

# A REVIEW OF 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 on partially saturated soils has gained increasing attention due to the widespread occurrence of unsaturated ground conditions in natural and engineered deposits. Conventional bearing capacity theories, originally developed for fully saturated or dry soils, neglect the influence of matric suction and hydraulic-mechanical coupling, leading to potential inaccuracies in design. This review synthesizes existing research on bearing capacity assessment of footings resting on partially saturated soils, with particular emphasis on modified constitutive approaches that incorporate suction-dependent behavior. The paper critically examines experimental investigations, including suction-controlled triaxial and plate load tests, and evaluates their contributions to understanding strength enhancement under partial saturation. It further reviews effective stress-based models, elasto-plastic formulations, critical state frameworks, and advanced constitutive models such as the Barcelona Basic Model and hypoplastic approaches, highlighting their theoretical foundations and practical applicability. Numerical implementations using finite element methods are also analyzed to assess predictive capabilities and parameter sensitivity. Comparative evaluation reveals that while suction-inclusive constitutive models significantly improve prediction accuracy, challenges remain in parameter calibration, field validation, and coupled hydro-mechanical modeling. The review identifies key knowledge gaps and proposes directions for future research aimed at achieving reliable and unified design methodologies for foundations under partially saturated conditions. The synthesis provided herein serves as a comprehensive reference for researchers and practicing geotechnical engineers engaged in advanced foundation analysis.

**Key Words:** Partially saturated soils; Bearing capacity; Matric suction; Modified constitutive models; Effective stress framework; Hydro-mechanical coupling; Finite element analysis; Unsaturated soil mechanics.

## 1. INTRODUCTION

The evaluation of bearing capacity is a fundamental component of shallow foundation design in civil engineering practice. Accurate prediction of ultimate load-carrying capacity ensures structural safety, serviceability, and economic efficiency. Classical formulations, developed under idealized assumptions, have historically provided the basis for design; however, increasing awareness of unsaturated

soil behavior has revealed important limitations in conventional approaches. In many field conditions, foundation soils exist in a partially saturated state, where matric suction contributes significantly to shear strength and stiffness. The interaction between hydraulic and mechanical processes under such conditions necessitates a more advanced modeling framework.

### 1.1 Importance of Soil Bearing Capacity in Foundation Design

#### 1.1.1 Role in Structural Stability and Serviceability

Bearing capacity represents the maximum pressure that soil can sustain without undergoing shear failure. Inadequate estimation may result in excessive settlement or catastrophic failure. The classical bearing capacity theory developed by Karl Terzaghi (1943) laid the foundation for modern geotechnical design by introducing limit equilibrium concepts for shallow foundations. Subsequent refinements by Geoffrey Meyerhof (1963) incorporated shape, depth, and inclination factors to enhance practical applicability. These formulations remain embedded in contemporary design codes and engineering practice.

#### 1.1.2 Economic and Safety Implications

Reliable bearing capacity assessment directly influences foundation dimensions and construction costs. Conservative estimates increase material usage, whereas unconservative predictions compromise safety. Modern infrastructure development in urban and semi-urban regions increasingly encounters soils in unsaturated states, making accurate modeling of strength characteristics under varying moisture conditions essential for sustainable and resilient design (Das and Sobhan, 2018).

### 1.2 Challenges Associated with Partially Saturated Soils

#### 1.2.1 Nature of Unsaturated Soil Systems

Partially saturated soils consist of a three-phase system involving solid particles, pore water, and pore air. The presence of matric suction, defined as the difference between pore air and pore water pressures, contributes to apparent cohesion and enhanced shear strength. Foundational work by Fredlund and Morgenstern (1977) established the independent stress state variables

framework for unsaturated soils, demonstrating that shear strength depends on both net normal stress and matric suction.

### 1.2.2 Hydraulic–Mechanical Coupling Effects

Unlike fully saturated soils, partially saturated soils exhibit strong coupling between hydraulic processes and mechanical response. Variations in moisture content due to rainfall, evaporation, or groundwater fluctuation can alter matric suction and, consequently, shear strength and stiffness. The Soil–Water Characteristic Curve (SWCC) governs this relationship and plays a critical role in constitutive modeling (Van Genuchten, 1980). Seasonal changes may therefore significantly influence foundation performance, complicating design assumptions based on constant soil properties.

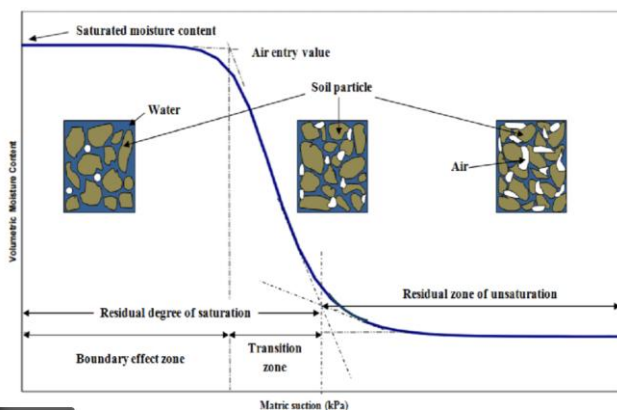


Figure-1: Soil–Water Characteristic Curve (SWCC)

### 1.3 Limitations of Classical Bearing Capacity Theories in Partially Saturated States

#### 1.3.1 Assumption of Saturated or Dry Conditions

Traditional bearing capacity theories implicitly assume either fully saturated or dry soil conditions and typically rely on effective stress concepts applicable to saturated soils. The general bearing capacity equation derived by Terzaghi (1943) does not explicitly incorporate matric suction or degree of saturation effects. Consequently, the additional shear strength arising from suction is not directly represented.

#### 1.3.2 Inadequacy Under Variable Suction Regimes

In partially saturated soils, shear strength varies nonlinearly with suction. Experimental evidence has shown that bearing capacity initially increases with suction and subsequently decreases as the soil approaches residual saturation. Classical formulations cannot capture this behavior without empirical correction factors. Moreover, the failure mechanisms predicted by limit equilibrium methods may not reflect the complex stress–strain response observed in

unsaturated soils (Vanapalli and Fredlund, 2000). This theoretical gap necessitates modified analytical or numerical approaches.

### 1.4 Necessity of Constitutive Modeling for Predictive Accuracy

#### 1.4.1 Role of Constitutive Relations in Geotechnical Analysis

Constitutive models describe the stress–strain–suction relationships governing soil behavior. For partially saturated soils, these models must incorporate additional state variables and account for suction-dependent hardening or softening mechanisms. The development of advanced elasto-plastic frameworks, such as the Barcelona Basic Model (Alonso et al., 1990), marked a significant advancement in capturing hydro-mechanical coupling effects.

#### 1.4.2 Improved Representation of Failure Mechanisms

Modified constitutive approaches enable simulation of progressive yielding, stiffness degradation, and collapse behavior associated with wetting. When implemented in numerical methods such as the finite element method, these models provide more realistic predictions of load–settlement response and ultimate bearing capacity compared to simplified analytical solutions. However, their reliability depends on appropriate parameter calibration and validation against experimental data.

### 1.5 Scope and Objectives of the Review

This review aims to synthesize and critically evaluate existing research on bearing capacity assessment of footings resting on partially saturated soils, with particular emphasis on modified constitutive approaches. The objectives are threefold:

- To examine experimental evidence highlighting the influence of matric suction on bearing capacity;
- To analyze theoretical and constitutive modeling frameworks developed to address unsaturated soil behavior; and
- To identify knowledge gaps and propose future research directions for improving predictive reliability in foundation design under partially saturated conditions.

By integrating theoretical developments, experimental findings, and numerical advancements, this review seeks to provide a structured knowledge base for researchers and practicing geotechnical engineers working in advanced foundation analysis.

## 2. BACKGROUND AND FUNDAMENTAL CONCEPTS

A rigorous understanding of partially saturated soil behavior and its implications for foundation engineering is essential before evaluating modified bearing capacity approaches. The mechanical response of soils under unsaturated conditions differs fundamentally from that of fully saturated systems due to the presence of matric suction and capillary effects. This section outlines the theoretical foundations of partially saturated soil mechanics, classical bearing capacity theory, and the role of constitutive modeling in geotechnical analysis.

### 2.1. Partially Saturated Soil Mechanics

#### 2.1.1. Definition and Significance of Partial Saturation

Partially saturated soils, often referred to as unsaturated soils, consist of three interacting phases: solid particles, pore water, and pore air. The degree of saturation varies between zero and unity, influencing the mechanical and hydraulic properties of the soil mass. Unlike saturated soils, where effective stress is governed solely by pore water pressure, partially saturated soils exhibit additional stress contributions arising from matric suction. The conceptual framework for stress state variables in unsaturated soils was formalized by Fredlund and Morgenstern (1977), who demonstrated that both net normal stress and matric suction independently influence shear strength. This distinction is particularly significant in near-surface soils, embankments, and shallow foundation systems where full saturation rarely exists.

#### 2.1.2 Water Retention Behaviour and Suction Concepts

Water retention behavior describes the relationship between soil suction and volumetric water content, typically represented through the Soil-Water Characteristic Curve (SWCC). The SWCC reflects the soil's pore-size distribution and governs hydraulic conductivity, compressibility, and strength parameters. The widely used model proposed by Van Genuchten (1980) provides a closed-form expression for fitting experimental retention data. Suction is commonly divided into matric suction ( $u_a - u_w$ ) and osmotic suction, though matric suction predominates in geotechnical problems involving shallow foundations. Variations in suction due to environmental changes can significantly modify stiffness and shear resistance, thereby affecting bearing performance.

#### 2.1.3 Suction-Stress Relationships

The incorporation of suction into stress analysis has been addressed through extended effective stress formulations. Bishop (1959) introduced an effective stress parameter ( $\chi$ ) to account for partial saturation effects, linking matric suction to shear strength enhancement. Later developments refined this concept by relating  $\chi$  to degree of saturation and

microstructural interactions within the soil skeleton. These formulations demonstrate that suction induces apparent cohesion, increasing shear strength up to an optimal saturation range before diminishing near residual conditions. Understanding this nonlinear suction-stress relationship is fundamental for modeling bearing capacity under partially saturated states.

### 2.2 Bearing Capacity of Footings

#### 2.2.1 Classical Bearing Capacity Theories: An Overview

The classical theory of bearing capacity is grounded in limit equilibrium and plasticity concepts. The pioneering work of Karl Terzaghi (1943) established the general bearing capacity equation incorporating cohesion, surcharge, and unit weight components. Subsequent refinements by Geoffrey Meyerhof (1963) and Vesic (1973) introduced correction factors to account for footing geometry, embedment depth, and load inclination. These formulations assume homogeneous, isotropic, and fully saturated or dry soil conditions, with shear strength parameters derived from conventional Mohr-Coulomb theory. While effective for saturated clays and sands, these models do not explicitly incorporate suction-dependent strength contributions.

#### 2.2.2 Influence of Saturation and Matric Suction on Bearing Capacity

In partially saturated soils, matric suction increases effective stress and enhances shear strength, thereby elevating ultimate bearing capacity. Experimental investigations have shown that bearing capacity may increase significantly at intermediate degrees of saturation due to capillary bonding between particles. However, this enhancement is not linear and diminishes as suction approaches residual levels or during wetting-induced collapse. Analytical extensions incorporating suction-dependent shear strength parameters have been proposed to address this limitation, but their applicability remains constrained by simplified assumptions (Vanapalli and Fredlund, 2000). Consequently, classical bearing capacity equations require modification or replacement when applied to unsaturated conditions.

### 2.3 Constitutive Models in Geotechnical Engineering

#### 2.3.1 Elastic-Plastic Frameworks

Constitutive models describe the stress-strain behavior of soils under mechanical and hydraulic loading. Traditional elastic-perfectly plastic models based on the Mohr-Coulomb criterion provide a simplified representation of failure but cannot capture suction-induced hardening or softening effects. Advanced elasto-plastic frameworks extend critical state soil mechanics to unsaturated conditions by introducing additional state variables. The Barcelona Basic Model (Alonso et al., 1990) represents a significant

milestone, incorporating suction-dependent yield surfaces and hardening laws within a thermodynamically consistent formulation. Such models enable prediction of collapse behavior during wetting and strength evolution under varying suction regimes.

### 2.3.2 Role of Capillary Effects and Structural Attraction

Capillary forces generated at air-water interfaces create interparticle bonding, often termed structural attraction, which increases apparent cohesion in partially saturated soils. These microstructural interactions influence stiffness, dilatancy, and failure mechanisms. Constitutive formulations that incorporate capillary stress tensors or suction stress concepts provide a more realistic representation of this behavior. Ignoring capillary effects may lead to underestimation of bearing capacity in arid or semi-arid regions where partial saturation dominates. Therefore, the inclusion of hydro-mechanical coupling in constitutive modeling is critical for accurate foundation analysis.

### 2.3.3 Importance for Unsaturated Soil Behaviour in Foundation Analysis

For shallow footings resting on partially saturated soils, load-settlement response and ultimate failure are governed by the combined effects of stress redistribution, suction variation, and plastic deformation. Constitutive models capable of representing these interactions offer improved predictive reliability compared to simplified analytical approaches. When integrated into numerical frameworks such as finite element analysis, these models allow simulation of progressive failure mechanisms and parameter sensitivity, thereby enhancing design confidence under complex field conditions.

## 3. CLASSICAL BEARING CAPACITY FRAMEWORK

The classical bearing capacity framework constitutes the theoretical foundation of shallow foundation design. Developed primarily within the limit equilibrium and plasticity paradigms, these formulations estimate ultimate load-carrying capacity by assuming a predefined failure mechanism beneath the footing. While these approaches remain embedded in contemporary design practice, their theoretical assumptions limit their applicability under partially saturated soil conditions. This section reviews the principal limit equilibrium solutions, examines their assumptions, and evaluates their relevance to unsaturated soil systems.

### 3.1 Limit Equilibrium Solutions

#### 3.1.1 Terzaghi-Type Formulations

The seminal contribution to bearing capacity theory was made by Karl Terzaghi (1943), who derived the general bearing capacity equation for strip footings based on limit

equilibrium analysis and assumed shear failure along well-defined zones beneath the foundation. The formulation decomposes ultimate bearing capacity into three components associated with soil cohesion, surcharge, and unit weight, expressed through dimensionless bearing capacity factors ( $N_c$ ,  $N_q$ ,  $N_\gamma$ ). Terzaghi's theory assumes a rigid-plastic soil model governed by the Mohr-Coulomb failure criterion, with homogeneous and isotropic soil conditions. Although simplified, this model provided a rational analytical framework that significantly advanced foundation engineering practice.

#### 3.1.2 Meyerhof and Vesic Extensions

Subsequent refinements enhanced the general applicability of Terzaghi's solution. Geoffrey Meyerhof (1963) introduced correction factors to account for footing shape, depth of embedment, and load inclination, thereby improving predictive capability for practical configurations. Vesic (1973) further refined bearing capacity factors and provided improved theoretical interpretations of failure mechanisms based on plasticity solutions. These extensions expanded the analytical versatility of limit equilibrium methods but retained the fundamental assumptions of classical soil mechanics, particularly regarding stress state and saturation conditions.

### 3.2 Assumptions and Constraints

#### 3.2.1 Homogeneity and Isotropy

Classical bearing capacity theories assume that the supporting soil mass is homogeneous and isotropic, with constant shear strength parameters throughout the failure zone. In reality, natural soil deposits often exhibit stratification, anisotropy, and spatial variability in density and fabric. Such simplifications may lead to discrepancies between predicted and observed bearing capacities, particularly in layered or structured soils. Furthermore, these theories idealize failure as a sudden shear mechanism, whereas actual behavior may involve progressive plastic deformation and strain localization.

#### 3.2.2 Saturated Condition Assumptions

A critical limitation of classical formulations is the implicit assumption of either fully saturated or completely dry soil conditions. Shear strength parameters ( $c$  and  $\phi$ ) are typically derived from saturated triaxial or direct shear tests and interpreted within the conventional effective stress framework proposed by Karl Terzaghi (1925). Under partially saturated conditions, however, matric suction contributes to apparent cohesion and modifies effective stress, effects that are not explicitly represented in traditional equations. Consequently, classical models may underestimate or misrepresent ultimate bearing capacity where suction plays a significant role.

### 3.3 Applicability to Partially Saturated Soils

#### 3.3.1 Theoretical Inconsistencies

The extension of classical bearing capacity equations to partially saturated soils introduces theoretical inconsistencies. Limit equilibrium solutions are derived under single-phase effective stress assumptions, whereas unsaturated soils require at least two independent stress state variables to describe mechanical behavior. The nonlinear relationship between matric suction and shear strength cannot be adequately captured through constant cohesion parameters. Moreover, failure mechanisms in partially saturated soils may be influenced by hydraulic boundary conditions and suction redistribution during loading, phenomena not addressed in conventional formulations.

#### 3.3.2 Empirical Correction Attempts

To address these shortcomings, researchers have proposed empirical modifications incorporating suction-dependent shear strength parameters into classical bearing capacity equations. For instance, shear strength expressions developed for unsaturated soils have been substituted into Terzaghi-type formulations to account for apparent cohesion induced by matric suction (Vanapalli and Fredlund, 2000). While such approaches improve predictive accuracy under controlled conditions, they often rely on simplified assumptions regarding suction distribution and uniformity beneath the footing. As a result, empirical corrections provide interim solutions but lack the comprehensive theoretical rigor required for fully coupled hydro-mechanical analysis.

## 4. LITERATURE REVIEW: EXPERIMENTAL INVESTIGATIONS

Experimental research has played a decisive role in advancing the understanding of bearing capacity behaviour of footings resting on partially saturated soils. Unlike saturated systems, where shear strength is governed primarily by effective stress, unsaturated soils exhibit suction-dependent strength enhancement and hydraulic-mechanical coupling. This section critically synthesizes laboratory and field investigations that have examined these mechanisms, identifies consistent behavioural trends, and evaluates methodological limitations.

### 4.1 Laboratory Studies

#### 4.1.1 Triaxial and Direct Shear Testing under Controlled Suction

Controlled laboratory experiments have provided fundamental insight into suction-dependent shear strength. The introduction of axis-translation techniques enabled independent control of matric suction in triaxial and direct

shear apparatus, significantly improving reliability of unsaturated soil testing. Early systematic studies demonstrated that shear strength increases with matric suction due to capillary bonding, with the relationship often expressed through extended Mohr-Coulomb formulations (Fredlund and Rahardjo, 1993).

Subsequent experimental programs refined this understanding by quantifying the contribution of suction to apparent cohesion and identifying threshold suction values beyond which incremental strength gain diminishes. Vanapalli et al. (1996) proposed predictive relationships linking shear strength to the Soil-Water Characteristic Curve (SWCC), thereby integrating hydraulic behaviour with mechanical response. These laboratory findings established the theoretical basis for incorporating suction into bearing capacity assessment.

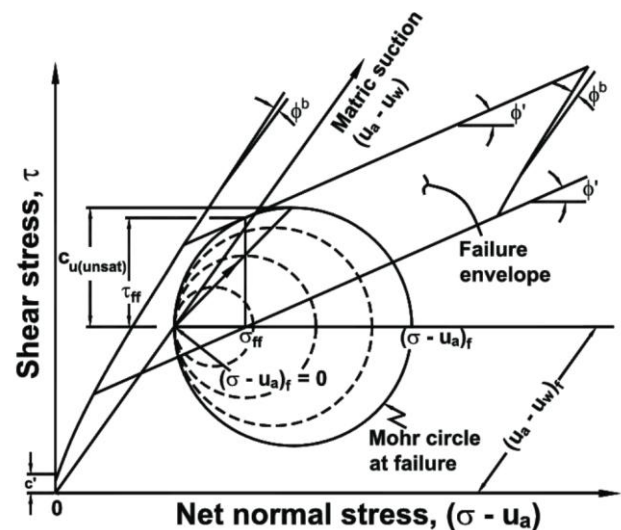


Figure-2: Extended Mohr-Coulomb Failure Envelope for Unsaturated Soils

#### 4.1.2 Plate Load Tests on Unsaturated Soil Beds

Beyond element-level testing, small-scale plate load experiments have been conducted to simulate shallow foundation behaviour under partially saturated conditions. These studies typically involve compacted soil beds prepared at controlled moisture contents, with suction measured using tensiometers or filter paper techniques. Results consistently indicate that ultimate bearing capacity increases at intermediate suction levels and decreases during wetting. Oh and Vanapalli (2011) demonstrated that suction-induced strength enhancement can significantly elevate ultimate load compared to saturated conditions, particularly in compacted silty sands. Such tests provide direct evidence linking laboratory-derived shear strength parameters to footing-scale response.

## 4.2 Field Investigations

### 4.2.1 Instrumented Footing Tests

Field-scale investigations offer essential validation of laboratory findings by capturing in-situ stress redistribution and environmental variability. Instrumented footing tests conducted on unsaturated compacted fills have shown that bearing capacity is sensitive to initial suction conditions and subsequent moisture changes. Toll (2000) highlighted the importance of monitoring suction profiles beneath shallow foundations to accurately interpret load-settlement behaviour. Field studies reveal that suction distribution beneath a footing is non-uniform and may evolve during loading, challenging simplified analytical assumptions.

### 4.2.2 Seasonal Suction Variation Effects

Long-term monitoring programs have further demonstrated that seasonal climatic variations influence foundation performance in unsaturated soils. Changes in rainfall, evaporation, and groundwater level modify matric suction, thereby altering stiffness and shear strength over time. Research on expansive and collapsible soils indicates that wetting events may trigger sudden reductions in bearing capacity due to suction loss and structural collapse (Ng and Shi, 1998). These findings underscore the dynamic nature of unsaturated soil systems and the need to consider environmental loading in design.

## 4.3 Observed Trends

### 4.3.1 Influence of Matric Suction on Shear Strength

A consistent outcome across laboratory and field investigations is the enhancement of shear strength with increasing matric suction within a specific range. This enhancement is primarily attributed to capillary stresses acting at particle contacts, which increase effective intergranular stress. However, the rate of strength increase diminishes at higher suction values as soils approach residual saturation. The relationship between suction and strength is therefore nonlinear and soil-type dependent, governed by pore-size distribution and plasticity characteristics.

### 4.3.2 Non-Linear Variation of Bearing Capacity with Degree of Saturation

Experimental plate load tests and numerical back-analyses indicate that bearing capacity does not vary linearly with degree of saturation. Instead, maximum bearing resistance is often observed at intermediate saturation levels, reflecting optimal capillary bonding. During wetting, rapid suction reduction can induce collapse settlements and substantial bearing capacity reduction. This non-monotonic behaviour complicates direct application of constant-strength parameters in design equations and highlights the

importance of incorporating hydraulic state variables in predictive models.

## 4.4 Limitations of Experimental Approaches

### 4.4.1 Suction Control Challenges

Despite advancements in testing techniques, accurate control and measurement of suction remain technically demanding. Axis-translation methods are limited to moderate suction ranges, while high-capacity tensiometers and osmotic techniques require careful calibration and maintenance. Time-dependent equilibration between pore air and pore water pressures can introduce experimental uncertainty. Moreover, achieving uniform suction distribution in large specimens or soil beds is difficult, potentially affecting reproducibility of results.

### 4.4.2 Scale Effects and Boundary Conditions

Laboratory plate load tests are inherently influenced by boundary confinement and scale effects. Small-scale experiments may not replicate stress paths, drainage conditions, or suction redistribution mechanisms observed in field foundations. Boundary friction and limited failure zone development can lead to overestimation or underestimation of bearing capacity. Field tests, while more representative, are costly and subject to environmental variability that complicates interpretation. Consequently, although experimental investigations provide critical insight, they must be integrated with robust constitutive modeling to achieve reliable predictive capability.

## 5. MODIFIED CONSTITUTIVE APPROACHES FOR PARTIALLY SATURATED SOILS

The limitations of classical bearing capacity formulations under partially saturated conditions have necessitated the development of advanced constitutive models capable of incorporating suction-dependent behaviour. Unlike saturated soil models, constitutive approaches for unsaturated soils must account for additional stress state variables, hydro-mechanical coupling, and suction-induced hardening or softening mechanisms. This section critically reviews the principal modeling frameworks used to simulate bearing capacity and stress-strain response of footings resting on partially saturated soils.

### 5.1 Effective Stress-Based Models

#### 5.1.1 Bishop-Type Stress Formulations

One of the earliest attempts to extend effective stress principles to partially saturated soils was proposed by Alan W. Bishop (1959). Bishop introduced a modified effective stress equation incorporating a parameter  $\chi$  to scale the contribution of matric suction to intergranular stress. The parameter  $\chi$  is commonly expressed as a function of degree

of saturation, thereby linking hydraulic state to mechanical response. This formulation preserves the conceptual simplicity of classical effective stress while enabling inclusion of suction effects in shear strength and deformation analysis. However, the selection and calibration of  $\chi$  remain subject to empirical interpretation, and its applicability may vary with soil type and stress history.

### 5.1.2 Suction-Dependent Shear Strength Models

Building on extended stress concepts, shear strength models have been developed that explicitly incorporate matric suction into the Mohr–Coulomb framework. Fredlund et al. (1978) proposed an equation expressing shear strength as a function of both net normal stress and matric suction, introducing an additional strength parameter related to suction friction angle. Later refinements linked suction contribution to the Soil–Water Characteristic Curve (SWCC), enabling predictive estimation based on hydraulic properties (Vanapalli et al., 1996). These models are particularly useful for modifying bearing capacity equations; however, they generally assume uniform suction distribution beneath the footing and do not capture progressive plastic deformation.

## 5.2 Elasto-Plastic Models for Unsaturated Soils

### 5.2.1 Stress–Strain Coupling

Elasto-plastic constitutive models extend classical plasticity theory to unsaturated conditions by incorporating suction as an independent stress variable. These models describe not only failure states but also pre-failure deformation behaviour, enabling prediction of load–settlement response under shallow foundations. The coupling between hydraulic and mechanical behaviour is introduced through suction-dependent elastic moduli and plastic flow rules. Such frameworks allow simulation of stiffness degradation during wetting and strength enhancement during drying, thereby providing improved representation of foundation performance compared to rigid–plastic models.

### 5.2.2 Yield Surface Evolution

In unsaturated elasto-plastic models, yield surfaces expand or contract in response to changes in suction, a phenomenon often termed suction hardening. As suction increases, the yield surface enlarges, reflecting increased apparent cohesion and stiffness; conversely, wetting induces contraction and potential collapse. The Barcelona Basic Model (BBM) proposed by Alonso et al. (1990) formalized this concept within a thermodynamically consistent framework. The BBM introduces a Loading–Collapse (LC) yield curve to represent volumetric collapse upon wetting, making it particularly relevant for foundations on collapsible soils. Yield surface evolution thus becomes central to predicting bearing capacity under transient hydraulic conditions.

## 5.3 Advanced Plasticity and Critical State Models

### 5.3.1 Barcelona-Type Frameworks

The BBM and its extensions represent a significant advancement in unsaturated soil constitutive modeling. Developed within critical state soil mechanics, the framework integrates suction-dependent hardening laws with elastoplastic stress–strain relations. By incorporating suction into both yield criteria and plastic potential functions, Barcelona-type models capture irreversible deformations induced by wetting or drying paths. These features make them suitable for finite element implementation in bearing capacity problems, where stress redistribution and progressive failure occur beneath footings.

### 5.3.2 Hardening Mechanisms Incorporating Suction

Advanced models incorporate dual hardening mechanisms: mechanical hardening due to plastic strain accumulation and hydraulic hardening driven by suction variation. This dual mechanism enables simulation of collapse settlements and strength recovery under cyclic wetting–drying conditions. Critical state-based extensions further account for changes in specific volume and suction-dependent critical state lines, enhancing predictive robustness for compacted and natural unsaturated soils.

## 5.4 Hypoplastic and Bounding Surface Models

### 5.4.1 Non-Linear Stiffness Behaviour

Hypoplastic models depart from classical yield surface concepts and instead define stress–strain behaviour through nonlinear rate equations. Extensions to unsaturated soils incorporate suction-dependent stiffness and strength parameters, enabling continuous representation of deformation without explicit yield surfaces. Such models effectively capture non-linear stiffness at small and intermediate strains, which is important for predicting settlement behaviour under working loads.

### 5.4.2 Cyclic and Collapse Behaviour under Varying Saturation

Bounding surface plasticity models provide a framework for simulating cyclic loading and progressive accumulation of plastic strains. When adapted for partially saturated soils, these models account for suction-induced hardening and wetting-induced softening within a unified stress–strain formulation. They are particularly useful in analyzing repeated loading or seasonal moisture fluctuations beneath shallow foundations. Nevertheless, increased mathematical complexity may limit their routine application in conventional design practice.

## 5.5 Parameter Calibration and Practical Constraints

### 5.5.1 Determination of Suction-Related Parameters

A major challenge in implementing modified constitutive models lies in parameter identification. Suction-related parameters often require specialized laboratory tests, including controlled-suction triaxial or oedometer experiments. Determination of SWCC parameters, suction hardening coefficients, and collapse indices demands rigorous testing protocols and careful interpretation. Variability in measurement techniques can introduce uncertainty, affecting predictive reliability in bearing capacity simulations.

### 5.5.2 Model Complexity versus Engineering Applicability

Although advanced constitutive models offer improved theoretical representation, their complexity may hinder widespread adoption in engineering practice. Increased computational demand, difficulty in parameter calibration, and sensitivity to initial conditions may discourage use in routine foundation design. Consequently, a balance must be achieved between theoretical rigor and practical applicability. Simplified effective stress-based approaches may suffice for preliminary design, whereas advanced elastoplastic or hypoplastic models are better suited for research-level analysis or critical infrastructure projects.

## 6. NUMERICAL MODELLING OF BEARING CAPACITY USING MODIFIED CONSTITUTIVE MODELS

The advancement of constitutive formulations for partially saturated soils has been closely accompanied by developments in numerical analysis techniques. Among these, the finite element method (FEM) has emerged as the dominant framework for simulating bearing capacity and load-settlement behaviour of shallow foundations under hydro-mechanically coupled conditions. Numerical modelling enables incorporation of complex stress paths, non-uniform suction distributions, and progressive failure mechanisms that cannot be adequately represented using analytical solutions.

### 6.1 Finite Element Implementation

#### 6.1.1 Coupled Hydro-Mechanical Analysis

In unsaturated soil modelling, hydro-mechanical coupling is essential because variations in pore water pressure directly influence effective stress and deformation. Coupled formulations simultaneously solve equilibrium equations and fluid flow equations, typically derived from Biot-type consolidation theory extended to unsaturated media. Alonso et al. (1990) demonstrated the feasibility of implementing suction-dependent elasto-plastic models within FEM frameworks to simulate collapse upon wetting. Later

developments incorporated transient seepage analysis to account for suction redistribution beneath loaded footings (Sheng et al., 2008). These coupled analyses provide realistic predictions of bearing capacity variation under environmental changes, particularly rainfall infiltration or groundwater fluctuations.

#### 6.1.2 Boundary Conditions and Mesh Considerations

Accurate representation of boundary conditions is critical in numerical bearing capacity simulations. Artificial confinement due to insufficient model dimensions may overestimate ultimate load. Mesh refinement near the footing-soil interface is required to capture stress concentration and shear band formation. Studies have shown that adaptive meshing or higher-order elements improve convergence and accuracy in modelling strain localization (Griffiths and Lane, 1999). Additionally, appropriate hydraulic boundary conditions must be defined to represent drainage or infiltration scenarios, as these significantly influence suction distribution and ultimate strength.

### 6.2 Comparison of Numerical and Experimental Results

#### 6.2.1 Accuracy of Predictions

Comparative studies between FEM simulations and laboratory plate load tests indicate that suction-inclusive constitutive models significantly improve agreement with experimental observations compared to classical Mohr-Coulomb models. Numerical analyses incorporating extended effective stress or Barcelona-type models have successfully reproduced non-linear load-settlement curves and suction-induced strength enhancement. However, predictive accuracy depends heavily on reliable calibration of hydraulic and mechanical parameters. Discrepancies often arise from assumptions of uniform initial suction or simplified hydraulic conductivity functions.

#### 6.2.2 Sensitivity to Constitutive Parameters

Parametric analyses reveal that bearing capacity predictions are highly sensitive to suction hardening parameters, SWCC fitting constants, and elastic stiffness moduli. Small variations in suction-related parameters can lead to substantial changes in predicted ultimate load. Sensitivity studies underscore the need for rigorous laboratory characterization and highlight the risk of over-parameterization in advanced models. The nonlinear relationship between suction and effective stress further amplifies this sensitivity, particularly under transient wetting conditions.

## 6.3 Challenges in Numerical Simulation

### 6.3.1 Convergence Issues

Implementation of advanced constitutive models often introduces numerical instability due to highly nonlinear yield surfaces and coupled hydraulic equations. Strain-softening behaviour and collapse mechanisms may lead to localization and mesh dependency, affecting convergence of iterative solvers. Regularization techniques or viscoplastic formulations are sometimes employed to mitigate numerical difficulties. Nonetheless, achieving stable solutions in fully coupled hydro-mechanical analyses remains computationally demanding.

### 6.3.2 Computational Cost

Coupled analyses with fine meshes and time-dependent seepage calculations significantly increase computational time and memory requirements. For practical engineering design, this computational burden may limit routine application. Simplified approaches, such as uncoupled analysis or reduced integration schemes, are sometimes adopted to reduce cost, though at the expense of predictive rigor. Therefore, computational efficiency remains an important consideration in selecting appropriate modelling strategies.

## 7. COMPARATIVE SYNTHESIS OF EXISTING APPROACHES

A systematic comparison of analytical, experimental, and numerical approaches is essential for evaluating their relative reliability and applicability in foundation engineering practice. Differences in theoretical assumptions, parameter requirements, and computational complexity influence model selection for partially saturated conditions.

### 7.1 Model Performance Comparison

#### 7.1.1 Strength Prediction Accuracy

Effective stress-based modifications provide moderate improvement over classical bearing capacity equations, particularly for conditions of uniform suction. Elasto-plastic and Barcelona-type models demonstrate higher predictive accuracy in simulating progressive failure and wetting-induced collapse. Hypoplastic and bounding surface models offer superior representation of nonlinear stiffness and cyclic effects but require extensive calibration. Overall, advanced constitutive models outperform simplified analytical corrections when validated against controlled experimental data.

## 7.2 Practical Implications for Foundation Design

### 7.2.1 Impacts on Safety Factors

Incorporating suction effects generally increases predicted bearing capacity, potentially reducing required footing dimensions. However, reliance on transient suction enhancement without accounting for possible wetting may compromise safety. Design safety factors should therefore consider worst-case hydraulic conditions rather than peak suction states. Reliability-based approaches may provide a more rational framework for incorporating variability in suction.

### 7.2.2 Design Recommendations under Partial Saturation

For routine design, incorporation of suction-dependent shear strength parameters into classical equations may be acceptable where environmental variability is limited. For critical infrastructure or collapsible soils, coupled hydro-mechanical numerical analysis using validated constitutive models is recommended. Long-term monitoring of suction profiles can further enhance reliability of design assumptions. Ultimately, integration of experimental characterization, advanced modelling, and environmental assessment is necessary to achieve robust foundation performance in partially saturated soils.

## 8. CONCLUSION

This review critically examined the bearing capacity evaluation of shallow footings resting on partially saturated soils, with particular emphasis on modified constitutive approaches and their numerical implementation. The synthesis of experimental investigations confirms that matric suction significantly enhances shear strength and ultimate bearing capacity within a specific saturation range, while wetting-induced suction loss may trigger substantial reductions in strength and collapse settlements. Classical bearing capacity theories, although foundational to geotechnical design, are theoretically constrained by their assumption of fully saturated or dry soil conditions and therefore require modification for unsaturated applications.

Effective stress-based extensions provide a practical transitional framework by incorporating suction contributions into shear strength formulations. However, advanced elasto-plastic and critical state models, particularly those incorporating suction-dependent hardening mechanisms, offer superior predictive capability by capturing hydro-mechanical coupling, yield surface evolution, and collapse behaviour. Finite element implementations of these models enable realistic simulation of progressive failure and transient hydraulic effects, albeit with increased parameter sensitivity and computational demand.

Overall, the review highlights that reliable bearing capacity prediction under partial saturation requires integration of experimental characterization, suction-dependent constitutive modelling, and coupled numerical analysis. Continued refinement of model calibration procedures and field validation is essential for translating advanced theoretical developments into robust foundation design practice.

## 9. LIMITATIONS OF THE REVIEW

This review is primarily conceptual and synthesis-based, relying on published experimental and modelling studies without conducting independent validation or meta-analytical quantification. Variability in testing methodologies, suction measurement techniques, and constitutive parameter calibration across different studies limits direct comparability of reported results. The review also focuses predominantly on shallow strip and circular footings, with limited discussion of complex geometries or layered soil systems. Furthermore, recent data-driven and probabilistic approaches were only briefly addressed, as the primary emphasis was placed on constitutive modelling frameworks. Finally, regional climatic variability and long-term field monitoring data remain underrepresented in the literature, constraining comprehensive evaluation of seasonal suction effects on foundation performance.

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