

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

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Abstract - Mat foundations are widely adopted for structures resting on soft or compressible soils because of their capacity to distribute loads over a large area and minimise differential settlement. Their hydro-mechanical performance, however, is strongly governed by fluctuations in the groundwater table that occur naturally through the year. This study presents a coupled hydro-mechanical finite element investigation of a 20 m × 20 m reinforced-concrete mat foundation resting on a homogeneous medium-stiff sandy clay, subjected to four representative seasonal groundwater levels: 8.0 m (summer, GW-1), 5.0 m (post-monsoon, GW-2), 2.5 m (monsoon, GW-3) and 1.0 m (extreme/flood, GW-4) below the ground surface. The soil-foundation system was modelled within a 60 m × 60 m × 30 m domain under a uniform structural pressure of 200 kPa, with pore water pressure generated through transient Darcian seepage coupled to mechanical equilibrium via Terzaghi's effective stress principle. Results show that as the groundwater table rose from 8.0 m to 1.0 m, maximum settlement increased by 80.1% (18.6 to 33.5 mm), differential settlement more than doubled (4.3 to 9.6 mm), maximum pore water pressure rose from 19.6 to 88.3 kPa, and maximum effective stress fell by 33.1% (214.8 to 143.7 kPa), with a corresponding 24% reduction in equivalent soil stiffness (25.0 to 18.9 MPa). Contact pressure beneath the foundation also redistributed, with the spread between its maximum and minimum values widening from 18.3 kPa to 47.8 kPa. The findings confirm that hydro-mechanical coupling is essential for realistic prediction of mat foundation response, and that shallow, wet-season groundwater levels rather than dry-season or long-term average conditions govern the design of mat foundations in regions of pronounced seasonal groundwater variability.

Key Words: Mat foundation; Hydro-mechanical coupling; Seasonal groundwater variability; Finite element analysis; Pore water pressure; Effective stress; Settlement

1. INTRODUCTION

1.1 Background and Motivation

Foundation performance depends not only on the structural loads it carries but also on the mechanical and hydraulic state of the supporting ground. Seasonal fluctuation of the groundwater table changes pore water pressure, effective stress and soil stiffness, and these changes can materially affect the settlement and stability of foundations resting on

it. Mat (raft) foundations, because of their large plan area and continuous contact with the ground, are especially sensitive to such hydro-mechanical changes. A realistic assessment of mat foundation performance therefore requires the hydraulic and mechanical responses of the soil to be evaluated together rather than independently, particularly in regions such as India where monsoon rainfall produces large seasonal swings in the water table.

1.2 Mat Foundations and Their Role

Mat foundations are large reinforced-concrete slabs that support an entire structure, or a group of columns and walls, by spreading the load over a wide area of soil. They are the foundation of choice on soft or compressible soils, in situations where isolated footings would overlap, and where uniform settlement of the whole structure is important for serviceability. Common configurations include flat-plate, beam-and-slab, cellular (box) and piled-raft mats, and typical applications include high-rise buildings, hospitals, commercial complexes, industrial facilities and water-retaining structures. Their principal advantages uniform load distribution, reduced differential settlement and suitability for weak soils are offset by higher material cost and by sensitivity to changes in the properties of the supporting ground, including those induced by groundwater.

1.3 Groundwater Variability and Hydro-Mechanical Coupling

The groundwater table marks the upper surface of the saturated zone, and its position controls pore water pressure, effective stress, soil strength and compressibility. In most parts of India the water table rises during and after the monsoon in response to rainfall recharge, and falls during the dry season because of evapotranspiration, drainage and abstraction, producing a seasonal cycle that repeats every year. Hydro-mechanical coupling describes the two-way interaction between this groundwater movement and the mechanical response of the soil skeleton: changes in pore pressure alter effective stress and stiffness and hence deformation while deformation of the soil skeleton in turn alters the pore structure and the pattern of seepage. Conventional foundation design, which typically adopts a single, worst-case or average groundwater level and treats the hydraulic and mechanical problems separately, cannot capture this interaction and may therefore misjudge

settlement, differential settlement and contact-pressure distribution beneath a mat foundation.

1.4 Research Gap and Significance

A substantial body of research exists on effective stress theory, unsaturated soil mechanics and hydro-mechanical constitutive modelling, and a smaller body of work has examined groundwater effects on pile and piled-raft foundations. However, comparatively few studies apply fully coupled hydro-mechanical finite element analysis to full-scale, stand-alone mat foundations across a realistic range of seasonal groundwater levels, and fewer still quantify side by side, under identical soil, geometry and loading the resulting changes in settlement, differential settlement, contact pressure, pore water pressure and effective stress. This gap limits the ability of practising engineers to judge how much allowance should be made in mat foundation design for seasonal groundwater rise. The present study addresses this gap directly, and its findings are detailed in Sections 2–6.

1.5 Objectives of the Study

The specific objectives of the present investigation are to:

- (i) investigate the influence of seasonal groundwater variability on the hydro-mechanical behaviour of soil supporting a mat foundation;
- (ii) evaluate the effect of varying groundwater level on settlement, contact pressure and effective stress;
- (iii) compare mat foundation performance across representative summer, post-monsoon, monsoon and extreme groundwater conditions;
- (iv) identify the groundwater condition that governs foundation design; and
- (v) recommend design considerations for mat foundations subjected to seasonal groundwater variability.

2. LITERATURE REVIEW

2.1 Effective Stress and Classical Consolidation Theory

The modern treatment of soil–water interaction begins with Terzaghi's effective stress principle [1], which established that the strength and deformation of soil are governed by the stress carried by the soil skeleton rather than by the total applied stress, and that pore water pressure must be subtracted from total stress to obtain the effective stress that controls soil behaviour. Biot [2] extended this idea into a fully coupled theory of poroelasticity, providing equations linking pore pressure change to soil deformation and vice versa; this remains the theoretical basis of essentially all coupled hydro-mechanical finite element formulations used today, including the one adopted in the present study. Building on these foundations, Poulos and Davis [3]

examined settlement of raft and mat foundations using analytical and numerical soil–structure interaction methods and showed that foundation flexibility and soil stiffness not load alone govern differential settlement, while Burland, Broms and de Mello [4] synthesised field case histories to show that groundwater fluctuation alters effective stress and compressibility over the long term and should not be assessed only under short-term loading.

2.2 Unsaturated Soil Mechanics and Constitutive Modelling

Because the soil supporting a mat foundation is often only partially saturated above the water table, a second strand of literature addresses unsaturated soil behaviour. Fredlund and Morgenstern [5] introduced independent stress-state variables (net stress and matric suction) to explain why effective stress alone cannot describe unsaturated soil response, and Fredlund and Rahardjo [6] subsequently compiled a comprehensive treatment of suction, the soil–water characteristic curve (SWCC), permeability and volume change under moisture cycling. Van Genuchten [7] provided the widely used closed-form SWCC relationship linking suction to water content and hydraulic conductivity that underlies most seepage solvers used in coupled analysis. Alonso, Gens and Josa [8] proposed the Barcelona Basic Model (BBM), the first constitutive model to couple suction-dependent yielding and stiffness within an elastoplastic framework; this was progressively refined by Gens [9], Sheng, Fredlund and Gens [10], and Gallipoli, Wheeler and Karstunen [11], and reviewed by Sheng [12] and by Wheeler, Gallipoli and Karstunen [13], who concluded that realistic prediction of foundation performance requires hydraulic and mechanical processes to be solved simultaneously rather than sequentially.

2.3 Coupled Hydro-Mechanical Studies under Seasonal and Cyclic Conditions

A more recent group of studies has applied coupled hydro-mechanical modelling specifically to seasonal or cyclic moisture change. Le, Gallipoli, Sanchez and Wheeler [14] used coupled finite element analysis to show that rainfall infiltration and groundwater fluctuation redistribute pore pressure and effective stress and can produce differential settlement where hydraulic properties vary spatially. Ng, Zhou and Chiu [15] reviewed climate-driven constitutive modelling and reported that seasonal groundwater fluctuation alters stiffness, permeability and strength enough to affect the bearing capacity and settlement of shallow foundations. Mahmoodabadi and Bryson [16], using a Sheng–Fredlund–Gens-type model validated against laboratory data, showed that repeated wetting–drying cycles progressively reduce stiffness and increase settlement, while Riad and Zhang [17] and Tran, Bui and Nguyen [18] reported comparable degradation from cyclic hydro-mechanical loading and desiccation–rewetting, respectively. Santos et al. [19] compared one-way and fully coupled solution strategies

and found that full coupling gives markedly better accuracy under rapid groundwater change, at the cost of additional computational effort, whereas partially coupled analysis may suffice for slower, routine cases. Felipe [20] and Liu et al. [21] extended this line of work to shallow-foundation settlement and to thermo-hydro-mechanical (THM) coupling, respectively, both concluding that neglecting transient hydraulic effects risks underestimating long-term deformation.

2.4 Groundwater-Foundation Interaction Studies

A parallel, more foundation-specific literature has examined groundwater level directly as a design variable for raft and piled-raft systems. Bind and Kumar [22] reviewed the influence of seasonal groundwater variability on the hydro-mechanical behaviour of mat foundations and concluded that repeated seasonal change modifies stiffness and bearing capacity enough to cause uneven foundation movement over a structure's service life. Doan [23] analysed raft foundations on marine clay under varying groundwater level, Amornfa, Quang and Tuan [24] used three-dimensional finite element analysis to quantify the effect of groundwater change on piled-raft foundations in Ho Chi Minh City, and Modak and Singh [25], together with a related Indian Geotechnical Journal study on pile-raft systems in clayey soil [26], both reported load-intensity-dependent settlement increases with rising groundwater. These studies confirm that groundwater level is a first-order design variable for raft-type foundations, but with the partial exception of Bind and Kumar [22] they largely address pile or piled-raft systems rather than a fully coupled analysis of a stand-alone mat foundation across a complete seasonal cycle.

2.5 Research Gap

Taken together, the literature establishes robust theoretical and constitutive foundations for hydro-mechanical coupling and demonstrates largely in the context of unsaturated soil mechanics or piled-raft systems that groundwater fluctuation materially affects foundation performance. However, few studies apply fully coupled hydro-mechanical finite element analysis to a full-scale, stand-alone mat foundation subjected to a complete set of realistic seasonal groundwater levels, and fewer still quantify settlement, differential settlement, contact-pressure redistribution, pore water pressure and effective stress together, under identical geometry, loading and material properties, so that results can be compared directly across seasons. This study addresses that gap by evaluating a single mat foundation-soil system under four seasonal groundwater scenarios within a single, fully coupled finite element framework.

3. MATERIALS AND METHODS

3.1 Numerical Modelling Approach

Because simultaneous laboratory reproduction of transient groundwater flow and mechanical loading on a full-scale mat foundation is impractical, a numerical, simulation-based research design was adopted. A three-dimensional hydro-mechanical coupled finite element model of the soil-foundation system was developed and analysed for four groundwater scenarios under otherwise identical soil properties, foundation geometry and structural loading, so that any difference in the computed response could be attributed to groundwater level alone. The research proceeded from literature review and parameter selection, through model development, application of groundwater and loading conditions, coupled analysis and result evaluation, to comparative analysis and design recommendations, as summarised in Table 1.

Table 1. Research workflow adopted in the present study.

Step	Activity	Purpose
1	Literature review	Identify research gap and objectives
2	Selection of soil and foundation parameters	Develop numerical model
3	Development of finite element model	Simulate soil-foundation system
4	Application of groundwater conditions	Represent seasonal groundwater variability
5	Hydro-mechanical coupled analysis	Evaluate soil-foundation interaction
6	Result evaluation	Determine settlement, stress and contact pressure
7	Comparative analysis	Compare groundwater scenarios
8	Conclusions and recommendations	Achieve research objectives

3.2 Soil Profile and Engineering Properties

A representative, generalised ground condition was adopted rather than a specific field site, to keep the findings broadly applicable. The soil profile consists of a single, homogeneous, isotropic layer of medium-stiff sandy clay extending 20 m below the mat foundation, continuous and free of major discontinuities representative of conditions commonly encountered beneath residential and commercial

construction in many parts of India. The mechanical and hydraulic properties, drawn from published geotechnical literature, are summarised in Table 2 and were held constant across all four analyses; only the groundwater table position was varied.

Table 2. Engineering properties of the soil adopted in the numerical model.

Soil type	—	Sandy clay
Unit weight	γ	18 kN/m ³
Saturated unit weight	γ_{sat}	20 kN/m ³
Young's modulus	E	25 MPa
Poisson's ratio	ν	0.30
Cohesion	c	20 kPa
Friction angle	ϕ	30°
Void ratio	e	0.65
Soil type	—	Sandy clay

3.3 Foundation and Soil-Domain Geometry

The mat foundation was modelled as a square, 20 m × 20 m, 1.0 m thick reinforced-concrete (M30) slab, representative of a medium-sized multi-storey building, and assumed to remain linearly elastic throughout the analysis. The foundation is set within a 60 m × 60 m × 30 m soil domain, sized to keep the model boundaries well clear of the stress bulb and seepage zone beneath the foundation, so as to avoid artificial boundary effects on the computed settlement and pore pressure (Table 3).

Table 3. Foundation and soil-domain geometry.

Parameter	Value
Mat foundation plan dimensions	20 m × 20 m (square)
Mat foundation thickness	1.0 m
Foundation material	Reinforced concrete, M30
Soil domain dimensions	60 m (L) × 60 m (W) × 30 m (D)

3.4 Governing Equations and Hydro-Mechanical Coupling

The coupled analysis solves the mechanical equilibrium equations for the soil skeleton simultaneously with Darcy's law governing transient groundwater seepage, linked through Terzaghi's effective stress principle:

$$\sigma' = \sigma - u \quad (1)$$

where σ' is effective stress, σ is total stress and u is pore water pressure. During each analysis step, groundwater flow updates the pore water pressure field; this changes the effective stress carried by the soil skeleton (Eq. 1) and hence its stiffness and deformation, while the resulting

deformation modifies the pore structure and feeds back into the seepage calculation. This two-way coupling rather than a one-way, sequential calculation allows the model to capture how a rising water table simultaneously softens the soil and increases the load it must carry per unit of remaining effective stress. Pore water pressure was generated automatically from the prescribed groundwater table and the hydraulic properties in Table 2, using a unit weight of water of 9.81 kN/m³ under transient flow conditions. The governing principles used for each part of the coupled formulation are summarised in Table 4.

Table 4. Governing equations used in the coupled hydro-mechanical formulation.

Analysis	Governing principle
Mechanical behaviour	Equilibrium equation
Groundwater flow	Darcy's law
Effective stress	Terzaghi's effective stress principle (Eq. 1)
Coupling	Two-way hydro-mechanical interaction

3.5 Boundary Conditions

Mechanical and hydraulic boundary conditions were applied as summarised in Table 5. The base of the model was fixed in all three directions to represent stable underlying strata; the vertical side boundaries were restrained horizontally but free to settle vertically, approximating an infinite soil medium; the ground surface was left free; and the foundation–soil interface was modelled as perfectly bonded, without separation or slip. Hydraulically, the ground surface was treated as freely draining, the base as impermeable and the side boundaries as closed to horizontal flow, with the prescribed groundwater table forming the variable hydraulic boundary that changes between analysis cases.

Table 5. Mechanical and hydraulic boundary conditions.

Boundary	Mechanical condition	Hydraulic condition
Bottom boundary	Fixed in X, Y and Z	Impermeable
Side boundaries	Horizontal movement restrained; vertical free	No horizontal flow
Ground surface	Free surface	Free drainage
Foundation–soil interface	Perfect contact, no separation	—
Groundwater table	—	Variable, per seasonal scenario (transient seepage)

3.6 Seasonal Groundwater Scenarios

Four groundwater table depths were selected to represent the seasonal cycle typically observed under Indian climatic conditions: 8.0 m below ground surface for the dry summer season (GW-1), 5.0 m for the post-monsoon transition (GW-2), 2.5 m for the monsoon season (GW-3), and 1.0 m for an extreme, prolonged-rainfall or flood-like condition (GW-4) (Table 6). Each case was analysed independently, holding soil properties, foundation geometry, loading and boundary conditions fixed, so that the difference between cases isolates the effect of groundwater level. A static, uniformly distributed pressure of 200 kPa, representative of a medium-rise reinforced-concrete building, was applied over the full plan area of the mat foundation in every case and increased gradually during the analysis to ensure stable numerical convergence; only static gravity loading was considered, and dynamic or seismic loading lay outside the scope of this study.

Table 6. Seasonal groundwater scenarios analysed.

Case	Groundwater depth below G.L.	Seasonal representation	Applied pressure
GW-1	8.0 m	Summer (low groundwater)	200 kPa
GW-2	5.0 m	Post-monsoon (normal)	200 kPa
GW-3	2.5 m	Monsoon	200 kPa
GW-4	1.0 m	Extreme high groundwater	200 kPa

3.7 Assumptions and Limitations of the Model

To keep the numerical analysis tractable while retaining engineering realism, the assumptions listed in Table 7 were adopted; their implications are discussed further as study limitations in Section 6.

Table 7. Principal modelling assumptions.

No.	Assumption	Description
1	Soil behaviour	Homogeneous and isotropic
2	Foundation material	Linear-elastic reinforced concrete
3	Soil–foundation contact	Perfect bonding, no slip
4	Groundwater variation	Horizontal groundwater table
5	Loading	Static structural loading only
6	Seismic effect	Not considered
7	Temperature / erosion effects	Neglected
8	Analysis type	Coupled hydro-

		mechanical finite element analysis
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4. RESULTS AND DISCUSSION

4.1 Groundwater Flow and Pore Water Pressure Response

Transient seepage, computed using Darcy's law with a hydraulic conductivity of 1×10^{-6} m/s held constant across all cases, produced an average seepage velocity that increased from 2.12×10^{-7} m/s at GW-1 to 6.37×10^{-7} m/s at GW-4 as the hydraulic head driving flow toward the foundation level increased. Correspondingly, the maximum pore water pressure generated beneath the foundation rose steadily and almost linearly with rising groundwater level, from 19.6 kPa at GW-1 (8.0 m) to 49.1 kPa at GW-2 (5.0 m), 73.6 kPa at GW-3 (2.5 m) and 88.3 kPa at GW-4 (1.0 m) (Table 8, Fig. 2). This near-fourfold increase in pore pressure across the seasonal range is the primary driver of the mechanical response discussed below.

4.2 Effective Stress and Soil Stiffness Variation

Consistent with Eq. (1), the rise in pore water pressure produced a corresponding fall in maximum effective stress, from 214.8 kPa at GW-1 to 187.2 kPa at GW-2, 161.5 kPa at GW-3 and 143.7 kPa at GW-4 an overall reduction of 33.1% between the driest and wettest cases (Table 8, Fig. 2). Because soil stiffness in the model is stress-dependent, this loss of effective stress was accompanied by a steady reduction in the equivalent Young's modulus of the supporting soil, from 25.0 MPa at GW-1 to 23.1 MPa at GW-2, 20.8 MPa at GW-3 and 18.9 MPa at GW-4 (Table 9, Fig. 4) a 24.4% reduction in stiffness over the same range. This stiffness degradation, rather than the pore-pressure rise alone, is the direct mechanical cause of the settlement increase reported in Section 4.3.

Table 8. Maximum pore water pressure and effective stress beneath the mat foundation.

Groundwater condition	GW depth (m)	Max. pore water pressure (kPa)	Max. effective stress (kPa)
GW-1 (Summer)	8.0	19.6	214.8
GW-2 (Post-monsoon)	5.0	49.1	187.2
GW-3 (Monsoon)	2.5	73.6	161.5
GW-4 (Extreme)	1.0	88.3	143.7

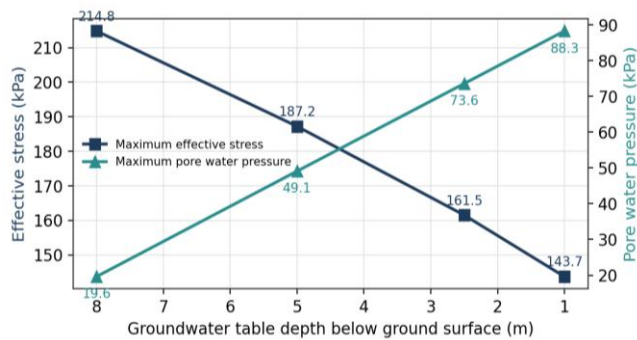


Fig. 1. Variation of maximum effective stress and pore water pressure with groundwater table depth.

Table 9. Equivalent soil stiffness under seasonal groundwater conditions.

Groundwater condition	Equivalent Young's modulus (MPa)
GW-1	25.0
GW-2	23.1
GW-3	20.8
GW-4	18.9

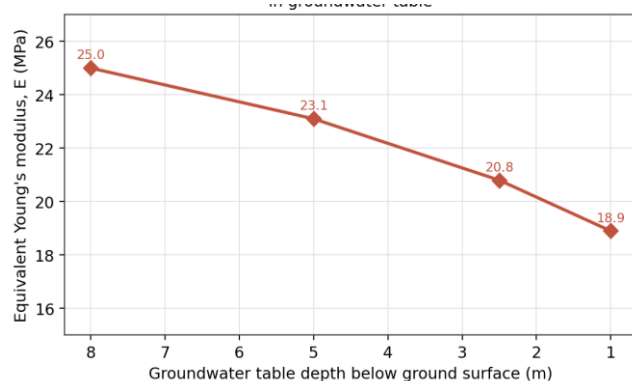


Fig. 2. Reduction of equivalent soil stiffness with rise in groundwater table.

4.3 Settlement Behaviour

Maximum settlement of the mat foundation increased steadily with groundwater rise, from 18.6 mm at GW-1 to 22.8 mm at GW-2 (+22.6%), 27.9 mm at GW-3 (+50.0%) and 33.5 mm at GW-4 (+80.1% relative to GW-1) (Table 10, Fig. 1). Differential settlement the difference between the maximum settlement recorded near the centre of the mat and the minimum settlement recorded toward its edges more than doubled over the same range, from 4.3 mm at GW-1 to 5.7 mm, 7.4 mm and 9.6 mm at GW-2, GW-3 and GW-4, respectively (Table 10, Fig. 1), because the stiffness lost beneath the heavily loaded centre of the foundation was not matched by an equal loss beneath its more lightly loaded

edges. Because differential settlement, rather than total settlement, is usually the governing serviceability criterion for cracking and structural distress, this more-than-doubling between summer and extreme-groundwater conditions is of particular design significance.

Table 10. Maximum and differential settlement of the mat foundation.

Groundwater condition	Max. settlement (mm)	Min. settlement (mm)	Differential settlement (mm)	Increase vs GW-1 (%)
GW-1	18.6	14.3	4.3	0.0
GW-2	22.8	17.1	5.7	22.6
GW-3	27.9	20.5	7.4	50.0
GW-4	33.5	23.9	9.6	80.1

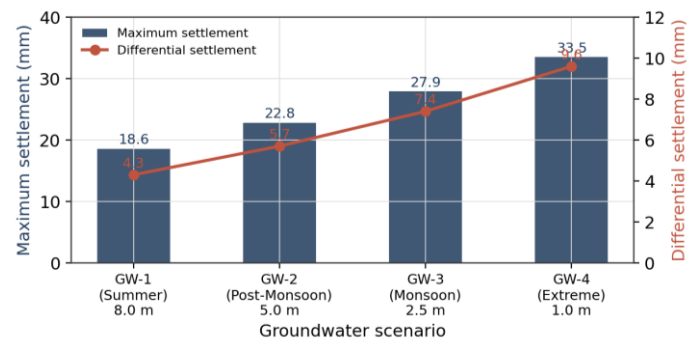


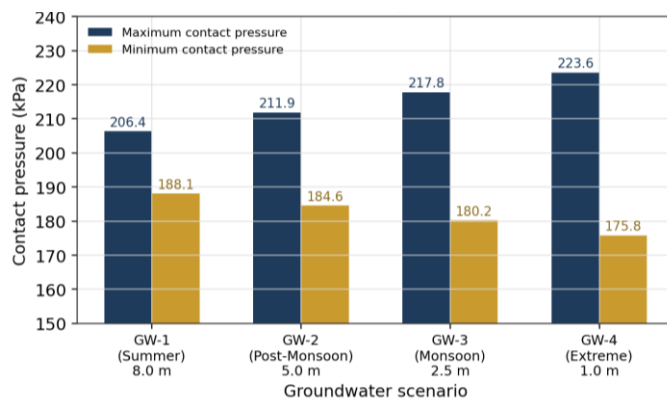
Fig. 3. Maximum and differential settlement of the mat foundation under seasonal groundwater scenarios.

4.4 Contact Pressure Redistribution

Although the applied structural pressure was held constant at 200 kPa in every case, the actual contact pressure mobilised at the foundation-soil interface became increasingly non-uniform as groundwater rose: the maximum contact pressure increased from 206.4 kPa at GW-1 to 211.9, 217.8 and 223.6 kPa at GW-2, GW-3 and GW-4, while the minimum contact pressure fell from 188.1 kPa to 184.6, 180.2 and 175.8 kPa over the same range (Table 11, Fig. 3), widening the spread between maximum and minimum contact pressure from 18.3 kPa at GW-1 to 47.8 kPa at GW-4. This progressive redistribution reflects non-uniform stiffness loss across the foundation footprint as the water table rises and reinforces the differential-settlement trend noted in Section 4.3: a mat foundation checked only against its nominal, uniformly applied pressure under summer groundwater conditions would understate both the peak contact pressure and its variation across the slab under monsoon or extreme conditions.

Table 11. Maximum and minimum contact pressure beneath the mat foundation.

Groundwater condition	Max. contact pressure (kPa)	Min. contact pressure (kPa)	Spread (kPa)
GW-1	206.4	188.1	18.3
GW-2	211.9	184.6	27.3
GW-3	217.8	180.2	37.6
GW-4	223.6	175.8	47.8

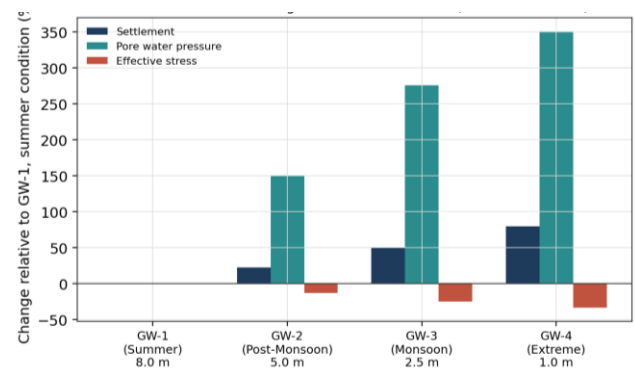

Fig. 4. Redistribution of contact pressure beneath the mat foundation under seasonal groundwater scenarios.

4.5 Comparative Evaluation and Critical Groundwater Condition

Table 12 collates all response parameters against groundwater depth and shows that settlement, differential settlement, contact-pressure spread and pore water pressure increase monotonically, while effective stress and soil stiffness decrease monotonically, as the water table rises from 8.0 m to 1.0 m. Figure 5 expresses the three most sensitive parameters relative to the GW-1 (summer) baseline and shows that pore water pressure is by far the most sensitive (a 350% increase at GW-4), followed by settlement (+80.1%) and effective stress (−33.1%). The extreme high groundwater condition, GW-4, consistently produced the most adverse response across every parameter examined, identifying the monsoon-to-flood range of groundwater levels broadly GW-3 to GW-4, i.e. a water table shallower than about 2.5 m as the governing condition for mat foundation design in a seasonally variable groundwater environment, rather than the long-term average or dry-season level that is sometimes assumed in routine practice.

Table 12. Comparative summary of hydro-mechanical response across groundwater scenarios.

Parameter	GW-1	GW-2	GW-3	GW-4
Groundwater depth (m)	8.0	5.0	2.5	1.0
Maximum settlement (mm)	18.6	22.8	27.9	33.5
Differential settlement (mm)	4.3	5.7	7.4	9.6
Maximum contact pressure (kPa)	206.4	211.9	217.8	223.6
Maximum effective stress (kPa)	214.8	187.2	161.5	143.7
Maximum pore water pressure (kPa)	19.6	49.1	73.6	88.3
Equivalent Young's modulus (MPa)	25.0	23.1	20.8	18.9


Fig. 5. Relative change in settlement, pore water pressure and effective stress across groundwater scenarios (GW-1 = baseline).

4.6 Implications for Foundation Design

Two practical implications follow. First, because settlement, differential settlement and contact-pressure variation all peak under the same wet-season groundwater condition, a mat foundation checked only against a dry-season or average water table will systematically under-predict its serviceability response in the season when it is actually most stressed; geotechnical design should therefore explicitly analyse the shallowest credible seasonal groundwater level, not merely a long-term average. Second, because the effective-stress loss and consequent stiffness loss is continuous and predictable with rising groundwater level, projects in regions of pronounced seasonal fluctuation may benefit from staged monitoring of the water table during and after the monsoon, so that observed settlement can be compared against the coupled-analysis prediction and design margins adjusted if required.

5. CONCLUSIONS

Based on the coupled hydro-mechanical finite element analysis of a 20 m × 20 m mat foundation on medium-stiff sandy clay under four representative seasonal groundwater levels, the following conclusions are drawn:

1. Seasonal groundwater fluctuation has a first-order effect on mat foundation performance: as the water table rose from 8.0 m to 1.0 m below ground surface, maximum settlement increased by 80.1% (18.6 to 33.5 mm) and differential settlement more than doubled (4.3 to 9.6 mm).
2. The mechanism is directly traceable through Terzaghi's effective stress principle: maximum pore water pressure rose from 19.6 to 88.3 kPa, maximum effective stress fell by 33.1% (214.8 to 143.7 kPa), and equivalent soil stiffness fell by 24.4% (25.0 to 18.9 MPa) over the same range.
3. Contact pressure beneath the foundation redistributed as groundwater rose, with the spread between maximum and minimum contact pressure widening from 18.3 kPa to 47.8 kPa, indicating increasingly non-uniform load transfer to the supporting soil.
4. The extreme high groundwater condition (GW-4, 1.0 m depth), representative of monsoon or flood conditions, produced the most critical response across every parameter examined, identifying shallow, wet-season groundwater levels rather than dry-season or average conditions as the governing case for design.
5. Hydro-mechanical coupling is essential to capture this behaviour realistically; analyses that treat the hydraulic and mechanical problems separately, or that adopt a single static groundwater level, are likely to under-predict both total and differential settlement of mat foundations in seasonally variable groundwater environments.

6. LIMITATIONS AND FUTURE SCOPE

The present analysis idealises the soil as a homogeneous, isotropic medium under static loading only, using a linear-elastic representation of the foundation and a simplified soil stress-strain response; natural soils are spatially variable and anisotropic, and their behaviour is generally nonlinear and time-dependent. The groundwater table was assumed to remain horizontal and uniform, temperature, erosion and chemical effects were neglected, and the results were not validated against field-instrumented data. The study is further limited to a single foundation geometry, soil type and loading intensity. Future work should extend the present framework with field monitoring and instrumentation to validate the numerical predictions; incorporate advanced elastoplastic constitutive models, such as the Barcelona Basic Model, to represent unsaturated soil subjected to cyclic wetting and drying more realistically; explore parametric

variation of soil type, foundation geometry and loading intensity; include dynamic, seismic and long-term consolidation effects; treat spatial variability and anisotropy stochastically; and, for regions with extreme thermal cycling, extend the coupling to a full thermo-hydro-mechanical (THM) formulation. Development of simplified design charts or empirical correlations from such extended parametric studies would help translate these findings into routine geotechnical design practice.

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REFERENCES

- [1] K. Terzaghi, "Theoretical Soil Mechanics," John Wiley & Sons, New York, NY, USA, 1943.
- [2] M. A. Biot, "General theory of three-dimensional consolidation," *J. Appl. Phys.*, vol. 12, no. 2, pp. 155–164, Feb. 1941.
- [3] H. G. Poulos and E. H. Davis, "Elastic Solutions for Soil and Rock Mechanics," John Wiley & Sons, New York, NY, USA, 1974.
- [4] J. B. Burland, B. B. Broms, and V. F. B. De Mello, "Behaviour of foundations and structures," in *Proc. 9th Int. Conf. Soil Mech. Found. Eng.*, Tokyo, Japan, 1977, vol. 2, pp. 495–546.
- [5] D. G. Fredlund and N. R. Morgenstern, "Stress state variables for unsaturated soils," *J. Geotech. Eng. Div.*, vol. 103, no. 5, pp. 447–466, May 1977.
- [6] D. G. Fredlund and H. Rahardjo, *Soil Mechanics for Unsaturated Soils*. New York, NY, USA: John Wiley & Sons, 1993.
- [7] M. T. van Genuchten, "A closed-form equation for predicting the hydraulic conductivity of unsaturated soils," *Soil Sci. Soc. Am. J.*, vol. 44, no. 5, pp. 892–898, 1980.
- [8] E. E. Alonso, A. Gens, and A. Josa, "A constitutive model for partially saturated soils," *Géotechnique*, vol. 40, no. 3, pp. 405–430, 1990.
- [9] A. Gens, "Constitutive modelling: Application to compacted soils," in *Proc. 1st Int. Conf. Unsaturated Soils*, Paris, France, 1995, vol. 3, pp. 1179–1200.
- [10] D. Sheng, D. G. Fredlund, and A. Gens, "A new modelling approach for unsaturated soils using independent stress variables," *Can. Geotech. J.*, vol. 45, no. 4, pp. 511–534, 2008.

- [11] D. Gallipoli, S. J. Wheeler, and M. Karstunen, "Modelling the variation of degree of saturation in a deformable unsaturated soil," *Géotechnique*, vol. 53, no. 1, pp. 105–112, 2003.
- [12] D. Sheng, "Review of fundamental principles in modelling unsaturated soil behaviour," *Comput. Geotech.*, vol. 38, no. 6, pp. 757–776, 2011.
- [13] S. J. Wheeler, D. Gallipoli, and M. Karstunen, "Comments on 'Use of the Barcelona Basic Model for unsaturated soils'," *Int. J. Numer. Anal. Methods Geomech.*, vol. 35, no. 12, pp. 1340–1355, 2011.
- [14] T. M. Le, D. Gallipoli, M. Sanchez, and S. J. Wheeler, "Rainfall-induced differential settlements of foundations on heterogeneous unsaturated soils," *Géotechnique*, vol. 63, no. 15, pp. 1346–1359, 2013.
- [15] C. W. W. Ng, C. Zhou, and A. K. L. Chiu, "Constitutive modelling of unsaturated soils: A review," *Eng. Geol.*, vol. 278, p. 105827, Dec. 2020.
- [16] M. Mahmoodabadi and L. S. Bryson, "Hydro-mechanical behaviour of unsaturated soils under seasonal hydrological variations," *Geotech. Geol. Eng.*, vol. 39, pp. 425–441, 2021.
- [17] M. Riad and X. Zhang, "Cyclic hydro-mechanical response of unsaturated soils subjected to wetting-drying," *Acta Geotech.*, vol. 17, pp. 589–604, 2022.
- [18] D. T. Tran, H. H. Bui, and G. D. Nguyen, "A coupled hydro-mechanical model for desiccation cracking in clayey soils," *Int. J. Solids Struct.*, vol. 228, p. 111098, 2021.
- [19] J. E. Santos et al., "Comparison of numerical approaches for hydro-mechanical coupled analysis of unsaturated soils," *Comput. Geotech.*, vol. 156, p. 105276, 2023.
- [20] F. Felipe, "Influence of transient groundwater conditions on shallow foundation performance," *J. Geotech. Geoenviron. Eng.*, vol. 150, no. 4, p. 04024012, 2024.
- [21] X. Liu et al., "Thermo-hydro-mechanical coupling models in geotechnical engineering: A review," *Geomech. Energy Environ.*, vol. 37, p. 100526, 2024.
- [22] H. Bind and U. Kumar, "Influence of seasonal groundwater variability on hydro-mechanical behaviour of mat foundations," *Int. J. Geotech. Eng.*, vol. 20, no. 3, pp. 1–18, 2026.
- [23] T. T. Doan, "Numerical analysis of raft foundation on marine clay ground with consideration of the groundwater level variations," Springer, 2025.
- [24] K. Amornfa, H. T. Quang, and T. V. Tuan, "Effect of groundwater level change on piled raft foundation in Ho Chi Minh City, Viet Nam using 3D-FEM," *Geomech. Eng.*, vol. 32, no. 4, pp. 387–396, 2023.
- [25] R. Modak and B. Singh, "Effect of groundwater level variation on the behavior of piled raft in clay soil," *AIP Conf. Proc.*, vol. 3262, no. 1, p. 020011, Feb. 2025.
- [26] "Influence of Groundwater Table Fluctuation on Load Intensity-Settlement Behavior of Pile-Raft Foundations in Clayey Soil," *Indian Geotech. J.*, 2026.