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

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Abstract -*The load–deformation behavior of shallow footings resting on clayey soils is a critical aspect of geotechnical design, particularly for soft or weak clay strata. Conventional ground improvement techniques, such as lime or cement stabilization, geosynthetic reinforcement, and vibro-compaction, have demonstrated limited effectiveness when applied individually under complex loading scenarios. Recent research has increasingly focused on hybrid ground improvement approaches, combining multiple techniques to optimize both the bearing capacity and deformation characteristics of clay soils. This review systematically examines the current state of knowledge regarding the load–deformation response of hybrid ground-improved clay strata supporting shallow footing systems. The study synthesizes findings from laboratory experiments, field trials, and numerical simulations, highlighting the influence of soil properties, improvement methods, and loading conditions on settlement, stress distribution, and overall foundation performance. Key trends indicate that hybrid systems—such as geosynthetic-reinforced stone columns or chemical stabilization combined with mechanical inclusions—significantly reduce differential settlement and improve load-bearing efficiency compared to single-method interventions. Despite these advancements, discrepancies exist between laboratory-scale and field-scale behavior, and standardized guidelines for hybrid design remain limited. The review also identifies research gaps related to long-term performance, modeling of complex hybrid systems, and optimization of combined techniques for various clay types. By critically analyzing past studies and highlighting emerging hybrid strategies, this paper provides a comprehensive framework to guide future research and engineering applications aimed at improving the stability and serviceability of shallow foundations on clay soils.*

Key Words: Load–deformation behavior, hybrid ground improvement, clay strata, shallow footings, settlement mitigation, soil–foundation interaction interaction

1. INTRODUCTION

1.1 Broad Background on Soil–Foundation Interactions

The interaction between soil and foundation is a fundamental concern in geotechnical engineering, as it governs the stability, settlement, and load-carrying capacity of structures (Das, 2016). The behavior of a foundation under applied loads is inherently linked to the mechanical properties of the supporting soil, which include strength, compressibility, and permeability. Accurate understanding of load–deformation behavior is essential to predict settlements and ensure serviceability requirements of structures (Coduto, 2016). In particular, shallow foundations, which are widely used for low- and medium-rise constructions, are highly sensitive to the mechanical response of the underlying soil layers, especially when these layers comprise fine-grained or clayey strata.

1.2 Significance of Clayey Soils in Geotechnical Engineering

Clay soils, due to their low shear strength, high compressibility, and pronounced time-dependent behavior, pose significant challenges for foundation design (Mitchell and Soga, 2005). Their susceptibility to consolidation and plastic deformations can lead to excessive settlement and differential movements, affecting structural integrity. In regions where clay strata are prevalent, such as floodplains or reclaimed lands, the necessity to understand and control the load–deformation characteristics becomes critical to prevent serviceability failures.

1.3 Challenges of Load–Deformation Behavior in Weak or Fluctuating Clay Strata

Weak or fluctuating clay strata exhibit complex stress–strain responses under applied loads, including non-linear deformation, creep, and possible shear failure (Lee et al., 2018). Conventional foundation design often underestimates these effects, which can result in excessive settlements and differential tilting. Additionally, environmental factors such as moisture variation further exacerbate the unpredictable deformation of clay soils, making foundation behavior less reliable without improvement interventions.

1.4 Hybrid Ground Improvement

To address the limitations of single-method soil improvement, hybrid ground improvement techniques have emerged, integrating multiple approaches to enhance both strength and stiffness of clay strata (Priebe, 1995). Hybrid systems are designed to combine the advantages of mechanical, chemical, or geosynthetic methods to achieve better load-bearing performance and reduce settlement compared to conventional methods used alone.

1.5 Definition of "Hybrid" Ground Improvement

In the context of shallow foundations on clay, "hybrid" ground improvement refers to the combination of two or more stabilization techniques, such as geosynthetic reinforcement with stone columns, or lime/cement stabilization combined with vertical drains (Meyerhof, 1976; Al-Refeai, 1993). The objective is to exploit synergistic effects that improve load transfer, minimize differential settlement, and provide long-term stability under applied loads.

1.6 Objective and Scope of this Review

The primary objective of this review is to critically analyze and synthesize the existing literature on load–deformation behavior of hybrid ground-improved clay strata supporting shallow footings. The review aims to identify key factors affecting performance, compare different hybrid approaches, highlight gaps in experimental and numerical studies, and provide insights for future research and practical design guidelines.

2. FUNDAMENTALS

This section establishes the basic theoretical concepts and terminology required to understand the load–deformation behavior of hybrid ground-improved clay strata supporting shallow footings. It covers soil behavior under load, mechanisms of settlement, and shallow footing systems commonly used in geotechnical engineering.

2.1 Soil Behavior under Load

Understanding how soils respond to applied loads is critical for designing safe and serviceable foundations. The stress–strain behavior of clay soils is highly non-linear and depends on factors such as water content, plasticity, density, and previous loading history (Mitchell and Soga, 2005). Clay exhibits low shear strength and high compressibility, which can lead to significant deformations under even moderate stresses.

2.1.1 Stress–Strain Characteristics of Clay

Under axial loading, clay typically shows an initial elastic response, followed by a plastic deformation stage, and finally, failure if the applied load exceeds its strength (Das, 2016). The elastic stage is generally small for soft clays, and plastic deformations dominate the settlement behavior. Stress–strain curves for clay often display pronounced non-linearity, hysteresis, and time-dependent behavior such as creep, which must be accounted for in design.

2.1.2 Elastic and Plastic Deformation Mechanisms

Elastic deformation in clay occurs when applied stresses are within the preconsolidation limit, and the soil returns to its original configuration after unloading. Plastic deformation arises when stresses exceed this limit, resulting in permanent volumetric changes and particle rearrangement (Bjerrum, 1967). Both mechanisms significantly influence the performance of foundations, especially under long-term loading conditions.

2.2 Settlement and Load–Deformation Responses

Settlement analysis is a central aspect of foundation design. It is essential to distinguish between immediate (elastic) settlement and long-term consolidation settlement in clay soils. Immediate settlement occurs instantaneously upon application of load, while consolidation settlement develops gradually as pore water pressure dissipates over time (Terzaghi and Peck, 1967).

2.2.1 Immediate vs Long-Term Settlement

Immediate settlement primarily depends on the shear strength and elastic properties of the clay, whereas long-term settlement is influenced by compressibility, consolidation rate, and drainage conditions. Both must be accurately estimated to avoid excessive differential settlement, which can compromise structural integrity.

2.2.2 Bearing Capacity vs Deformation Criteria

While bearing capacity determines the maximum load a foundation can support without failure, deformation criteria evaluate the permissible settlements under service loads (Bowles, 1996). In soft clay, excessive settlement often governs design rather than ultimate load-bearing capacity, making deformation prediction a key consideration in ground improvement strategies.

2.3 Shallow Footing Systems

Shallow footings are commonly employed for low- to medium-rise structures and are designed to distribute structural loads to near-surface soils. Their performance is influenced by soil properties, foundation geometry, and load characteristics (Coduto, 2016).

2.3.1 Types of Shallow Footings

Common types include strip footings, square or rectangular footings, and circular footings. Strip footings are used for walls and linear structures, whereas square and circular footings are suitable for column-supported structures. Each type interacts differently with the supporting clay, affecting both stress distribution and settlement patterns.

2.3.2 Typical Performance Metrics

Key metrics to evaluate shallow footing performance include ultimate bearing capacity, total and differential settlement, and load–settlement behavior under service conditions. Monitoring these parameters is essential, particularly when implementing ground improvement measures, to ensure the foundation meets structural and serviceability requirements.

3. GROUND IMPROVEMENT TECHNIQUES: AN OVERVIEW

Ground improvement techniques are employed to enhance the engineering properties of weak or problematic soils, such as soft clays, to ensure the stability and serviceability of shallow foundations. These techniques can modify strength, stiffness, permeability, and deformation characteristics of the soil, making it capable of supporting applied structural loads. The choice of technique depends on soil type, loading conditions, environmental constraints, and cost considerations (Das, 2016; Littlejohn, 2011).

3.1 Conventional Methods

Conventional ground improvement methods have been widely used due to their simplicity, reliability, and well-established design procedures. They generally aim at densifying, stabilizing, or preloading the soil to improve its bearing capacity and reduce settlement.

3.1.1 Preloading and Surcharge

Preloading involves applying temporary loads or surcharges on the ground surface to accelerate consolidation and settlement of compressible soils before foundation construction (Terzaghi and Peck, 1967). This method increases effective stress and improves bearing capacity, reducing post-construction settlements. It is often combined with vertical drains to expedite pore water dissipation in soft clay deposits.

3.1.2 Vertical Drains

Vertical drains, such as sand or prefabricated vertical drains, facilitate the escape of pore water from compressible soils during preloading. By shortening the drainage path, these drains accelerate consolidation and reduce time-dependent settlements, particularly in thick clay layers (Barksdale and Bachus, 1983).

3.1.3 Lime/Cement Stabilization

Chemical stabilization using lime or cement improves soil properties by altering clay mineralogy and binding soil particles together. This increases shear strength, reduces plasticity, and limits compressibility (Bell, 1996). Cement stabilization is more effective in moderately soft soils, while lime is preferred for highly plastic clays.

3.2 Modern and Innovative Methods

Modern techniques focus on reinforcing soils with inclusions, synthetic materials, or advanced additives to achieve improved performance under load.

3.2.1 Geosynthetics

Geosynthetics, including geogrids and geotextiles, enhance soil stiffness and load distribution when placed within or beneath the soil mass. Geogrids improve bearing capacity and reduce settlement, while geotextiles prevent lateral spreading and improve reinforcement efficiency (Koerner, 2012).

3.2.2 Stone Columns and Vibro Techniques

Stone columns or vibro-compacted inclusions increase strength and stiffness by displacing weak clay with granular material, which also accelerates consolidation. These techniques are particularly effective for deep soft clay deposits where traditional preloading may be insufficient (Priebe, 1995).

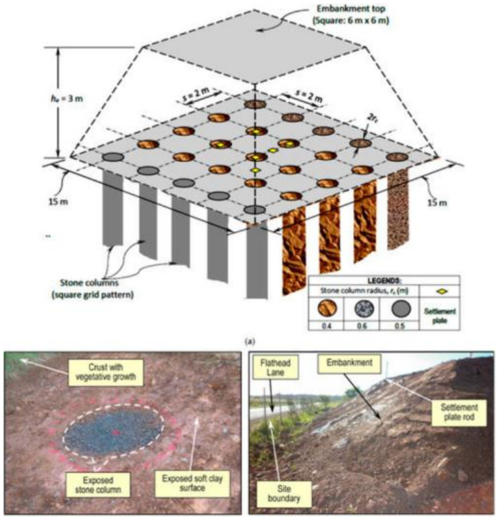

Figure 1. Schematic of stone column reinforcement in soft clay strata

3.2.3 Nano-Material Additives

Emerging research has explored the use of nanomaterials, such as nano-silica or nano-clay, to enhance microstructural bonding within clay matrices. These additives can improve strength, reduce compressibility, and enhance durability (Siddique et al., 2019).

3.2.4 Bio-Soil Methods

Bio-mediated soil improvement techniques, including microbial-induced calcite precipitation (MICP), promote in-situ cementation of clay particles. These environmentally friendly methods increase stiffness and bearing capacity without chemical pollutants (DeJong et al., 2013).

1.3 Hybrid Ground Improvement Approaches

Hybrid approaches integrate two or more improvement techniques to exploit synergistic effects, combining mechanical, chemical, or geosynthetic methods to maximize soil performance under load.

1.3.1 Definitions and Classification

Hybrid ground improvement is defined as the simultaneous or sequential application of multiple techniques to achieve superior engineering properties compared to single-method approaches (Lee et al., 2018). These can be broadly classified into mechanical–chemical, mechanical–geosynthetic, or chemical–geosynthetic hybrids.

1.3.2 Typical Combinations

Common hybrid systems include stone columns reinforced with geogrids, lime or cement stabilization combined with vertical drains, and geosynthetic-reinforced vibro-compacted soils. Such combinations improve load-bearing capacity, reduce settlement, and enhance long-term stability, particularly in soft clay deposits supporting shallow foundations (Priebe, 1995; Meyerhof, 1976).

4. LITERATURE REVIEW

The literature review forms the central framework of this study, providing a systematic, critical, and thematic analysis of existing research on the load–deformation behavior of hybrid ground-improved clay supporting shallow footings. Studies have been classified into experimental, numerical, and field-based investigations to highlight methodological trends and knowledge gaps.

4.1 Classification of Studies

A diverse range of studies has been conducted to evaluate soil–foundation interactions, which can be broadly categorized into experimental, numerical modeling, and field implementation studies.

4.1.1 Experimental Investigations

Laboratory-based experiments have been widely employed to understand the stress–strain and settlement behavior of clay under shallow footings. Typical setups include model footings over treated and untreated clay layers, allowing controlled assessment of deformation responses under varying load levels (Lee et al., 2018). These studies help in quantifying the influence of soil properties, footing geometry, and ground improvement techniques.

4.1.2 Numerical Modelling Studies

Numerical simulations, using finite element or finite difference approaches, provide insights into complex soil–structure interactions that are difficult to capture experimentally. Constitutive models such as Modified Cam-Clay and Mohr–Coulomb have been commonly used to simulate the non-linear behavior of clay under shallow footings, both for conventional and hybrid improvement methods (Santamarina and Cho, 2004).

4.1.3 Field Implementations

Field studies offer practical evidence of ground improvement performance, including settlement monitoring, load testing, and long-term observation of shallow footings over improved clay layers. They validate laboratory and numerical findings while highlighting scale effects and construction challenges (Priebe, 1995).

4.2 Load–Deformation Behavior in Clay Soils

The load–deformation response of clay soils is influenced by intrinsic soil properties such as plasticity, water content, and density. Studies indicate that higher plasticity and moisture content increase compressibility and lead to larger settlements, while denser clays exhibit stiffer behavior under the same loads (Mitchell and Soga, 2005). Under shallow footings, deformation is typically non-linear, with immediate elastic settlement followed by consolidation-induced long-term settlement.

4.3 Effects of Individual Improvement Techniques

Individual ground improvement methods alter load–deformation characteristics by enhancing soil stiffness, reducing settlement, or redistributing stresses.

4.3.1 Geosynthetics

Geosynthetic inclusion, such as geogrids, improves load distribution and reduces lateral spreading, resulting in reduced settlement and improved stiffness (Koerner, 2012).

4.3.2 Columnar Inclusions

Stone or cemented columns increase stiffness and accelerate consolidation, improving bearing capacity and reducing total settlement (Priebe, 1995).

4.3.3 Chemical Stabilizers

Lime or cement stabilization increases shear strength and reduces plasticity of clay, which directly enhances load–settlement performance under footings (Bell, 1996).

4.3.4 Relief Drains

Vertical drains, often used in conjunction with preloading, expedite pore water dissipation, shortening consolidation time and reducing post-construction settlements (Barksdale and Bachus, 1983).

4.4 Hybrid Systems in Literature

Hybrid ground improvement techniques combine multiple approaches to exploit synergistic effects, achieving superior performance compared to single-method interventions.

Studies have investigated combinations such as geosynthetic-reinforced stone columns, cement/lime stabilization with vertical drains, and vibro-compacted granular inclusions with reinforcement layers. These systems show reduced differential settlement, enhanced stiffness, and improved bearing capacity (Lee et al., 2018). Mechanistically, the hybrid approach enhances load transfer through reinforcement and reduces pore pressure buildup, leading to improved load–deformation responses.

4.5 Numerical and Analytical Modelling Studies

Constitutive models for hybrid-improved clay often extend classical models (Modified Cam-Clay, Mohr–Coulomb) to incorporate inclusion effects and reinforcement behavior. Numerical studies allow parametric analysis of footing size, load levels, soil properties, and improvement techniques. However, predictive capabilities are limited by assumptions in model calibration, and validation against field-scale data remains a challenge (Santamarina and Cho, 2004). Gaps exist in modelling complex hybrid systems, particularly for long-term deformation and time-dependent consolidation.

4.6 Synthesis of Findings

A synthesis of existing studies reveals that hybrid systems consistently outperform single-method improvements in terms of settlement reduction and bearing capacity enhancement. Comparative analyses highlight the influence of soil plasticity, inclusion type, reinforcement geometry, and load magnitude. Tabular and graphical summaries in recent literature demonstrate the correlation between improvement techniques, load levels, and observed deformation responses across various clay types (Lee et al., 2018; Priebe, 1995).

4.7 Critical Assessment

Despite numerous studies, inconsistencies exist in methodologies, soil characterization, and reporting of deformation data. Laboratory-scale tests may not capture field-scale effects, while standardized protocols for hybrid ground improvement evaluation are lacking. Additionally, many studies focus on short-term performance, leaving long-term settlements under hybrid systems insufficiently explored. Methodological shortcomings and scale effects present significant challenges in generalizing results for design applications (Mitchell and Soga, 2005).

5. DISCUSSION

The discussion section synthesizes insights from the reviewed literature, providing an integrative interpretation of outcomes and highlighting mechanistic understanding, the influence of soil and improvement design parameters, and best practices for hybrid ground improvement systems supporting shallow footings.

5.1 Integrative Interpretation of Review Outcomes

The literature indicates that hybrid ground improvement approaches consistently enhance the load–deformation performance of shallow foundations on clay compared to single-method interventions. Experimental and field studies reveal reductions in total and differential settlements, increased stiffness, and improved bearing capacity under both service and ultimate loads (Lee et al., 2018; Priebe, 1995). Numerical simulations support these observations, demonstrating that combining mechanical, chemical, and geosynthetic techniques provides synergistic benefits that cannot be achieved by any individual method. The integration of multiple techniques allows load transfer to be more uniformly distributed, minimizing stress concentrations that can lead to localized failure in untreated clay strata.

5.2 Mechanistic Understanding of Hybrid Improvement in Clay

Mechanistically, hybrid systems improve clay performance through several interrelated processes. Geosynthetics increase lateral confinement and distribute loads over a broader area, while columnar inclusions provide localized stiffness and facilitate accelerated consolidation (Koerner, 2012). Chemical stabilizers, such as lime or cement, enhance shear strength and reduce plasticity, further limiting deformations. In combination, these mechanisms act synergistically: the reinforcement elements control immediate settlement, while the improved soil matrix reduces long-term consolidation and creep. The overall effect is a more predictable and reliable load–deformation response, which is critical for the serviceability of shallow foundations.

5.3 Influence of Soil Parameters and Improvement Design on Load–Deformation

Soil properties, including plasticity, water content, and density, significantly influence the effectiveness of hybrid improvement techniques (Mitchell and Soga, 2005). Highly plastic clays benefit more from chemical stabilization, whereas soft, low-density clays respond better to columnar inclusions combined with geosynthetics. Design parameters such as column spacing, reinforcement depth, and proportion of chemical additives must be optimized according to the specific soil profile to achieve maximal deformation control. Load magnitude and footing geometry also dictate the interaction between improved soil layers and the foundation, affecting settlement distribution and stiffness enhancement.

5.4 Best Practices and Effective Hybrid Configurations

Based on the review, best practices for hybrid ground improvement involve selecting complementary techniques tailored to site-specific conditions. Effective configurations include geosynthetic-reinforced stone columns for soft, saturated clay, lime or cement stabilization coupled with vertical drains for high-plasticity clays, and bio-mediated or nano-additive interventions where environmental sustainability is prioritized. Design should be guided by both laboratory and field-scale data, ensuring proper consideration of long-term settlements, consolidation behavior, and load-transfer mechanisms. Employing a combination of numerical modeling, laboratory testing, and field validation is recommended to optimize hybrid system performance and predict foundation behavior accurately (Santamarina and Cho, 2004).

6. CONCLUSION

This review comprehensively analyzed the load–deformation behavior of hybrid ground-improved clay strata supporting shallow footings. The synthesis of experimental, numerical, and field studies indicates that hybrid improvement techniques consistently outperform conventional single-method interventions by enhancing bearing capacity, increasing stiffness, and reducing both immediate and long-term settlements. Mechanistic insights suggest that combining mechanical inclusions, geosynthetics, and chemical stabilizers leverages complementary effects: reinforcement elements control immediate deformation, while stabilized clay matrices improve long-term load transfer and mitigate consolidation-induced settlement. Soil parameters such as plasticity, density, and moisture content significantly influence the effectiveness of hybrid systems, emphasizing the need for site-specific design and optimization. Best practices include geosynthetic-reinforced stone columns for soft clays, lime or cement stabilization coupled with vertical drains for highly plastic clays, and innovative bio-mediated or nano-additive interventions for sustainable improvement. While numerical modeling provides valuable predictive capabilities, validation against field-scale performance is essential to account for scale effects and real-world variability. Overall, hybrid ground improvement offers a reliable and efficient solution for enhancing shallow foundation performance in challenging clay strata, bridging the gap between laboratory insights and practical engineering applications. This review highlights both the progress achieved and the areas requiring further investigation to develop standardized, optimized design methodologies for hybrid systems.

7. LIMITATIONS OF THE REVIEW

This review has several limitations. First, the analysis is restricted to published studies available in English, potentially excluding relevant data from other languages or unpublished field reports. Second, significant variability exists in experimental methodologies, soil characterization techniques, and reporting standards, which limits direct comparison across studies. Third, while numerical models offer insights into hybrid system behavior, they often rely on simplifying assumptions that may not fully capture long-term or complex field conditions. Additionally, many studies focus on short-term performance, leaving gaps in understanding time-dependent behavior such as creep or secondary consolidation. Finally, hybrid techniques are highly site-specific, and conclusions drawn from one soil type or improvement configuration may not be universally applicable. These limitations highlight the need for standardized testing protocols, broader datasets, and long-term monitoring to strengthen the reliability of hybrid ground improvement recommendations.

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