BEARING CAPACITY EVALUATION OF FOOTINGS ON PARTIALLY SATURATED SOILS USING MODIFIED CONSTITUTIVE APPROACHES

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Abstract - *The evaluation of bearing capacity of shallow foundations is a fundamental aspect of geotechnical engineering design. Conventional bearing capacity theories, such as those proposed by Terzaghi and Meyerhof, are primarily developed for dry or fully saturated soil conditions and do not consider the effects of partial saturation. However, in real field conditions, soils often exist in a partially saturated state where matric suction significantly influences their mechanical behavior. This study investigates the bearing capacity of shallow footings resting on partially saturated soils using modified constitutive approaches that incorporate suction-dependent stress parameters. A combined analytical and numerical framework is adopted, integrating unsaturated soil mechanics concepts with advanced constitutive models such as the Fredlund two-stress state variable approach and the Barcelona Basic Model. The modified effective stress concept is used to account for the contribution of matric suction to soil strength. A parametric study is conducted to evaluate the influence of degree of saturation, matric suction, footing size, and soil type on bearing capacity and load–settlement behavior. The results indicate a significant increase in bearing capacity with decreasing degree of saturation due to the enhancement in apparent cohesion. The modified approach provides more realistic and less conservative predictions compared to classical methods. The findings highlight the importance of incorporating unsaturated soil behavior for accurate and economical foundation design.*

Key Words: Bearing capacity; Unsaturated soil; Matric suction; Constitutive modeling; Shallow foundations; Soil-water characteristic curve

1. INTRODUCTION

1.1 Background

1.1.1 Importance of Bearing Capacity in Foundation Design

Bearing capacity is a critical parameter in geotechnical engineering that determines the maximum load a soil can safely support without undergoing shear failure or excessive settlement. It directly governs the design and stability of shallow foundations such as isolated footings, strip footings, and raft foundations. Accurate estimation of bearing capacity ensures structural safety and serviceability while also enabling economical design by avoiding over-conservative assumptions. Classical bearing capacity theories, developed based on limit equilibrium concepts, consider soil strength parameters such as cohesion, internal friction angle, and unit weight. However, these approaches often rely on simplified assumptions of soil behavior, which may not fully represent complex field conditions (Terzaghi, 1943; Meyerhof, 1963).

1.1.2 Real Field Condition: Partially Saturated Soils

In natural conditions, soils are rarely fully saturated or completely dry; instead, they exist predominantly in a partially saturated state, particularly above the groundwater table. In such conditions, the presence of both air and water within soil pores leads to the development of matric suction, which significantly influences soil strength and stiffness. Matric suction contributes to apparent cohesion, enhancing the load-bearing capacity of soil under certain moisture conditions. However, this behavior is highly dependent on environmental factors such as rainfall, evaporation, and seasonal changes, making soil response more complex and variable compared to saturated conditions (Fredlund and Rahardjo, 1993).

1.2 Problem Statement

1.2.1 Limitations of Classical Theories

Classical bearing capacity theories, including those proposed by Terzaghi and Meyerhof, are widely used in engineering practice due to their simplicity and practicality. These theories assume that soil is either fully saturated or dry and do not account for intermediate states of saturation. Consequently, they neglect the influence of matric suction and its contribution to shear strength. This limitation restricts their applicability in real-world scenarios where soils are partially saturated, leading to discrepancies between predicted and actual foundation performance (Hansen, 1970).

1.2.2 Ignoring Matric Suction and Resulting Inaccuracies

The exclusion of matric suction in classical formulations results in inaccurate estimation of bearing capacity, often leading to conservative designs. While conservative designs may enhance safety, they can also increase construction costs unnecessarily. Conversely, under certain conditions, ignoring moisture variations may lead to unsafe predictions if suction decreases due to wetting. Therefore, the inability of traditional models to capture suction-dependent behavior highlights the need for improved analytical approaches that incorporate unsaturated soil mechanics principles (Vanapalli et al., 1996).

1.3 Research Gap

1.3.1 Limited Integration of Constitutive Models in Design

Although significant advancements have been made in constitutive modeling of unsaturated soils, their integration into routine geotechnical design practice remains limited. Advanced models such as the Barcelona Basic Model and Fredlund's two-stress variable framework provide a more realistic representation of soil behavior by incorporating suction effects. However, these models are often confined to research applications and are not widely adopted in standard design procedures due to their complexity and requirement for additional parameters (Alonso et al., 1990).

1.3.2 Lack of Coupling Between SWCC and Bearing Capacity

The Soil-Water Characteristic Curve (SWCC) is a fundamental tool in unsaturated soil mechanics that defines the relationship between matric suction and degree of saturation. Despite its importance, there is a lack of unified frameworks that directly integrate SWCC into bearing capacity analysis. This disconnect limits the ability to accurately predict how variations in moisture content affect soil strength and foundation performance. Bridging this gap is essential for developing comprehensive models that can simulate real field conditions more effectively (Lu and Likos, 2004).

1.4 Objectives

1.4.1 Evaluation Using Modified Constitutive Approaches

The primary objective of this study is to evaluate the bearing capacity of shallow footings resting on partially saturated soils using modified constitutive approaches. These approaches incorporate suction-dependent stress variables and provide a more realistic representation of soil behavior compared to classical methods.

1.4.2 Comparison with Classical Methods

Another key objective is to compare the results obtained from modified constitutive models with those predicted by classical bearing capacity theories. This comparison helps quantify the influence of matric suction and highlights the limitations of traditional design approaches.

1.4.3 Analysis of Saturation and Suction Effects

The study also aims to analyze the effect of degree of saturation and matric suction on bearing capacity and load–settlement behavior. By conducting a parametric evaluation, the research seeks to understand how variations in moisture conditions influence foundation performance, thereby contributing to more accurate and reliable geotechnical design practices.

2. LITERATURE REVIEW

2.1 Unsaturated Soil Mechanics

2.1.1 Matric Suction and Effective Stress Concepts

Unsaturated soil mechanics extends classical soil mechanics by considering the presence of both air and water within soil pores. A key parameter governing the behavior of such soils is matric suction, defined as the difference between pore-air pressure and pore-water pressure. This suction induces negative pore-water pressure, which enhances inter-particle bonding and contributes to the apparent cohesion of soil. Consequently, partially saturated soils often exhibit higher shear strength and stiffness compared to fully saturated soils under similar stress conditions. The concept of effective stress in unsaturated soils has been modified to include suction effects, enabling a more realistic representation of stress distribution within the soil matrix. These developments form the theoretical foundation for analyzing the mechanical behavior of soils in natural field conditions (Fredlund and Rahardjo, 1993).

2.2 Classical Bearing Capacity Theories

2.2.1 Terzaghi, Meyerhof, and Hansen Approaches

Classical bearing capacity theories have long been used as the basis for foundation design. Terzaghi's theory introduced the concept of ultimate bearing capacity based on soil shear strength parameters and assumed a simplified failure mechanism beneath shallow foundations. Meyerhof extended this formulation by incorporating factors such as footing shape, depth, and load inclination, thereby improving its applicability to practical problems. Hansen further refined the approach by introducing additional correction factors to account for real field conditions. These models collectively provide a systematic framework for estimating bearing capacity and remain widely used in engineering practice due to their simplicity and reliability under conventional conditions (Terzaghi, 1943; Meyerhof, 1963).

2.2.2 Limitations under Unsaturated Conditions

Despite their widespread use, classical bearing capacity theories are limited in their ability to represent unsaturated soil behavior. These methods assume that soil is either fully saturated or completely dry, thereby neglecting the influence of matric suction. As a result, they fail to capture the additional strength contribution arising from partial saturation. This limitation leads to discrepancies between predicted and actual bearing capacity, particularly in regions where soil moisture conditions vary significantly.

Consequently, the application of these theories to unsaturated soils often results in conservative or inaccurate design outcomes (Hansen, 1970).

2.3 Constitutive Models for Unsaturated Soils

2.3.1 Bishop's Effective Stress Approach

Bishop proposed an extension to the classical effective stress concept by introducing a suction-dependent parameter that accounts for the degree of saturation. This formulation modifies the effective stress by incorporating the contribution of matric suction, thereby enabling the prediction of shear strength in partially saturated soils. Although this approach provides a useful framework, it involves simplifications regarding the variation of the suction parameter with saturation (Bishop, 1959).

2.3.2 Fredlund Two-Variable Approach

A more advanced representation of unsaturated soil behavior was developed through the two stress state variable approach, which considers both net normal stress and matric suction as independent variables. This framework allows for a more comprehensive description of soil behavior, including strength, deformation, and volume change characteristics under varying moisture conditions. It has become one of the most widely accepted theoretical models in unsaturated soil mechanics due to its flexibility and accuracy (Fredlund and Morgenstern, 1977).

2.3.3 Barcelona Basic Model (BBM)

The Barcelona Basic Model (BBM) is a widely recognized constitutive model that incorporates suction as a key variable influencing the yield surface of soil. It is based on an elastoplastic framework and accounts for hardening and softening behavior under loading and wetting conditions. BBM effectively captures the coupling between mechanical and hydraulic responses of soil, making it suitable for advanced numerical simulations of geotechnical problems involving unsaturated soils (Alonso et al., 1990).

2.4 Bearing Capacity in Unsaturated Soils

2.4.1 Experimental and Analytical Findings

Research on the bearing capacity of unsaturated soils has demonstrated that soil strength is significantly influenced by moisture conditions. Experimental studies have shown that as the degree of saturation decreases, matric suction increases, leading to higher shear strength and improved load-carrying capacity. Analytical models incorporating suction effects have also been developed to predict this behavior, often showing good agreement with experimental observations. These findings highlight the importance of considering unsaturated soil mechanics in foundation design (Vanapalli et al., 1996).

2.4.2 Influence of Suction on Soil Strength

Matric suction plays a crucial role in enhancing the shear strength of partially saturated soils by increasing apparent cohesion. This effect is particularly significant in sandy and silty soils, where suction can develop rapidly due to high permeability. However, the contribution of suction is highly sensitive to changes in moisture content, which may vary due to environmental factors such as rainfall and evaporation. As a result, the bearing capacity of soils under unsaturated conditions is not constant but varies with saturation levels, making it essential to incorporate suction-dependent models for accurate prediction of foundation performance (Lu and Likos, 2004).

3. METHODOLOGY

3.1 Research Framework

3.1.1 Analytical and Numerical Approach

The present study adopts a combined analytical and numerical framework to evaluate the bearing capacity of shallow footings on partially saturated soils. The analytical approach is based on modified bearing capacity formulations that incorporate suction-dependent stress parameters, enabling a theoretical understanding of soil behavior. In parallel, numerical modeling is employed to simulate the complex stress–strain response of soil under footing loads, capturing nonlinearity and spatial variation in soil properties. This integrated methodology ensures that both simplified theoretical predictions and detailed simulation results are obtained, enhancing the overall reliability of the study.

3.1.2 Comparison with IS Code

To validate the effectiveness of the modified approach, results obtained from analytical and numerical models are compared with classical predictions based on IS 6403 provisions. The IS code assumes saturated or dry soil conditions and does not consider matric suction. Therefore, it serves as a baseline reference to quantify the improvement achieved through suction-based modeling. This comparison helps in identifying the limitations of conventional design practices and demonstrates the need for incorporating unsaturated soil behavior in foundation analysis.

3.2 Soil Properties and Parameters

3.2.1 Soil Types Considered

The study considers representative soil types commonly encountered in foundation engineering, including sandy soil, silty sand, and clayey sand. These soils are selected to capture a range of permeability and suction characteristics, as the influence of partial saturation varies significantly across different soil classifications. Sandy soils typically exhibit rapid suction changes, while clayey soils show gradual variation due to lower permeability.

3.2.2 Geotechnical Parameters

Key geotechnical parameters used in the analysis include unit weight (γ), cohesion (c), angle of internal friction (φ), elastic modulus (E), and Poisson's ratio (ν). In addition, Soil-Water Characteristic Curve (SWCC) parameters are incorporated to define the relationship between suction and degree of saturation. These parameters collectively govern the strength, stiffness, and hydraulic behavior of the soil under partially saturated conditions.

3.3 Constitutive Model

3.3.1 Model Selection

The study utilizes advanced constitutive models such as the Barcelona Basic Model (BBM) or the Fredlund two-stress variable approach to represent unsaturated soil behavior. These models incorporate suction as an independent variable influencing soil strength and deformation characteristics.

3.3.2 Justification of Selection

The selected models are capable of capturing suction-dependent stress–strain relationships and are widely validated in unsaturated soil mechanics research. Their ability to simulate both elastic and plastic behavior under varying moisture conditions makes them suitable for analyzing footing performance in partially saturated soils.

3.4 Incorporation of Matric Suction

3.4.1 Modified Effective Stress Concept

Matric suction is incorporated into the analysis using a modified effective stress framework. In this approach, effective stress is expressed as a function of net normal stress and suction, with a parameter that accounts for the degree of saturation. This formulation enables the inclusion of suction-induced strength in the analysis, thereby providing a more realistic representation of soil behavior compared to classical effective stress concepts.

3.5 SWCC Integration

3.5.1 Relationship between Suction and Saturation

The Soil-Water Characteristic Curve (SWCC) is integrated into the modeling framework to establish the relationship between matric suction and degree of saturation. The SWCC serves as a critical link between hydraulic and mechanical behavior, allowing the variation of soil strength parameters with moisture content to be captured. This integration enhances the accuracy of constitutive modeling and bearing capacity prediction.

3.6 Bearing Capacity Formulation

3.6.1 Classical Equation (Baseline)

The classical bearing capacity equation is used as a baseline for comparison. It considers soil cohesion, unit weight, and friction angle, along with bearing capacity factors, under the assumption of saturated or dry conditions. This formulation provides a reference point for evaluating the influence of suction.

3.6.2 Modified Equation with Suction

A modified bearing capacity formulation is developed by incorporating suction-dependent cohesion and effective stress. In this approach, matric suction contributes to apparent cohesion, resulting in increased shear strength and higher bearing capacity. The modified equation thus reflects the influence of partial saturation on soil behavior and provides more realistic predictions.

4. RESULTS AND DISCUSSION

4.1 Validation of Model

4.1.1 Comparison with IS 6403 / Classical Results

The validity of the proposed modified constitutive approach is assessed by comparing the predicted bearing capacity with values obtained from classical methods based on IS 6403 and traditional theories. The classical approach assumes saturated or dry soil conditions and therefore provides relatively lower and constant bearing capacity values. In contrast, the modified model incorporates suction effects and shows higher bearing capacity under partially saturated conditions. The comparison demonstrates that the proposed approach aligns with classical results under saturated conditions, thereby confirming its consistency, while also extending the prediction capability to more realistic field scenarios.

4.2 Effect of Matric Suction

4.2.1 Increase in Bearing Capacity

The analysis clearly indicates that matric suction plays a significant role in enhancing the bearing capacity of soil. As suction increases, the apparent cohesion of soil also increases, leading to improved shear strength. This additional strength allows the soil to sustain higher loads before failure. The results show that even moderate levels of suction can produce noticeable improvement in bearing capacity compared to classical predictions.

4.2.2 Nonlinear Trend

The relationship between matric suction and bearing capacity is observed to be nonlinear. At lower suction levels, the increase in bearing capacity is gradual; however, as suction increases further, the rate of improvement becomes more pronounced. This nonlinear behavior is attributed to the complex interaction between soil particles, pore water, and air within the soil matrix. The results highlight that suction effects are more dominant within a specific range of partial saturation.

4.3 Effect of Degree of Saturation

4.3.1 Influence on Bearing Capacity

The degree of saturation is found to be a governing factor influencing bearing capacity. As the degree of saturation decreases, the amount of air in the soil pores increases, leading to higher matric suction. This results in an increase in soil strength and, consequently, higher bearing capacity. The study shows that soils at lower saturation levels exhibit significantly greater load-carrying capacity compared to fully saturated conditions.

4.4 Load–Settlement Behaviour

4.4.1 Higher Stiffness in Unsaturated Soils

The load–settlement response indicates that partially saturated soils exhibit higher stiffness compared to saturated soils. This is reflected in the initial portion of the load–settlement curve, where smaller settlements are observed for the same applied load. The increased stiffness is primarily due to the contribution of matric suction, which enhances inter-particle bonding and resistance to deformation.

4.4.2 Delayed Failure Response

Another important observation is the delayed failure behavior in unsaturated soils. The footing is able to sustain higher loads before reaching ultimate failure, and the progression of settlement is more gradual. This indicates improved performance and stability of foundations under partially saturated conditions when compared to classical saturated assumptions.

4.5 Comparison: Classical vs Modified Models

4.5.1 Quantitative Improvement (%)

A quantitative comparison between classical and modified approaches reveals a significant improvement in bearing capacity when suction effects are considered. The percentage increase varies depending on soil type and degree of saturation but generally shows a substantial enhancement under partially saturated conditions. The classical model consistently underestimates bearing capacity, whereas the modified model provides more realistic predictions, highlighting the importance of incorporating unsaturated soil behavior in design.

4.6 Effect of Soil Type

4.6.1 Sandy Soils – Highest Improvement

The results indicate that sandy soils exhibit the highest improvement in bearing capacity due to suction effects. This is because sandy soils have higher permeability, allowing rapid development of matric suction. As a result, the contribution of suction to apparent cohesion is more pronounced, leading to significant enhancement in load-carrying capacity.

4.6.2 Clayey Soils – Moderate Response

In contrast, clayey soils show a more moderate response to suction. Due to their low permeability, the development and variation of suction occur more slowly. While suction still contributes to strength improvement, the overall increase in bearing capacity is less significant compared to sandy soils. This behavior reflects the influence of soil type on unsaturated soil mechanics.

4.7 Effect of Footing Geometry

4.7.1 Influence of Footing Width

Footing width is found to influence the distribution of stress within the soil mass. Smaller footings tend to concentrate stress over a limited area, making the effect of matric suction more pronounced. In contrast, larger footings distribute the load over a wider area, reducing the relative contribution of suction per unit stress. Thus, the percentage improvement in bearing capacity due to suction is higher for smaller footing sizes.

4.7.2 Shape Factor (Square vs Strip Footing)

The shape of the footing also affects bearing capacity. Square footings exhibit slightly higher bearing capacity compared to strip footings due to more uniform stress distribution in two directions. This allows better mobilization of soil strength, including suction effects. Strip footings, on the other hand, show relatively lower capacity due to one-dimensional load distribution. These observations are consistent with classical shape factor concepts, with additional influence from unsaturated soil behavior.

5. CONCLUSION

This study presents a comprehensive evaluation of the bearing capacity of shallow footings resting on partially saturated soils using modified constitutive approaches. The findings clearly demonstrate that classical bearing capacity theories, which assume fully saturated or dry soil conditions, are inadequate for representing real field scenarios where soils are predominantly partially saturated. The incorporation of matric suction into the analysis significantly enhances the prediction of soil strength and bearing capacity. Results indicate that bearing capacity increases with decreasing degree of saturation due to the development of suction-induced apparent cohesion, leading to improved load-carrying capacity and stiffness of the soil.

The load–settlement analysis further reveals that partially saturated soils exhibit higher initial stiffness and delayed failure compared to classical predictions, highlighting their improved performance under foundation loading. The comparison between classical and modified models shows that conventional approaches tend to underestimate bearing capacity, resulting in conservative designs. Additionally, the influence of soil type and footing geometry is found to be significant, with sandy soils showing greater improvement due to rapid suction development, while clayey soils exhibit moderate enhancement. Smaller footing widths and square geometries demonstrate a more pronounced effect of suction.

Overall, the study confirms that incorporating unsaturated soil mechanics through modified constitutive models leads to more realistic, reliable, and economical foundation design, particularly in regions with variable moisture conditions.

6. FUTURE SCOPE

Future research should focus on field-scale validation of suction-based bearing capacity models through instrumented footing tests under controlled and natural moisture conditions. Long-term monitoring of foundations subjected to seasonal wetting and drying cycles would provide valuable insights into the temporal variation of matric suction and its impact on soil performance. Further studies are required to develop simplified design procedures that integrate suction effects into standard codes such as IS 6403 for practical application. Advanced numerical modeling using coupled hydro-mechanical analysis can improve the understanding of transient moisture flow and stress interaction. Additionally, extending the research to different foundation systems, including raft and pile foundations, and exploring machine learning-based predictive models can enhance the applicability and efficiency of unsaturated soil analysis in geotechnical engineering.

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