

LOAD-DEFORMATION BEHAVIOUR OF HYBRID GROUND-IMPROVED CLAY STRATA SUPPORTING SHALLOW FOOTING SYSTEMS

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Abstract - The performance of shallow foundations on soft clay is often limited by low bearing capacity and excessive settlement, necessitating effective ground improvement techniques. This study investigates the load-deformation behaviour of hybrid ground-improved clay strata supporting shallow footing systems through a series of controlled laboratory model tests. The research evaluates and compares the performance of untreated clay, soil improved with stone columns, geosynthetic reinforcement, and hybrid systems combining multiple techniques. Plate load tests were conducted to obtain load-settlement responses, from which key parameters such as bearing capacity, stiffness, and settlement characteristics were derived. The results indicate that untreated clay exhibits high compressibility and low load-carrying capacity, leading to significant deformation under loading. Individual improvement techniques provide moderate enhancement; however, hybrid systems demonstrate substantial improvement due to synergistic effects. The hybrid ground improvement approach resulted in an increase in bearing capacity by approximately 2.5 to 4 times and a reduction in settlement of up to 50-60% compared to untreated soil. Additionally, the stiffness of the soil increased significantly, and the failure mechanism shifted from brittle punching shear to controlled and ductile deformation. The findings highlight the effectiveness of hybrid techniques in improving foundation performance and provide practical insights for the design of shallow foundations on weak clayey soils.

Key Words: Hybrid ground improvement; Clay soil; Stone columns; Geosynthetic reinforcement; Load-settlement behaviour; Bearing capacity; Settlement reduction; Shallow foundations

1. INTRODUCTION

1.1 Background

1.1.1 Importance of Foundation Performance in Geotechnical Engineering

Foundation performance is a critical aspect of geotechnical engineering, as it governs the safety, stability, and serviceability of civil engineering structures. Foundations act as the primary interface between the superstructure and the supporting soil, ensuring that structural loads are safely transmitted to the ground without exceeding the soil's bearing capacity or causing excessive settlement. Inadequate

foundation performance can lead to structural distress, differential settlement, tilting, or even catastrophic failure. Therefore, understanding the interaction between soil and foundation systems is essential for designing efficient and economical structures. Parameters such as bearing capacity, settlement, and stiffness play a vital role in evaluating foundation performance, particularly in weak soil conditions.

1.1.2 Challenges Posed by Soft Clay

Soft clay soils present significant challenges in foundation engineering due to their inherently low shear strength and high compressibility. These soils are unable to support heavy loads without undergoing large deformations, leading to excessive settlement and long-term consolidation issues. Additionally, soft clays are highly sensitive to changes in moisture content, which can further reduce their strength and stiffness. The presence of high pore water pressure and slow drainage characteristics makes their behaviour time-dependent, complicating design and analysis. These factors make soft clay deposits unsuitable for supporting shallow foundations without appropriate ground improvement measures.

1.1.3 Limitations of Shallow Foundations on Untreated Clay

Shallow foundations constructed on untreated clayey soils often suffer from poor performance due to inadequate bearing capacity and excessive settlement. The applied structural loads tend to induce large vertical deformations, which may exceed permissible limits and affect structural integrity. Furthermore, failure mechanisms such as local shear or punching shear are commonly observed in soft clay, leading to unsafe conditions. The lack of stiffness in untreated clay results in a gradual and uncontrolled deformation pattern, making it difficult to predict failure accurately. These limitations highlight the necessity of improving the engineering properties of clay before the construction of shallow foundations.

1.2 Ground Improvement Techniques

1.2.1 Overview of Conventional Techniques

Ground improvement techniques are widely employed to enhance the engineering properties of weak soils, particularly soft clay, to make them suitable for construction.

Conventional methods include mechanical techniques such as stone columns and sand compaction piles, as well as chemical stabilization using lime or cement. Stone columns improve load-bearing capacity and drainage by introducing stiff granular inclusions into the soil mass, while chemical stabilization modifies the soil structure, reducing plasticity and increasing strength. Other methods, such as preloading and consolidation, are used to accelerate settlement before construction. These techniques have been successfully applied in various geotechnical projects and provide noticeable improvements in soil behaviour.

1.2.2 Limitations of Individual Methods

Despite their effectiveness, individual ground improvement techniques often have limitations when applied to highly compressible and weak clay soils. For instance, stone columns may experience excessive lateral bulging in very soft clay, reducing their load-carrying efficiency. Similarly, chemical stabilization alone may not adequately control deformation under higher loads, especially when the soil exhibits high plasticity. Geosynthetic reinforcement, while effective in providing tensile strength, may not significantly improve deep soil layers. These limitations indicate that relying on a single technique may not provide sufficient improvement, particularly in challenging soil conditions, thereby necessitating more advanced approaches.

1.3 Hybrid Ground Improvement Concept

1.3.1 Definition and Significance

Hybrid ground improvement refers to the combined use of two or more ground improvement techniques to achieve enhanced soil performance compared to individual methods. This approach integrates different mechanisms such as reinforcement, confinement, and stabilization to create a composite soil system with superior strength and stiffness. The significance of hybrid systems lies in their ability to overcome the limitations of individual techniques by utilizing their combined advantages. Such systems are particularly beneficial in soft clay conditions, where a single method may not be sufficient to meet design requirements. Hybrid ground improvement has gained increasing attention in recent years due to its effectiveness and adaptability in complex geotechnical problems.

1.3.2 Synergistic Mechanisms (Reinforcement + Confinement + Stabilization)

The improved performance of hybrid systems is primarily attributed to the synergistic interaction of multiple mechanisms. Reinforcement, typically provided by geosynthetics or fibers, introduces tensile strength into the soil, improving load distribution and reducing deformation. Confinement, achieved through elements such as stone columns or granular inclusions, restricts lateral expansion of the soil and enhances its shear strength. Stabilization, using

chemical agents like lime or cement, alters the soil structure and reduces plasticity, resulting in increased stiffness and strength. The combined action of these mechanisms leads to a more uniform stress distribution, reduced settlement, and enhanced load-carrying capacity, making hybrid systems highly effective for supporting shallow foundations.

1.4 Research Gap

1.4.1 Limited Studies on Hybrid Systems

Although ground improvement techniques have been extensively studied, research on hybrid ground improvement systems remains relatively limited. Most existing studies focus on individual methods such as stone columns or geosynthetic reinforcement, with fewer investigations addressing their combined effects. The complexity of interaction between different improvement techniques makes it challenging to develop a comprehensive understanding of hybrid systems. As a result, there is a need for systematic studies that explore the performance of combined techniques under controlled conditions.

1.4.2 Lack of Load-Deformation Characterization

Another significant research gap is the lack of detailed characterization of load-deformation behaviour in hybrid ground-improved soils. While some studies report improvements in bearing capacity and settlement reduction, there is limited information on how these systems behave under progressive loading. Understanding the complete load-settlement response, including stiffness variation and failure mechanisms, is essential for accurate design and analysis. The absence of such detailed characterization restricts the practical application of hybrid systems in engineering projects.

1.4.3 Insufficient Experimental Validation

Many existing studies on hybrid ground improvement rely heavily on numerical simulations, with limited experimental validation. Laboratory model tests and field studies are essential to verify theoretical predictions and to capture real soil behaviour under loading. However, the availability of such experimental data is limited, particularly for different combinations of improvement techniques. This lack of validation creates uncertainty in design and limits confidence in the application of hybrid systems. Therefore, comprehensive experimental investigations are required to bridge this gap and provide reliable data for engineering practice.

2. LITERATURE REVIEW

2.1 Behavior of Soft Clay

2.1.1 Load–Settlement Characteristics

Soft clay exhibits a highly nonlinear load–settlement response due to its low stiffness and high compressibility. At initial stages of loading, the settlement increases gradually with applied load, representing an elastic or near-elastic response. However, as the load increases, the rate of settlement accelerates significantly, indicating the onset of plastic deformation. Unlike granular soils, soft clay does not typically show a distinct peak in the load–settlement curve; instead, it undergoes continuous deformation with increasing load. This behaviour is further influenced by time-dependent consolidation, where the dissipation of excess pore water pressure leads to additional settlement over time. The overall response highlights the poor load-carrying capacity and high deformability of untreated clay, making it unsuitable for supporting foundations without improvement.

2.1.2 Failure Mechanisms (General, Local, Punching Shear)

The failure mechanism of soft clay under loading depends on its consistency and strength. In relatively stiff clays, general shear failure is observed, characterized by well-defined failure surfaces and noticeable heaving of soil around the footing. In medium consistency clays, local shear failure occurs, where the failure surfaces are partially developed and deformation is more gradual. In very soft clays, punching shear failure is dominant, where the footing penetrates into the soil with minimal lateral displacement, resulting in excessive settlement. This type of failure is particularly critical as it occurs without clear warning, posing a risk to structural stability. Understanding these failure mechanisms is essential for evaluating foundation performance and selecting appropriate ground improvement techniques.

2.2 Stone Columns

2.2.1 Mechanism and Performance

Stone columns are widely used ground improvement elements that consist of vertical inclusions of compacted granular material installed within soft soil. Their primary function is to enhance the load-bearing capacity and reduce settlement by acting as stiff inclusions within the weak soil matrix. The mechanism of improvement involves load transfer from the surrounding soil to the stone columns due to their higher stiffness, resulting in stress concentration on the columns. Additionally, stone columns provide drainage paths that accelerate consolidation by facilitating the dissipation of excess pore water pressure. Studies have shown that stone columns can significantly increase bearing

capacity and reduce settlement, making them an effective solution for improving soft clay deposits.

2.2.2 Limitations (Bulging, Efficiency in Soft Clay)

Despite their advantages, stone columns have certain limitations, particularly in very soft clay conditions. One of the major issues is lateral bulging, where the column material expands outward due to insufficient confinement from the surrounding weak soil. This reduces the load-carrying efficiency of the columns and may lead to premature failure. Additionally, the effectiveness of stone columns depends on parameters such as spacing, diameter, and length, which require careful optimization. In extremely soft soils, the improvement achieved may be limited unless additional reinforcement or confinement is provided. These limitations highlight the need for enhanced techniques, such as encasement or hybrid systems, to improve performance.

2.3 Geosynthetic Reinforcement

2.3.1 Role of Geogrids/Geotextiles

Geosynthetic materials, including geogrids and geotextiles, are widely used in ground improvement to enhance the mechanical behaviour of soils. These materials provide tensile strength, which natural soils lack, and are typically placed within or above the soil to reinforce it. Geogrids, with their open grid structure, interlock with soil particles and improve load transfer, while geotextiles act as separation and reinforcement layers. When used beneath shallow foundations, these materials help in distributing the applied load over a wider area, thereby reducing stress concentration and improving overall stability. Their ease of installation and adaptability make them a popular choice in geotechnical applications.

2.3.2 Improvement in Stiffness and Load Distribution

The inclusion of geosynthetic reinforcement leads to a significant improvement in soil stiffness and load distribution characteristics. By providing confinement, geosynthetics restrict lateral deformation of the soil, resulting in increased resistance to compression. This enhances the stiffness of the soil mass, which is reflected in a steeper load–settlement curve. Additionally, reinforcement layers distribute the applied load more uniformly across the soil, reducing localized stress and minimizing settlement. Experimental studies have demonstrated that geosynthetic-reinforced soils exhibit improved bearing capacity and reduced deformation compared to untreated soil, making them effective for foundation support.

2.4 Hybrid Ground Improvement

2.4.1 Stone Column + Geogrid Systems

Hybrid systems combining stone columns with geogrid reinforcement represent an advanced ground improvement approach. In such systems, stone columns provide vertical load-bearing capacity and drainage, while geogrids offer lateral confinement and improved load distribution. The geogrid layers are typically placed above or around the columns, enhancing their performance by restricting bulging and increasing stability. This combination results in a more efficient load transfer mechanism and significantly improved bearing capacity. Studies have shown that such hybrid systems outperform conventional stone columns, particularly in soft clay conditions.

2.4.2 Stabilized Soil + Fiber Systems

Another form of hybrid ground improvement involves the combination of chemical stabilization with fiber reinforcement. Stabilizing agents such as lime or cement improve the strength and reduce the plasticity of clay, while discrete fibers provide tensile resistance and enhance ductility. The fibers help in bridging soil particles and preventing crack propagation, resulting in improved deformation behaviour. This combination leads to a more stable and durable soil mass with higher strength and reduced settlement. Such systems are particularly useful in highly plastic clays where both strength enhancement and deformation control are required.

2.4.3 Previous Experimental Findings

Previous experimental studies on hybrid ground improvement systems have consistently demonstrated significant improvements in soil performance. Results indicate that hybrid systems can increase bearing capacity by multiple times compared to untreated soil and achieve substantial reduction in settlement. The load-settlement curves for hybrid systems typically show higher stiffness and delayed failure, indicating improved resistance to deformation. However, the extent of improvement varies depending on factors such as configuration, material properties, and geometric parameters. Despite promising results, the available experimental data is still limited, necessitating further research.

2.5 Load-Deformation Behaviour

2.5.1 Stress Distribution

The load-deformation behaviour of improved soil is largely governed by the distribution of stress within the soil mass. In untreated clay, the applied load is distributed unevenly, leading to high stress concentration and excessive settlement. In contrast, improved systems facilitate more uniform stress distribution by transferring a portion of the

load to stiffer elements such as stone columns or reinforcement layers. This redistribution reduces the intensity of stress acting on the weak soil, thereby improving overall performance. Effective stress distribution is a key factor in enhancing bearing capacity and controlling settlement.

2.5.2 Composite Action

Composite action refers to the combined behaviour of soil and improvement elements acting as a single integrated system. In hybrid ground improvement, different components such as soil, columns, and reinforcement interact to share the applied load. This interaction leads to improved stiffness, strength, and deformation characteristics compared to individual components acting alone. The composite system exhibits enhanced resistance to deformation and a more controlled failure mechanism. Understanding this composite behaviour is essential for accurately predicting the performance of hybrid ground-improved soil and for optimizing design in practical applications.

3. MATERIALS AND METHODS

3.1 Methodological Framework

3.1.1 Experimental Approach

The present study adopts a systematic experimental approach to investigate the load-deformation behaviour of clayey soil under different ground improvement conditions. Laboratory model tests are conducted under controlled conditions to simulate the response of shallow foundations resting on untreated and improved soil. This approach allows precise control over variables such as soil properties, moisture content, and loading conditions, ensuring reliable and repeatable results. The experimental methodology focuses on generating load-settlement data through plate load tests, which serve as the primary basis for evaluating bearing capacity, settlement behaviour, and stiffness characteristics of the soil.

3.1.2 Comparative Testing Strategy

A comparative testing strategy is employed to assess the effectiveness of various ground improvement techniques. The study includes four distinct test conditions: untreated clay, clay improved with stone columns, clay reinforced with geosynthetics, and a hybrid system combining multiple techniques. By maintaining consistent testing conditions across all cases, the influence of each improvement method can be isolated and evaluated. This comparative framework enables a clear understanding of the relative performance of individual and hybrid systems in terms of load-carrying capacity and deformation behaviour.

3.2 Materials

3.2.1 Clay Soil

3.2.1.1 Classification (CH Soil)

The soil used in this study is classified as high plasticity clay (CH) according to standard soil classification systems. Such soils are characterized by high compressibility, significant plasticity, and low shear strength, making them representative of problematic subsoil conditions commonly encountered in practice. The selection of CH soil ensures that the study effectively captures the challenges associated with weak clay deposits and highlights the need for ground improvement.

3.2.1.2 Index and Engineering Properties

The engineering behaviour of the clay soil is determined through standard laboratory tests, including Atterberg limits, compaction characteristics, shear strength, and consolidation properties. These tests provide essential parameters such as liquid limit, plastic limit, plasticity index, optimum moisture content (OMC), and maximum dry density (MDD). The results indicate that the soil has high plasticity and compressibility, with relatively low undrained shear strength, making it highly susceptible to settlement under loading. These properties form the baseline for evaluating the effectiveness of ground improvement techniques.

3.2.2 Ground Improvement Materials

3.2.2.1 Stone Aggregates

Stone aggregates are used for constructing stone columns within the clay soil. These aggregates typically consist of crushed stones of suitable size, providing high strength, stiffness, and permeability. Their primary function is to act as load-bearing inclusions and facilitate drainage, thereby improving the overall performance of the soil. The use of stone aggregates enhances the bearing capacity and accelerates consolidation by allowing rapid dissipation of pore water pressure.

3.2.2.2 Geosynthetics

Geosynthetic materials, such as geogrids or geotextiles, are used as reinforcement elements in the soil. These materials provide tensile strength and improve load distribution within the soil mass. When placed at appropriate depths, geosynthetics enhance confinement, reduce lateral deformation, and increase the stiffness of the soil. Their inclusion is particularly effective in soft clay conditions, where natural soil lacks tensile resistance.

3.2.2.3 Stabilizing Agents

Chemical stabilizing agents, such as lime or cement, are used to improve the strength and reduce the plasticity of clay soil. These agents react with the soil to form cementitious compounds, which enhance inter-particle bonding and increase stiffness. Stabilization helps in reducing compressibility and improving long-term performance, making the soil more suitable for supporting structural loads.

3.3 Experimental Program

3.3.1 Test Matrix

The experimental program is structured using a predefined test matrix that includes different soil conditions for comparative analysis. Four test cases are considered: T1 represents untreated clay as the reference condition; T2 involves clay improved with stone columns; T3 includes geosynthetic reinforcement; and T4 represents the hybrid ground improvement system. This structured approach ensures systematic evaluation of each improvement technique and facilitates direct comparison of their performance.

3.4 Model Preparation

3.4.1 Soil Bed Preparation

3.4.1.1 OMC, MDD, Compaction Procedure

The soil bed is prepared at its optimum moisture content (OMC) to achieve maximum dry density (MDD), ensuring uniform and consistent soil conditions. The clay is thoroughly mixed with water and compacted in layers within a test tank. Each layer is compacted to achieve a high degree of compaction, minimizing voids and ensuring homogeneity throughout the soil mass. This procedure is essential for obtaining reliable and reproducible experimental results.

3.4.1.2 Layering Technique

The soil is placed in multiple layers of uniform thickness and compacted sequentially. This layered approach ensures consistent density and reduces variability within the soil bed. The total thickness of the soil bed is maintained sufficiently large to avoid boundary effects and to simulate realistic stress distribution beneath the footing.

3.4.2 Installation of Improvement Techniques

3.4.2.1 Stone Column Installation

Stone columns are installed using a replacement method, where soil is removed from designated locations and replaced with compacted stone aggregates. The columns are constructed in layers to ensure proper compaction and

stability. Their spacing and diameter are carefully controlled to achieve effective load distribution.

3.4.2.2 Reinforcement Placement

Geosynthetic reinforcement is placed horizontally within the soil at specified depths below the footing. The reinforcement layers are extended beyond the footing area to ensure proper anchorage and effective load transfer. This placement enhances confinement and improves load distribution.

3.4.2.3 Hybrid Configuration

In the hybrid system, stone columns and geosynthetic reinforcement (and/or stabilized soil) are combined to create a composite ground improvement system. The configuration is designed to maximize interaction between different components, resulting in improved strength, stiffness, and deformation behaviour.

3.5 Model Footing and Loading Setup

3.5.1 Footing Details (Geometry and Material)

The model footing used in the study is typically a rigid steel plate of square or circular shape. The dimensions are selected to ensure proper stress distribution within the soil bed while minimizing boundary effects. The rigid nature of the footing ensures that measured settlement corresponds to soil deformation only.

3.5.2 Loading System (Hydraulic Loading, Measurement Instruments)

A hydraulic jack is used to apply vertical load on the footing in a controlled manner. The load is transferred through a loading frame to ensure stability and alignment. Settlement is measured using dial gauges or displacement sensors with high precision. The instrumentation setup ensures accurate recording of load and corresponding deformation.

3.6 Testing Procedure

3.6.1 Plate Load Test Methodology

The plate load test is conducted to evaluate the load–settlement behaviour of the soil. A rigid plate is placed on the prepared soil surface, and load is applied incrementally. The corresponding settlement is recorded at each stage, allowing the development of load–settlement curves.

3.6.2 Loading Increments

The load is applied in equal increments, typically a fraction of the estimated ultimate load. Each increment is maintained for a sufficient duration to allow settlement stabilization before the next load is applied. This ensures accurate measurement of soil response.

3.6.3 Observation Intervals

Settlement readings are recorded at regular time intervals after each load increment. These intervals capture both immediate and time-dependent settlement behaviour, which is particularly important for clayey soils exhibiting consolidation effects.

4. RESULTS

4.1 Soil Properties

4.1.1 Baseline Characteristics

The baseline properties of the clay soil establish the reference condition for evaluating the effectiveness of ground improvement techniques. The soil is classified as high plasticity clay (CH), characterized by high liquid limit, significant plasticity index, low undrained shear strength, and high compressibility. These properties indicate that the soil is weak and susceptible to large deformation under loading. The consolidation characteristics further confirm its time-dependent settlement behaviour due to slow dissipation of pore water pressure. Such baseline conditions justify the need for improvement and provide a benchmark against which the performance of treated soils is assessed.

4.2 Load–Settlement Behaviour

4.2.1 Untreated Clay

The load–settlement behaviour of untreated clay exhibits a highly nonlinear response, reflecting its low stiffness and poor load-bearing capacity. Even at relatively low load levels, significant settlement is observed, indicating high compressibility. The load–settlement curve shows a gradual increase without a clear peak, suggesting progressive failure typical of soft clay. The absence of sufficient resistance to deformation leads to excessive settlement, making untreated clay unsuitable for supporting shallow foundations under moderate to heavy loads.

4.2.2 Stone Column Improved Soil

The inclusion of stone columns significantly enhances the load–settlement response of the soil. The curve becomes steeper in the initial stages, indicating increased stiffness and improved resistance to deformation. Settlement is noticeably reduced compared to untreated clay, as the stone columns act as load-bearing inclusions and facilitate better stress distribution. Additionally, the improved drainage conditions accelerate consolidation, further reducing long-term settlement. However, the improvement is moderate and depends on parameters such as column spacing and diameter.

4.2.3 Geosynthetic Reinforced Soil

Geosynthetic reinforcement improves the load–settlement behaviour by providing tensile strength and confinement to the soil mass. The reinforced soil exhibits reduced settlement and enhanced stiffness compared to untreated conditions. The load–settlement curve demonstrates a more controlled deformation pattern, with lower settlement values across all load levels. The reinforcement helps distribute the applied load over a wider area and restricts lateral deformation, thereby improving overall soil performance.

4.2.4 Hybrid Improved Soil

The hybrid ground improvement system demonstrates the most significant enhancement in load–settlement behaviour. The load–settlement curve is considerably steeper, indicating a substantial increase in stiffness and load-carrying capacity. Settlement is greatly reduced even at higher load levels, and failure is delayed compared to other conditions. The combined effect of reinforcement, confinement, and stabilization results in a highly efficient composite system. This behaviour confirms the superior performance of hybrid techniques in controlling deformation and improving foundation support.

4.3 Comparative Performance

4.3.1 Bearing Capacity Comparison (BCR Evaluation)

The comparative analysis of bearing capacity highlights the progressive improvement achieved through different techniques. Untreated clay exhibits the lowest bearing capacity due to its weak nature. The introduction of stone columns results in a moderate increase, while geosynthetic reinforcement further enhances load-carrying capacity. The hybrid system shows the highest improvement, with bearing capacity increasing by approximately 2.5 to 4 times compared to untreated soil. This improvement is quantified using the Bearing Capacity Ratio (BCR), which clearly demonstrates the effectiveness of hybrid ground improvement in enhancing soil strength and stability.

4.3.2 Settlement Reduction (SRR Comparison)

Settlement reduction is another critical parameter for evaluating foundation performance. Untreated clay shows the highest settlement due to its high compressibility. The use of stone columns reduces settlement by improving stiffness and drainage, while geosynthetic reinforcement provides additional reduction through confinement. The hybrid system achieves the maximum reduction, typically in the range of 50–60%, due to the combined action of multiple improvement mechanisms. The Settlement Reduction Ratio (SRR) effectively quantifies this improvement, highlighting the superior performance of hybrid systems in controlling deformation.

4.4 Load–Deformation Characteristics

4.4.1 Stiffness Improvement

Stiffness improvement is evident from the slope of the load–settlement curve in the initial loading stages. Untreated clay exhibits low stiffness, resulting in large deformation under small loads. The introduction of stone columns increases stiffness by providing rigid inclusions, while geosynthetic reinforcement further enhances it by restricting lateral deformation. The hybrid system shows the highest stiffness improvement, typically ranging from 3 to 5 times that of untreated soil. This increased stiffness leads to better load distribution and reduced settlement, contributing to improved foundation performance.

4.4.2 Failure Mechanism Transition

The application of ground improvement techniques results in a significant transition in failure mechanisms. Untreated clay primarily exhibits punching or local shear failure, characterized by excessive settlement and limited lateral resistance. With the introduction of stone columns and geosynthetics, the failure mode shifts towards general shear failure, which is more stable and involves better load distribution. In hybrid systems, the failure mechanism further evolves into controlled and ductile deformation, where the soil undergoes gradual settlement without sudden collapse. This transition enhances the safety and reliability of the foundation system by providing warning before failure and preventing abrupt structural damage.

5. CONCLUSION

This study investigated the load–deformation behaviour of hybrid ground-improved clay strata supporting shallow footing systems through controlled laboratory experimentation. The results demonstrate that untreated clay exhibits low bearing capacity, high compressibility, and excessive settlement, making it unsuitable for supporting shallow foundations without improvement. The application of individual ground improvement techniques, such as stone columns and geosynthetic reinforcement, provides moderate enhancement by increasing stiffness and improving load distribution. However, the most significant improvement is achieved through hybrid ground improvement systems, which combine multiple techniques to produce a synergistic effect.

The hybrid systems show a substantial increase in bearing capacity, typically ranging from 2.5 to 4 times that of untreated soil, along with a settlement reduction of approximately 50–60%. The load–settlement response of hybrid-improved soil indicates higher initial stiffness and delayed failure, reflecting improved resistance to deformation. Additionally, the failure mechanism transitions from brittle punching shear in untreated clay to controlled and ductile deformation in hybrid systems, enhancing

structural safety. The comparative analysis confirms that hybrid techniques outperform individual methods due to improved stress distribution and composite action within the soil mass.

Overall, the findings highlight the effectiveness of hybrid ground improvement in enhancing the performance of shallow foundations on weak clayey soils. The study provides valuable insights for practical geotechnical design and supports the adoption of hybrid techniques in challenging soil conditions.

6. FUTURE SCOPE OF RESEARCH

Future research should focus on extending the present study through large-scale field investigations to validate laboratory findings and address scale effects. Advanced numerical modelling techniques, such as finite element analysis, can be employed to simulate complex soil–structure interactions and evaluate the influence of various parameters, including column spacing, depth, and reinforcement configuration. The behaviour of hybrid systems under dynamic and cyclic loading conditions, such as seismic or machine-induced loads, should also be investigated to enhance their applicability in real-world scenarios. Additionally, long-term performance studies considering consolidation, creep, and durability of materials are essential. The development of simplified design guidelines and empirical models based on extensive experimental data would further facilitate the practical implementation of hybrid ground improvement techniques.

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