utility shifting, and soil sampling for the Ram Van Gaman Path project
    - Mother’s Pride Infrastructures Pvt. Ltd. – assisted in planning, design, maintenance, quality control, and safety aspects of projects
    - Subject Matter Expert at iTutorly – provided solutions to civil engineering problems and conducted online tutoring sessions
- Participated in live projects in finance and operations with Prodmark Consultants