P14

Infiltration Analysis of Unsaturated Soil Slopes

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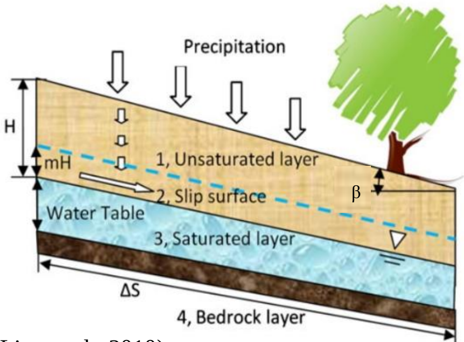
1. Introduction

Landslides are often catastrophic, posing significant threats to communities, with rainfall induced occurrences being among the most prevalent. Researchers often study the intricate relationship between rainfall infiltration and slope failures considering a wide range of crucial factors. Moreover, early warning systems heavily rely on rainfall as it is impractical to incorporate many other boundary conditions such as heterogeneous soil profiles and subterraneous flows if slopes are not instrumented and monitored properly. Current methods utilize the integration of GIS-based susceptibility mapping, a satellite-based precipitation monitoring and forecasting system, along with rainfall-induced landslide prediction model. The most crucial determinant in this context is the soil's infiltration capacity. As soil saturation leads to a loss of shear strength and subsequent failure, an accurate prediction of early warning relies heavily on assessing this critical parameter. Therefore, this study aims to review existing models on rainfall infiltration in unsaturated soil slopes and validate by comparing the analytical solution with the experimental result.

2. Review of Existing Infiltration Models

Valentino and Montrasio, 2008 developed a mathematical model that translates the physical phenomenon of rainfall triggering process through a simplified water-flow model. It directly relates the safety factor of a slope with rainfall amount incorporating the parameter *m* that describes infiltration. *m* represents the dimensionless thickness of the saturated part of the soil layer as depicted in Fig. 1 and is a fractional parameter between 0 and 1. As the rainfall infiltrates the soil layers, it brings about a significant rise in *m* parameter which indicates soil saturation. However, the intricate processes causing water loss are simplified into a negative exponential function governed by K_T which represents the global drainage capability of the slope. The representative equation describing infiltration in this original model is given by Eq. 1.

$$m(t) = \Sigma_i e^{-k_T \cdot \frac{\sin\beta}{n \cdot L \cdot (1-S_r)} \cdot (t - t_{0i})} \cdot \frac{h(t_{0i})}{n \cdot H \cdot (1-S_r)} \qquad (1)$$



(Liao et al., 2010)

Fig. 1. Schematic illustration describing the phenomenon.

In line with the preceding study, Liao et al. (2010) introduced the SLIDE model whereby Eq. 1 was revised and rewritten differentially to better evaluate the effects of single rainfall discrepantly as shown in Eq. 2. Konagai (2022) further modified the SLIDE model (which will be referred to as the modified SLIDE model) by incorporating the variation of m_t with respect to the slope length and flow divergence, as depicted in Eq. 3. The K_T parameter that signifies global drainage capability of the slope lacked clear definition in previous literatures. However, Eq. 3 specifically considers K_t as the hydraulic conductivity of the soil, thereby simplifying its application in the analysis.

$$
\begin{aligned}
m_1 &= 0 \\
O_t &= K_T . \sin\beta . m_t . H . \cos\beta . \Delta t \\
\Delta m_t &= \frac{(I_t - O_t)}{H . n . (1 - S_r)} \\
m_{t+1} &= m_t + \Delta m_t
\end{aligned}
\tag{2}
$$

$$
\begin{aligned}
m_1 &= 0 \\
O_t &= -K_t . H . m_t . \left(\frac{\partial m_t}{\partial x} + \tan\beta\right) . \Delta t \\
\Delta m_t &= \frac{\left(I_t \Delta t - \frac{\partial O_t}{\partial x}\right)}{n . (1 - S_r)} \\
m_{t+1} &= m_t + \Delta m_t
\end{aligned}
\tag{3}
$$

3. Comparison of Infiltration Models

The comparison between the original model and the modified SLIDE model was studied using a set of parameters for the analysis to generate *m* parameter. The comparison result of *m* vs. *t* is depicted in Fig. 2.

There is an exponential growth in the soil saturation as the rainfall infiltration progresses in the original model with a peak value of *m* = 1. This indicates that there is a complete soil saturation in 48 hours, which is impractical and could mean that the model does not adequately capture the outflow. On the other hand, the modified SLIDE model observes a peak value of *m* = 0.62 at the lower end of the slope, which is well within the bounds. It indicates that 62% of the unsaturated soil layer gets saturated as a result of rainfall infiltration. Moreover, the saturation is not uniform within the slope length and exhibits lower levels at the upper end of the slope.

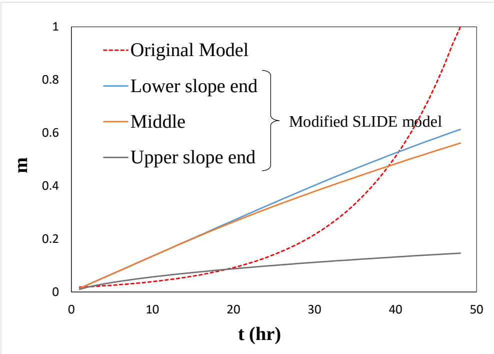


Fig. 2. m vs. t plot for original and modified SLIDE models

4. Validation with experimental result

The modified SLIDE model (analytical model), given its better representation of the infiltration phenomenon was used for validation against the experimental results. Data of centrifuge experiments (Jayakody, 2023) conducted on unsaturated soil slopes subjected to rainfall application were used. The comparison of *m* values for the corresponding pore pressure transducers in the experimental setup for experimental and analytical results is shown below.

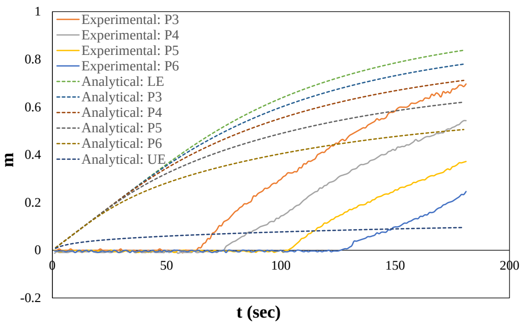


Fig. 3. Comparison of analytical and experimental values

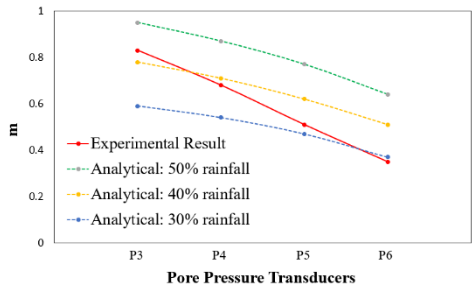


Fig. 4. m vs. t plot for analytical and experimental data

5. Result and Conclusion

Comparing *m* values for varying rainfall intensities in the analytical model with the experimental result shows discrepancies observed in the values. This implies that *m* parameter in the analytical model is highly sensitive to rainfall intensity and is important to consider effective rainfall that infiltrates into the soil layers resulting in soil saturation. Fig. 4 shows the *m* vs. *t* plot between the two models. The analytical model assumes immediate saturation upon rainfall infiltration neglecting the infiltration time needed for soil saturation, as demonstrated by the experimental results. To address this limitation, incorporating a simple one-dimensional infiltration model in the modified SLIDE model could effectively address this issue.

References

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