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Numerical Modelling of Matric Suction in Unsaturated Soil under Shallow Foundation Under Varying Soil and Hydrological Conditions

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ABSTRACT

In recent times, extreme hydrological events have disrupted the performance of various structures, particularly the structural foundations responsible for transferring the superstructure's weight to the natural ground. This disruption underscores the significance of matric suction and soil saturation, which are influenced by hydrological conditions like precipitation, soil shear strength, and foundation settlement. These factors are essential when designing structures in specific locations with distinct geotechnical parameters. To address these challenges, our research employs Plaxis 2D numerical modeling to investigate the dynamic changes in matric suction within soil beneath shallow foundations under varying rainfall conditions. Our approach involves a fully-coupled flow method, incorporating the Van Genuchten hydraulic model. In recognition of practical constraints, we utilize fundamental soil classification parameters for model configuration. Our findings reveal the substantial impact of matric suction fluctuations during rainfall on soil deformation, as indicated by displacement patterns. This highlights the critical importance of matric suction in comprehending soil behavior. Furthermore, we observe that higher initial water table levels correlate with reduced variations in matric suction and soil deformation during rainfall, emphasizing the regulatory role of water table depth. In conclusion, this study emphasizes the necessity of considering matric suction and water table depth in structural design and geotechnical analysis, particularly when faced with extreme hydrological events. By comprehending these factors, we can enhance our understanding of soil behavior, improve foundation stability, and develop more effective design strategies for structures in various environmental conditions.

Keywords: Shallow Foundation; Unsaturated soil; Matric Suction; Rainfall

INTRODUCTION

The foundation of any building plays a pivotal role in transferring the weight of the structure to the soil. During the construction of a footing, it is essential to have a thorough understanding of the soil type, its behavior, and its load-bearing capacity. Overloading the soil during footing construction must be avoided as it can result in shear failure, where the soil slides away from the structure leading to catastrophic failure (Hakro, Kumar, Almani, & Shah, 2022).

The design and construction of shallow foundations have been widely used in unsaturated soils, which commonly exhibit suction. The presence of suction in the soil can lead to reduced stability of shallow foundations as rainfall infiltrates the ground and reduces suction. This process of decreasing suction is time-dependent and can result in uneven settlements. (Kawai, Iizuka, Hayakawa, & Wang, 2007) explored the effects of rainfall infiltration on the settlement patterns of dense soil masses.

Structural design places a strong emphasis on prioritizing safety considerations and assessing loads based on worst-case scenarios. It involves evaluating the minimum strength of materials while calculating external loads under the most adverse environmental conditions. The strength of soil is intrinsically tied to its saturation level, which indicates the presence of fluids in its pores. This saturation level can vary with seasonal fluctuations, leading to changes in soil strength (Russo, Marone, & Di Girolamo, 2021) (Ahmed, bt Taib, Ayadat, & Hasan, 2022).

Furthermore, soil profiles may display varying levels of saturation, and these different saturation levels within the soil layers can significantly influence the behavior of the soil structure. Additionally, the interfaces between the soil and the structure may develop voids or cracks due to factors such as volume changes, arid conditions, or disruptive events like earthquakes or explosions. The impact of these gaps on the system's stability depends on their location and the surrounding environmental conditions. For instance, heavy rainfall or surface flow can saturate the soil, resulting in moisture-induced failure. Consequently, it is crucial to consider the implications of seasonal and climate changes during the design process to avoid potentially dangerous situations(Hassan, Shitote, & Kiplangat, 2022) .

Recent research in geotechnical engineering highlights the importance of modeling the entire soil continuum, encompassing both saturated and unsaturated zones. Nevertheless, characterizing the physical properties of unsaturated soil presents a considerable challenge. Recent findings indicate that all physical parameters within the unsaturated zone exhibit nonlinear relationships with soil suction or negative pore pressure. Soil suction, with a potential range from zero to one million kPa, can undergo substantial fluctuations in response to varying weather conditions. This variability has a profound influence on soil behavior and stability. Consequently, the accurate modeling of the unsaturated zone stands as a critical necessity for geotechnical engineers, particularly when assessing soil behavior under diverse weather conditions(Weber, Durner, Streck, & Diamantopoulos, 2019) .

Geotechnical problems often arise from the deformation of soil structure and fluid movement through the void spaces between soil particles. These challenges can include issues such as seepage-related failures, settlement and pollutant migration, moisture-induced failure, slope instability caused by rainfall, and resulting swelling and shrinkage of soil due to increase in moisture content of soil to changes in water content (Onyelowe et al., 2023).

The utilization of unsaturated soil procedures in geotechnical-engineering applications requires knowledge of unsaturated soil parameters. However, the direct measurement of such parameters is often too expensive for clients. To overcome this issue, correlations between saturated and unsaturated soil properties can be used to extend unsaturated soil properties across the entire range of soil suctions. Suction does not indicate a stress state but instead refers to the energy or potential of soil water. Any measurement of suction is based on achieving an energy balance between water in the soil and the measuring device, rather than tension or pressure. The potential of soil water has two components: osmotic and matrix. The capillary component of the osmotic component results from air-water edges in the macropores of soil, and this is a stress caused by the difference in air and water pressures. The matrix component is also a stress resulting from the difference in air and water pressures (ua–uw), while the adsorption component resulting from physiochemical interactions between clay minerals and water cannot be described as a stress(Fredlund & Fredlund, 2020) .

Over the years, there has been a considerable amount of research on the finite element analysis of soil structures, resulting in significant progress since its initial publications. When there is limited soil data, the finite element method can provide valuable insight into the behavior of soil, which is helpful in making design decisions. Numerical modeling has emerged as a valuable tool for studying volumetric distortion in detail. The finite element method enables the analysis of practical scenarios, which are more realistic compared to hypothetical solutions relying on simplified assumptions. Researchers have utilized this approach to investigate various aspects of expansive subgrades and flexible pavements constructed on expansive ground.

For instance, Hedayati (2014) conducted a study focusing on volume change and unsaturated moisture diffusion in expansive subgrades using numerical modeling with PLAXIS 2D software. Similarly, another study employed the same software to investigate the behavior of flexible pavements on expansive ground. This involves incorporating suction as a variable in the stress space. Recent research consistently emphasizes the influence of suction and saturation index on the mechanical response of unsaturated soils.

Oh & Vanapalli (2011) conducted the numerical modelling of shallow foundation settlement and bearing capacity of unsaturated soil. The study utilized a combination of theoretical modeling, in-situ load experiments, and model footing tests to investigate these aspects. The authors emphasized the importance of understanding the moisture variation and infiltration behavior beneath the foundation surface for evaluating long-term foundation performance, particularly in expansive soils.

Model footing experiments were conducted by (Vanapalli, Oh, & Puppala, 2007) on unsaturated glacial till, known as Indian Head till. The Total Stress approach, which is based on the unconfined compression strength of unsaturated soils, has been found to offer a more accurate estimation of sustaining capability. This approach takes into account the total stress acting on the soil, including both the effective stress and the pore water pressure. By considering the unconfined compression strength, which reflects the soil's ability to resist deformation and maintain its structural integrity, the Total Stress approach provides

a realistic assessment of the soil's capacity to withstand external loads. The assessment of bearing capacity in unsaturated soils was dependent on factors such as draining conditions, pore air, pore water, and soil type.

The influence of overconsolidation and net normal stress on soil suction balance and the soil-water characteristic curve (SWCC) was investigated (Huang, Fredlund, & Barbour, 1998). Soil suction and SWCC were affected by these factors, with relatively stable SWCC observed under low typical pressures.

Numerical modeling was employed to study the influence of suction variability on the behavior of foundation slabs constructed on expansive soils (M. Fredlund, Stianson, Fredlund, Vu, & Thode, 2006). The investigation focused on volumetric deformation resulting from moisture movement in the active zone and the associated suction fluctuations.

A method for predicting the rate of heave progression in residential buildings based on moisture infiltration was proposed by (Nelson, Overton, & Chao, 2010). The importance of considering the structure's design life relative to the time required for total predicted heave was highlighted to avoid overestimating construction assumptions.

The paragraph concludes by emphasizing the intricate nature of stress-pore pressure interactions in unsaturated soil, which has hindered a thorough exploration of swelling and shrinking behavior through numerical analysis. However, it highlights the potential of the advanced features provided by PLAXIS 2D (FE) software for future research in transient mode. This paper seeks to address this research gap by introducing a numerical model that investigates the distribution of pore pressure during rainfall processes, identifies areas where soil stability might be compromised, analyzes the hysteresis effects on matric suction using the soil-water characteristic curve (SWCC), and explores how varying hydrological and soil parameters can influence soil stability.

SOIL TO WATER CHARACTERISTIC CURVE (SWCC)

The notion that soil suction is the primary state variable responsible for changes in unsaturated soil behavior has been widely accepted. It is believed that suction is the dominant state variable that governs unsaturated soil behavior, and therefore, the drying SWCC is used as the basis for defining unsaturated soil property functions through estimation processes.

The determination of the effective stress state, permeability, and shear strength of unsaturated soil requires knowledge of the matric suction relationship, which is the difference between ua and uw. The SWCC plays a crucial role in characterizing unsaturated soil properties, as it reflects the relationship between water content or saturation and matric suction. The SWCC can determine a wide range of properties, including volume distortion, hydraulic conductivity, and shear strength parameters (Chowdepalli & Watanabe, 2023).

In addition to stress-strain relationships, accurately simulating the moisture-to-suction relationship and permeability-to-suction variation is essential for determining the true behavior of unsaturated soils. SWCC models are used to calculate the moisture-to-suction relationship, and the soil-water characteristic curve represents the relationship between the soil's moisture content and suction. The amount of moisture present in the soil can be represented by the degree of saturation, volumetric moisture content, and gravimetric moisture content (Chowdepalli & Watanabe, 2023).

Several curve fit models are available for the SWCC, including the Gardner model, Fredlund-Xing model, and van Genuchten model (Sillers, Fredlund, & Zakerzadeh, 2001). (Van Genuchten, 1980) model is one of the most widely used.

$$S_e = \frac{\theta_w - \theta_r}{\theta_w - \theta_s} = \frac{1}{(1+(\psi/a)^n)^m} \quad (1)$$

"where S_e is an effective saturation; θ_w, is the volumetric moisture content; θ_r and θ_s are the residual and saturated volumetric moisture contents, respectively; ψ represents the matric suction; and a, n and m are the curve fit parameters of SWCC, and it is assumed that m=1-1/n".

$$k_w = k_s S_e^{\frac{1}{2}} \left[1 - \left(1 - S_e^{\frac{1}{m}} \right)^m \right]^2 \quad (2)$$

$$\tau_f = c' + (\sigma - U_a)\tan'\phi + \{S_{eff}(U_a - U_w)\}\tan'\phi \quad (3)$$

The equation represents the total shear stress (τ_f) in soil and takes into account the contributions of effective cohesion (c'), effective internal friction (φ), effective stress (S_{eff}), and the differences between pore water pressures (Ua - Uw) and their impact on shear stress. The nonlinear relation amid suction and shear strength of soil was described or predicted using the approach defined in accordance with the Mohr-Coulomb failure criterion.

A two-dimensional water flow study can be used to analyze the water flow in unsaturated soil beneath shallow

foundation. The fundamental partial differential relationship of isotropic flow of water in an unsaturated soil may be produced by combining fundamental partial differential relationship, principal continuity equation, and Darcy's law as in the equation written below;

$$\frac{d}{dx}\left(k_w \frac{dh_w}{dx}\right) + \frac{d}{dy}\left(k_w \frac{dh_w}{dy}\right) + q = \frac{d\theta_w}{dt}$$

Where, t represents the time; q as applied boundary flux; and h_w as hydraulic head.

The application of analytical calculus yields findings for one-dimensional or vertical unsaturated steady-state moisture penetration along an unsaturated region. As an alternative to the traditional analytical approach (AA), a simulation was performed utilizing the finite element method (FEM) provided by the PLAXIS 2D programme.

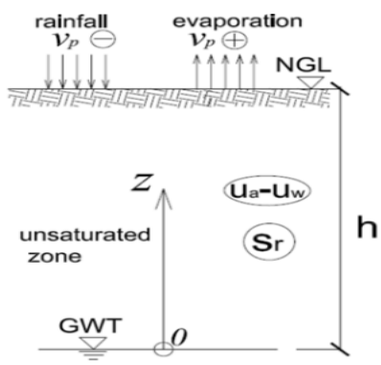

FIGURE 1. Sketch of unsaturated soil

During numerical modelling, selecting unsaturated permeability and flow parameters is challenging as they are specific to the soil conditions in the field and require real-time measurements from laboratory tests (Ahmed & Hossain, 2022). Measuring the soil water characteristic curve is a time-consuming process, although it is crucial for evaluating infiltration activities in unsaturated soils. As a result, these functions are often estimated instead of being measured, and most models use particle size distribution or dry unit weight as input parameters (Sitarenios, Bardanis, & Kavvadas, 2012).

RESEARCH METHODOLOGY

In numerical modeling, selecting unsaturated permeability and flow parameters is challenging as they depend on specific field conditions, ideally obtained through lab tests conducted in real-time. Soil water characteristic curve (SWCC) measurements, which are essential for evaluating infiltration activities in unsaturated soils, are time-consuming, and so these functions are often estimated instead of measured. Most models use particle size distribution or dry unit weight as an input. M. Fredlund hypothesized that previously measured SWCC data could be used to build a knowledge-based database (Fredlund, 2006; Fredlund & Fredlund, 2020).

The Finite Element Method (FEM) is a numerical technique that approximates partial differential equations, predominantly solving equilibrium equations. Plaxis software uses FEM, as described in the Plaxis Scientific Manual. This study employed numerical investigation using the commercially available Plaxis-2D tool. The physical domain was discretized using fifteen-noded triangular elements, and the model components were specified by five node pairs. The sequential numerical analysis process involved defining problem geometry, designating material attributes, applying boundary conditions, and applying the load. The finite-element calculations were carried out once these initial conditions were established, and the corresponding applied load's settlement was noted. To characterize soil behavior, elastoplastic or elastic constitutive models were used, with elastic models being less complex but less accurate in predicting genuine stress to strain soil behavior. In contrast, elastoplastic models can better characterize stress to strain soil behavior.

This study's model consisted of two components: material soil and raft foundation. A two-layer soil domain was represented by an elastic and completely plastic material using the Mohr-Coulomb model. Mohr-Coulomb is commonly used in geotechnical problems because it is basic, easy to use, and computations are generally fast. Another part of the foundation was produced using the linear elastic model, grounded on Hook's law of isotropous elasticity. The foundation was activated with a line load applied as a distributed load in Plaxis using staged construction. After defining the model's geometry and assigning material properties, the geometry was separated into elements for mesh production. A medium-sized mesh was used to increase accuracy and program processing speed.

When analyzing the mechanical behavior of partially or fully saturated soils using numerical approaches like FEM, both deformation and groundwater flow must be included, resulting in linked hydro-mechanical relationships of pore pressure and displacement that must be resolved concurrently. The program has two options for specifying stresses: "K_O process" and "gravity loading," with the "K_O technique" being generally employed in case of a horizontal surface, any phreatic line parallel to the surface, or any layer of soil.

The model was assigned the groundwater flow and distortion boundaries based on simulation conditions desired. The distortion boundaries utilised in study restrict the translation of vertical sides in horizontal direction and translation of model's base in both the horizontal and vertical directions. Flow through horizontal and vertical sides of domain is limited by adding closed flow boundary ailments to flow boundaries. Numerical modelling is performed utilising an approved Plaxis-2D v.21

RESULTS AND DISCUSSION

The soil specimens were gathered from test pits and borings, classified grounded on sieve analysis (ASTM 422-63). The grain size distribution curve was plotted as percent passing versus particle diameter, as shown in Figure 2.

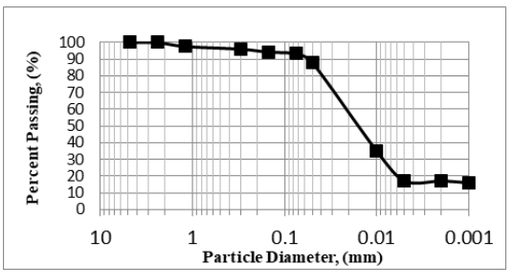

FIGURE 2. Sieve analysis curve

Soil permeability was assessed in the laboratory using a custom-made permeability apparatus. The results indicated permeability values ranging from 0.01728 m/day to 0.027 m/day. The laboratory analysis also involved determining the soil's input parameters, which are provided in Table 1.

TABLE 1. Mohar-Coloumb model parameters of shale

Parameters	Values
Angle of Internal Friction ϕ (degrees),	11^0
Cohesion (kN/m^2)	22
E (kN/m^2)	24711 (E=180 cu)
Poisson's ratio ν	0.3
Dilatancy angle (Ψ)	0

The shear strength values cohesion and angle of internal friction determined with AASHTO T236 and T208 for unconfined compression test and from the correlation given by (Sivrikaya & Toğrol, 2006) modulus of elasticity was determined (E=180 cu) and cu as unconfined compression strength. Negative variations in pore pressure in unsaturated soils were primarily attributed to factors like precipitation, irrigation, or evaporation. The infiltration and seepage of rainwater induced changes in pore pressure, which in turn affected the soil's stress distribution and deformation patterns. It was observed that stress variations played a crucial role in influencing seepage behavior by altering the hydraulic properties of the soil. Consequently, the issues of soil distortion and seepage were found to be interconnected in unsaturated soils subjected to rainfall (Agraine et al., 2020).

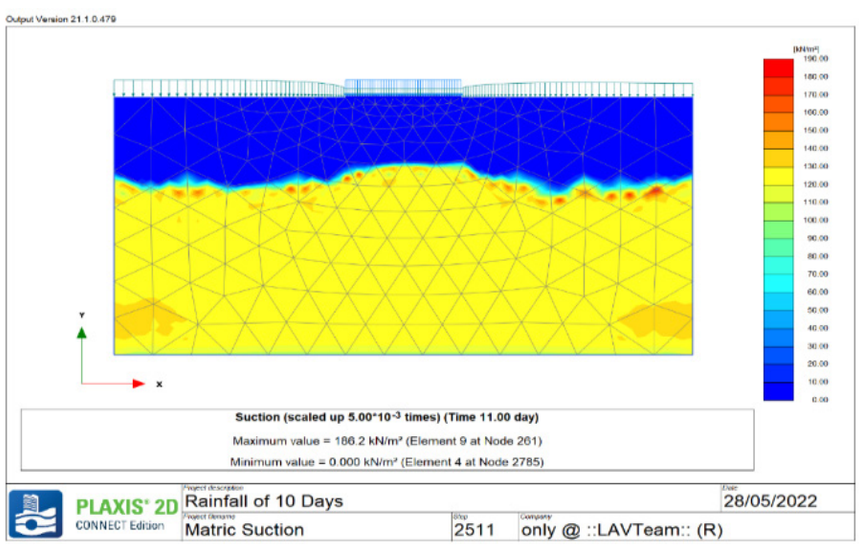

FIGURE 3. Initial matric suction

The study also emphasized the importance of assessing variations in matric suction during rainfall. Matric suction, which represents the soil's ability to retain water under negative pressure, is considered a key stress state variable that significantly influences the behavior of partially saturated soils. It serves as a critical parameter for predicting mechanical characteristics and swelling potential. This statement aligns with established principles of soil mechanics. The relationship between matric suction, soil moisture, and soil deformation has been extensively studied in the field of geotechnical engineering. Past studies on unsaturated soils, such as those by (Fredlund & Rahardjo, 1993) and (Vanapalli & Mohamed, 2007), have shown that matric suction is a key factor influencing soil behavior. These studies provide theoretical support for the impact of matric suction on soil deformation during rainfall. The findings suggested that variations in matric suction due to different durations of rainfall were of particular significance in understanding the response of the soil. These variations were analyzed and presented in Figures 3 to 8.

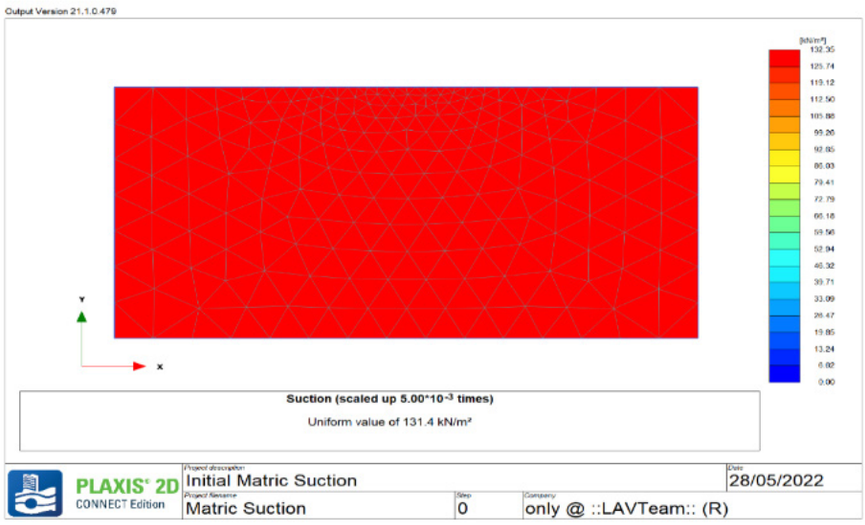

FIGURE 4. Days of rainfall and matric suction

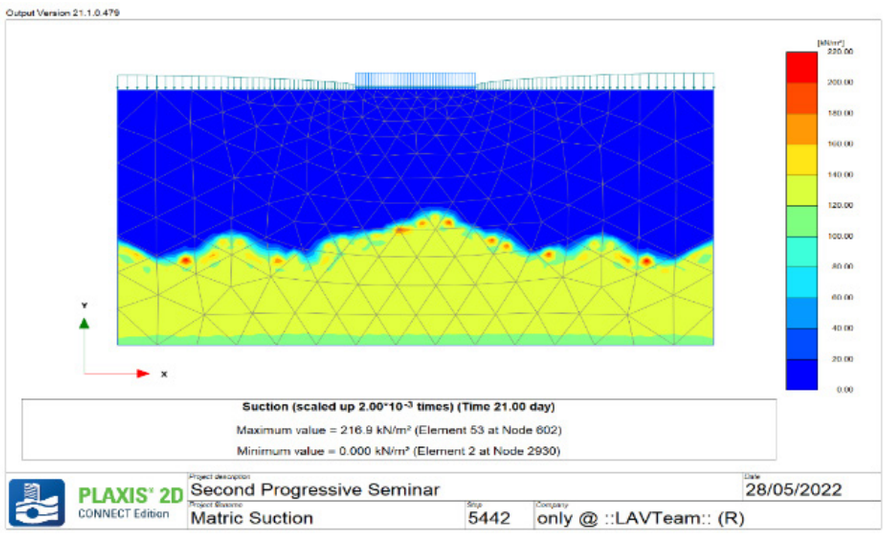

FIGURE 5. 20 Days of rainfall and matric suction

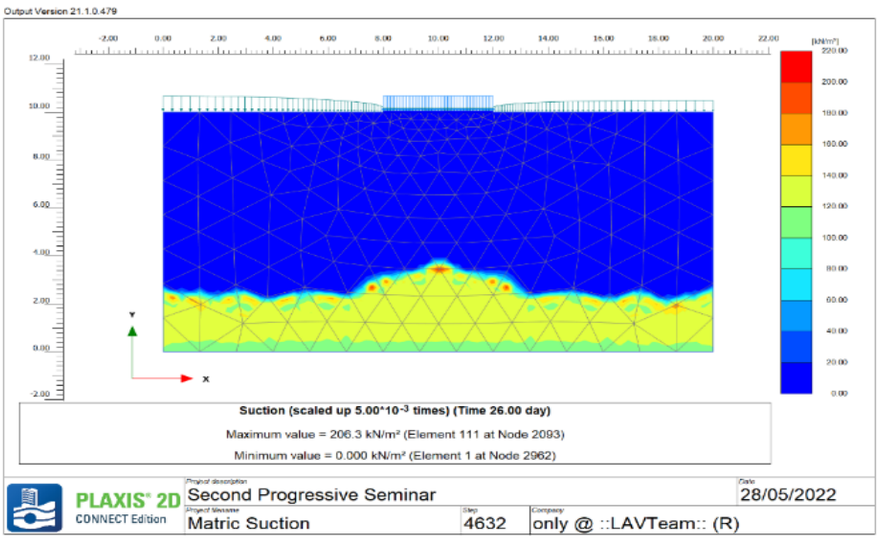

FIGURE 6. 30 Days of rainfall and matric suction

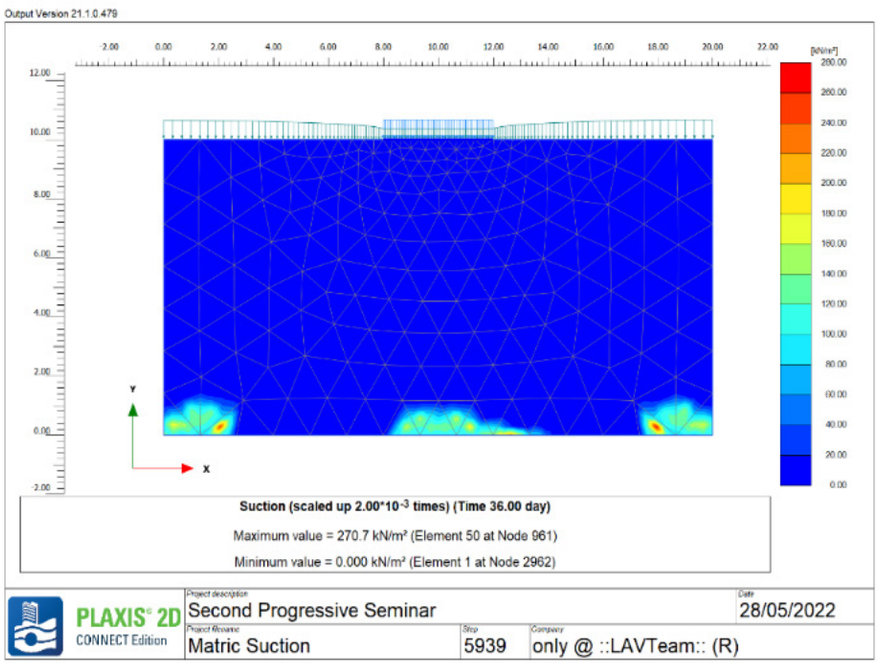

FIGURE 7. 35 Days of rainfall and matric suction

Negative changes in pore pressure in unsaturated soils are commonly triggered by precipitation, irrigation, or evaporation. The infiltration and seepage of rainwater can induce alterations in pore pressure, leading to modifications in soil stresses and deformation. Furthermore, stress fluctuations can influence seepage behavior by affecting the hydraulic properties of the soil. Hence, the issues of soil distortion and seepage are closely intertwined in unsaturated soils exposed to rainwater.

Assessing variations in matric suction during rainfall holds significant importance since soil suction is considered a stress state variable that plays a crucial role in understanding the behavior of partially saturated soils and predicting their mechanical characteristics, particularly regarding swelling. Forecasting relationships for swelling often rely on the concept of soil suction.

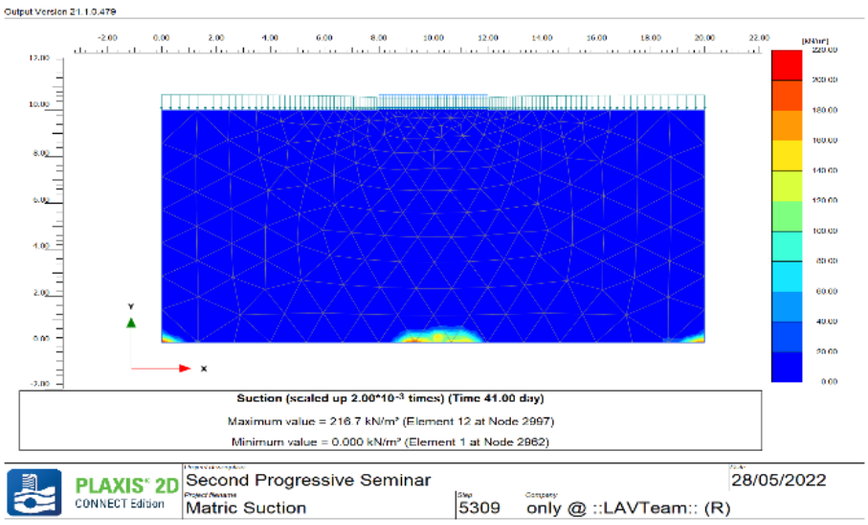

FIGURE 8. 40 Days of rainfall and matric suction

To accurately model geotechnical problems influenced by water, such as phreatic levels within soil layers and surface precipitation, it is essential to discretize and model them using appropriate initial and hydraulic boundary conditions (HBC). Suction, which refers to the negative pore pressure in unsaturated soils, plays a significant role in determining compressibility and strength parameters. In numerical modeling, the impact of suction on the soil's stiffness is incorporated through effective stress relationships, which consider both soil suction and active compression stresses. The UNSTRUCT software was employed in this study to perform numerical computations and simulate the stress-strain relationship, specifically considering the influence of suction on the soil's stiffness (Lope et al., 2021).

The numerical model assumed a uniform mass for the soil, with a degree of saturation of 70% and a corresponding matric suction of 131 kPa. With an intensity of rainfall equal to 0.02 m/day, the matric suction gradually decreased as the wetting front advanced downwards. This behavior is consistent with the findings of a previous study(Rajeev & Kodikara, 2011) which attributed it primarily to the

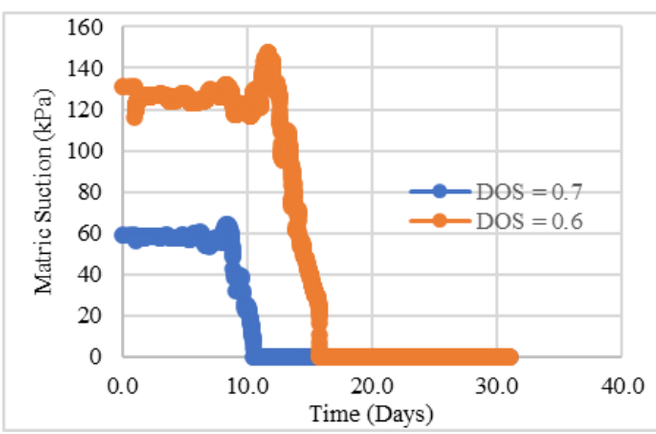

FIGURE 9. Degree of saturation and matric suction variation.

vertical flow of water, causing upper zones to become saturated before lower zones. Additionally, the variation in volume, directly related to changes in suction with depth and the soil-water characteristic curve (SWCC) and hydraulic conductivity (K), also contributes to this behavior.

Figure 9 illustrates the variation of soil suction beneath the footing under a load of 100 kPa for two different degrees of saturation (DOS) - 0.6 and 0.7. Figure 10 shows the variation of matric suction at different depths. The Higher rainfall intensity results in a rapid decrease in matric suction. The matric suction reached zero within 4 days for a rainfall intensity of 0.08 m/day, 6 days for 0.05 m/day, and 13 days for 0.02 m/day, as shown in Figure 11. The decrease in suction is associated with volume changes and soil deformations.

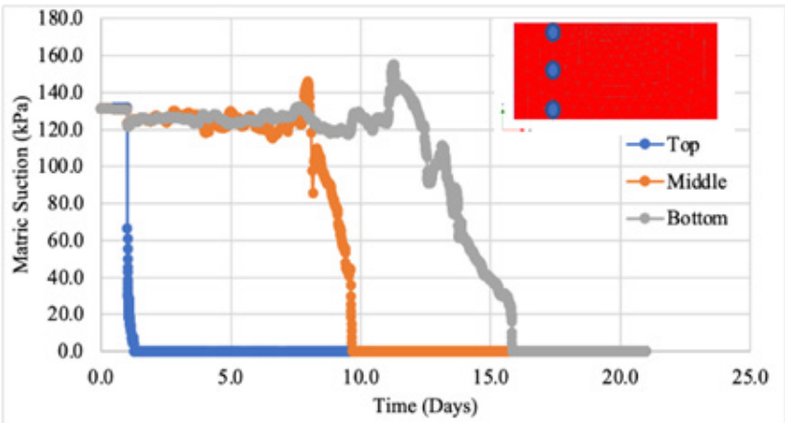

FIGURE 10. Matric suction variation at different depths

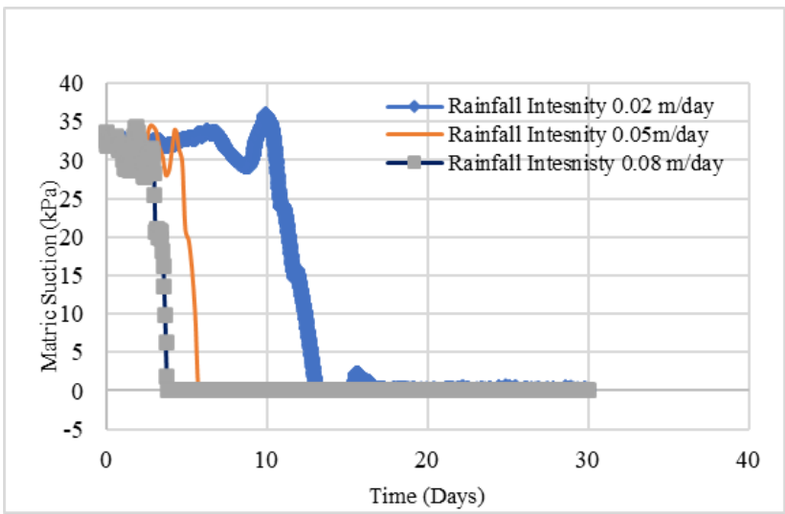

FIGURE 11. Effect of Rainfall intensity on matric suction

The study by (Chatra, Dodagoudar, & Maji, 2019), found that slopes with loose soil conditions experienced greater increases in pore pressure during rainfall compared to slopes with medium dense and dense conditions. This is attributed to the higher porosity and permeability of loose soils. The hydraulic conductivity, which determines the soil's ability to transmit water, is an important factor in managing soil moisture flow (Van Genuchten, 1980). Saturated hydraulic conductivity is influenced by factors such as soil particle characteristics and the presence of fractures. Cracked soils were found to have exceptionally high saturated hydraulic conductivity, which can lead to excessive wetting beneath structures and potential damage. The Figure 12 results indicate that soils with higher permeability allow for faster infiltration and larger pore pressures, resulting in greater deformations (Garcia

Aristizabal et al., 2011). The relationship between hydraulic and mechanical behavior in unsaturated soils is well-established, with wetting leading to changes in matric suction and subsequent volumetric deformation. In the study by (Noorany, Frydman, & Detournay, 2020), a model was developed to analyze slope response and predict moisture-induced deformations. The model incorporated an incremental approach using Hooke's equation and moistening strain to estimate moistening stresses, which were then added to the primary stresses in the soil for equilibrium analysis.

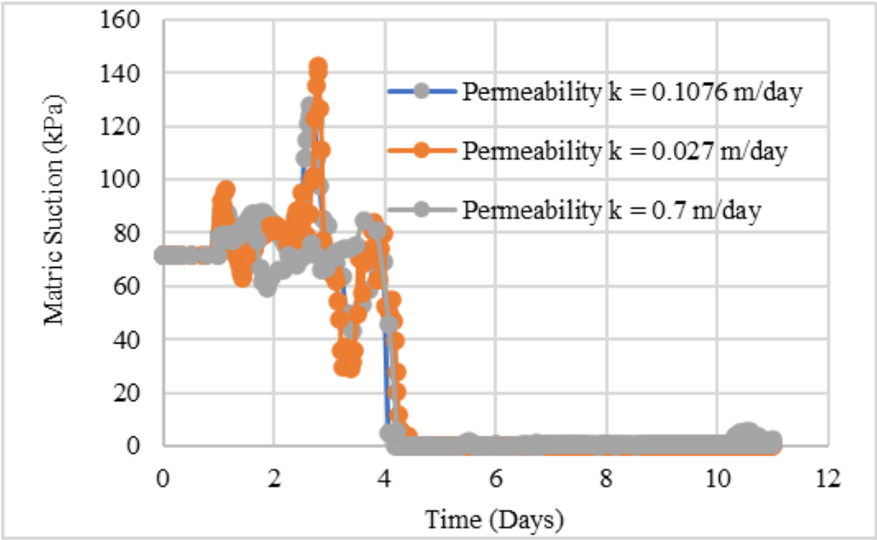

FIGURE 12. Effect of permeability on matric suction

Overall, the study highlights the significance of soil properties, including porosity, permeability, and hydraulic conductivity, in understanding and managing the effects of rainfall on soil behavior and deformation. (Rajeev & Kodikara, 2011) conducted practical and numerical analyses to study the relationship between soil suction reduction and heave in submerged pipelines affected by swelling movements. Their research focused on the impact of swelling movements on pipelines that experienced an increase in soil water content, reaching saturation levels due to capillary effects.

CONCLUSION

This study utilized numerical modeling in Plaxis 2D to examine the changes in matric suction within soil beneath a shallow foundation under varying rainfall conditions. The simulation employed a fully-coupled flow approach with the Van Genuchten hydraulic model. Due to the challenges and time constraints associated with determining laboratory parameters, basic soil classification parameters were utilized for selecting model parameters. The following conclusions were drawn from the numerical investigation:

1. The fluctuation of matric suction during rainfall had a significant impact on soil deformation, as evidenced by the displacement results. Matric suction played a crucial role in determining the soil's behavior.
2. Higher initial water table levels resulted in smaller variations in matric suction and soil deformation during rainfall.
3. It is crucial to consider suction in simulations, particularly when the water table is located far below the foundation. Deeper water table depths during rainfall led to greater suction fluctuations. These suction variations affected the soil's stress distribution and the stability of the foundation.
4. The effective stress of unsaturated soil was found to be of utmost importance. It influenced the coupling of flow and deformation models, as well as the stress-strain relationship of the soil structure.

The successful application of finite element analysis in this study for assessing soil suction opens up opportunities to investigate a wide range of additional issues related to unsaturated soils. It enables the analysis of foundation bearing capacity under different suction and moisture conditions, taking into account varying water table levels. Furthermore, this formulation can be extended to examine

the interaction between unsaturated soils and other geotechnical structures, such as retaining walls and piles.

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DECLARATION OF COMPETING INTEREST

None

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