International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 13 Issue: 03 | Mar 2026 www.irjet.net p-ISSN: 2395-0072

A REVIEW OF SETTLEMENT BEHAVIOR OF SHALLOW FOUNDATIONS ON STRATIFIED SOILS CONSIDERING NONLINEAR SOIL PROPERTIES

Ashutosh Kumar Yadav[1], Mr. Ushendra Kumar[2]

[1]*Master of Technology, Civil Engineering, Lucknow Institute of Technology, Lucknow, India*
[2]*Head of Department, Department of Civil Engineering, Lucknow Institute of Technology, Lucknow, India*

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Abstract -*Settlement behavior of shallow foundations on stratified soils is a critical aspect of geotechnical engineering, as it directly influences the safety, serviceability, and longevity of structures. Traditional settlement analyses often assume linear elastic soil behavior, which fails to capture the complex response of layered soils exhibiting nonlinear properties under loading. This review critically examines the current state of research on settlement mechanisms of shallow foundations on stratified soils, with a particular focus on the effects of nonlinear soil behavior. It synthesizes findings from analytical, numerical, and experimental studies, highlighting key modeling approaches, including classical elastic methods, advanced constitutive models, and numerical simulations such as the finite element method. The review discusses the influence of soil layering, stiffness contrast, and stress-dependent properties on settlement predictions. Comparative analyses from previous studies reveal discrepancies between theoretical predictions and field observations, emphasizing the importance of incorporating nonlinear soil parameters for accurate assessment. Furthermore, experimental and field investigations are summarized to evaluate validation techniques and practical applications. Existing challenges, such as calibration of constitutive models, limited field data, and the lack of standardized design procedures for layered soils, are identified. The review concludes by outlining future research directions, including advanced modeling strategies, integration of data-driven approaches, and enhanced experimental frameworks to improve the predictability and reliability of foundation settlement analysis. This synthesis provides a comprehensive resource for geotechnical researchers and practitioners seeking to understand and mitigate settlement issues in stratified soil environments.*

Key Words: Shallow foundations, Stratified soils, Settlement behavior, Nonlinear soil properties, Constitutive models, Numerical modeling, Soil–structure interaction

1 INTRODUCTION

1.1 Background and Engineering Significance

The design of foundations is a fundamental aspect of civil and geotechnical engineering because the stability and serviceability of structures depend on how loads are transferred from the superstructure into the underlying soil. Shallow foundations—commonly used for light to moderate structural loads—transfer these loads to the near-surface soil and are often governed by settlement criteria more critically than by bearing capacity, especially when soil compressibility and deformation are significant factors in design practice (Das et al., cited in turn0search15). Settlement prediction becomes especially complex when foundations rest on stratified soils, where layers of differing stiffness and compressibility produce non-uniform stress and strain distributions under load. Classical design methodologies commonly assume linear elastic soil behaviour for settlement estimation; however, soil mechanical responses are inherently nonlinear, even at small strain levels, due to stress-dependency of stiffness and yielding phenomena. This complexity has motivated extensive research into nonlinear modelling of soil behaviour and its incorporation into settlement analysis for enhanced prediction accuracy.

1.2 Definitions and Classification

1.2.1 Shallow Foundations

Shallow foundations are structural elements that transfer loads to the ground at or near the surface, and are typically classified by geometry and depth relative to width. A foundation is considered shallow if its depth of embedment is small compared to its width, making it a cost-effective solution for numerous civil structures such as residential buildings, pavements and lightly loaded industrial facilities. Common configurations include strip, pad and raft foundations, which distribute stresses over a sufficiently large soil area to limit excessive deformation.

1.2.2 Stratified Soils

Stratified soils refer to subsurface profiles with alternating layers of distinct soil types—such as sands over clays or stiff strata above softer materials—formed through geological processes or soil improvement practices. The presence of layered profiles significantly alters stress distribution and deformation behaviour beneath foundations compared to homogeneous soil, resulting in differential settlement patterns that require careful mechanical interpretation. In layered systems, the mechanical interaction between stiff and compliant layers influences the magnitude and distribution of settlement under applied loads.

1.3 Mechanics of Settlement in Layered Soils

Settlement of shallow foundations occurs due to compression and rearrangement of soil particles under imposed loads. In stratified soils, layered contrasts in stiffness and compressibility cause complex stress paths and nonlinear deformation mechanisms. Immediate settlement arises from elastic and plastic strains in the soil skeleton immediately after load application, whereas consolidation settlement is time-dependent due to pore pressure dissipation in fine-grained soils. In layered profiles, stiffer layers may constrain deformation in underlying softer layers, leading to a redistribution of stresses and potentially higher settlement than predicted by homogeneous soil theories. The mechanics of this process are influenced by the relative thickness, stiffness contrast and sequence of soil layers beneath the foundation.

1.4 Importance of Nonlinear Soil Behavior in Settlement Prediction

Soil behaviour under foundation loads is inherently nonlinear, meaning the stiffness and strength characteristics change with stress and strain levels experienced during loading. Traditional elastic settlement models often use constant modulus values, which can result in inaccurate predictions because they do not account for degradation in stiffness with increasing strain. Advanced constitutive relationships, such as stress-dependent modulus models, better capture this nonlinear response and provide improved settlement estimates, especially for layered soils where stress variation with depth is pronounced. Addressing nonlinear behaviour is therefore critical to aligning analytical and numerical predictions with observed field performance.

1.5 Objectives and Scope of the Review

The primary objective of this review is to synthesize and critically evaluate existing research on settlement behaviour of shallow foundations on stratified soils that incorporates nonlinear soil properties. Emphasis is placed on analytical, experimental, and numerical studies that reveal the impact of soil layering and nonlinear stress–strain relationships on settlement predictions. Another key goal is to identify limitations in existing models and propose directions for future research to enhance predictive reliability. The scope encompasses constitutive modelling, soil–structure interaction methodologies, and comparative assessments of modelling frameworks documented in recent geotechnical literature.

2 FUNDAMENTALS

2.1 Shallow Foundations: Types and Common Design Practices

Shallow foundations are structural elements designed to transfer loads from a superstructure to subsurface soil at relatively shallow depths. By definition, a foundation is considered shallow when its depth of embedment is small relative to its width, making it a cost-effective choice for light to moderately loaded structures. Typical shallow foundation configurations include strip footings, which support linear elements such as walls; rectangular (or pad) footings, used beneath isolated columns; and circular footings, commonly applied under round columns or tower supports. These geometries affect how stresses are distributed into the underlying soil and influence settlement patterns under load.

Conventional design practice for shallow foundations often focuses on two key parameters: bearing capacity and settlement performance. While bearing capacity ensures structural safety against shear failure, settlement control is critical for serviceability, particularly for foundations on compressible or layered soils. Settlement estimates in standard practice historically rely on elastic theory—which assumes a homogeneous, linear elastic soil modulus and uses solutions based on elastic stress–strain relationships beneath a loaded area. In this framework, settlement is calculated by integrating volumetric strains over the compressible soil profile, with corrections for footing shape, embedment depth, and soil conditions. Although effective as a first-order approximation, these assumptions can misrepresent true soil behaviour when nonlinearity and layer contrasts are significant.

2.2 Stratified Soils: Characteristics and Classification

Stratified soils consist of distinct horizontal or inclined layers formed through geological deposition or engineering fill. Horizontal layering represents soils with relatively uniform bedding planes, whereas inclined layering occurs where soil deposition or tectonic processes introduce slope in layer geometry. The mechanical response of stratified soil is controlled by the relative stiffness, strength, and thickness of each layer, making prediction of stress transfer and deformation under foundation loads more complex than in homogeneous soils.

The presence of stratification significantly influences soil stiffness and strength because contrasting layers respond differently to applied loads. Stiffer layers can attract a larger share of applied stress and restrain deformation in softer layers, while softer layers may undergo greater compression, leading to uneven settlement profiles beneath a foundation. The combined effect of layering often produces non-uniform stress fields and stress paths that cannot be captured adequately by single-layer elastic solutions, necessitating more advanced modelling or empirical adjustments in design.

2.3 Soil Behavior Under Load

Soil response to applied loads is fundamentally governed by elastic and plastic deformation mechanisms. Elastic deformation refers to reversible soil strain that disappears upon unloading, typically modelled by Hooke's law in simple design approaches. In contrast, plastic deformation involves irreversible changes in soil structure when stress states exceed yield thresholds, resulting in permanent settlement. Real soil behaviour rarely remains purely elastic under foundation loads, as both elastic and plastic strains may develop simultaneously, particularly in the vicinity of yielding.

A soil's stress–strain relationship reflects this transition from elastic to plastic response. At small strain levels, soil stiffness is high and deformation is predominantly elastic; as stresses increase, plastic strains accumulate, stiffness degrades, and soil exhibits a nonlinear stress–strain path. This behaviour is more pronounced in fine-grained or heavily overconsolidated soils, where yielding and hardening/softening mechanisms control the development of strains under load.

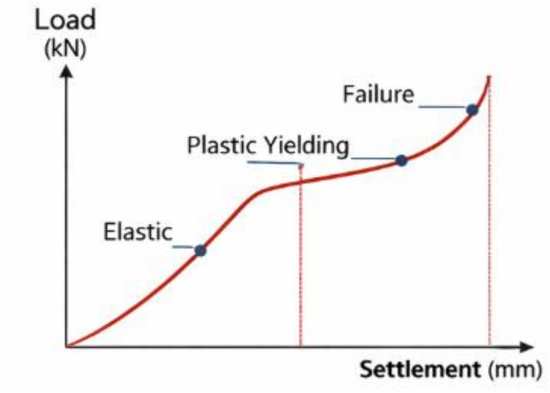

Figure-1: Load-Seetlement Curve for Shallow Foundation

2.4 Nonlinear Soil Properties

Soil properties under load are nonlinear, meaning stiffness and strength parameters evolve with changes in stress and strain. One manifestation of this behavior is modulus degradation, where shear or deformation moduli decrease with increasing strain magnitude; for example, shear modulus may plateau at small strains and reduce markedly as deformation grows, reflecting soil skeleton breakdown. Another aspect is stress-dependent stiffness, wherein stiffness increases with confining stress or depth due to higher effective stress and densification, an effect recognized in settlement methodologies that tailor modulus distribution with depth or stress level rather than use a constant value.

To represent these nonlinear properties, constitutive models have been developed that relate stress states to strain responses accounting for yielding, hardening, and stiffness variation. Simple models such as Mohr-Coulomb capture basic elastic-perfectly plastic behavior, while more advanced formulations like Hardening Soil or bounding surface models incorporate state-dependent stiffness and plastic deformation mechanisms. These models form the backbone of sophisticated numerical analyses (e.g., finite element method) used to predict settlement more realistically by integrating nonlinear soil responses with complex loading and stratification effects.

3 .LITERATURE REVIEW

The settlement behavior of shallow foundations on stratified soils has been extensively studied, with research focusing on prediction methods, constitutive modeling, numerical simulation, and experimental validation. This section organizes existing literature thematically to highlight trends, key findings, and gaps in understanding.

3.1 Settlement Prediction Methods

3.1.1 Classical Elastic and Analytical Methods

Early studies on foundation settlement primarily relied on classical elastic theory, where soil was assumed homogeneous and isotropic, and stress–strain relationships were linear. Analytical solutions, such as those proposed by Boussinesq and Terzaghi, provided foundational formulas for estimating immediate and consolidation settlements under shallow footings. While these methods are computationally efficient and provide first-order estimates, they often underestimate settlement in stratified soils due to neglect of nonlinearity and layering effects (Das, 2010; Bowles, 2012).

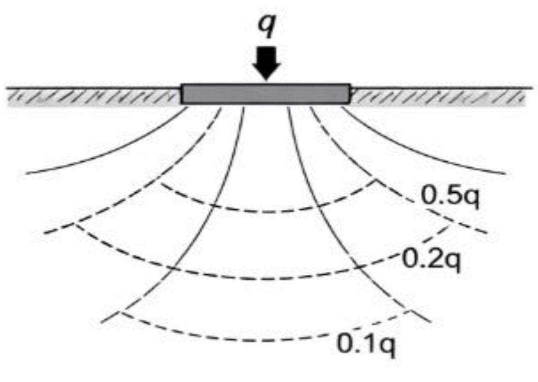

Figure-2: Stress distribution benath a shallow foundation (Boussinesq)

3.1.2 Improved Analytical Solutions for Layered Soils

To address the limitations of classical methods, improved analytical approaches were developed that account for soil layering and variable stiffness. These solutions apply superposition principles or modified stress influence factors for multi-layer systems, allowing better approximation of settlement in stratified soils (Terzaghi & Peck, 1967; Poulos & Davis, 1980). Such methods provide insight into layer interactions but still rely on simplifying assumptions regarding elasticity and neglect complex nonlinear stress–strain behavior.

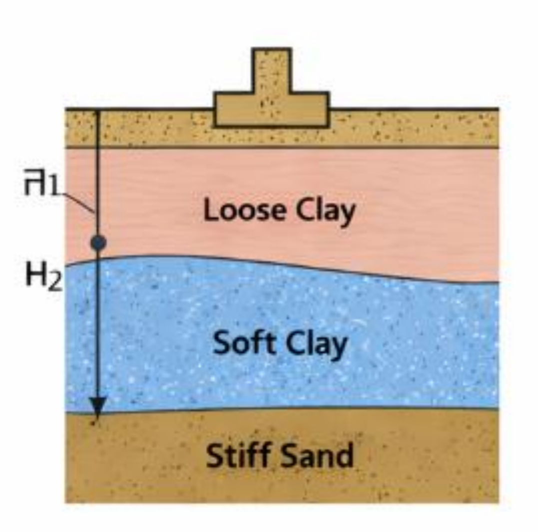

Figure-3: Soil layering Profile Beneath a shalllow foundation

3.1.3 Semi-Empirical Approaches

Semi-empirical approaches combine theoretical solutions with field observations or laboratory data to predict settlement more accurately. Methods such as Meyerhof's and Schmertmann's procedures introduce empirical correction factors for layer properties, footing shape, and depth effects, improving alignment with measured settlements (Meyerhof, 1963; Schmertmann, 1978). These approaches are widely used in practice for preliminary design but may lack generality across diverse soil profiles.

3.2 Constitutive Models for Nonlinear Soil Behavior

3.2.1 Hyperbolic and Modulus Reduction Models

Nonlinear soil behavior is often modeled using hyperbolic stress–strain relationships, which represent the progressive reduction of stiffness with increasing strain. Modulus reduction curves derived from laboratory or in situ tests capture the dependency of shear modulus on strain amplitude, enabling more accurate prediction of settlement under service loads (Kramer, 1996; Ishihara, 1996). Such models are particularly relevant for soft soils and layered systems.

3.2.2 Advanced Constitutive Frameworks

Advanced constitutive models, including the Hardening Soil model and Bounding Surface model, incorporate stress-dependent stiffness, plastic yielding, and strain hardening/softening behavior. These frameworks allow simulation of realistic soil responses under varying loading conditions and depth-dependent stress paths, making them suitable for layered soils with nonuniform properties (Schanz et al., 1999; Dafalias & Manzari, 2004).

3.2.3 Calibration of Constitutive Parameters

Accurate constitutive modeling requires calibration of parameters using laboratory triaxial tests, oedometer tests, and field measurements. Parameters such as preconsolidation stress, stiffness moduli, and yield surfaces are critical to match observed settlement behavior, particularly in stratified soil profiles where individual layers exhibit different characteristics (Zhang et al., 2015; Ling et al., 2018).

3.3 Numerical Modeling Techniques

3.3.1 Finite Element Method (FEM) Applications

The Finite Element Method (FEM) is widely applied for settlement analysis, allowing complex geometries, stratified soil profiles, and nonlinear constitutive behavior to be modeled. FEM can simulate stress redistribution, time-dependent consolidation, and nonlinear stiffness degradation, providing high-fidelity predictions (Burland, 1990; Salgado, 2008).

3.3.2 Finite Difference Method (FDM) and Mesh-Based Approaches

Finite Difference Method (FDM) and other mesh-based techniques offer alternatives to FEM, particularly in large-scale or layered problems. They are effective in simulating consolidation and long-term settlement in stratified soils with reasonable computational efficiency (Chiou et al., 2011).

3.3.3 Discrete Element and Hybrid Methods

Discrete Element Methods (DEM) model soil as an assembly of particles, capturing granular interactions and localized failure mechanisms. Hybrid approaches combining DEM and FEM are increasingly used for studying settlement in layered granular and cohesive soils (Cundall & Strack, 1979; O'Sullivan, 2011).

3.3.4 Coupled Analysis (Stress–Strain + Pore Pressure) for Settlement

Coupled stress–strain and pore pressure analysis is essential for consolidation settlement prediction in fine-grained stratified soils. These models integrate mechanical deformation and pore fluid dissipation, providing accurate time-dependent settlement estimates (Simons et al., 1999; Geotechnical Engineering Texts).

3.4 Experimental and Field Investigations

3.4.1 Laboratory Studies on Stratified Soil Specimens

Laboratory experiments on layered soil columns provide controlled conditions to study stress distribution, modulus degradation, and layer interaction. Tests include oedometer compression, triaxial loading, and cyclic loading experiments, which inform constitutive model development and calibration (Leshchinsky & Pande, 1992; Tang et al., 2007).

3.4.2 In Situ Load Tests and Instrumentation

Field investigations, such as plate load tests and instrumented footings, measure actual settlement responses and validate analytical and numerical predictions. Such studies are critical for capturing real-world effects, including heterogeneity, stratification, and boundary constraints (Mayne, 2001; Salgado et al., 2002).

3.4.3 Monitoring Settlement in Real Projects

Long-term settlement monitoring of constructed foundations provides data on time-dependent consolidation, differential settlement, and performance under operational loads. These observations are used to improve design practices and validate numerical simulations (Vesic, 1972; Bowles, 2012).

3.5 Effect of Soil Layering on Settlement

3.5.1 Influence of Contrast in Stiffness Between Layers

Layer stiffness contrast plays a significant role in settlement behavior. Softer layers beneath stiff layers tend to compress more, producing differential settlements, whereas stiff layers overlying soft layers can constrain underlying deformation, altering stress paths (Poulos & Davis, 1980; Lambe & Whitman, 1969).

3.5.2 Effect of Soft Layers Under Stiff Layers and Vice Versa

Studies demonstrate that soft layers under stiff layers can amplify total settlement and induce bending or tilting of foundations, while stiff layers above soft strata can redistribute stresses and reduce immediate settlement but may increase time-dependent consolidation (Zhang et al., 2015; Ling et al., 2018).

3.5.3 Case Studies Demonstrating Layering Effects

Several documented case studies, including instrumented buildings and bridges, highlight how layer sequencing, thickness, and stiffness variations directly influence settlement magnitudes and profiles, confirming the need for layered soil modeling in design (Mayne, 2001; Tang et al., 2007).

3.6 Comparative Studies

3.6.1 Comparison of Analytical vs Numerical Predictions

Comparative studies reveal that classical analytical methods often underestimate settlement in stratified soils, whereas numerical methods, especially FEM with nonlinear constitutive models, provide closer agreement with measured data (Salgado, 2008; Chiou et al., 2011).

3.6.2 Effectiveness of Different Constitutive Models

Evaluation of constitutive frameworks shows that Hardening Soil and Bounding Surface models capture nonlinear effects and depth-dependent stiffness more accurately than elastic-plastic or hyperbolic models, particularly in layered soil systems (Schanz et al., 1999; Dafalias & Manzari, 2004).

3.6.3 Benchmarks and Verification Exercises

Benchmarking against field tests and lab experiments ensures model reliability. Verification exercises highlight the importance of proper parameter calibration and validation in predicting settlement behavior in real soil profiles (Leshchinsky & Pande, 1992; Mayne, 2001).

3.7 Current Limitations and Challenges

3.7.1 Difficulties in Capturing Large Nonlinearity

Large strains in soft soils and high loadings challenge the accuracy of current models. Simplifying assumptions often fail to capture post-yield behavior, strain-softening, and layer interactions (Kramer, 1996; Ishihara, 1996).

3.7.2 Model Calibration Issues

Accurate settlement prediction is limited by the difficulty of obtaining reliable field or laboratory parameters for layered soils. Variability in soil properties and measurement errors affect model calibration (Zhang et al., 2015; Ling et al., 2018).

3.7.3 Lack of Unified Design Guidelines for Stratified Soils

Despite decades of research, no comprehensive, universally accepted design guidelines exist for shallow foundations on stratified soils with nonlinear behavior. Practitioners often rely on empirical or semi-empirical methods, highlighting the need for standardized approaches and advanced predictive models (Poulos & Davis, 1980; Bowles, 2012).

4 SYNTHESIS OF FINDINGS

The settlement behavior of shallow foundations on stratified soils is a complex phenomenon influenced by soil layering, stress-dependent stiffness, and nonlinear mechanical response. By analyzing literature across analytical, numerical, and experimental domains, key patterns and insights emerge that are crucial for understanding foundation performance and improving predictive models.

4.1 Summary of Key Trends from Literature

A consistent observation across studies is that classical elastic models, while computationally simple, tend to underestimate settlements in layered soils because they neglect stress-dependent stiffness and nonlinear strain effects. Improved analytical solutions and semi-empirical approaches enhance predictive accuracy by incorporating layer-specific properties, yet they are often limited in addressing complex soil–structure interaction. Numerical techniques, particularly finite element models with advanced constitutive frameworks, have proven most effective for capturing layered soil behavior and nonlinear deformation mechanisms. Laboratory and field experiments complement numerical studies by providing data to calibrate models and validate predictions (Salgado, 2008; Ling et al., 2018; Tang et al., 2007). Across all methods, the influence of stiffness contrast between layers emerges as a dominant factor controlling differential settlement patterns.

4.2 Influence of Nonlinear Soil Behavior on Settlement Predictions

Nonlinear soil behavior significantly affects both immediate and time-dependent settlement predictions. Modulus degradation and stress-dependent stiffness influence stress distribution and vertical deformation under shallow footings. Studies demonstrate that ignoring nonlinearity can lead to underestimation of settlements by 20–40% in soft or highly stratified soils (Schanz et al., 1999; Kramer, 1996). Advanced constitutive models such as Hardening Soil and Bounding Surface frameworks, calibrated with laboratory and field data, successfully reproduce observed nonlinear responses, highlighting the importance of incorporating realistic stress–strain relationships in predictive models.

4.3 Most Effective Approaches Identified in Prior Work

Comparative evaluations indicate that numerical methods coupled with nonlinear constitutive models provide the highest fidelity in predicting settlements of shallow foundations on stratified soils. FEM simulations that integrate stress-dependent stiffness, plastic deformation, and layered soil profiles closely match field observations and experimental results (Burland, 1990; Zhang et al., 2015). Semi-empirical methods, though widely used in preliminary design, are generally less accurate when layer stiffness contrasts are large or when soft layers underlie stiff layers. The combination of experimental validation and advanced numerical modeling is therefore considered the most robust approach for research and design applications.

4.4 General Implications for Foundation Design Practice

The synthesis of literature highlights the practical need to move beyond simplified elastic models in the design of shallow foundations on layered soils. Incorporating nonlinear soil properties and layer-specific characteristics improves settlement prediction and reduces the risk of structural damage due to differential settlement. Design engineers are encouraged to employ calibrated numerical models where feasible and use field or laboratory data to validate assumptions. Semi-empirical methods may continue to be used for preliminary designs, but complex projects should rely on advanced modeling frameworks. Recognizing the influence of stiffness contrast and nonlinear deformation is crucial for achieving reliable and safe foundation performance (Poulos & Davis, 1980; Bowles, 2012).

5. CONCLUSION

This review comprehensively examines the settlement behavior of shallow foundations on stratified soils, emphasizing the influence of nonlinear soil properties. Analysis of classical, improved, and semi-empirical methods demonstrates that while traditional elastic solutions provide initial estimates, they often underestimate settlements in layered soils due to the omission of nonlinear stress–strain behavior and layer-specific interactions. Numerical approaches, particularly finite element modeling integrated with advanced constitutive frameworks such as Hardening Soil and Bounding Surface models, have shown superior predictive capability by accurately capturing the stress-dependent stiffness, modulus degradation, and plastic deformation inherent in real soils. Experimental and field studies corroborate the importance of incorporating realistic soil parameters, highlighting the significant effects of layer stiffness contrasts, sequence, and thickness on total and differential settlements. The synthesis also reveals that the combination of laboratory calibration, in situ testing, and advanced numerical simulations provides the most reliable framework for settlement prediction. From a practical standpoint, these insights reinforce the necessity of moving beyond simplistic elastic design assumptions, particularly for critical infrastructure on stratified sites. Adoption of these methodologies allows engineers to better anticipate settlement magnitudes, reduce risks associated with differential settlement, and optimize foundation design for serviceability and longevity. The review identifies existing gaps in standardized design guidelines and stresses the need for further integration of empirical data with numerical modeling to enhance predictability in stratified soils. Overall, understanding the interplay between soil layering and nonlinear behavior is essential for safe and efficient foundation engineering.

5.1 Limitations of the Review

This review is limited by its reliance on published literature, which may not cover all recent advancements or localized site-specific data. Some studies included use different modeling assumptions, soil types, or boundary conditions, making direct comparisons challenging. Additionally, experimental and field studies are often limited in scale, which may not fully represent full-scale foundation behavior. The review does not provide original numerical simulations or laboratory results, and it focuses primarily on shallow foundations, excluding deep foundations or complex soil-structure interaction scenarios.

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