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# A REVIEW OF HYDRO-MECHANICAL COUPLED ANALYSIS OF MAT FOUNDATIONS SUBJECTED TO SEASONAL GROUNDWATER VARIABILITY

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**Abstract -** *Seasonal groundwater variability significantly influences the performance of shallow foundation systems, particularly mat foundations constructed on compressible or partially saturated soils. Fluctuations in the groundwater table induce changes in pore water pressure, effective stress distribution, and hydraulic gradients, which in turn affect settlement behaviour, bearing capacity, and soil–structure interaction mechanisms. Conventional foundation design methods frequently adopt uncoupled or simplified approaches that may neglect the complex interaction between hydraulic and mechanical responses of soil. In contrast, hydro-mechanical coupled analysis, grounded in poroelastic and elastoplastic frameworks, provides a more rigorous representation of transient seepage–deformation interactions.*

*This review synthesizes existing theoretical developments, numerical formulations, and experimental investigations related to hydro-mechanical coupled analysis of mat foundations subjected to seasonal groundwater variations. The paper critically examines governing theories, constitutive modelling approaches, and computational techniques such as finite element-based coupled simulations. Comparative evaluation of analytical, numerical, and field-based studies is presented to identify prevailing trends, modelling limitations, and practical implications for engineering design. Particular emphasis is placed on the effects of cyclic groundwater rise and drawdown on differential settlement and long-term foundation stability. The review concludes by highlighting key research gaps, including the need for field validation studies and advanced modelling strategies incorporating unsaturated soil behaviour and climate-driven hydrological variability.*

**Key Words: Hydro-mechanical coupling; Mat foundation; Seasonal groundwater fluctuation; Soil–structure interaction; Poroelasticity; Finite element analysis**

## 1. INTRODUCTION

### 1.1 Background

#### 1.1.1 Importance of Foundation Design in Civil Engineering

Foundation systems form the primary load-transfer mechanism between superstructures and supporting soils, governing serviceability, safety, and long-term durability of civil engineering infrastructure. In particular, mat (raft) foundations are widely adopted for medium- to high-rise buildings and heavily loaded industrial structures due to their ability to distribute loads over large areas and mitigate differential settlement. The performance of such systems is strongly influenced by soil compressibility, stress history, drainage characteristics, and time-dependent consolidation behavior. Classical soil mechanics principles establish that settlement and bearing capacity are functions of effective stress, which itself depends on pore water pressure conditions (Terzaghi, 1943; Bowles, 1996). Advanced soil–structure interaction (SSI) frameworks further demonstrate that neglecting interaction effects may lead to unconservative predictions of deformation and stress redistribution (Poulos and Davis, 1974). Consequently, accurate modelling of foundation behaviour requires integration of both mechanical and hydraulic processes governing subsoil response.

#### 1.1.2 Significance of Seasonal Groundwater Variability

Seasonal groundwater fluctuations, driven by climatic cycles such as monsoon recharge, evapotranspiration, and anthropogenic extraction, induce temporal variations in pore water pressures and matric suction in both saturated and unsaturated zones. These variations alter effective stress paths, stiffness parameters, and shear strength characteristics of foundation soils (Fredlund and Rahardjo, 1993). In fine-grained soils, cyclic groundwater rise and drawdown may accelerate consolidation, swelling, or shrinkage phenomena, resulting in differential settlement beneath mat foundations. Furthermore, transient hydraulic gradients can modify seepage forces and stress distribution profiles, affecting stability and serviceability. Contemporary geotechnical research recognises that climate-driven hydrological variability is an increasingly critical factor in foundation performance assessment (Lu and Likos, 2004).

### 1.2 Motivation for Review

#### 1.2.1 Influence of Hydro-Mechanical Effects on Mat Foundation Performance

Hydro-mechanical coupling refers to the interdependence between pore fluid flow and soil deformation, where changes in stress state influence permeability and, conversely, pore pressure evolution modifies effective stress. Biot's poroelastic framework provides the theoretical basis for analysing such coupled behaviour in saturated media (Biot, 1941). For mat foundations, seasonal groundwater fluctuations generate cyclic variations in pore pressure, leading to non-uniform settlement patterns and redistribution of contact stresses. Traditional uncoupled analyses—where seepage and mechanical response are treated independently—may underestimate long-term deformation or fail to capture transient responses during groundwater drawdown or recharge events. Numerical studies employing fully coupled finite element formulations have demonstrated significant deviations between coupled and uncoupled predictions, particularly in compressible or layered soil deposits (Zienkiewicz and Shiomi, 1984). These findings underscore the necessity of integrating hydro-mechanical interaction in foundation assessment.

### 1.2.2 Need for Summarizing Existing Models and Findings

Although substantial research has been conducted on consolidation theory, unsaturated soil mechanics, and soil–structure interaction, the literature remains fragmented with respect to mat foundations subjected specifically to seasonal groundwater variability. Existing studies vary in constitutive assumptions, hydraulic boundary conditions, and coupling strategies, making it difficult for practitioners and researchers to draw consolidated conclusions. A systematic review is therefore required to synthesise theoretical developments, numerical modelling approaches, and experimental validations within a unified framework. By critically comparing modelling methodologies and reported outcomes, this review aims to identify consistent trends, methodological limitations, and areas requiring further investigation.

## 1.3 Scope and Objectives

### 1.3.1 Definition of Review Boundaries

This review focuses exclusively on hydro-mechanical coupled analysis of mat foundations under conditions of seasonal or cyclic groundwater fluctuation. The scope includes saturated and partially saturated soils, poroelastic and elastoplastic constitutive modelling, and numerical simulation techniques such as finite element-based coupled formulations. Deep foundations, purely structural raft analyses without soil interaction, and studies addressing only steady-state seepage without mechanical coupling are excluded. Emphasis is placed on transient groundwater scenarios representative of climatic variability rather than short-term construction-induced dewatering.

### 1.3.2 Focus on Coupled Analysis Methods and Soil Response Mechanisms

The primary objective is to evaluate how coupled hydro-mechanical formulations capture soil response mechanisms such as consolidation, swelling–shrinkage, stiffness degradation, and stress redistribution beneath mat foundations. Particular attention is given to governing equations derived from poromechanics, implementation strategies in computational frameworks, and comparative assessment of field, laboratory, and numerical studies. Through this focused synthesis, the review seeks to clarify the extent to which current modelling approaches realistically represent seasonal groundwater effects and to delineate pathways for advancing predictive capability in geotechnical foundation engineering.

# 2. FUNDAMENTALS OF HYDRO-MECHANICAL COUPLING

## 2.1 Hydro-Mechanical Interaction in Soils

### 2.1.1 Definitions: Coupling, Poroelasticity, and Saturation Effects

Hydro-mechanical (HM) coupling in geomaterials refers to the interdependent interaction between hydraulic processes (fluid flow and pore pressure evolution) and mechanical processes (stress, strain, and deformation). In saturated soils, this interaction is commonly described using poroelasticity theory, where soil is idealised as a deformable porous skeleton fully saturated with fluid. The fundamental concept underlying this framework is the effective stress principle, which states that the mechanical behaviour of soil is governed by the effective stress, defined as the total stress minus pore water pressure (Terzaghi, 1943). Biot later generalised this principle into a rigorous continuum formulation for three-dimensional consolidation, incorporating both equilibrium and fluid continuity equations (Biot, 1941).

In partially saturated soils, coupling becomes more complex due to the presence of matric suction and variable degrees of saturation. Changes in groundwater level alter suction distribution, thereby modifying shear strength and stiffness parameters. The behaviour of unsaturated soils is governed by the interaction between stress state variables—net normal stress and matric suction—which jointly control deformation and strength (Fredlund and Rahardjo, 1993). Thus, hydro-mechanical coupling encompasses both saturated poroelastic effects and unsaturated suction-controlled responses, particularly relevant under seasonal groundwater variability.

### 2.1.2 Governing Principles

The governing equations of hydro-mechanical coupling are derived from three fundamental principles: (i) equilibrium of forces in the porous medium, (ii) conservation of mass for the pore fluid, and (iii) constitutive relationships for soil skeleton behaviour. In saturated conditions, these equations combine Darcy's law for fluid flow with stress–strain relations of the solid matrix. The resulting system forms the basis of consolidation theory and transient seepage–deformation analysis. Modern computational formulations express these relationships in fully coupled finite element frameworks, where displacement and pore pressure are treated as primary variables (Zienkiewicz and Taylor, 2000).

For unsaturated soils, extended formulations incorporate soil–water characteristic curves (SWCC) and permeability functions dependent on degree of saturation, reflecting nonlinear coupling effects (Lu and Likos, 2004). These governing principles allow prediction of time-dependent settlement, stress redistribution, and pore pressure dissipation beneath foundation systems subjected to fluctuating hydraulic conditions.

## 2.2 Seasonal Groundwater Variability

### 2.2.1 Typical Fluctuation Patterns

Seasonal groundwater variability arises from climatic and anthropogenic influences. In monsoon-dominated regions, intense rainfall leads to groundwater recharge and rising water tables, whereas dry seasons promote drawdown due to evapotranspiration and pumping. Such cyclic rise and fall create alternating wetting and drying regimes in the vadose zone. Capillary rise above the phreatic surface further modifies moisture distribution, particularly in fine-grained soils where capillary fringes can extend several metres. These processes induce temporal changes in pore water pressure and effective stress profiles, affecting consolidation and swelling–shrinkage behaviour. Observational hydrogeological studies confirm that groundwater levels may fluctuate significantly within annual cycles, directly influencing geotechnical performance (Freeze and Cherry, 1979).

### 2.2.2 Hydraulic Boundary Conditions Relevant to Foundation Behaviour

From a modelling perspective, seasonal groundwater variation is introduced through time-dependent hydraulic boundary conditions. These may include prescribed pore pressure heads at specific depths, infiltration fluxes at ground surface, or transient seepage boundaries reflecting recharge and discharge phases. Changes in boundary conditions alter hydraulic gradients and seepage forces within the soil mass, thereby affecting stress distribution beneath mat foundations. Accurate representation of these conditions is critical, as simplified steady-state assumptions may underestimate transient settlement or differential deformation. Advanced numerical simulations therefore incorporate variable water table elevations and unsaturated flow characteristics to capture realistic field scenarios (Bear, 1972).

## 2.3 Characteristics of Mat Foundations

### 2.3.1 Structural Behaviour

Mat foundations, also termed raft foundations, consist of large reinforced concrete slabs supporting multiple columns or load-bearing walls. Structurally, they function as rigid or semi-rigid plates distributing loads over a wide area to reduce contact pressure intensity. Their performance depends on flexural rigidity, load configuration, and subgrade stiffness. Unlike isolated footings, mat foundations exhibit global bending and differential deformation influenced by soil stiffness variability. Plate theory and elastic continuum approaches are commonly used to model structural response, while interaction with deformable soil requires integrated soil–structure analysis (Poulos and Davis, 1974).

### 2.3.2 Soil–Foundation Interaction Fundamentals

Soil–foundation interaction (SFI) describes the mutual influence between foundation structural behaviour and supporting soil response. Under hydro-mechanical conditions, changes in pore pressure alter soil stiffness and effective stress, leading to redistribution of contact stresses beneath the mat. Differential settlement may arise from spatial variation in permeability or groundwater fluctuation intensity. Classical elastic solutions provide simplified insight into contact stress patterns; however, realistic prediction necessitates coupled consolidation analysis accounting for transient seepage and deformation. Modern approaches integrate poromechanics with structural plate modelling to simulate time-dependent settlement and bending response under fluctuating groundwater conditions. Such integrated analysis is essential for evaluating serviceability and long-term stability of mat-supported structures.

# 3. GOVERNING THEORY AND NUMERICAL FORMULATIONS

## 3.1 Biot's Theory of Poroelasticity

### 3.1.1 Basic Equations

Biot's theory of poroelasticity provides the fundamental continuum framework for analysing hydro-mechanical coupling in saturated porous media. The formulation integrates the equilibrium equation of the deformable soil skeleton with the fluid mass conservation equation. The stress–strain relationship incorporates the concept of effective stress and introduces Biot's coefficient to account for the compressibility of the solid grains and pore fluid. The coupled field equations are expressed in terms of displacement and pore pressure as primary variables, linking mechanical deformation with pore pressure diffusion through Darcy's law. These equations extend classical one-dimensional consolidation to fully three-dimensional, transient conditions (Biot, 1941).

Mathematically, the governing system consists of: (i) the momentum balance equation for the porous skeleton, (ii) the continuity equation for pore fluid flow, and (iii) constitutive relations describing elastic behaviour. This coupled system captures both instantaneous elastic deformation and time-dependent consolidation effects under changing hydraulic conditions.

### 3.1.2 Relevance to Groundwater and Soil Deformation

Biot's framework is directly applicable to problems involving groundwater fluctuations beneath foundations. Variations in groundwater level modify pore water pressure distributions, which alter effective stresses and induce volumetric strain in compressible soils. Under seasonal recharge and drawdown, the transient diffusion term in the governing equations controls the rate of settlement and pore pressure dissipation. This is particularly significant for mat foundations constructed on soft clays, where consolidation settlement may evolve over prolonged periods. Modern poromechanics applications extend Biot's theory to account for nonlinear soil behaviour and variable permeability, enhancing its relevance for real geotechnical scenarios (Detournay and Cheng, 1993).

## 3.2 Coupled Hydro-Mechanical Models

### 3.2.1 Fully Coupled vs. Partially Coupled Formulations

Hydro-mechanical models are broadly classified into fully coupled and partially coupled (or sequential) approaches. In fully coupled formulations, the equilibrium and fluid continuity equations are solved simultaneously, ensuring direct interaction between deformation and pore pressure fields at each time step. This approach offers higher accuracy for transient problems involving rapid groundwater variation or low-permeability soils. In contrast, partially coupled methods solve seepage and mechanical analyses sequentially, transferring pore pressure results to the mechanical model without iterative feedback within the same time increment. Although computationally efficient, sequential methods may neglect important interaction effects in strongly coupled systems. Comparative studies indicate that fully coupled formulations are essential where permeability changes significantly with deformation or where cyclic groundwater fluctuations induce nonlinear responses (Lewis and Schrefler, 1998).

### 3.2.2 Soil Constitutive Models (Elastoplastic and Consolidation Theory)

Accurate hydro-mechanical simulation requires appropriate constitutive modelling of soil behaviour. Linear elastic models provide simplified approximations suitable for preliminary assessment but fail to capture yielding and plastic volumetric strains. Elastoplastic constitutive models, such as Modified Cam-Clay, incorporate stress-path dependency and hardening rules, allowing realistic prediction of consolidation and shear-induced deformation. Consolidation theory, originally developed for one-dimensional conditions, has been generalized within poromechanics to multi-dimensional elastoplastic frameworks. Incorporating such models improves prediction of settlement under fluctuating groundwater conditions, particularly where cyclic loading induces irreversible strains. Advanced formulations may also integrate unsaturated soil mechanics principles to account for suction-dependent stiffness variations (Wood, 1990).

## 3.3 Numerical Implementation Techniques

### 3.3.1 Finite Element Method (FEM)

The Finite Element Method is the most widely adopted numerical technique for hydro-mechanical coupled analysis in geotechnical engineering. FEM discretises the soil domain into elements where displacement and pore pressure are interpolated using appropriate shape functions. Mixed formulation elements (e.g., displacement–pore pressure elements) are commonly employed to ensure numerical stability and avoid spurious pressure oscillations. Time integration schemes are used to capture transient consolidation behaviour. The flexibility of FEM allows modelling of complex geometries, layered soil profiles, and nonlinear constitutive laws, making it particularly suitable for analysing mat foundations subjected to seasonal groundwater variability (Zienkiewicz et al., 1999).

### 3.3.2 Finite Difference Method (FDM)

The Finite Difference Method solves governing differential equations by approximating derivatives using discrete difference expressions over a grid. FDM is especially effective for problems with relatively simple geometries and boundary conditions. In hydro-mechanical applications, it is frequently implemented in geotechnical software for coupled seepage and deformation analysis. The method provides computational efficiency and conceptual simplicity; however, it is less flexible than FEM for irregular domains or complex soil–structure interfaces. Despite these limitations, FDM remains valuable for parametric studies of groundwater fluctuation effects on foundation settlement.

### 3.3.3 Coupled FEM–BEM and DEM Approaches

Hybrid numerical strategies combine the strengths of multiple techniques to enhance modelling capability. Coupled Finite Element–Boundary Element Method (FEM–BEM) approaches are advantageous in reducing computational domain size, particularly for problems involving infinite or semi-infinite soil media. The Boundary

Element Method efficiently represents far-field stress and pore pressure conditions, while FEM handles nonlinear behaviour near the foundation.

Discrete Element Method (DEM) approaches, though less common in foundation-scale analyses, provide insight into micro-mechanical behaviour and particle-scale hydro-mechanical interactions. DEM-based coupled simulations can capture fabric evolution and permeability changes due to deformation, offering advanced understanding of soil response under cyclic groundwater variation. Such multi-scale modelling strategies represent an emerging frontier in computational geomechanics.

## 4. REVIEW OF LITERATURE

### 4.1 Early Foundational Studies

#### 4.1.1 Pioneering Work on Poroelastic Modelling for Foundations

The conceptual foundation of hydro-mechanical coupling in geotechnical engineering originates from the development of effective stress theory and three-dimensional consolidation analysis. The effective stress principle established the mechanical dependence of soil deformation on pore pressure variations (Terzaghi, 1943). Subsequently, Biot extended consolidation theory into a general poroelastic formulation applicable to three-dimensional, transient problems, thereby enabling rigorous modelling of soil–fluid interaction (Biot, 1941). These early formulations provided the theoretical basis for analysing settlement beneath foundations subjected to changing groundwater conditions. Later advancements in computational geomechanics incorporated these governing equations into finite element frameworks, allowing practical simulation of soil–structure interaction problems involving coupled seepage and deformation (Zienkiewicz and Taylor, 2000).

#### 4.1.2 Classical Consolidation and Unsaturated Soil Theories

Beyond saturated consolidation, research expanded toward unsaturated soil behaviour, recognising the role of matric suction in controlling stiffness and shear strength. Constitutive frameworks incorporating suction as a stress state variable enhanced prediction of deformation under fluctuating moisture conditions (Fredlund and Rahardjo, 1993). Parallel developments in critical state soil mechanics introduced elastoplastic models capable of capturing irreversible strains under varying stress paths (Wood, 1990). These theoretical advancements laid the groundwork for analysing seasonal groundwater effects where soils transition between saturated and partially saturated states.

### 4.2 Hydro-Mechanical Coupled Models Applied to Shallow Foundations

#### 4.2.1 Key Studies Developing or Applying Coupled Models

With the maturation of numerical methods, researchers began applying fully coupled hydro-mechanical models to shallow foundation systems. Early computational studies demonstrated that pore pressure dissipation and deformation must be solved simultaneously to capture realistic consolidation beneath footings and rafts (Lewis and Schrefler, 1998). Subsequent work extended these approaches to nonlinear elastoplastic soils, incorporating stress-dependent permeability and time-dependent loading conditions. Applications to shallow foundations revealed that coupled analysis predicts larger transient settlements compared to uncoupled methods, particularly in low-permeability clays. These studies highlighted the importance of representing both hydraulic boundary evolution and soil constitutive nonlinearity in foundation design assessments.

#### 4.2.2 Comparison of Modelling Strategies and Simplifications

Literature reveals diverse modelling strategies ranging from simplified one-dimensional consolidation approximations to fully three-dimensional finite element simulations. Simplified analytical approaches assume homogeneous soil layers and linear elastic behaviour, providing closed-form or semi-analytical solutions suitable for preliminary design. In contrast, advanced numerical simulations incorporate layered stratigraphy, nonlinear stress–strain laws, and transient seepage conditions. While simplified models offer computational efficiency, they often neglect lateral deformation and stress redistribution effects. Comprehensive reviews of computational geomechanics demonstrate that fully coupled formulations significantly improve predictive accuracy in scenarios involving cyclic groundwater fluctuations (Zienkiewicz et al., 1999).

#### 4.2.3 Analytical vs. Numerical Solutions

Analytical solutions for consolidation beneath uniformly loaded areas have been derived under idealised assumptions of linear elasticity and constant permeability. These solutions provide fundamental insight into pore pressure diffusion and settlement rates. However, real foundation systems involve geometric irregularities and nonlinear material behaviour that limit analytical applicability. Numerical methods—particularly finite element and finite difference approaches—have therefore become dominant in recent decades. Comparative studies show that numerical models more effectively capture complex soil–structure interaction and transient hydraulic conditions, albeit at increased computational cost (Desai and Christian, 1977).

### 4.3 Seasonal Groundwater Effects on Mat Foundations

#### 4.3.1 Field Investigations

Field monitoring studies have documented correlations between seasonal groundwater fluctuations and differential settlement of shallow foundations. Observations indicate that rising water tables reduce effective stress and may induce softening in clayey soils, whereas drawdown can lead to consolidation and additional settlement. Hydrogeological investigations have demonstrated that cyclic groundwater changes alter stress paths within the soil mass, affecting long-term serviceability (Freeze and Cherry, 1979). Such empirical evidence underscores the need for incorporating transient groundwater conditions into foundation analysis.

#### 4.3.2 Laboratory Experimental Studies

Laboratory experiments using oedometer and triaxial apparatus have been conducted to simulate cyclic wetting–drying and controlled pore pressure variations. Results indicate that repeated groundwater fluctuations can accelerate volumetric strain accumulation and modify stiffness parameters. Experimental findings also reveal hysteresis effects in unsaturated soils, where wetting and drying paths produce different deformation responses. These observations provide validation benchmarks for numerical hydro-mechanical models and highlight the importance of constitutive formulations capable of capturing cyclic behaviour.

#### 4.3.3 Influence on Settlement, Stress Distribution, and Bearing Capacity

The literature consistently reports that seasonal groundwater variability affects settlement magnitude, stress redistribution beneath raft foundations, and, in some cases, bearing capacity. Elevated groundwater levels reduce effective stress and shear strength, potentially lowering ultimate capacity. Conversely, groundwater drawdown may increase effective stress but trigger consolidation settlement. Time-dependent analyses demonstrate that cyclic variations may induce differential settlement patterns due to spatial variability in permeability and soil compressibility. These findings reinforce the necessity of coupled hydro-mechanical modelling for serviceability assessment.

### 4.4 Comparative Studies

#### 4.4.1 Uncoupled vs. Coupled Analysis Outcomes

Comparative investigations evaluating uncoupled and fully coupled approaches reveal significant discrepancies in predicted deformation and pore pressure fields. Uncoupled analyses typically treat seepage and mechanical response independently, neglecting feedback mechanisms between deformation-induced permeability changes and pore pressure evolution. Fully coupled models, in contrast, simulate simultaneous interaction, yielding more realistic settlement predictions under transient groundwater conditions. Studies in computational poromechanics demonstrate that differences between the two approaches become pronounced in low-permeability soils or under rapid groundwater drawdown scenarios (Detournay and Cheng, 1993).

#### 4.4.2 Performance under Different Groundwater Scenarios

Parametric analyses examining various groundwater fluctuation amplitudes and frequencies indicate nonlinear settlement responses. High-amplitude seasonal variations can lead to cumulative plastic strains in elastoplastic soils, whereas minor fluctuations may produce predominantly elastic behaviour. Sensitivity analyses further show that soil permeability, compressibility, and foundation stiffness significantly influence system response. These comparative assessments provide critical insight for risk-informed design in regions experiencing pronounced seasonal hydrological cycles.

## 5. DISCUSSION

### 5.1 Synthesis of Results

#### 5.1.1 Integration of Outcomes across Studies

The reviewed literature consistently demonstrates that hydro-mechanical (HM) coupling plays a decisive role in predicting the time-dependent behaviour of mat foundations subjected to seasonal groundwater fluctuations. Foundational poromechanics theory established that deformation and pore pressure evolution are intrinsically linked (Biot, 1941), while consolidation theory clarified the time-dependent dissipation of excess pore pressures under loading (Terzaghi, 1943). Contemporary computational investigations extend these principles to three-dimensional soil–structure interaction problems, revealing that coupled analyses generally predict greater transient settlement and more realistic stress redistribution compared to simplified approaches (Zienkiewicz and Taylor, 2000).

Across analytical, numerical, and experimental studies, a common trend emerges: groundwater rise reduces effective stress and stiffness in compressible soils, whereas drawdown induces consolidation and potentially irreversible volumetric strains. The magnitude of these effects depends on soil permeability, compressibility, and fluctuation amplitude. Studies incorporating unsaturated soil mechanics further highlight that matric suction variations significantly influence stiffness and settlement in partially saturated strata (Fredlund and Rahardjo, 1993). Overall, the literature converges on the necessity of transient, coupled modelling for reliable prediction under seasonal hydraulic variability.

### 5.1.2 Contrasts between Modelling Approaches and Empirical Observations

Despite theoretical consistency, discrepancies are often observed between model predictions and field measurements. Analytical models typically assume homogeneous soil conditions and linear elasticity, which may underestimate differential settlement. Fully coupled finite element simulations offer improved realism but remain sensitive to constitutive parameter calibration. Field investigations frequently report nonlinear accumulation of settlement under cyclic groundwater variation, suggesting that elastoplastic behaviour and permeability evolution must be adequately represented (Lewis and Schrefler, 1998). These contrasts underscore the importance of integrating field validation with advanced numerical modelling.

## 5.2 Modelling Challenges and Limitations

### 5.2.1 Constitutive Model Limitations

A major limitation in HM analysis lies in constitutive representation of soil behaviour. Linear elastic models cannot capture yielding, hardening, or cyclic degradation effects. Even advanced elastoplastic models, such as critical state frameworks, may not fully represent suction-dependent stiffness variations in unsaturated soils (Wood, 1990). Additionally, stress-dependent permeability and anisotropy are often simplified, limiting predictive accuracy during significant groundwater fluctuations. Incorporating realistic constitutive behaviour increases computational complexity and parameter uncertainty.

### 5.2.2 Boundary Condition Assumptions

Accurate modelling of seasonal groundwater variability requires realistic hydraulic boundary conditions. Many studies idealise groundwater fluctuation as uniform water table movement, whereas actual field conditions involve spatial variability, delayed recharge, and complex seepage pathways. Simplified boundary assumptions can significantly influence predicted pore pressure gradients and settlement patterns. Hydrogeological principles indicate that transient recharge–discharge processes are inherently nonlinear and site-specific (Freeze and Cherry, 1979), making generalisation challenging.

### 5.2.3 Scale Effects and Field Data Availability

Scale effects present another challenge. Laboratory experiments are typically conducted on small specimens under controlled conditions, which may not capture field-scale heterogeneity or stress history. Numerical models often assume homogeneous soil layers, while natural deposits exhibit stratification and anisotropy. Furthermore, long-term field monitoring data correlating groundwater variation with foundation performance remain limited. This scarcity restricts validation of coupled models and hinders calibration of advanced constitutive parameters.

## 5.3 Practical Implications for Engineering Design

### 5.3.1 Influence of Hydro-Mechanical Coupling on Mat Foundation Design

Understanding HM coupling has direct implications for mat foundation design in regions experiencing seasonal groundwater variation. Coupled analysis enables engineers to predict time-dependent settlement, assess differential deformation risks, and evaluate bearing capacity under fluctuating effective stress conditions. Design methodologies that neglect transient pore pressure evolution may underestimate long-term settlement in low-permeability clays or overestimate stability during high groundwater stages. Incorporating coupled consolidation analysis enhances serviceability assessment and improves reliability of soil–structure interaction modelling.

### 5.3.2 Design Recommendations and Cautionary Notes

Based on the literature, several recommendations emerge. First, fully coupled numerical analysis should be adopted for sites characterised by significant seasonal groundwater fluctuation and compressible soil strata. Second, constitutive model selection must reflect soil type and stress history, with consideration of elastoplastic and suction-dependent behaviour where applicable. Third, site-specific hydrogeological investigations are essential for defining realistic boundary conditions. Finally, long-term monitoring of groundwater levels and settlement performance should be integrated into design validation strategies. While advanced modelling improves predictive capability, engineers must remain cognizant of parameter uncertainty and inherent variability in soil behaviour, applying appropriate safety factors and sensitivity analyses.

## 6. CONCLUSIONS

This review critically examined the theoretical foundations, numerical formulations, and applied studies concerning hydro-mechanical coupled analysis of mat foundations subjected to seasonal groundwater variability. The synthesis of classical poromechanics, consolidation theory, and contemporary computational approaches demonstrates that pore pressure evolution and soil deformation are intrinsically interdependent processes governing foundation performance. Evidence from analytical, numerical, laboratory, and field-based investigations consistently indicates that seasonal groundwater rise and drawdown significantly influence effective stress distribution, settlement magnitude, and differential deformation patterns beneath mat foundations.

Fully coupled hydro-mechanical formulations, particularly those implemented within finite element frameworks, provide superior predictive capability compared to uncoupled or sequential approaches, especially in low-permeability and compressible soils. Incorporation of elastoplastic constitutive models and unsaturated soil behaviour further enhances realism under cyclic hydraulic conditions. However, predictive reliability remains sensitive to soil parameter selection, hydraulic boundary representation, and field variability.

Overall, the literature affirms that transient groundwater fluctuations should be explicitly considered in mat foundation design to ensure serviceability and long-term stability. Future research should prioritise field validation, advanced constitutive modelling, and integration of climate-driven hydrological projections to strengthen the robustness of hydro-mechanical assessment methodologies in geotechnical engineering practice.

## 7. LIMITATIONS OF THE REVIEW

This review is limited to hydro-mechanical coupled analysis of mat foundations under seasonal groundwater variability and does not comprehensively address deep foundation systems or dynamic loading effects. The synthesis relies primarily on published theoretical and numerical studies, while long-term field validation data remain comparatively scarce. Variations in modelling assumptions, constitutive frameworks, and hydraulic boundary conditions across studies introduce challenges in direct comparison. Additionally, emerging approaches such as machine learning-assisted prediction and fully multi-scale modelling were only briefly discussed due to limited available literature specific to mat foundations.

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