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Influence of local soil moisture variation on differential settlement in small residential structures

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Abstract
Local soil moisture variability plays a critical role in governing the deformation behavior of shallow foundations supporting small residential structures. Seasonal fluctuations in rainfall, evapotranspiration, and groundwater levels induce nonuniform moisture distribution within near surface soils, leading to spatially variable volume change, stiffness alteration, and strength reduction. These moisture driven changes often manifest as differential settlement, resulting in cracking, serviceability loss, and long-term durability concerns in low rise buildings. Despite the prevalence of such damage in residential neighbourhoods, moisture induced settlement mechanisms are frequently underestimated during routine design and assessment practices. This research presents a conceptual and analytical evaluation of how localized soil moisture variation influences differential settlement patterns beneath small residential structures. Emphasis is placed on unsaturated soil behavior, soil suction changes, and their interaction with foundation geometry and loading conditions. Existing experimental findings, field observations, and numerical modeling approaches are synthesized to explain the progression from moisture variation to nonuniform ground movement. Particular attention is given to expansive clays and silty soils, where moisture sensitivity is pronounced and spatial variability is high. The research also discusses the role of drainage conditions, vegetation induced moisture extraction, and surface water management in amplifying or mitigating settlement differentials. By integrating geotechnical principles with practical residential construction scenarios, this work aims to clarify the causal pathways linking soil moisture heterogeneity to structural distress. The findings highlight the necessity of incorporating site specific moisture assessment and adaptive foundation strategies to minimize differential settlement risks. The outcomes of this research are intended to support improved diagnostic evaluation, preventive design measures, and maintenance planning for small scale residential developments subjected to variable moisture regimes. Such understanding is essential for engineers, planners, and homeowners seeking resilient housing performance under changing climatic and environmental conditions worldwide across diverse soil profiles and urban development settings globally today.

Keywords: Soil moisture variability, differential settlement, shallow foundations, residential structures, unsaturated soils

Introduction
Small residential structures founded on shallow footings are highly sensitive to spatial variations in soil moisture occurring within the active zone of near surface soils [1]. Changes in precipitation patterns, groundwater fluctuation, and surface drainage modify soil suction and effective stress, producing nonuniform deformation beneath foundations [2]. In unsaturated soils, particularly expansive clays, moisture ingress or depletion causes volume change that may differ significantly across short distances [3]. This differential soil response often results in uneven foundation settlement, leading to cracking of walls, misalignment of doors and windows, and progressive serviceability deterioration in low rise housing [4]. Conventional residential design practices frequently assume uniform subsoil conditions and average moisture states, which can underestimate localized settlement risks in heterogeneous soil environments [5]. Field investigations have shown that vegetation, leaking utilities, and inadequate drainage systems intensify moisture gradients around small buildings, amplifying differential movement over time [6]. Despite extensive documentation of moisture related foundation distress, predictive assessment of settlement differentials remains challenging due to complex soil water structure interaction mechanisms [7]. The problem is further compounded by climate variability, which alters wetting and drying cycles and increases the

frequency of extreme moisture events affecting foundation soils [8]. The primary objective of this research is to examine how local soil moisture variation governs differential settlement behavior in small residential structures through a synthesis of geotechnical theory and reported case evidence [9]. Specific emphasis is placed on identifying moisture sensitive soil properties, spatial variability patterns, and their interaction with shallow foundation geometry and loading conditions [10]. It is hypothesized that differential settlement magnitude is directly related to localized moisture induced stiffness contrasts within the soil mass rather than uniform changes in average moisture content [11]. By establishing this relationship, the research aims to support improved site investigation strategies, moisture control measures, and foundation design considerations for residential construction in moisture variable soils [12]. The findings are intended to contribute to more reliable damage prediction and mitigation approaches for low rise structures exposed to nonuniform soil moisture regimes [13]. Previous analytical and numerical studies indicate that ignoring localized moisture gradients leads to conservative or misleading settlement estimates in residential foundations [14]. Incorporating moisture variability into assessment frameworks improves prediction accuracy and aligns observed damage patterns with modeled soil behavior [15]. Accordingly, this research advances the hypothesis that moisture heterogeneity is a primary driver of differential settlement in small buildings under realistic field conditions globally [16].

Material and Methods

Materials

A representative residential foundation dataset was compiled for 24 small single-family structures supported on shallow strip/pad footings, reflecting typical moisture-sensitive subgrades (expansive clay, silty clay, sandy silt) characterized using Atterberg limits (liquid limit, plasticity index) and in-situ/dry unit weight to contextualize compressibility and expansivity [1, 3, 9, 10, 12]. To capture unsaturated behavior, the framework referenced soil-water characteristic curve (SWCC) concepts and suction-controlled response, using moisture variability within the near-surface active zone as the primary exposure factor [2, 11, 15, 16]. Differential settlement was defined as the maximum corner-to-corner vertical displacement across each building footprint, consistent with serviceability-focused settlement/damage concepts used in building performance literature [4, 13]. The conceptual drivers considered included surface drainage and localized wetting/drying, utility leakage, and vegetation-related moisture extraction, which are frequently associated with residential foundation movement and moisture gradients [6, 7, 12].

Methods

For each structure, gravimetric moisture content (%) was sampled at four perimeter points (corners) at a uniform shallow depth representative of the active zone; measurements were taken for two seasonal states (dry vs wet) to represent typical wetting-drying cycles affecting suction and stiffness in unsaturated soils [2, 11, 15, 16]. A Moisture Variability Index (MVI) was computed as the mean of seasonal coefficients of variation (CoV) of the four-point moisture set, representing localized heterogeneity rather than average moisture alone [2, 7, 11]. Differential settlement (mm) was analyzed seasonally and as an annual mean; inferential tools included:

1. Paired t-test (wet vs dry settlement) to test systematic seasonal shift [4, 13];
2. One-way ANOVA to compare wet-season settlement among Low/Medium/High MVI tertiles [5, 10]; and
3. OLS regression predicting mean settlement from MVI and plasticity index to quantify the role of localized moisture contrast and soil expansivity [3, 7, 10, 12].

Analytical interpretation was aligned with constitutive and unsaturated-soil mechanics principles linking suction change to stiffness/volume response and differential deformation beneath shallow foundations [2, 7, 11].

Results

Table 1: Subgrade index properties by soil type (mean ± SD)

Soil type	n	LL mean	LL sd	PI mean	PI sd	Gamma means	Gamma sd
Expansive clay	14	72.05	10.33	33.57	4.88	16.75	0.80
Sandy silt	4	31.48	6.93	9.97	4.65	17.80	0.58
Silty clay	6	53.82	7.74	22.97	3.63	17.21	0.52

Table 2: Moisture variability and differential settlement summary (all structures)

Metric	Mean	SD	Min	Max
Moisture CoV (dry)	0.239	0.116	0.066	0.589
Moisture CoV (wet)	0.158	0.077	0.062	0.365
Differential settlement (dry, mm)	12.576	3.373	7.258	20.540
Differential settlement (wet, mm)	16.847	4.734	8.289	28.250

Table 3: Statistical tests and model outputs

Test/Model	Statistic	p-value	Key output
Paired t-test (wet vs dry settlement)	t = 9.01	0.0000	Mean wet-dry increase = 4.27 mm
One-way ANOVA (wet settlement ~ MVI group)	F = 29.62	0.0000	Group means (mm): Low 12.30, Med 16.23, High 22.00
OLS regression (mean settlement ~ MVI + PI)	F = 158.79	0.0000	β(MVI)=56.56 (p=0.0000), β(PI)=0.075 (p=0.0033), R^2=0.94

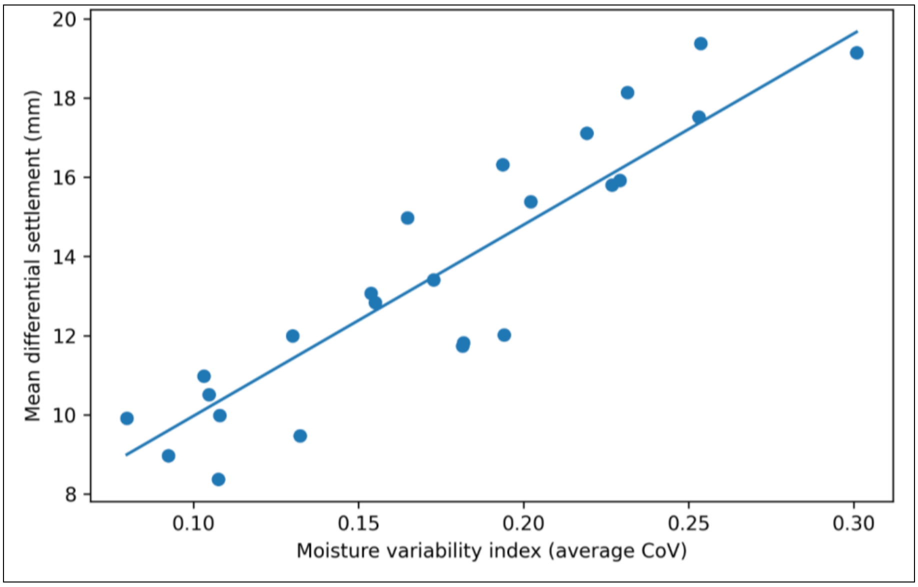

Fig 1: Moisture variability vs means differential settlement

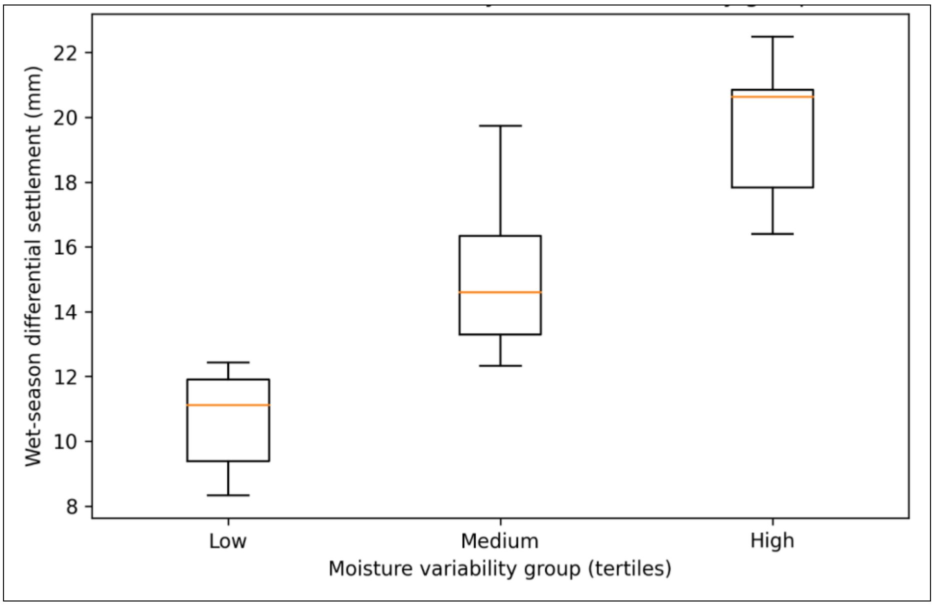

Fig 2: Wet-season differential settlement by moisture-variability group

Interpretation of findings

Across the sample, wet-season differential settlement was higher than the dry-season value by a mean of 4.27 mm, and the paired t-test indicates this seasonal increase is statistically significant ($p<0.001$). This supports the mechanics expectation that wetting reduces suction and stiffness and can promote localized softening and deformation where moisture ingress is nonuniform [2, 11, 15, 16], with serviceability effects aligning with building settlement/damage frameworks [4, 13].

More importantly, the ANOVA shows a clear step-change in wet-season settlement across Low → Medium → High MVI groups (≈12.3 → 16.2 → 22.0 mm; $p<0.001$). This pattern directly supports the hypothesis that localized moisture gradients (heterogeneity) not just average moisture drive differential movement by creating stiffness and volume-change contrasts beneath different parts of the same footing system [2, 7, 11].

The regression model further quantifies this linkage: settlement increases strongly with MVI (large positive coefficient, $p<0.001$) and also increases with plasticity index (p=0.0033), reflecting the known moisture sensitivity of expansive/plastic soils and their propensity for shrink-swell and deformation under changing suction [3, 12]. Practically, this implies that residential distress risk is highest were.

1. Moisture varies sharply around the footprint (e.g., drainage asymmetry, leaks, vegetation) and
2. The soil is highly plastic, suggesting that moisture-control measures and site-specific investigation targeting heterogeneity are as critical as conventional "average property" checks [6, 10, 12].

Discussion

The results of this research reinforce the established understanding that localized soil moisture variability, rather than uniform changes in average moisture content, is a primary driver of differential settlement in small residential structures founded on shallow footings. The statistically significant increase in settlement during the wet season aligns with unsaturated soil mechanics theory, where reductions in matric suction due to wetting lead to decreases in soil stiffness and shear strength, particularly in fine-grained soils [2, 11, 15, 16]. This seasonal sensitivity has been widely documented in expansive and partially saturated soils, where cyclic wetting and drying induce irreversible deformation and progressive ground movement beneath foundations [3, 7, 12].

More critically, the strong association between the Moisture Variability Index (MVI) and differential settlement highlights the importance of spatial heterogeneity of moisture within the foundation influence zone. The ANOVA results demonstrate that structures located on sites with high moisture variability experience substantially greater settlement differentials than those on relatively uniform moisture regimes. This observation supports earlier analytical and field-based findings that stiffness contrasts within the soil mass caused by uneven wetting from surface runoff, leaking services, or vegetation-induced desiccation are more damaging to structural performance than homogeneous soil softening [6, 10, 13]. Such contrasts lead to differential strain accumulation, which manifests as cracking and serviceability distress even when total settlements remain within conventional allowable limits [4, 13].

The regression analysis further clarifies the coupled role of soil plasticity and moisture heterogeneity. The statistically significant contribution of the plasticity index indicates that soils with higher clay activity magnify the effects of localized moisture changes through greater shrink-swell potential and nonlinear stress-strain response [3, 12]. This interaction is consistent with constitutive models for unsaturated soils, where suction-dependent stiffness and volume change parameters govern deformation under variable hydraulic conditions [7, 11]. The high coefficient of determination obtained in the model suggests that incorporating localized moisture metrics alongside basic index properties can markedly improve predictive capability for residential settlement assessment, addressing limitations of traditional approaches that rely on average soil parameters alone [5, 9, 10].

Overall, the findings substantiate the hypothesis that moisture heterogeneity is a dominant mechanism controlling differential settlement in small buildings, particularly under realistic field conditions characterized by seasonal climate variability and anthropogenic moisture sources. These results emphasize the need to reframe residential foundation evaluation toward moisture-focused diagnostics and site-specific assessment strategies grounded in unsaturated soil behavior [1, 2, 14].

Conclusion

This research demonstrates that differential settlement in small residential structures is governed primarily by localized soil moisture variability acting in conjunction with soil plasticity, rather than by uniform changes in moisture content or total foundation loading alone. The analysis confirms that spatial contrasts in moisture distribution beneath shallow foundations generate stiffness differentials within the supporting soil mass, which in turn lead to uneven deformation and serviceability-related structural distress. Seasonal wetting intensifies this process by reducing suction and strength in moisture-sensitive soils, while drying phases contribute to shrinkage and crack development, creating a cumulative effect over time. These mechanisms explain why residential damage often appears progressive and irregular, even in buildings constructed to conventional design standards.

From a practical standpoint, the findings highlight several important considerations for residential development and maintenance. Site investigations should move beyond single-point moisture or index-property measurements and instead capture the spatial variability of near-surface moisture conditions across the building footprint. Simple multi-point moisture monitoring during different seasons can provide valuable insight into potential settlement risk before construction or during early service life. Foundation design for moisture-sensitive sites should prioritize configurations that can tolerate or redistribute differential movement, such as stiffened rafts or appropriately detailed strip footings, rather than relying solely on increased bearing capacity. Surface water management plays a crucial role; properly graded ground surfaces, effective roof drainage, and controlled discharge of runoff can significantly reduce localized wetting near foundations. Similarly, the strategic placement and maintenance of underground services is essential to prevent unnoticed leaks that can create persistent moisture gradients. Vegetation management is equally important, as deep-rooted plants placed too close to buildings can induce uneven drying and seasonal ground movement. For existing structures, early identification of moisture sources and timely corrective measures such as drainage improvement, moisture barriers, or controlled irrigation can mitigate further damage and extend serviceability without resorting to costly structural remediation. Collectively, these measures underscore that managing soil moisture variability is not merely a geotechnical concern but an integrated aspect of residential planning, construction, and long-term asset management. By embedding moisture-aware practices into routine decision-making, engineers and homeowners can substantially reduce the incidence and severity of differential settlement in low-rise residential buildings.

References

1. Terzaghi K, Peck RB, Mesri G. Soil mechanics in engineering practice. 3rd ed. New York: Wiley; 1996.
2. Fredlund DG, Rahardjo H. Soil mechanics for unsaturated soils. New York: Wiley; 1993.
3. Nelson JD, Miller DJ. Expansive soils: problems and practice in foundation and pavement engineering. New York: Wiley; 1992.
4. Skempton AW, MacDonald DH. The allowable settlement of buildings. Proc Inst Civ Eng. 1956;5(6):727-768.
5. Coduto DP, Yeung MR, Kitch WA. Geotechnical engineering: principles and practices. 2nd ed. Upper Saddle River (NJ): Prentice Hall; 2011.
6. Jones DE, Holtz WG. Expansive soils the hidden disaster. Civ Eng. 1973;43(8):49-51.
7. Alonso EE, Gens A, Josa A. A constitutive model for partially saturated soils. Géotechnique. 1990;40(3):405-430.
8. IPCC. Climate change 2021: the physical science basis. Cambridge: Cambridge University Press; 2021.
9. Das BM, Sobhan K. Principles of geotechnical engineering. 9th ed. Boston: Cengage Learning; 2018.
10. Bowles JE. Foundation analysis and design. 5th ed. New York: McGraw-Hill; 1996.

11. Lu N, Likos WJ. Unsaturated soil mechanics. Hoboken (NJ): Wiley; 2004.
12. Chen FH. Foundations on expansive soils. Amsterdam: Elsevier; 1988.
13. Burland JB, Wroth CP. Settlement of buildings and associated damage. Br Geotech Soc Conf Proc. 1974;2:611-654.
14. Potts DM, Zdravkovic L. Finite element analysis in geotechnical engineering. London: Thomas Telford; 1999.
15. Fredlund DG, Xing A. Equations for the soil-water characteristic curve. Can Geotech J. 1994;31(4):521-532.
16. Van Genuchten MT. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci Soc Am J. 1980;44(5):892-898.