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Preliminary Investigation on the Behavior of Pore Air Pressure During Rainfall Infiltration

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Abstract. This paper focused on the preliminary investigation of pore air pressure behaviour during rainfall infiltration in order to substantiate the mechanism of rainfall induced slope failure. The actual behaviour or pore air pressure during infiltration is yet to be clearly understood as it is regularly assumed as atmospheric. Numerical modelling of one dimensional (1D) soil column was utilized in this study to provide a preliminary insight of this highlighted uncertainty. Parametric study was performed by using rainfall intensities of 1.85 x 10-3m/s and 1.16 x 10-4m/s applied on glass beads to simulate intense and modest rainfall conditions. Analysis results show that the high rainfall intensity causes more development of pore air pressure compared to low rainfall intensity. This is because at high rainfall intensity, the rainwater cannot replace the pore air smoothly thus confining the pore air. Therefore, the effect of pore air pressure has to be taken into consideration particularly during heavy rainfall.

1. Introduction

The investigation of rainfall induced slope failure mechanism often involves the study of rainfall infiltration either in the laboratory or field [1-4]. These studies typically monitor the matric suction and water content in response to infiltration. Although the decrease in matric suction and increase in water content have been acknowledged as the main factor that leads to slope failure, there is still an important component of unsaturated soil that has been neglected which is the pore air pressure. Since unsaturated soil mainly consists of four components namely solid, water, air and contractile skin, the air component if regularly assume as atmospheric [5]. Hence, the behaviour of pore air pressure subjected to rainfall infiltration is eventually neglected. Initial study carried out by Sako et al. [6] has observed the development of air bubbles after a river dike failure due to flood. Therefore, this indicates that pore air pressure may influence the seepage flow in unsaturated soil which requires further attention.

The behaviour of pore air pressure during rainfall infiltration is yet to be clearly understood due to the assumption as being similar to the atmospheric pressure. However, during rainfall infiltration, pore air pressure may build up due to the resistance of the water flow especially at high rainfall intensity. This increase in pore water pressure may influence the behaviour of unsaturated soil subsequently slope stability. Therefore, this study focused on the investigation of pore air pressure behaviour during rainfall infiltration in order to substantiate the mechanism of rainfall induced slope failure. The utilization of numerical modelling has been proven to be effective in simulating rainfall induced slope failure mechanism [7-9]. Thus, it can be utilized in this study to provide the insight regarding the behaviour of pore air pressure subjected to rainfall.

2. Methodology

One dimensional (1D) laboratory soil column was extensively used for infiltration study. As a preliminary study to investigate the behaviour of pore air pressure, numerical modelling was carried out to simulate the rainfall infiltration process in a 1D soil column. The 1D soil column adopted in this study was modified based on the comprehensive infiltration experiment carried out by Yang et al., (2004) [10]. Glass beads which resemble sand were used as the material in the 1D soil column. The basic soil properties of glass beads were determined using laboratory tests such as sieve analysis and permeability test. The results of basic soil properties for glass beads are summarized in **Table 1**.

Table 1: Particle size distribution and basic soil parameters for glass beads

Properties	Values
Gravel (%)	0
Sand (%)	99
Silt (%)	1
Clay (%)	0
Diameter corresponding to 10% finer, D_{10}	0.48
Diameter corresponding to 30% finer, D_{30}	0.6
Diameter corresponding to 60% finer, D_{60}	0.8
Uniformity coefficient, C_u	1.667
Coefficient of gradation, C_c	0.9375
Saturated hydraulic conductivity, K_{sat} (m/s)	1.329×10^{-2}

2.1 Governing equations

The numerical modelling was carried out by using the finite element method that incorporates unsaturated-saturated seepage flow and air flow. Water flow through the saturated and unsaturated soils is both governed by the Darcy's law [5]. The major difference between water flow in saturated and unsaturated soils is that the coefficient of hydraulic conductivity which is assumed to be a constant in saturated soils is a function of volumetric water content or matric suction in the unsaturated soils. The general governing equation for water flow through a 2D unsaturated soil element may be represented by Richard's equation as expressed as:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial h}{\partial y}\right) + Q = \left(\frac{\partial \theta_w}{\partial t}\right) \qquad (1)$$

where h is total hydraulic head, k_x and k_y is the coefficient of hydraulic conductivity in x and y direction, Q is the applied boundary flux such as evaporation, infiltration etc and θ_w is the volumetric water content. Eq. 1 presents that the total rates of change of flows in both x and y direction plus an external applied flux is equal to the rate of change of the volumetric water content with respect to time. It can also be noted that **Equation. 1** is highly non-linear since the hydraulic head and the coefficient of hydraulic conductivity are functions of the volumetric water content of the soil. A change in the volumetric water content can be related to a change in pore water pressure by:

$$\partial \theta_w = m_w \partial u_w \qquad (2)$$

where m_w is equal to the slope of SWCC and u_w is the pore water pressure. Substituting **Equation. 2** into **Equation 1** will lead to the final form of differential equation for water flow in unsaturated soil:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial h}{\partial y}\right) + Q = m_w\left(\frac{\partial u_w}{\partial t}\right) \quad . \qquad (3)$$

In order to incorporate air flow in this study, Fick's law is adopted and can be expressed as [11]:

$$v_a = -k_a \frac{\partial h_a}{\partial y} \qquad (4)$$

where va is the volume rate of the air flow across a unit area of the soil at the exit point of flow, ka is the air coefficient of permeability and ha is the pore air pressure head. Since the governing equations of both seepage and air flow are non-linear, numerical method such as finite element method (FEM) is required to be used for to solve for the complex computation. The geotechnical finite element computer programs to compute and solve these equations are Seep/W [12] integrated with Air/W [13] developed by Geo-Slope International Ltd.

2.2 Hydraulic properties

The input parameters are important to ensure an accurate and reliable modelling. Hence, the hydraulic properties of glass beads such as volumetric water content and hydraulic conductivity functions play an important role in this numerical modelling. Since determining these hydraulic properties are time consuming and require sophisticated laboratory instruments, the predictive methods was utilized to estimate the volumetric water content and hydraulic conductivity functions of glass beads (Krahn, 2004). The particle size distribution of glass beads was used to determine the volumetric water content function subsequently followed by the estimation of hydraulic conductivity function by using Fredlund et al, (1994) method [14]. The estimated volumetric water content and hydraulic conductivity functions are shown in **Figure 1** and **Figure 2.**

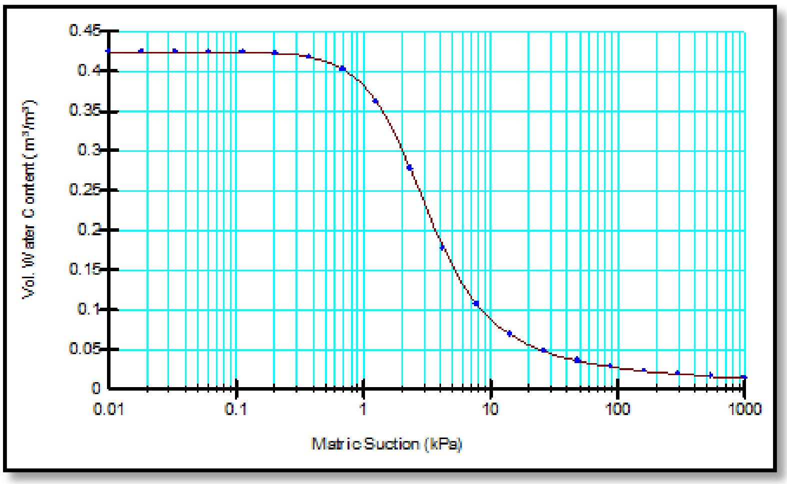

Figure 1. Volumetric water content function for glass beads.

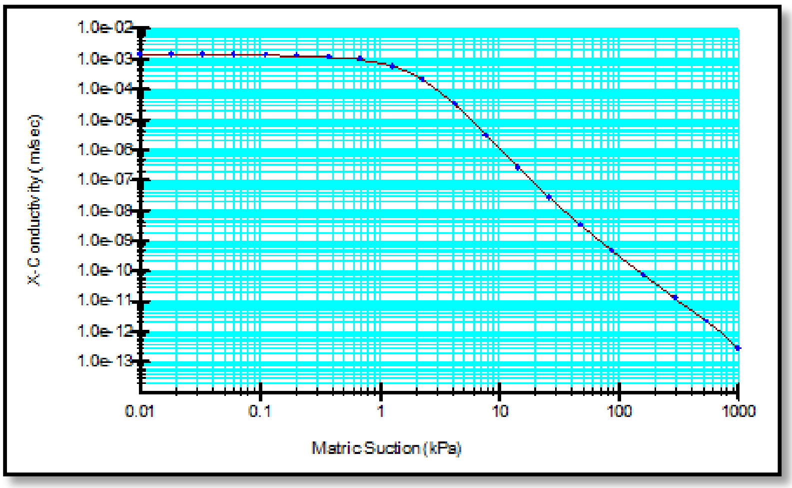

Figure 2. Hydraulic conductivity function for glass beads.

2.3 Numerical simulation

The soil column was modelled as a rectangular domain measuring at 200mm width and 1m length as shown in **Figure 3**. The basic properties of glass beads were then assigned to the model to replicate the actual condition during the 1D soil column experiment.

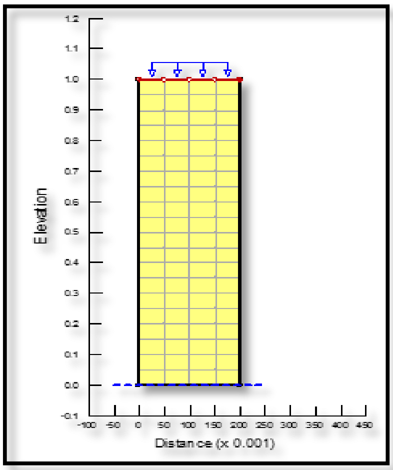

Figure 3. Finite element model for 1D soil column.

The analyses were carried out in two conditions namely steady state and transient condition. Steady state analysis was performed in order to obtain the initial condition of the soil column while transient analysis was performed to analyze the infiltration process. During the steady state analysis, no boundary condition was assigned on the top surface of the soil column but for transient analysis, a simulated 2 hours of rainfall was assigned on the top of the column with the influx boundary condition of 1.85 x 10^{-3} m/s and 1.16 x 10^{-4} m/s. These boundary conditions were selected to replicate an intense and low daily rainfall. The analysis configuration for the numerical modelling is summarized in **Table 2**. The bottom of the soil column was assumed as the initial groundwater table thus the boundary condition was assigned as the atmospheric pressure. After the assignment of the properties and boundary conditions, the model was discretized into finite elements for computation of results.

Table 2. Analysis configuration for numerical modelling.

Analysis	Rainfall intensity (m/s)	Rainfall duration (hr)
E1	1.85 x 10^{-3}	2
E2	1.16 10^{-4}	2

3. Results and Discussion

Three types of parameters versus the elevation in soil column are investigated based on the results of numerical analysis namely matric suction, volumetric water content and pore air pressure.

3.1 Matric suction

Figure 4 and **Figure 5** present the results of matric suction obtained by numerical modelling for E1 and E2. It can be observed that matric suction decreases as the wetting front descends into the soil column. The initial matric suction in the soil column is decreasing uniformly from 10kPa to 0kPa from the top to the bottom of the soil column. When the rainfall is applied, the matric suction begins to decrease from the top to the bottom of the soil column. Higher rainfall intensity results in quicker reduction of matric suction. However, it can be observed that the matric suction decreases to approximately 1kPa towards the end of the simulation for both E1 and E2. This indicates that the soil column is yet to be fully saturated due to the presence of pore air.

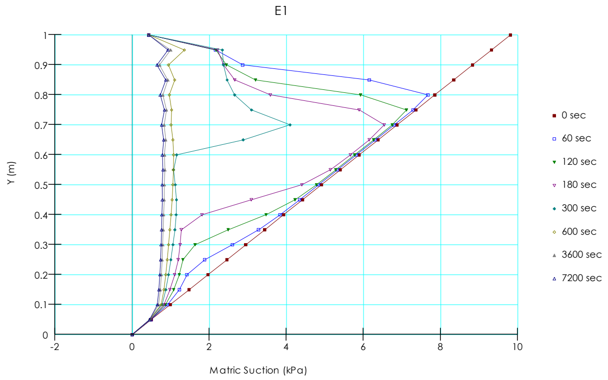

Figure 4. Matric suction profile for E1.

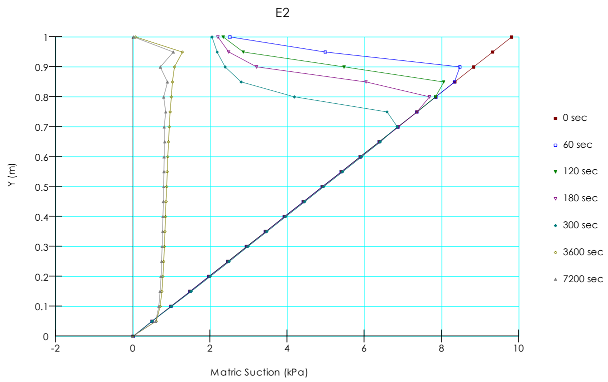

Figure 5. Matric suction profile for E2.

3.2 Volumetric water content

Figure 6 and **Figure 7** present the volumetric water content profile for E1 and E2 respectively. It can be observed that the volumetric water content increases behind the wetting front. This is because the infiltrated water filled in the pore space thus resulting in the increase in water content. The descending of wetting front is quicker for higher rainfall intensity which leads to quicker response of volumetric water content. Hence, it can be observed that at t=300s the volumetric water content for E1 at 0.7m is equal to 0.18 whereas for E2 at 0.7m is equal to 0.12.

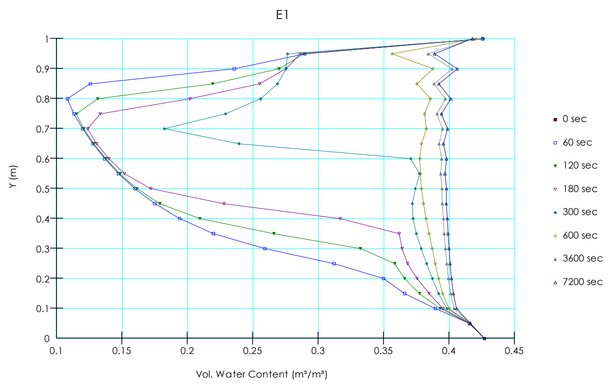

Figure 6. Volumetric water content profile for E1.

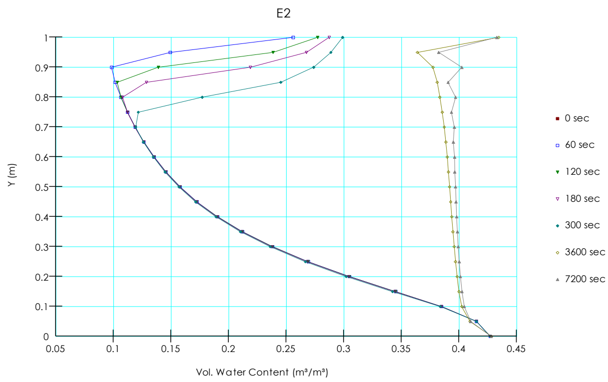

Figure 7. Volumetric water content profile for E2.

3.3 Pore air pressure

The results of pore air pressure profiles for E1 and E2 are presented in **Figure 8** and **Figure 9** respectively. The profiles show that higher rainfall intensity result in more pore air pressure build up during infiltration. For E1, the pore air pressure at t=60s for the soil column measures at about 2.5kPa whereas for E2 measures at approximately 0kPa. These results indicate that higher rainfall intensity causes more trapped air inside the pores that cannot be drained. For lower rainfall intensity, the pore air can be replaced smoothly by the rainwater thereby resulting in less pore air pressure build up. Hence, higher rainfall intensity will contribute to higher pore air pressure because the rainwater cannot replace the pore air smoothly. However, the pore air pressure for both E1 and E2 gradually increases towards the end of the simulation where the soil column is fully filled with rainwater. The pore air pressure profiles indicate that the final pore air pressure increase uniformly with depth in the soil column in which 0 to 12kPa for E1 and 0 to 10kPa for E2.

From this preliminary investigation, the influence of pore air pressure is regarded to be significant in unsaturated soil mechanics especially involving high rainfall intensity. The pore air pressure may produce resistance to rainfall infiltration on the soil surface subsequently resulting in more surface runoff. This condition may contribute to erosion that can lead to slope failure. However, more comprehensive studies such as laboratory experiments and field studies have to be conducted in order to determine other influencing factors of pore air pressure behaviour besides rainfall intensity.

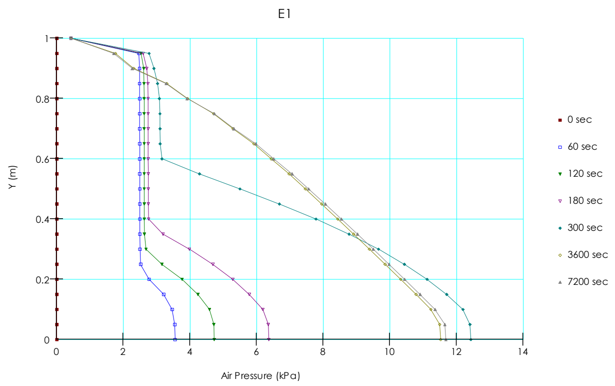

Figure 8. Pore air pressure profile for E1.

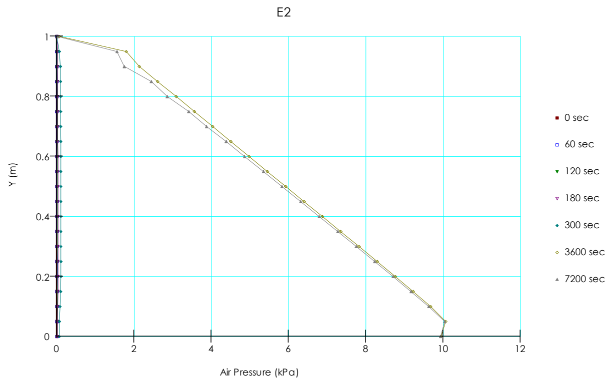

Figure 9. Pore air pressure profile for E2.

4. Conclusion

This study provides a preliminary insight on the behaviour of pore air pressure during rainfall infiltration. It can be concluded that rainfall intensity play an important role in the development of pore air pressure. Intense rainfall causes the difficulties of rainwater to replace the pore air smoothly thus confining the pore air. This leads to the increase in pore air pressure which can influence the rainfall infiltration mechanism subsequently slope stability. Therefore, the effect of pore air pressure should be further investigated in order to establish a comprehensive rainfall infiltration mechanism correspond to slope stability.

The authors are planning to work on the laboratory physical modelling using 1D soil column to assess the effect of rainfall characteristics and soil properties on the behaviour of pore air pressure.

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