Compaction Sensitivity in Tailings Stack Infiltration Modeling: Unsaturated Properties Uncertainty Analysis

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Abstract

Filtered tailings stacks have become increasingly prevalent in the mining industry since the 1990s, particularly in regions with arid climates. However, the adoption of filtered tailings technology has expanded globally, regardless of climatic conditions, as mining operations seek to reduce water in tailings to improve safety. Nonetheless, the implementation of tailings stacks in high-rainfall areas contradicts conventional practices, as filtered tailings operations are typically associated with regions of low precipitation due to compaction challenges during rainy periods. This poses significant challenges for tailings stacking in high-rainfall conditions, including their unsaturated characteristics and the absence of specific guidelines tailored to such environments.

Consequently, numerical modeling of infiltration under the principles of Unsaturated Soil Mechanics offers a promising approach to optimize recharge calculations, enabling more precise assessment of various factors such as moisture content, compaction, and drain sizing for these stacks. While optimized values are expected through modeling, inherent uncertainties exist in calibrating soil water retention curves (SWCC) and permeability functions, which involve Van Genuchten parameters, thereby affecting both parameter definition and model results. This study utilized tailings properties from a Brazilian mine, along with site climatic data, and employed a Bayesian approach to address calibration uncertainties. A hypothetical two-dimensional (2D) section of a test pad was considered for the study, and a software that simulates the movement of water and solutes in variably saturated media, for obtaining infiltration rates by solving the Richards Equation, was employed. In addition to calibration uncertainties, the simulation assessed the compaction sensitivity (different void ratios) on the SWCC, revealing that both factors influenced infiltration rates and pressure head fluctuations. These findings underscore the critical importance of proper compaction control and suitable drainage system design.

Introduction

The mining industry is a cornerstone of many economies, significantly contributing to employment, income generation, and the supply of raw materials to various industrial sectors. Understanding the entire mining production process is crucial to ensure the adoption of the best technologies and operational practices for more sustainable mining. As part of this effort, companies are continuously seeking innovative solutions to improve their ore treatment processes, enhance recovery rates, and extract minerals that were previously regarded as waste.

Waste and tailings management is a vital aspect of mining operations, and extensive research is being conducted to find better uses for these materials. However, these applications are often limited by the physical and chemical properties of the materials and the high costs associated with their logistical deployment. Given the technical and economic limitations of repurposing a large portion of mining tailings, it becomes imperative to dispose of these materials in geotechnical structures such as dams and stacks. Traditionally, tailings dams have been the preferred method in high-rainfall regions due to established engineering practices, regional topography, and climate conditions. However, recent changes in legislation and licensing processes, particularly after several catastrophic tailings dam failures in Brazil, have led to a growing interest in alternative methods, such as tailings filtration and stack disposal.

In some mining operations, filtered tailings stacks have gained prominence due to their potential for safer and more efficient waste management. As mentioned by Davies (2011), the installation of tailings stacks has grown significantly since the 1990s, particularly in countries such as Australia, Zambia, Chile, Mexico, and the United States (Ulrich and Coffin, 2013). However, areas with substantial annual rainfall require careful evaluation of this method. Considering operational criteria during the rainy season is essential, and understanding how these stacks behave given the variability in geotechnical parameters influenced by the moisture content of the filtered tailings from industrial processes is crucial. According to Patterson et al. (2016), the success of filtered tailings stacks depends on site conditions, operation scale, and the geotechnical and geochemical properties of the tailings.

Therefore, the implementation of tailings stacks in high-rainfall areas poses significant challenges, including their unsaturated characteristics and the absence of specific guidelines tailored to such environments. Key factors influencing this scenario include: (i) the moisture content of dewatered tailings, influenced by processing plants and precipitation; (ii) high infiltration and transient anisotropic seepage associated with precipitation, compaction, and tailings properties; and (iii) evaporation rate. Moreover, the constant need for tailings disposal exacerbates operational difficulties in compaction during rainy seasons.

Consequently, numerical modeling of infiltration under the principles of unsaturated soil mechanics offers a promising approach to optimize recharge calculations (Watson et al., 1995), enabling more precise assessment of various factors such as moisture content and drain sizing for these stacks. While optimized values are expected through modeling, inherent uncertainties exist in calibrating soil water retention curves (SWCC) and permeability functions, which involve van Genuchten (1980) parameters, thereby affecting both parameter definitions and model results.

This paper proposes to address calibration uncertainties using a Bayesian approach and discuss their implications for the results of numerical infiltration modeling in tailings stacks based on sensitivity analyses of the compaction void ratio. Tailings properties from a mine in a high-rainfall area in Brazil were used as a case study, along with site climatic data. A fictional 2D section of a test pad was considered for the study, and a software that simulates the two-dimensional movement of water and solutes in variably saturated media, for obtaining infiltration rates by solving the Richards Equation (1931), was employed.

Methodology

This research focuses on a hypothetical filtered tailings stack located in a high-rainfall region. Data for the tailings were obtained from a mining company. Although tailings stacks are typically raised progressively, this study considers a three months long simulation in a test pad with a single raise.

While classical soil mechanics assumes that saturated pores between soil grains are completely filled with liquid below the water table and with gas above it – simplistically filled with water or air, respectively – unsaturated soil mechanics studies the simultaneous presence of water and air in different proportions between soil grains. Thus, a soil can present three distinct zones of saturation above the water table: the capillary zone, the two-phase zone, and the dry zone (Fredlund, 2017). The potential variation in the degree of saturation in the "two-phase" zone highlights the need to define the properties of unsaturated soil through functions.

The determination of the soil-water characteristic curve (SWCC) is the fundamental distinction between the behavior of saturated and unsaturated soils (Morgenstern, 2012). The SWCC is a curve that represents the nonlinear relationship between moisture content and pressure head in a given soil under a specific compaction state. In laboratory settings, the SWCC is obtained by measuring the soil suction at different moisture contents. A mathematical fit is then used to calibrate the curve. The following van Genuchten (1980) equation is one of the most widely used models for the SWCC (Gitirana et al., 2023) and it was adopted for the current study calibration.

$$\theta_w(\psi) = \theta_r + (\theta_s - \theta_r)\frac{(1+(\alpha\cdot\psi)^n)^{\frac{1}{n}}}{1+(\alpha\cdot\psi)^n}$$

Where: θ_w is the volumetric moisture content; θ_r is the residual volumetric moisture content; θ_s is the saturated volumetric moisture content; ψ is pressure head; α is the air-entry value; and n is a fitting parameter of the model that determines the curve inclination.

The van Genuchten parameters are calibrated using a Bayesian approach via the Markov Chain Monte Carlo (MCMC) method with the DREAM algorithm (Gomes et al., 2017). Calibration involves data collection through hanging column tests on different void ratio compactions. The MCMC calibration is implemented in MATLAB, involving the generation of one hundred combinations of possible van Genuchten parameters for each one of the three void ratio specimens that will be analyzed. With the volumetric moisture content function, the hydraulic conductivity function can be obtained as per the following equation (van Genuchten, 1980).

$$K(\theta) = K_s \cdot S_e(\psi)^L \left\{1 - \left[1 - S_e(\psi)^{\frac{1}{m}}\right]^m\right\}^2$$

Where: K_s is saturated hydraulic conductivity; S_e is effective saturation; ψ is pressure head; m is $1 - 1/n$; and L is a pore-connectivity parameter (commonly equal to 0.5).

In possession of the parameters input, the flow can be simulated with Richards Equation (1931). Based on Darcy's Law (1856), Buckingham (1907) developed an equation for flow in unsaturated porous media, also known as the Darcy-Buckingham Equation, which relates hydraulic conductivity, suction, and moisture content. Later, Richards (1931) developed a differential equation that describes water movement in unsaturated soil using the Darcy-Buckingham Equation and Bernoulli's Equation. Due to its complexity, the Richards Equation (1931), presented below, is typically solved through numerical modeling.

$$\frac{\delta\theta}{\delta t} = \frac{\delta}{\delta z}\left[K(\theta) \cdot \left(\frac{\delta\psi}{\delta z} + 1\right)\right]$$

Where: θ is the volumetric soil moisture content (m/m); t is time (s); z is gravitational potential (m); ψ is pressure head (m); and $K(\theta)$ is the hydraulic conductivity (m/s) function based on soil moisture content.

The numerical modeling of infiltration presented here is conducted using Hydrus-2D software (Šimůnek et al., 2008), which simulates the bidimensional movement of water and solutes in variably saturated media by solving the Richards Equation. Input data for the model include the one hundred sets of van Genuchten parameters derived from soil-water retention curves (SWCC) calibration for each void ratio compaction, saturated hydraulic conductivity, relevant meteorological data, and the physical dimensions of the tailings stack.

The sets of one hundred infiltration results from these simulations are analyzed to assess the impact of parameter uncertainty arising from the calibration of the non-linear SWCC. This analysis involves comparing infiltration rates, moisture contents, and pressure heads while evaluating the variability introduced by the different combinations of possible van Genuchten parameters for each one of the three void ratio specimens that are being analyzed. Average values and 95% confidence intervals were calculated for each set of one hundred simulations, facilitating meaningful comparisons of the impact of different void ratios. A 95% confidence interval is widely used in statistical analysis because it offers a balance between precision and reliability. This interval means that if many samples were taken and an interval estimate were built from each, 95% of these intervals would contain the true population parameter. A 95% confidence level is considered a standard in many fields because it provides reasonable certainty without excessively wide intervals, which can occur with higher confidence levels (Moore et al., 2017). This comprehensive methodology aims to account for inherent uncertainties in soil properties in infiltration modeling, providing optimized results for recharge calculations within the framework of unsaturated soil mechanics.

Data and discussion

Tailings characterization

The tailings investigated in this study are produced from niobium beneficiation, resulting from a flotation process. The particle size distribution testing, provided by the mining company, indicates that the tailings are primarily sand (~60%), with the remainder consisting of fines that pass through a No. 200 sieve. According to the Unified Soil Classification System (USCS), the authors classified the material as silty sand (SM), as the Atterberg limits testing indicates that the material exhibits non-plastic behavior. The selected sample for this study yielded a specific gravity of 4.44 g/cm³. Flexible wall permeability tests were conducted, according to ASTM D 5084, on the tailings sample at various stress levels and void ratios, and the results are presented in Table 1.

Table 1: Saturated hydraulic conductivity test results

Confining stress (kPa)	Void ratio (e)	K_{20} (cm/s)
400	0.89	9.15E-05
800	0.88	6.42E-05
100	0.73	1.91E-04
400	0.73	8.61E-05
800	0.73	5.33E-05
	Average:	1.22E-04

As a simplification of the treated uncertainties, and considering the available data and significant variability often encountered in hydraulic conductivity values, a saturated permeability input of 10^{-4} cm/s was uniformly defined for all simulations. Therefore, calibration of different hydraulic conductivity functions was not performed and the uncertainty was evaluated based on the SWCC parameters (θ_r, θ_s, α and n).

Parameters calibration

Three specimens from the same filtered tailings sample were compacted to achieve saturated void ratios (e) of 0.85, 0.71, and 0.69. The hanging column test, specified by ASTM D6836, was conducted for each specimen, and the results are presented as data in the SWCC calibration shown in Figure 1.

Since volumetric moisture content is the volume of water divided by the total volume, in a saturated condition, the volume of water is equivalent to the volume of voids. Therefore, since soil porosity is defined as the volume of voids divided by the total volume, θ_s is equivalent to the porosity of saturated soil. In this context, truncating saturated moisture content could be considered for the calibration presented here, given that porosity is determined by a straightforward indexing formula using void ratio as input. However, the curves showed the best fit when no truncation was applied to the SWCC parameters, as shown in the calibration results presented in Figure 1. Therefore, from the obtained uncertainty limits, one hundred sets of parameters (θ_r, θ_s, α and n) were generated to perform 100 simulations for each analyzed void ratio.

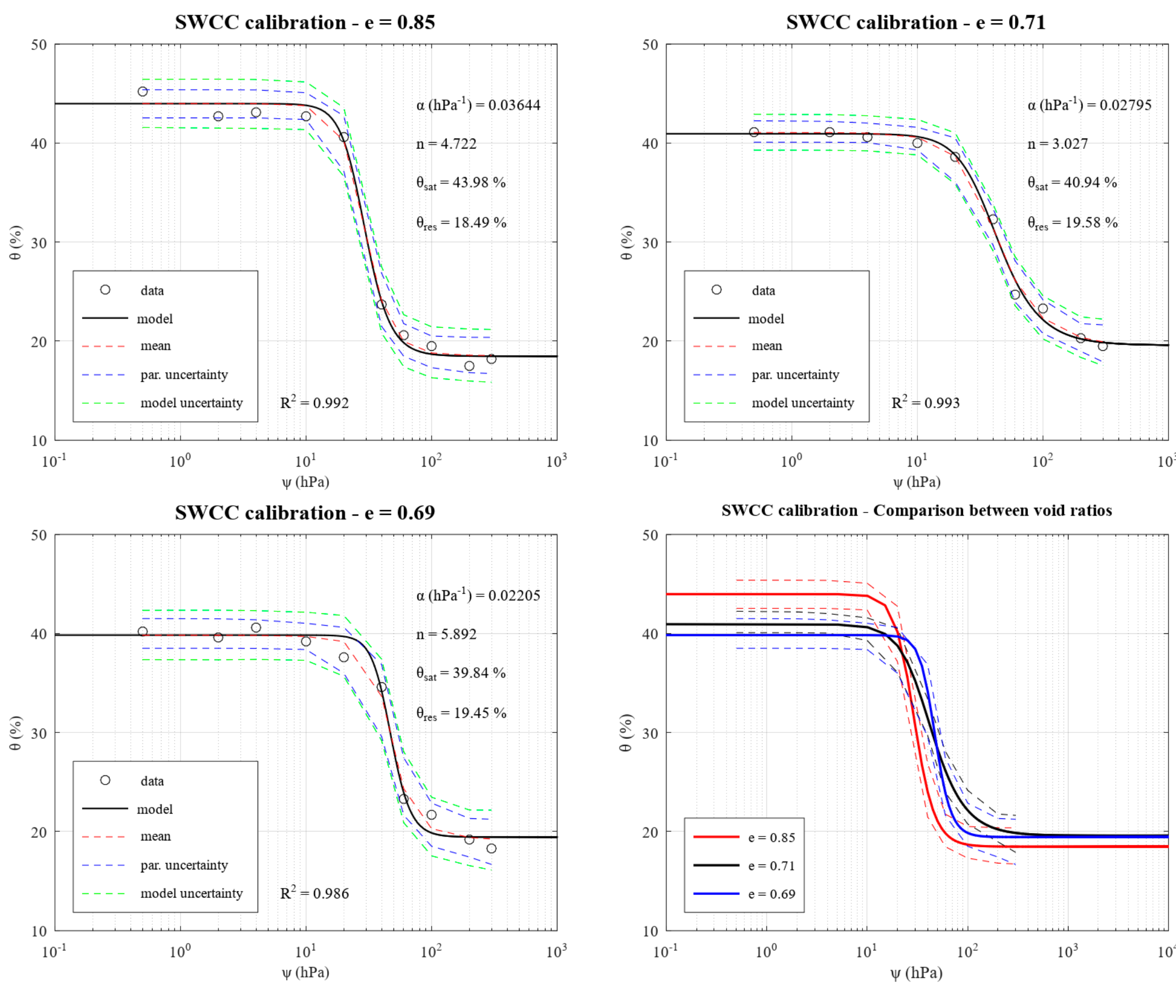

Figure 1: Calibration of van Genuchten parameters

As can be observed from the calibration results, in which each curve corresponds to a specimen with a specific void ratio, there is a noticeable relationship between the decrease in void ratio and the reduction in saturated volumetric moisture content. This relationship is attributed to the correlation between void ratio and porosity, which, as mentioned, corresponds to θ_s. Furthermore, the decrease in the parameter α when there is a decrease in void ratio can be explained by its role as the air-entry value. In saturated conditions, a smaller volume of voids hinders air entry, thereby influencing the observed decrease in α. However, the obtained parameter n does not clearly exhibit a direct relationship with void ratio. Since this parameter represents the curve's inclination, it suggests that, from an unsaturated perspective, moisture content may not necessarily increase with larger void ratios as typically observed in saturated conditions, indicating that it depends on the suction conditions at the time.

Hypothetical filtered stack and climatic conditions

The hypothetical filtered stack section shown in Figure 2 was developed to support the current study. The boundary conditions include an atmospheric boundary, where rainfall and evaporation are applied, and a seepage face at the stack bottom, indicating the location for drain installation. Observation nodes were placed at the bottom, top, and middle of the stacks. These nodes are specific points in the mesh marked to evaluate variations in moisture content and pressure head. To simulate the compaction process, an optimum moisture content of 33% was selected and used as the initial condition for all simulations.

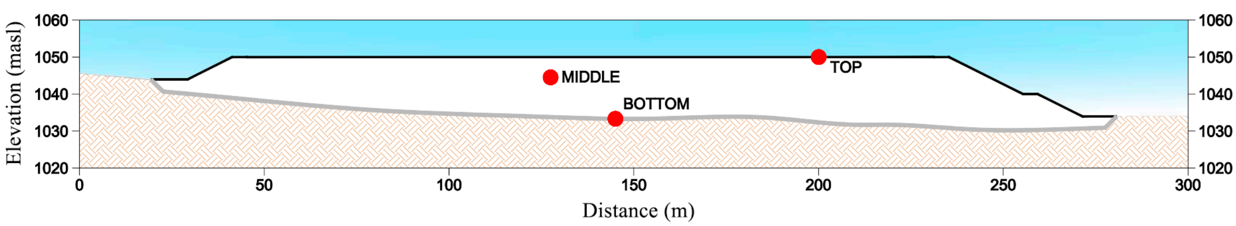

Figure 2: Hypothetical filtered stack

The climatic conditions used as input data included rainfall and evaporation, sourced from a specific location in Triângulo Mineiro (the Minas Triangle), Minas Gerais, Brazil. Evaporation was standardized to a daily value of 3.7 mm/day due to data availability. Actual daily rainfall data from the rainy season (January through March) of a particularly wet year (2013) in Minas Gerais were provided by the mining company's own weather station. This data was utilized in the simulations and is presented alongside the results in the following section.

Results

A total of 100 sets of parameters were simulated for each void ratio (0.85, 0.71, and 0.69). Some numerical models did not converge and were excluded as outliers. The flux across the seepage face and the average head pressure at the seepage face were obtained for each simulation. From the results, the average and 95% confidence interval were calculated for each set of void ratio results, as presented in Figure 3.

The results indicate that uncertainties exert a greater influence on the bottom of the stack during the initial stages, immediately after the simulation begins, prior to saturation. Additionally, the differences in void ratio are evident from the beginning, as each calibrated SWCC exhibits unique behavior, leading to variability in the three sets of simulations before reaching saturation. The numerical model results align with the obtained SWCC, particularly highlighting the variability of the parameter n mentioned previously. This variability indicates that, depending on the head pressure, different void ratio inputs can result in significantly different moisture content. Notably, saturation at the base of the stack under high rainfall is anticipated by the model, emphasizing the need for a suitable drainage system installation. As the initial peak of flux diminishes when saturation is achieved at the bottom, the variability between the results of different void ratios and uncertainties limits also decreases, resulting in similar outcomes. This indicates that over time, after operational phases, the variability resulting from compaction and parameter uncertainties for infiltration levels becomes less significant.

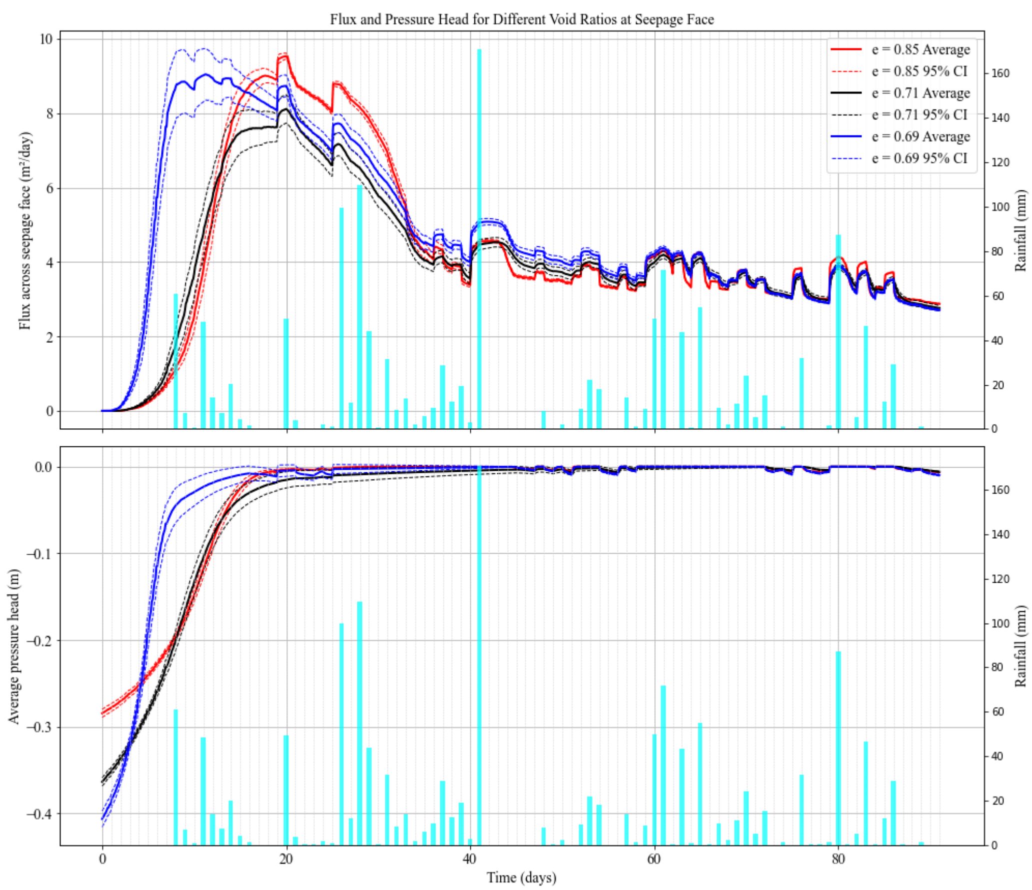

Figure 3: Seepage face results

The same data treatment applied to the results of the seepage face was also applied to the results of the observation nodes from each of the 100 simulation sets. Based on the results, presented in Figures 4, 5, and 6, it is noticeable that nodes at higher elevations are more significantly affected by climatic conditions than expected.

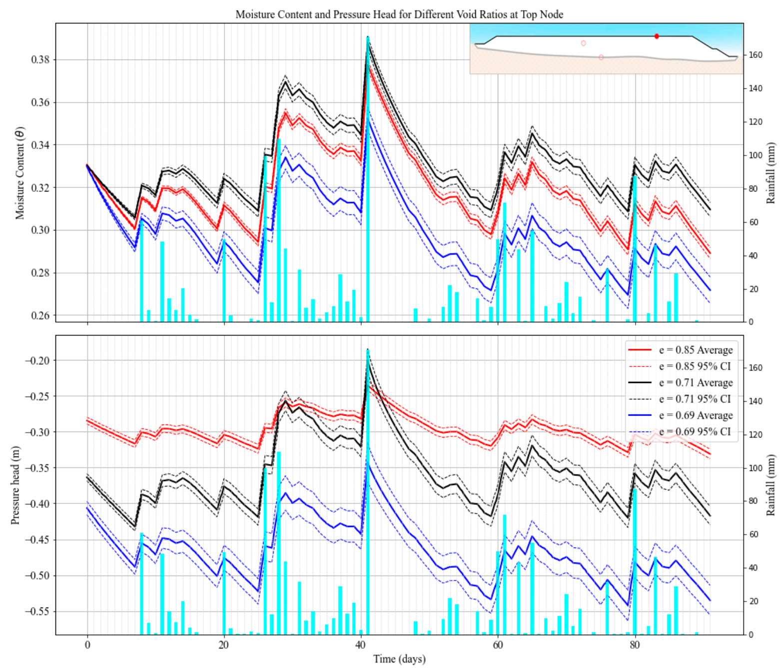

Figure 4: Top node results

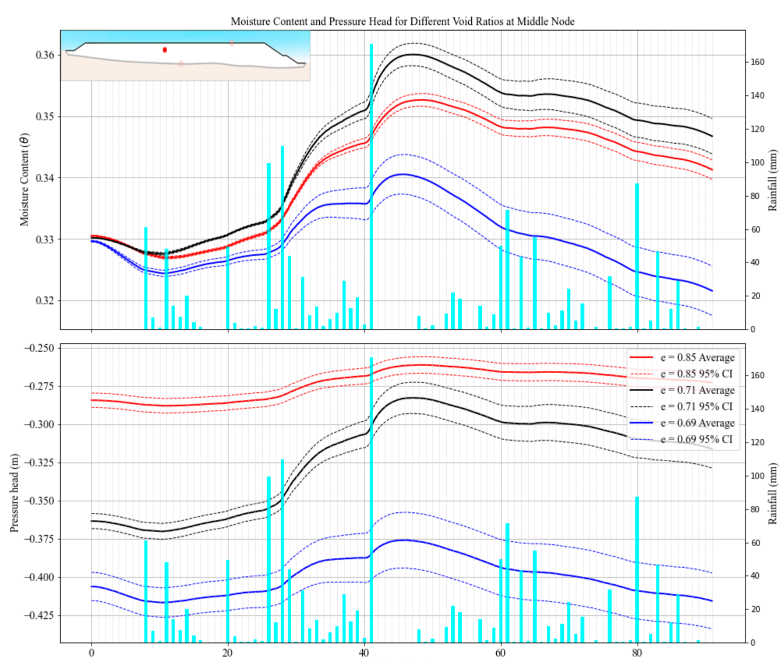

Figure 5: Middle node results

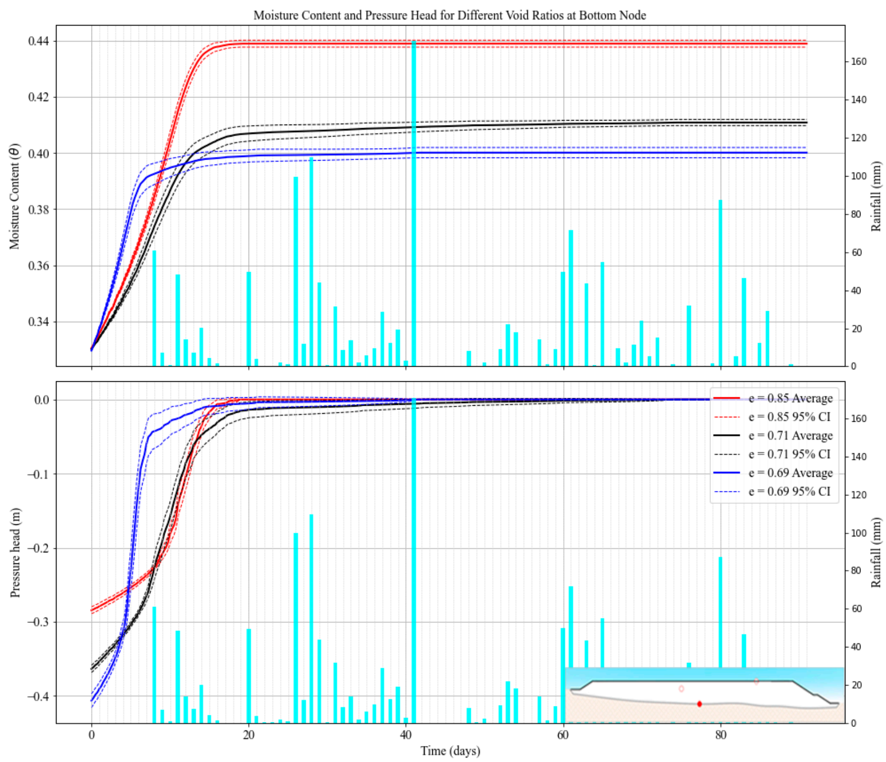

Figure 6: Bottom node results

The top node begins drying almost immediately, likely due to evaporation and drainage of the moisture used for compaction, and never reaches saturation, fluctuating with rainfall events. This lack of saturation results in greater variability influenced by both the initial void ratio and uncertainties from the calibration process, which are observable throughout the analyzed period.

The middle node exhibits an intermediate behavior, showing a delayed peak and smoother fluctuations with rainfall events. Like the top node, it also does not achieve saturation, presenting similar variability in behavior. Considering this variability and the possibility that a slip surface could pass through a similar middle area, it is important to further evaluate the potential impact of these uncertainties on Factor of Safety evaluations. As for the lower node, installed at the seepage face, its behavior closely resembles that of the seepage face, as anticipated, and it was monitored for validation purposes.

In this case study, due to the complexity of the simulation, it was assumed that a single lift would be constructed. However, in reality, the stack undergoes continuous raising during its operational phase. Therefore, the modeling highlights the critical importance of the operational phase, emphasizing the necessity for accurately sizing drainage with a suitable factor of safety and ensuring proper compaction control. This approach addresses both the inherent uncertainties in the model's design aspects and the variability encountered in field conditions, ensuring a more robust and reliable outcome.

Conclusion

In conclusion, this study emphasizes the significant challenges and complexities associated with implementing filtered tailings stacks in high-rainfall regions. The research employed advanced numerical modeling techniques underpinned by unsaturated soil mechanics principles to evaluate the infiltration behavior of tailings stacks, particularly focusing on the calibration of van Genuchten parameters using a Bayesian approach. The results underscored the significant influence of uncertainties in parameter calibration on infiltration rates and moisture content fluctuations during initial compaction stages. However, over time, these impacts diminished considerably. This comprehensive approach not only highlighted the variability introduced by different void ratios but also demonstrated the critical role of appropriate drainage design in managing saturation risks, particularly at the bottom of the stack during intense rainfall events.

Moving forward, further advancements in understanding the interactions between tailings properties, climatic conditions, and drainage systems will be essential for enhancing the reliability and efficiency of filtered tailings stacks in such challenging environments. This includes refining the impact of continuous raising on simulations and incorporating real-time data feedback mechanisms to improve predictive accuracy. Additionally, evaluating the impacts of uncertainties on stability analyses will be crucial. By addressing these complexities, future research can contribute to more sustainable mining practices that mitigate environmental risks and optimize operational outcomes in regions prone to high rainfall.

In summary, while the implementation of filtered tailings stacks in high-rainfall areas presents formidable engineering hurdles, integrating sophisticated modeling approaches and empirical data offers promising avenues for advancing the field of tailings management towards greater sustainability and resilience in diverse geographic contexts.

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