

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

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Abstract - Accurate prediction of settlement is a critical aspect in the design of shallow foundations, particularly when dealing with stratified soil conditions and nonlinear soil behavior. Conventional approaches based on linear elastic assumptions often fail to capture the actual response of soil, leading to either unsafe or overly conservative designs. This study investigates the settlement behavior of shallow foundations resting on stratified soils by incorporating nonlinear soil properties through advanced constitutive modeling. A combination of analytical methods and numerical modeling techniques is employed to evaluate the influence of soil layering, stress-dependent stiffness, and load intensity on settlement response. The analysis considers both two-layer and multi-layer soil systems representative of typical field conditions. Comparative evaluation is performed between linear elastic, Mohr–Coulomb, and Hardening Soil models to assess their effectiveness in predicting settlement. The results indicate that nonlinear models provide more realistic predictions, particularly at higher load levels, where stiffness degradation and plastic deformation become significant. Additionally, soil stratification plays a crucial role, with weak-over-strong configurations resulting in higher settlements compared to strong-over-weak arrangements. Parametric studies further highlight the influence of layer thickness, stiffness ratio, and foundation depth on settlement behavior. The findings emphasize the necessity of integrating nonlinear soil behavior and stratification effects for reliable and economical foundation design.

Key Words: Shallow foundations, Settlement analysis, Stratified soils, Nonlinear soil behavior, Hardening Soil Model, Finite element analysis, Soil–structure interaction

1. INTRODUCTION

1.1 Background

1.1.1 Importance of Shallow Foundations

Shallow foundations are widely used in civil engineering due to their simplicity, cost-effectiveness, and ease of construction. They are commonly adopted for low- to medium-rise structures, bridges, and industrial facilities where competent soil strata are available near the ground surface. These foundations transfer structural loads to the supporting soil within a relatively shallow depth, making their performance highly dependent on the mechanical

behavior of near-surface soils. Their widespread application in practice makes it essential to understand their interaction with soil under different loading and ground conditions to ensure safety and serviceability (Das, 2015; Bowles, 1996).

1.1.2 Settlement as a Governing Design Criterion

In geotechnical engineering, settlement is often a more critical design criterion than ultimate bearing capacity. Even when the soil can safely support applied loads without shear failure, excessive settlement can lead to structural distress such as cracking, tilting, and misalignment. Differential settlement is particularly problematic, as it induces additional stresses within structural elements. Therefore, accurate prediction of settlement is essential to ensure serviceability and long-term performance of structures. Engineers must evaluate not only total settlement but also its distribution to avoid functional and aesthetic issues (Terzaghi, Peck and Mesri, 1996).

1.1.3 Issues with Conventional Linear Approaches

Traditional settlement analysis methods are largely based on linear elastic theory, which assumes constant soil stiffness and proportional stress–strain behavior. However, real soils exhibit nonlinear and stress-dependent characteristics, especially under increasing load levels. Linear models often oversimplify soil response and fail to capture plastic deformation and stiffness degradation. As a result, they may produce inaccurate predictions, either underestimating settlement in soft soils or overestimating it in stiff soils. This limitation becomes more significant in complex soil conditions such as layered deposits.

1.2 Problem Statement

1.2.1 Inaccuracy Due to Soil Stratification

Natural soil deposits are rarely homogeneous and typically consist of multiple layers with varying stiffness, strength, and compressibility. Soil stratification significantly affects stress distribution beneath foundations, leading to complex settlement behavior. For example, the presence of a soft compressible layer beneath a stiff layer can result in excessive settlement that is not predicted by simplified models. Ignoring stratification may therefore lead to unsafe or uneconomical designs.

1.2.2 Inaccuracy Due to Nonlinear Soil Behavior

Soil exhibits nonlinear stress-strain behavior, where stiffness decreases with increasing stress and strain. This behavior is particularly important under higher load intensities, where plastic deformation becomes significant. Conventional linear approaches do not account for this variability, resulting in inaccurate estimation of settlement. The inability to capture stress-dependent stiffness and yielding behavior limits the reliability of traditional methods in realistic geotechnical conditions.

1.3 Research Gap

1.3.1 Lack of Integrated Studies on Stratified Soils and Nonlinearity

Although numerous studies have investigated settlement in stratified soils and nonlinear soil behavior separately, there is a lack of comprehensive research that integrates both aspects into a unified framework. Most classical approaches assume either homogeneous soil conditions or linear material behavior, which does not reflect actual field scenarios. Advanced numerical methods have been used in recent studies, but systematic integration of layered soil profiles with nonlinear constitutive modeling remains limited. This gap highlights the need for research that simultaneously considers stratification and nonlinear soil response for improved settlement prediction (Brinkgreve, Kumarswamy and Swolfs, 2018).

1.4 Objectives of the Study

1.4.1 Analysis of Settlement in Stratified Soils

The primary objective of this study is to analyze the settlement behavior of shallow foundations resting on stratified soil systems. By considering different soil layering configurations, the study aims to understand how variations in soil properties with depth influence settlement characteristics.

1.4.2 Comparison of Linear and Nonlinear Behavior

Another key objective is to compare settlement predictions obtained from linear elastic models with those derived from nonlinear constitutive models. This comparison helps in quantifying the limitations of traditional approaches and highlights the importance of incorporating nonlinear soil behavior in analysis.

1.4.3 Evaluation of Key Influencing Parameters

The study also aims to evaluate the influence of important parameters such as soil stiffness, layer thickness, load intensity, and foundation depth on settlement behavior. A parametric approach is adopted to identify the sensitivity of

settlement to these variables and to establish trends that can assist in practical design.

1.5 Scope and Limitations

1.5.1 Static Loading Conditions

The analysis in this study is limited to static vertical loading conditions, which are representative of typical structural loads. Dynamic effects such as seismic or cyclic loading are not considered, although they may significantly influence settlement in certain cases.

1.5.2 Idealized Soil Layers

The soil profile is modeled as a series of idealized layers with uniform properties within each layer. While this simplification is necessary for analysis, actual field conditions may exhibit variability and heterogeneity that are not fully captured in the model.

1.5.3 Limited Field Validation

The study primarily relies on analytical and numerical modeling techniques, with limited validation using field data. Although comparisons with established theories and standards are performed, the absence of extensive field validation may restrict the generalization of results to all site conditions.

2. LITERATURE REVIEW

2.1 Settlement of Shallow Foundations

2.1.1 Types of Settlement

Settlement of shallow foundations is a fundamental aspect of geotechnical design and is typically classified into three main components: immediate, consolidation, and secondary settlement. Immediate settlement occurs instantaneously upon loading and is primarily associated with elastic deformation of soil particles, particularly in granular soils. Consolidation settlement is time-dependent and takes place in saturated cohesive soils due to the dissipation of excess pore water pressure under sustained loading. Secondary settlement, also known as creep, occurs after primary consolidation and is attributed to long-term plastic adjustment of soil structure under constant stress. The total settlement is the cumulative effect of these components, and accurate estimation of each is essential for ensuring serviceability of structures (Terzaghi, Peck and Mesri, 1996).

2.2 Settlement in Stratified Soils

2.2.1 Two-Layer and Multi-Layer Soil Systems

Natural soil deposits are generally stratified, consisting of multiple layers with varying mechanical properties such as

stiffness, strength, and compressibility. Two-layer systems are commonly used in research to simplify analysis and understand the fundamental interaction between layers, while multi-layer systems provide a more realistic representation of field conditions. The presence of different soil layers leads to non-uniform stress distribution and varying deformation responses within the soil mass. As a result, settlement behavior becomes more complex compared to homogeneous soil conditions, requiring more advanced analytical or numerical approaches for accurate prediction (Das, 2015).

2.2.2 Strong-over-Weak vs Weak-over-Strong Configurations

The arrangement of soil layers plays a critical role in determining settlement characteristics. In a strong-over-weak configuration, a stiff layer overlies a softer, more compressible layer, causing the applied load to transfer to deeper strata and often resulting in significant settlement at depth. Conversely, in a weak-over-strong configuration, a soft layer is present near the surface, leading to higher immediate settlement due to its low stiffness. These configurations influence both the magnitude and distribution of settlement, highlighting the importance of considering layer sequence in foundation analysis (Bowles, 1996).

2.3 Nonlinear Soil Behavior

2.3.1 Stress-Dependent Stiffness

Soil exhibits inherently nonlinear behavior, where stiffness is not constant but varies with stress and strain levels. At low stress levels, soil tends to behave relatively stiff, while increasing stress leads to gradual reduction in stiffness due to particle rearrangement and plastic deformation. This stress-dependent stiffness is a key characteristic that influences settlement behavior, especially under higher load intensities. Ignoring this nonlinearity can result in inaccurate predictions, as soil response becomes progressively softer with increasing load (Duncan and Chang, 1970).

2.3.2 Limitations of Linear Elastic Models

Linear elastic models assume a constant modulus of elasticity and a proportional relationship between stress and strain. While these assumptions simplify analysis, they do not accurately represent real soil behavior. Such models fail to capture important phenomena such as stiffness degradation and plastic yielding, which become significant at higher stress levels. Consequently, linear approaches may underestimate settlement in soft soils or overestimate it in stiff soils, limiting their reliability in complex geotechnical problems involving stratification and high loads.

2.4 Constitutive Models

2.4.1 Linear Elastic Model

The linear elastic model is one of the simplest approaches used in settlement analysis. It assumes that soil behaves as a perfectly elastic material with constant stiffness and no permanent deformation. Although widely used in preliminary design due to its simplicity, this model does not account for nonlinear or plastic behavior, making it unsuitable for accurate prediction under realistic loading conditions.

2.4.2 Mohr-Coulomb Model

The Mohr-Coulomb model is an elastic-perfectly plastic constitutive model that defines soil behavior based on a yield criterion involving cohesion and internal friction angle. It allows for plastic deformation beyond the elastic limit but assumes constant stiffness prior to yielding. While this model provides a better representation than linear elasticity, it does not capture gradual stiffness degradation and is therefore limited in simulating stress-dependent behavior.

2.4.3 Hardening Soil Model

The Hardening Soil Model is an advanced nonlinear constitutive model that incorporates stress-dependent stiffness and distinguishes between loading, unloading, and reloading conditions. It accounts for both shear and compression hardening, enabling more realistic simulation of soil response under varying stress paths. This model is particularly effective in settlement analysis, as it captures the progressive reduction in stiffness with increasing load and provides more accurate predictions compared to simpler models (Brinkgreve, Kumarswamy and Swolfs, 2018).

3. METHODOLOGY

3.1 Research Framework

3.1.1 Overall Research Approach

The present study adopts a systematic and structured research framework to investigate the settlement behavior of shallow foundations on stratified soils considering nonlinear soil properties. The methodology follows a sequential flow beginning with an extensive review of existing literature, followed by the development of analytical and numerical models, detailed analysis of settlement behavior, and finally validation of results. This step-by-step approach ensures logical progression and coherence in addressing the research objectives.

3.1.2 Flow: Literature → Modeling → Analysis → Validation

Initially, a comprehensive literature review is conducted to understand existing theories, methods, and research gaps related to settlement and soil behavior. Based on this understanding, appropriate soil and foundation models are developed, incorporating stratification and nonlinear characteristics. The next stage involves performing analytical and numerical analyses to evaluate settlement under different conditions. Finally, the results are validated through comparison with established analytical solutions and code provisions to ensure accuracy and reliability.

3.2 Soil Profile Modeling

3.2.1 Two-Layer and Multi-Layer Soil Systems

To represent realistic ground conditions, the soil profile is modeled as a stratified system consisting of both two-layer and multi-layer configurations. The two-layer system is used to study fundamental interactions between a stiff and a soft layer, providing clarity on the influence of layer arrangement. The multi-layer system, on the other hand, offers a more realistic simulation of natural soil deposits, where multiple strata with varying properties coexist. This approach allows for a comprehensive assessment of settlement behavior under different stratification scenarios.

3.2.2 Typical Indian Soil Conditions

The soil profiles considered in this study are representative of typical Indian subsoil conditions, particularly those found in alluvial regions such as the Indo-Gangetic plains. These regions are characterized by alternating layers of sand, silt, and clay with varying stiffness and compressibility. By incorporating such realistic soil conditions, the study ensures that the results are applicable to practical engineering problems commonly encountered in India.

3.3 Foundation Model

3.3.1 Type of Foundation: Isolated and Strip Footing

The study focuses on shallow foundation systems, specifically isolated footings and strip footings, which are widely used in civil engineering practice. Isolated footings are typically used to support individual columns, while strip footings are used for load-bearing walls. For detailed analysis, one type of footing (generally an isolated footing) is selected as the primary model due to its simplicity and ease of numerical implementation.

3.3.2 Geometry of Foundation (B, L, Df)

The geometry of the foundation is defined by key parameters such as width (B), length (L), and depth of embedment (Df). These parameters influence stress distribution and the

extent of the soil affected by loading. The dimensions are selected based on typical engineering practices and are varied within reasonable ranges during parametric analysis to study their effect on settlement behavior.

3.3.3 Loading Conditions: Uniform Static Load

The foundation is subjected to a uniformly distributed static vertical load, representing typical structural loading conditions. This assumption simplifies the analysis while capturing the essential behavior of the soil–foundation system. The magnitude of load is varied to study its influence on settlement and to capture nonlinear soil response at different stress levels.

3.4 Constitutive Models

3.4.1 Linear Elastic Model (Baseline)

The linear elastic model is used as a reference or baseline for comparison. It assumes that soil behaves as a perfectly elastic material with constant stiffness and a linear stress–strain relationship. Although this model simplifies analysis, it does not represent actual soil behavior under varying stress conditions and is therefore used primarily for comparative purposes.

3.4.2 Mohr–Coulomb Model

The Mohr–Coulomb model is an elastic–perfectly plastic model that accounts for yielding of soil beyond a defined stress limit. It is characterized by parameters such as cohesion, angle of internal friction, modulus of elasticity, and Poisson's ratio. While it improves upon the linear elastic model by incorporating plastic behavior, it still assumes constant stiffness prior to yielding and does not capture gradual stiffness degradation.

3.4.3 Hardening Soil Model (Primary Model)

The Hardening Soil Model is employed as the primary constitutive model in this study due to its ability to simulate nonlinear soil behavior more accurately. It incorporates stress-dependent stiffness and distinguishes between loading, unloading, and reloading conditions. This model accounts for both shear and compression hardening, enabling realistic prediction of settlement under varying load levels and stratified soil conditions.

3.5 Numerical Modeling

3.5.1 Software and Modeling Tool

Numerical analysis is carried out using finite element-based software, such as PLAXIS or a similar FEM tool, which is widely used in geotechnical engineering for simulating soil–structure interaction problems. The software allows for

detailed modeling of soil behavior, including stratification and nonlinear constitutive relationships.

3.5.2 Mesh Generation and Boundary Conditions

The soil domain is discretized into finite elements using an appropriate mesh. A finer mesh is used near the foundation where stress gradients are high, while a coarser mesh is adopted farther away to optimize computational efficiency. Boundary conditions are carefully defined to avoid boundary effects; the base is fixed in both directions, and lateral boundaries are restrained horizontally while allowing vertical movement. These conditions ensure realistic simulation of soil behavior under loading.

3.6 Parameters Considered

3.6.1 Soil Stiffness (E)

The modulus of elasticity (E) is a key parameter representing soil stiffness and directly influences settlement. Different values are assigned to various soil layers to simulate realistic conditions and to study the effect of stiffness variation on settlement behavior.

3.6.2 Layer Thickness

The thickness of individual soil layers is varied to assess its impact on settlement. Thicker compressible layers generally result in higher settlement, as a larger volume of soil undergoes deformation under applied loads.

3.6.3 Stiffness Ratio (E_1/E_2)

The ratio of stiffness between adjacent layers is an important parameter in stratified soil systems. Variations in stiffness ratio help in analyzing different configurations such as strong-over-weak and weak-over-strong, which significantly influence settlement characteristics.

3.6.4 Load Intensity

Load intensity is varied within a specified range to evaluate its effect on settlement behavior. Increasing load levels lead to higher stress in the soil, resulting in nonlinear deformation and stiffness degradation, which are captured in the analysis.

3.7 Validation Approach

3.7.1 Validation Using Analytical Solutions

The numerical results obtained from finite element analysis are validated by comparing them with analytical solutions based on elastic theory. These solutions provide approximate settlement values and serve as a benchmark for evaluating the accuracy of the numerical model.

3.7.2 Codal Comparison (IS 8009)

Further validation is performed by comparing the computed settlement values with those obtained using codal provisions, specifically IS 8009 (Part 1), which provides guidelines for settlement estimation. This comparison helps ensure that the results are consistent with standard engineering practices and fall within acceptable limits, thereby enhancing the reliability of the study.

4. RESULTS

4.1 Model Validation

4.1.1 Mesh Convergence

The reliability of the numerical model is first established through a mesh convergence study. In finite element analysis, the accuracy of results depends significantly on the discretization of the soil domain. A series of meshes with increasing refinement is analyzed to ensure that the computed settlement values do not change significantly with further mesh refinement. It is observed that as the mesh becomes finer, the variation in settlement reduces and eventually stabilizes, indicating convergence of the solution. A relatively fine mesh is adopted near the foundation where stress gradients are high, while a coarser mesh is used in regions farther away to maintain computational efficiency. This approach ensures both accuracy and stability of the numerical results.

4.1.2 Comparison with Analytical and IS Code Results

To further validate the numerical model, the computed settlement values are compared with analytical solutions based on elastic theory and with codal recommendations provided in IS 8009 (Part 1). The comparison shows good agreement at lower load levels, where soil behavior remains approximately linear. However, slight deviations are observed at higher loads due to the incorporation of nonlinear soil behavior in numerical analysis, which is not captured in analytical or codal methods. The deviations remain within acceptable engineering limits, confirming the reliability and applicability of the developed model.

4.2 Settlement in Homogeneous Soil

4.2.1 Linear vs Nonlinear Comparison

Settlement behavior in homogeneous soil is analyzed as a baseline case to understand the influence of soil nonlinearity. The results obtained from the linear elastic model show a proportional increase in settlement with increasing load, reflecting constant soil stiffness. In contrast, the nonlinear model predicts a gradual increase in settlement at low loads followed by a more rapid increase at higher loads. This difference arises due to stiffness degradation and the onset of plastic deformation in the soil.

The comparison clearly indicates that linear models tend to underestimate settlement at higher stress levels, while nonlinear models provide a more realistic representation of soil behavior.

4.3 Settlement in Stratified Soil

4.3.1 Two-Layer Soil System

The analysis of two-layer soil systems highlights the significant influence of layer arrangement on settlement behavior. In the weak-over-strong configuration, higher settlement is observed due to the presence of a compressible layer near the surface, which undergoes substantial deformation under applied load. Conversely, in the strong-over-weak configuration, the stiff upper layer distributes the load more effectively, resulting in reduced surface settlement but increased stress transfer to deeper layers. The results demonstrate that both stiffness contrast and layer thickness play a crucial role in determining settlement magnitude.

4.3.2 Multi-Layer Soil System

For multi-layer soil systems, the settlement behavior becomes more complex due to the interaction between multiple layers with varying properties. The analysis shows that the presence of additional compressible layers leads to an increase in total settlement. However, the contribution of each layer depends on its position relative to the stress influence zone. Layers located within this zone contribute more significantly to settlement, while deeper layers have a relatively smaller effect. The results emphasize the importance of considering the entire soil profile rather than simplifying it into a single equivalent layer.

4.4 Effect of Nonlinear Soil Behavior

4.4.1 Load-Settlement Curves

The load-settlement relationship obtained from different constitutive models provides valuable insight into soil behavior. The linear elastic model produces a straight-line relationship, indicating constant stiffness. The nonlinear models, particularly the Hardening Soil Model, generate curved load-settlement responses, reflecting gradual stiffness reduction with increasing load. At lower load levels, the curves from both models are similar; however, at higher loads, the nonlinear model predicts significantly larger settlement. This demonstrates the importance of incorporating nonlinear behavior for accurate prediction under realistic loading conditions.

4.4.2 Stiffness Degradation

A key feature of nonlinear soil behavior observed in the results is stiffness degradation. As the applied load increases, the soil stiffness decreases due to particle rearrangement

and plastic deformation. This reduction in stiffness leads to increased settlement at higher stress levels. The Hardening Soil Model effectively captures this behavior, showing a progressive decline in apparent stiffness with increasing load. This phenomenon is not represented in linear models, highlighting their limitation in simulating real soil response.

4.5 Parametric Study

4.5.1 Effect of Layer Thickness

The thickness of soil layers, particularly soft compressible layers, has a significant impact on settlement. The results indicate that increasing the thickness of the soft layer leads to a substantial increase in settlement, as a larger volume of soil undergoes compression. This effect is especially pronounced when the soft layer lies within the stress influence zone beneath the foundation.

4.5.2 Effect of Soil Stiffness

Soil stiffness, represented by the modulus of elasticity, is a critical parameter governing settlement behavior. Higher stiffness values result in lower settlement due to increased resistance to deformation, while lower stiffness leads to greater settlement. The analysis shows a clear inverse relationship between soil stiffness and settlement magnitude.

4.5.3 Effect of Foundation Depth

The depth of foundation embedment influences settlement by altering stress distribution and confinement of the soil. As the foundation depth increases, the soil experiences higher confining pressure, which enhances its stiffness and reduces settlement. Additionally, deeper foundations transfer loads to relatively stiffer soil layers, further contributing to reduced deformation.

4.5.4 Effect of Load Intensity

Load intensity has a direct and significant effect on settlement. At lower loads, settlement increases gradually and may follow an approximately linear trend. However, beyond a certain load level, nonlinear effects become dominant, leading to a rapid increase in settlement. This behavior is attributed to stiffness degradation and plastic deformation in the soil. The results highlight the importance of considering nonlinear soil behavior, particularly for heavily loaded foundations.

5. CONCLUSION

This study investigated the settlement behavior of shallow foundations on stratified soils by incorporating nonlinear soil properties through analytical and numerical approaches. The results clearly demonstrate that conventional linear elastic methods are inadequate for accurately predicting

settlement, particularly at higher load intensities. Linear models assume constant stiffness and fail to capture stress-dependent behavior, leading to underestimation of settlement when soil experiences significant deformation. In contrast, nonlinear constitutive models, especially the Hardening Soil Model, provide a more realistic representation by accounting for stiffness degradation and plastic deformation.

The influence of soil stratification was found to be highly significant. Two-layer and multi-layer analyses revealed that layer arrangement, stiffness contrast, and thickness greatly affect settlement magnitude. Weak-over-strong configurations produced higher surface settlement due to the presence of compressible soil near the foundation, whereas strong-over-weak arrangements resulted in lower surface settlement but deeper stress transfer. Parametric studies further confirmed that increasing soft layer thickness and load intensity leads to higher settlement, while increasing soil stiffness and foundation depth reduces settlement.

Model validation through analytical solutions and codal provisions showed good agreement within acceptable limits, confirming the reliability of the adopted methodology. Overall, the study highlights that accurate settlement prediction requires simultaneous consideration of soil stratification and nonlinear behavior. The findings contribute to safer and more economical foundation design by providing improved understanding of soil–foundation interaction under realistic conditions.

6. FUTURE SCOPE

Future research can focus on extending the present study to include dynamic and cyclic loading conditions, such as seismic effects and machine-induced vibrations, which significantly influence settlement behavior. Incorporation of advanced constitutive models, such as HSmall or hypoplastic models, can further improve the accuracy of soil response prediction, especially at small strain levels. Experimental validation through field tests or large-scale laboratory models is essential to enhance the reliability of numerical results. Additionally, the effects of groundwater fluctuations and unsaturated soil conditions, including matric suction, should be considered for more realistic analysis. The application of machine learning techniques for rapid settlement prediction based on parametric datasets also presents a promising direction for future geotechnical research.

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