

# RELATIONSHIP BETWEEN AIR PRESSURE AND VOLUMETRIC WATER CONTENT AT STEADY STATE IN RAINFALL-INDUCED LANDSLIDE BASED ON MODIFIED COLUMN TESTS

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**ABSTRACT:** The increasing frequency of localized heavy rainfall events exacerbates the problem of accurately predicting and mitigating rainfall-induced landslides. This study used a model test to clarify the relationship between air pressure and volumetric water content during quasi-saturation. A series of one-meter-high, 10-cm-diameter modified column tests were utilized to replicate slope conditions during rainfall. This study included five-column tests with different relative densities, all subjected to uniform rainfall intensity, to examine how air pressure variations influence the soil's quasi-saturated state. The test results revealed a correlation between the change in air pressure and the soil's quasi-saturated state. Specifically, increased volumetric water content at higher relative densities was accompanied by increased air pressure, reflecting a more complex interaction within the denser soil. Even after the water content reached a quasi-steady state, air pressure variations persisted, suggesting continuous adjustments within the soil structure. Entirely uniform saturation across all column heights was not achieved, with air entrapment contributing to persistent partial saturation. The conclusion drawn from this study is that air pressure dynamics play a pivotal role in the soil's response to hydrological stresses. By integrating air pressure measurements into the assessment of quasi-saturated soils, these findings can help predict the onset of landslides. This research contributes to a more comprehensive understanding of soil behaviour under unsaturated conditions, with significant implications for environmental management, particularly in regions prone to heavy rainfall-induced landslides.

*Keywords: Air pressure, Quasi-saturation, Landslide, Volumetric water content, Modified column test*

## 1. INTRODUCTION

Rain-induced slope breakdowns rank among the most severe natural disasters affecting shallow slopes worldwide, leading to significant human casualties and financial losses. Despite decades of research on rain-induced slope breakdowns, these events pose substantial threats due to their unpredictability and the changing global climate patterns exacerbating their occurrence [1, 2]. The challenge of accurately predicting and effectively mitigating landslide risks has become more pronounced, highlighting the limitations of traditional predictive methods in the face of rapid slope failures induced by intense rainfall events [4–9]. Historically, the scientific community's approach to understanding rain-induced landslides has transitioned from relying solely on empirical models to adopting more sophisticated techniques integrating comprehensive hydrological and geotechnical factors.

Among these advancements, the soil–water characteristic curve (SWCC) has proven to be instrumental in elucidating the complex behavior of water storage in soils under varying suction pressures. This has paved the way for a diversified research agenda focusing on predictive methods for SWCC, spanning empirical formulas to advanced AI-based models. Such studies underscore the

pivotal role of soil properties, particularly under unsaturated conditions, in accurately forecasting the potential for shallow landslides [11–14].

With these developments, the present study introduces an often-overlooked aspect of landslide prediction models: air pressure's influence during quasi-saturation rainfall infiltration periods. This study builds upon previous findings on quasi-saturation [3]. The present research topic is highly relevant to the modern era, marked by increased extreme weather occurrences and their profound effects on areas such as Tajikistan. Here, landslides are a constant hazard to human life and infrastructure, and heavy rains often make landslides more frequent and severe. Such observations underscore the imperative need for advanced predictive models capable of addressing the challenges posed by climate change and its contribution to increasing landslide occurrences [15].

This research delves into the dynamics of volumetric water content in soils during rainfall infiltration, particularly emphasizing the quasi-saturated state and its interaction with air pressure. The findings reveal that fluctuations in air pressure within the soil matrix during quasi-saturation critically affect the soil's structural stability and capacity to withstand external hydrological pressures. This study proposes innovative

approaches for predicting and mitigating landslide risks, highlighting this dynamic relationship, especially in regions prone to heavy rainfall. The implications of this research extend beyond the academic realm, offering significant insights into environmental management and geotechnical engineering. By contributing to the development of more accurate landslide prediction models, this work holds the potential to enhance infrastructure resilience, reduce economic losses, and save lives. This approach advocates for a shift in disaster mitigation strategies, placing a newfound emphasis on the critical role of air pressure during quasi-saturation.

Exploring the interaction between air pressure and soil moisture during rainfall infiltration events offers a ground-breaking perspective on the dynamics of landslides.

By potentially revolutionizing traditional approaches to landslide prediction and mitigation, the insights garnered from this study aim to significantly bolster the safety and sustainability of communities that are globally vulnerable to rain-induced landslides. This work marks a critical step forward in the ongoing effort to mitigate the impacts of natural disasters on society.

## 2. RESEARCH SIGNIFICANCE

This research primarily aims to determine the role of air pressure in influencing the quasi-saturated state, particularly under heavy rainfall conditions. This objective is pursued through model tests and analyses designed to illuminate the intricate interplay among soil, water, and air.

By focusing on this aspect, the study seeks to fill a critical gap in the current understanding, as most existing research predominantly concentrates on volumetric water content during quasi-saturation [7,8,10], often neglecting the potential impact of air pressure dynamics. The anticipated outcome provides a more comprehensive understanding of soil behaviour under quasi-saturated conditions. This approach will significantly enhance predictive models for landslide initiation and improve strategies for mitigating landslide impacts.

## 3. TEST MATERIAL

Edosaki sand, which is part of the marine Narita layer that was deposited during the Quaternary epoch, forms a plateau extending from the southern Ibaraki Prefecture to the northern area of Chiba Prefecture. This sand, often considered mountain sand, is used in model tests. Figure 1 illustrates the grain size distribution.

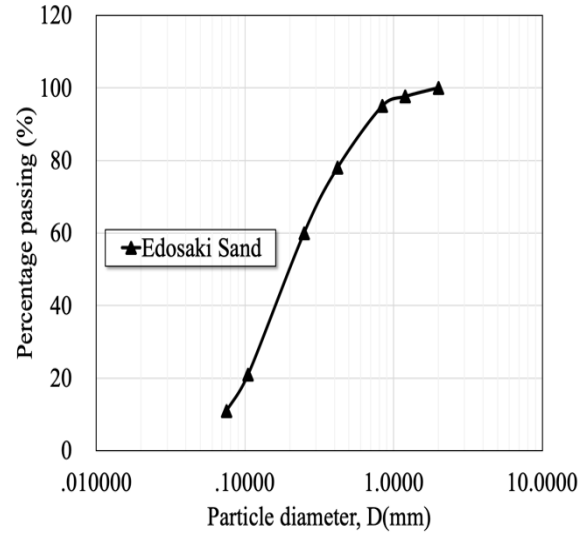


Fig. 1 Grain size distribution of Edosaki sand

As depicted in Figure 2, the compaction test results provide critical insights into the optimal moisture levels for Edosaki sand. These test results suggest that the ideal soil moisture content ranges between 13.89% and 17.17%.

The soil exhibits its most favourable compaction characteristics within this specific moisture range, achieving a maximum dry density of approximately 1.76 g/cm<sup>3</sup>. This density is crucial for understanding the structural integrity and stability of soils, particularly under varying environmental conditions. The significance of these findings is underscored by their alignment with established standards, closely matching the soil sample compaction curves of ASTM D698-70 [16].

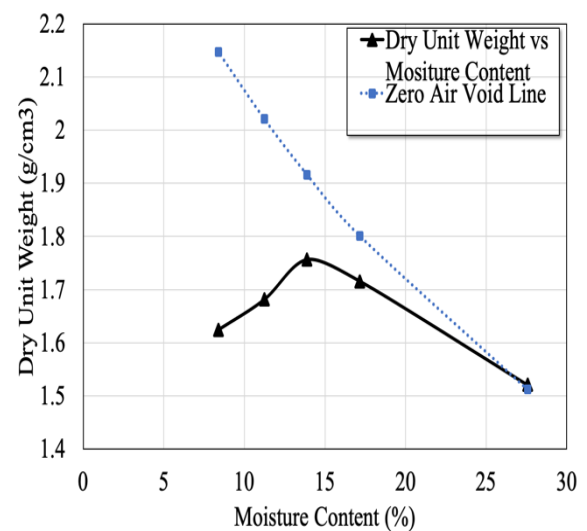


Fig. 2 Compaction curve of Edosaki sand

#### 4. TESTING PROCEDURES

##### 4.1 Model Test

This study analyses five distinct column test cases, as outlined in Table 1. While previous studies have utilized a column test approach [10,17], the modified version includes volumetric water content measurements, pore water pressure, and air pressure. Table 1 details the cases examined, focusing on air behaviour during quasisaturation. The pore water pressure is also measured, as shown in Table 1. However, this study analyses the volumetric water content and air pressure measurements.

Table 1 Model tests

Test	$D_r$ (%)	Soil type	Rainfall (mm/h)	Sensors
Case-1	60	Edosaki	120	VWC <sup>1</sup> , AP <sup>2</sup>
Case-2	60	Edosaki	120	VWC <sup>1</sup> , AP <sup>2</sup>
Case-3	40	Edosaki	120	VWC <sup>1</sup> , AP <sup>2</sup>
Case-4	70	Edosaki	120	VWC <sup>1</sup> , AP <sup>2</sup>
Case-5	80	Edosaki	120	VWC <sup>1</sup> , AP <sup>2</sup>

Note: <sup>1</sup>VWC – volumetric water content, <sup>2</sup>AP – air pressure,  $D_r$  – relative density.

Table 1 presents a detailed overview of the experimental design, highlighting that each of the five cases studied exhibits a distinct variation in relative density, a critical factor in understanding soil behaviour under different conditions.

Despite this variation, a consistent element across all the cases is the rainfall intensity, which is deliberately maintained at the same level for each test. This consistency in rainfall intensity is critical for the scope of related research. It is essential to clarify that the primary objective of this study is not to investigate the effects of varying rainfall intensities on soil behaviour. The focus is shifted towards examining the steady state of volumetric water content within the context of consistent, high precipitation levels. This approach allows for a more controlled and precise analysis of the soil's response to moisture, eliminating the variable of differing rainfall intensities.

This approach aims to isolate and enhance the understanding of the specific impacts of sustained high moisture levels on the soil's quasisaturated state. This approach is particularly relevant in scenarios where consistent heavy rainfall is a significant factor, as it enables us to predict more accurately and model soil behaviour under such conditions, which is crucial for planning and mitigating potential landslide risks.

##### 4.2 Column Test

This study includes a laboratory experiment utilizing a one-metre-tall acrylic column with a diameter of 10 cm, through which rainfall was simulated. Unlike previous studies in which column test saturation was predominantly achieved through capillary action [17], this approach seeks to mimic rainfall-induced landslides more accurately. The primary aim is to investigate the equilibrium state of the volumetric water content in soil.

The column is equipped with sensors at various depths to ensure that a comprehensive understanding can be obtained from real-time data via volumetric water content and air pressure measurements. These insights are pivotal in understanding the dynamic changes occurring during rainfall. The relevance of the column test to an actual slope scenario is shown in Figure 3. Here, consider a slope subjected to rainfall likely to fail over time. A column test models an element of such a slope exposed to water infiltration. This increases the volumetric water content, elevating the soil's degree of saturation and reducing suction. These changes cause the soil properties to transition from unsaturated to saturated states, potentially triggering instability. Furthermore, the findings of such an experiment are valuable for developing predictive models for landslide occurrence and enhancing disaster preparedness and mitigation strategies.

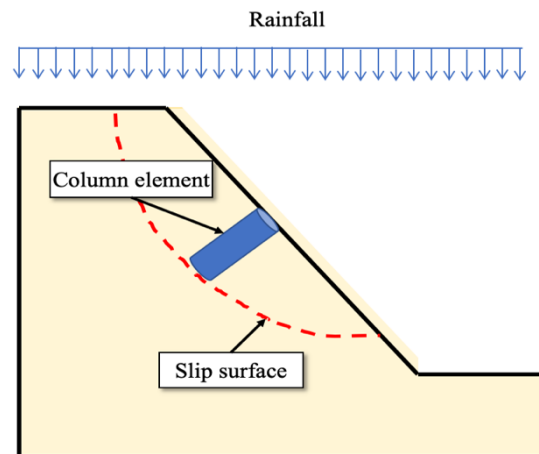


Fig. 3 Visual representation of the column test in a slope scenario before failure

Figure 4 utilizes an acrylic column that is one metre in height and 10 cm in diameter to assess the quasisaturation behaviour within a one-dimensional column test. This careful setup allows the soil to transition to a quasisaturated state. At the top of the column, rainwater is delivered to simulate natural rainfall conditions, and changes in pore water pressure and volumetric water content at various

saturation levels are tracked. The column test is valuable for tracking moisture content and pressure changes as the soil approaches saturation.

The volumetric water content, pore water pressure, and air pressure are recorded during the experiment at three distinct heights: the top, middle, and bottom of the column. Figure 5 provides a schematic representation of the acrylic column test setup, complemented by a visual representation of the model employed. The setup includes a 10 cm gravel layer at the base for efficient drainage and a fixed container positioned at the column's foot to collect the drained water, ensuring a continuous flow mimicking natural processes. The placement of sensors along the column is methodically divided into sections to ensure thorough coverage and facilitate visualization. Sensors 20 cm from the base are tasked with measuring the volumetric water content, pore water pressure, and air pressure and are labelled the "Bottom Position" sensors. Sensors at 50 cm from the base are designated the "Middle Position" sensors, aligning with the midpoint of the column. The highest set of sensors, located 80 cm from the base, are the "Top Position" sensors. This strategic segmentation into bottom, middle, and top positions ensures a structured approach to data gathering. This approach enables a detailed, tiered analysis of soil behaviour across different saturation levels, ensuring that all column aspects are monitored.

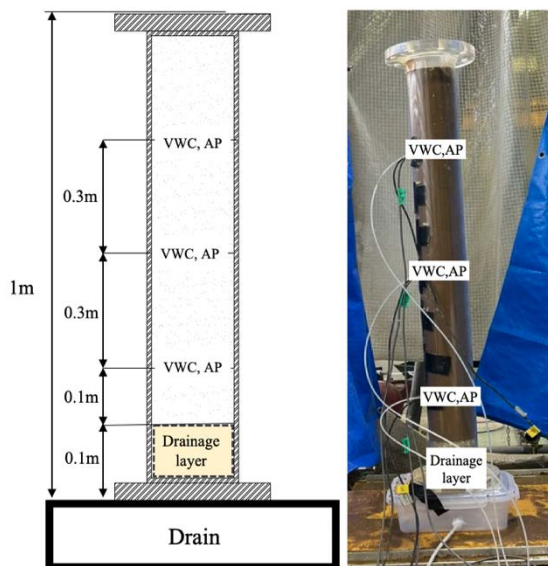


Fig. 4 Outline of the column test and sensor positions (VWC - volumetric water content, AP - air pressure)

### 4.3 Air Pressure Measurement

In the present study, an innovative approach was used to investigate the steady state before slope failure by measuring the air pressure changes during

quasisaturation. Previous researchers have concluded that during rainfall and stable infiltration, an initial quasisaturated state occurs; subsequently, after reaching this state, displacement may occur if the volumetric water content is allowed to increase. Therefore, the authors posit that a relationship exists between the steady state of volumetric water content—which remains constant for a period—and the air pressure within the soil. The pore water pressure sensor was modified to measure the air pressure. Figures 5 and 6 illustrate the modifications made to the pore water pressure sensor to measure both positive and negative (suction) air pressures during the model test.

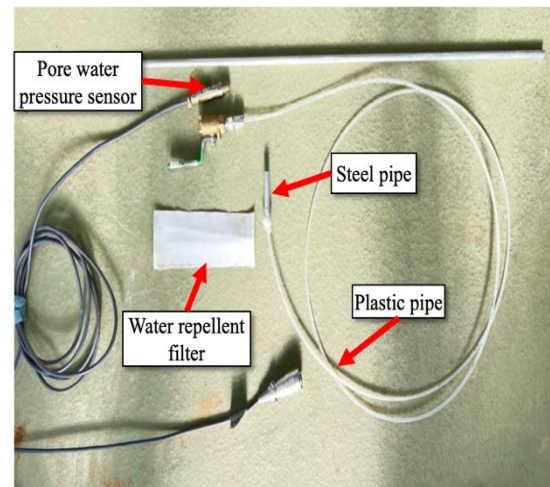


Fig. 5 Air pressure sensor setup

Six Kyowa PGMC-A pressure transducers were utilized for the current model test. Three were used to measure the pore water pressure, and three were modified to measure the air pressure (as shown in Figures 5 and 6).

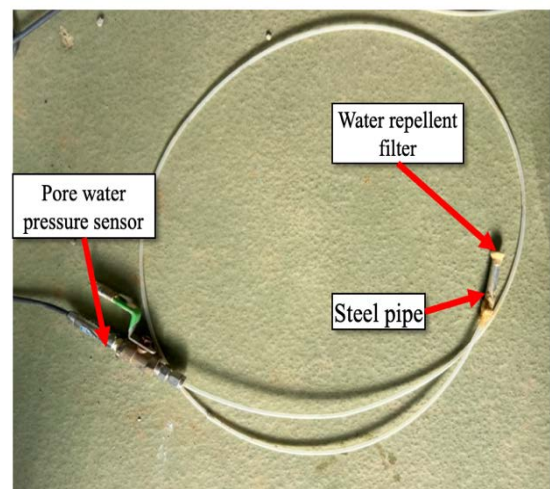


Fig. 6 A sensor used to measure the air pressure during the model test

Figure 5 and Figure 6 showcase the detailed modifications to the sensors for measuring air pressure. Each sensor was connected to a data logger, establishing a reliable and secure link for uninterrupted data transmission.

This arrangement involves switching from a sturdy plastic pipe to a steel pipe that is only 5 cm long and 10 mm wide. The water-repellent filter is securely wrapped around the firmly bonded steel component. This filter ensures that the air pressure measurements are not tainted by water. The steel pipe was then carefully buried in the ground, after which changes in air pressure were recorded during the test. Thus, this assembly collects data on air pressure while carefully avoiding any differences that could be caused by water. This approach ensured that the air pressure readings remained accurate even when the soil has different moisture contents. This systematic approach emphasizes the dedication to obtaining accurate, unbiased data to comprehend the soil's dynamic behaviours that may affect the stability and prediction of landslides.

## 5. TEST RESULTS AND DISCUSSION

Figure 7 shows the relationship between the volumetric water content and air pressure observed during water infiltration. The solid blue, red, and black lines represent the positions of the volumetric water content sensors, and the dashed lines measure air pressure at the same positions. This process was recorded over an extended duration, for approximately 2200 minutes, at a relative density of 60%. All the graphs illustrate infiltration during continuous rainfall applied from the top. Figure 7 shows a noticeable but slight increase in air pressure, especially at the top position. The air pressure stays negative throughout the wetting phase and correlates with increasing volumetric water content. The negative air pressure readings exhibit a modest reduction after the water content reaches a steady state.

Throughout the experiment, the soil column experienced only partial saturation. At times, the bottom portion remained entirely unsaturated; at other moments, partial saturation was achieved. This behaviour demonstrates that, despite heavy rainfall, unsaturated conditions can persist, likely due to air entrapment within the soil preventing full saturation across the column. The black line indicating the top sensor positions in Figure 7 shows the wetting stage and an increase in volumetric water content around 250 minutes, marking the beginning of quasisaturation. This increase in moisture content progressively extends downwards, as evidenced by subsequent rises first in the middle sensor readings and then at the

bottom, as illustrated by the blue line. The entire saturation process, or wetting stage, occurs approximately 250 minutes after the beginning of rainfall.

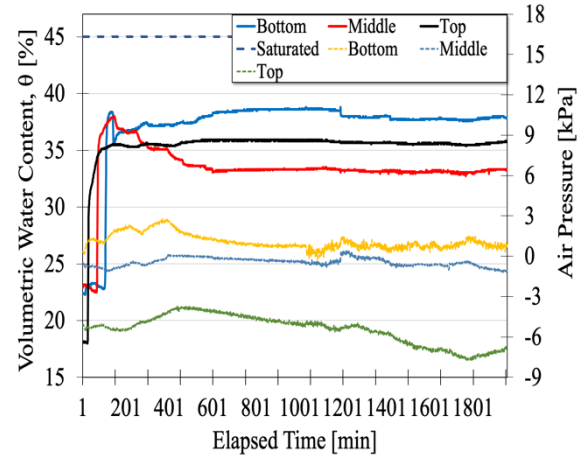


Fig. 7. Case 1 with Dr60%, showcasing the time history of volumetric water content and air pressure without a gravel layer

Compared to Case 1 (Fig. 7), Case 2 (Fig. 8) exhibits similar soil properties and rainfall intensity but differs in the presence of a gravel layer. Case 1 (Fig. 7) features a column filled without a gravel layer at the bottom, whereas Case 2 (Fig. 8) includes a gravel layer at the bottom of the column. In Case 2, the bottom sensor position reaches full saturation at 45%, mirroring the desired saturation threshold. In contrast, the top and middle positions do not achieve full saturation, only between 60 and 80% of the observations in Case 1. Notably, a steady volumetric water content is observed after the initial wetting stage in both cases.

A key distinction arises when examining air pressure. In Case 2, as the volumetric water content increases, a decrease in air pressure is observed, reaching more negative values than in Case 1. This inverse relationship is evident in Fig. 8, where a reduction in air pressure accompanies an increase in water content. This trend contrasts with the behaviour noted in Case 1, for which the volumetric water content and air pressure at the bottom position increases during the wetting stage.

A comparison of the two cases suggests that despite similar soil conditions and saturation levels at the top and middle positions, the air pressure response to saturation differs markedly. This could imply variations in the soil's air permeability or initial air entrapment between the two cases. The more negative air pressure values in Case 2 during periods of increased water content may indicate more efficient air displacement by infiltrating water

or more initial air entrapment than that in Case 1. This updated description improves the study of soil behaviour under specified test conditions.

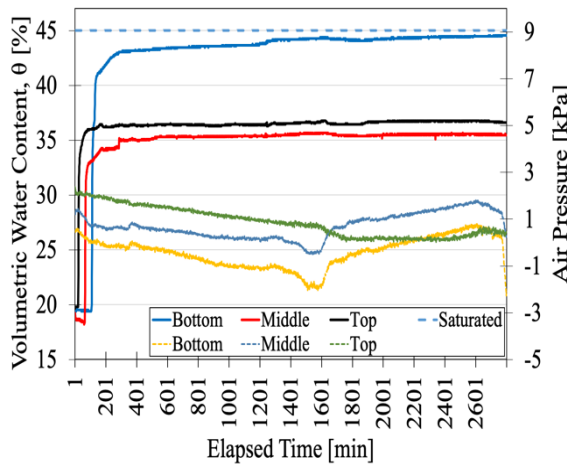


Fig. 8 Case 2 with Dr60%, which shows the time history of the volumetric water content and air pressure

In Fig. 9 (Case 3), where the ground density is reduced to Dr40%, there are distinct variations in the volumetric water content and air pressure compared to those in the 60% relative density scenarios, as shown in Fig. 8 and Fig. 7. Initially, after the wetting stage, the soil reaches a quasisaturated state, suggesting a rapid increase in volumetric water content to a certain threshold. This phase is crucial because any further increase in water content could lead to slope displacement due to oversaturation.

Fig. 9 shows a noticeable increase in air pressure that correlates with the increase in water content, especially at the top of the column. This trend indicates that air entrapment within the soil is more efficiently displaced by infiltrating water at lower densities. However, it is essential to note that full saturation (dashed blue line), defined as 49% for this case, was not achieved in any part of the model.

Most significantly, after reaching initial quasisaturation, there is a pronounced increase in air pressure as the water content increases again. This observation is particularly evident in the top part of the model. The wetting stage results in a 40% water content at the bottom of the column.

The observed data show the impact of ground density on the soil response to quasisaturation. As the density decreases, the soil structure changes, affecting the volumetric water content and air pressure. In a less dense soil structure, as exemplified by Dr40% in Fig. 9 (Case 3), there is likely more void space available for water and air movement. This can result in a quicker time to reach

the initial water content (quasisaturation) and more pronounced air pressure changes as water displaces air within the soil.

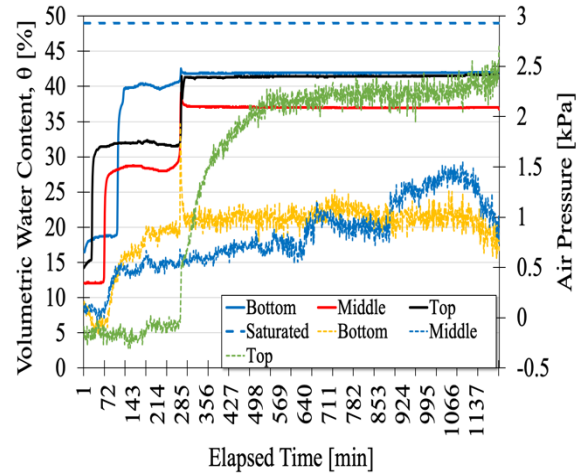


Fig. 9. Case 3 with Dr40%, which shows the time history of the volumetric water content and air pressure

As Case 4 (Fig. 10), with an increased relative density relative to Case 1, the air pressure increases during and after the wetting stage at all depths of the soil column, from top to bottom. This increase in air pressure could indicate water replacing the air within the soil pores, leading to compression of the air phase and an increase in pressure.

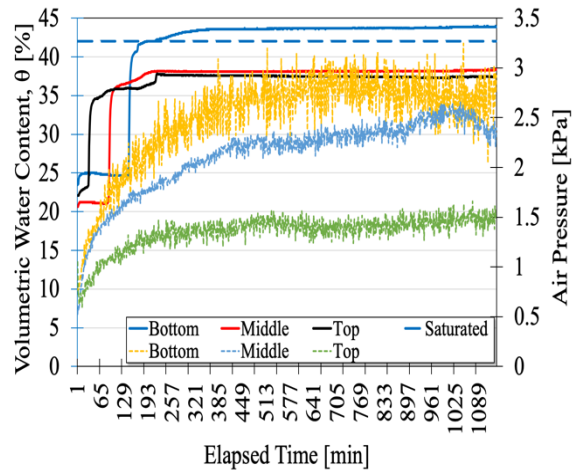


Fig. 10. Case 4 with Dr70%, presenting the time history of volumetric water content and air pressure

For Case 5 (Fig. 11), with a relative density of 80%, a trend similar to that of Case 4 can be observed. An increase in volumetric water content is coupled with increased air pressure. However, Case 5 is unique in that even after the volumetric water content reaches a steady state, the air pressure

continues to vary. This suggests that the denser soil matrix of Case 5 allows for more complex interactions between the water and air phases. The air pressure nevertheless fluctuates, reflecting the complex processes within the soil, even if the responses of the middle and upper portions of the soil column to rising water content are primarily consistent with the steady state of volumetric water content.

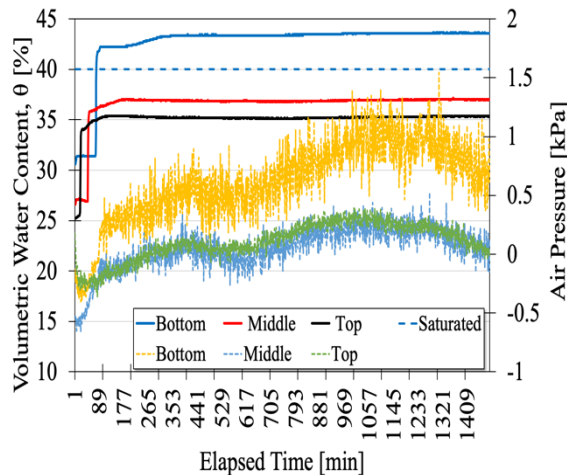


Fig. 11. Case 5 with Dr80%, presenting the time history of volumetric water content and air pressure

Water flow and failure modes are significantly impacted by the unsaturated hydraulic conductivity in the coarse layer, as evidenced by multilayered slopes subjected to severe rainfall [18].

This is especially pertinent to Cases 4 and 5, when various soil densities showed variable air pressure and volumetric water content responses. This revised description enhances the original by clarifying the relationship between soil density, volumetric water content, and air pressure, and it considers the complexities introduced by higher-density conditions. This approach provides a more thorough understanding of the hydrological characteristics impacting slope stability. These findings emphasize the significance of considering these factors when forecasting and controlling slope stability during extreme weather conditions.

## 6. CONCLUSION

This study explores the intricacies of soil behaviour under quasisaturated circumstances to improve the accuracy of landslide prediction. This study carefully documents how soil reacts to constant water content and air pressure. This work

provides crucial insights into soil stability dynamics and the likelihood of landslide events.

- This research reveals a difference between the air pressure and volumetric water content in soils under quasisaturated conditions and that fluctuations in air pressure within the soil matrix are critical in determining the stability of soil, thereby influencing its vulnerability to landslides.
- This study emphasizes the necessity of creating comprehensive landslide prediction models. The relevance of volumetric water content in predicting slope failures under quasisaturation conditions has been the main focus of traditional models. On the other hand, the current research offers a fresh viewpoint and supports incorporating soil air pressure dynamics as a crucial component in these models. This change in emphasis is based on the discovery that air pressure dynamics significantly impact the precision with which landslides are predicted. This indicates that earlier models may need to include essential details for evaluating slope stability.
- The current study extends beyond landslide prediction, contributing to the broader understanding of soil behaviour under unsaturated conditions.

## 7. ACKNOWLEDGEMENTS

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