Integrated Simulation Modeling Approach for Investigating Pore Water Pressure Induced Landslides

Sahila Beegum (beegumsahila@gmail.com)
University of Nebraska-Lincoln https://orcid.org/0000-0003-3623-4426
P J Jainet
Kerala State Council for Science Technology and Environment
Dawn Emil
Kerala State Council for Science Technology and Environment
K P Sudheer
Kerala State Council for Science Technology and Environment
Saurav Das
University of Nebraska-Lincoln

Research Article

Keywords: Landslide, Factor of safety, HYDRUS-2D/3D, GeoStudio-Slope/W, Pressure head, Pore water pressure, Extreme rainfall events

Posted Date: January 13th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1186263/v1

Integrated simulation modeling approach for investigating pore water pressure induced landslides

Sahila Beegum[*1], Jainet P J[2], Dawn Emil[2], K P Sudheer[2,3], Saurav Das[4]

1. *Nebraska Water Center, part of the Robert B. Daugherty Water for Food Global Institute, University of Nebraska, Lincoln, NE, USA*
2. *KSCSTE-Centre for Water Resources Development and Management, Kozhikode, Kerala, India*
3. *Department of Agricultural and Biological Engineering, Purdue University, West Lafayette, IN, USA*
4. *Department of Agronomy and Horticulture, University of Nebraska, Lincoln, NE, USA*

***Corresponding author:** Dr. Sahila Beegum, Nebraska Water Center, part of the Robert B. Daugherty Water for Food Global Institute, University of Nebraska, Lincoln, NE, USA. Email: beegumsahila@gmail.com

Abstract

Soil pore water pressure analysis is crucial for understanding landslide initiation and prediction. However, field-scale transient pore water pressure measurements are complex. This study investigates the integrated application of simulation models (HYDRUS-2D/3D and GeoStudio–Slope/W) to analyze pore water pressure-induced landslides. The proposed methodology is illustrated and validated using a case study (landslide in India, 2018). Model simulated pore water pressure was correlated with the stability of hillslope, and simulation results were found to be co-aligned with the actual landslide that occurred in 2018. Simulations were carried out for natural and modified hill slope geometry in the study area. The volume of water in the hill slope, temporal and spatial evolution of pore water pressure, and factor of safety were analysed. Results indicated higher stability in natural hillslope (factor of safety of 1.243) compared to modified hill slope (factor of safety of 0.946) despite a higher pore water pressure in the natural hillslope. The study demonstrates the integrated applicability of the physics-based models in analyzing the stability of hill slopes under varying pore water pressure and hill slope geometry and its accuracy in predicting future landslides.

Keywords: Landslide, Factor of safety, HYDRUS-2D/3D, GeoStudio-Slope/W, Pressure head, Pore water pressure, Extreme rainfall events

Highlights:

- Demonstration of the integrated application of physics-based models in analyzing the stability of hill slopes under varying pore water pressure and hill slope geometry
- Correlation of evolution of pore water pressure, factor of safety, and geometry of hill slope to the landslide occurrence

1. Introduction

According to World Health Organization (WHO), landslides affected 4.8 million people and caused more than 18,000 deaths in the world between 1988 - 2017 (WHO, 2018). Prolonged and heavy rainfalls are the major factors causing landslides (Petley, 2012). In the past several years, the frequency of rainfall-induced landslides has increased with extreme rainfall events and anthropogenic activities (Marc et al., 2018; Rahimi et al., 2010). Climate change and frequent flash floods have also aggravated the landslide issues. Slope stability analysis can help understand the causes and potential triggers for a slope failure and aid in its mitigation. In the case of stability analysis of rainfall-induced landslides, it is essential to correlate the rainfall threshold and pore water pressure (PWP) threshold with the factor of safety by considering the changes in the physical and hydraulic properties of the soil. An accurate prediction of pore water pressure is fundamental for assessing slope stability in saturated soils. Though the landslide occurs within minutes, the soil moisture condition building up that ultimately triggers the landslides may take several hours to days. During a rainfall event, the pore water pressure varies temporally and spatially based on the (a) intensity and duration of the rainfall, (b) geometry of the soil layers and hillslope, (c) soil hydraulic properties and index properties, and (d) land use and land cover (Huang et al., 2012; Rahardjo et al., 2008b). Variations in the pore water pressure will impact the matric suction, effective stress, and soil stability (Rahardjo et al., 2008b). It is essential to account for these variabilities through accurate physical representation while investigating the slope stability. These parameters are crucial for understanding the initiation of landslide processes in a location and future landslide prediction for the mitigation approach (Carey et al., 2019; Kim et al., 2017; Liang, 2020).

There are several limitations in analyzing the real-time pore water pressure evolution in field-scale/ laboratory-scale studies during the occurrence of a landslide. In most cases, the piezometers and other instruments installed to monitor real-time pore water pressure and landslide displacement gets damaged during landslides with large displacements (Matsuura et al., 2008). Besides, pore water pressure determination becomes more complex when the hill slope has highly heterogeneous soil layers, leading to complex flow dynamics in the unsaturated-saturated soil zone. Since the pore water pressure distribution rarely follows a linear distribution along the depth or a uniform response across the slope, accurate measurement of pore pressure would require a large number of sensors. The measurements become more complex in the presence of subsurface conduits (soil pipes, burrows, etc.) (Fannin & Jaakkola, 1999; Hopkins et al., 1975; Johnson & Sitar, 1990). Due to these limitations, transient nature pore water pressure is mainly studied as an approximation of the actual response (Kuriakose et al., 2008; Oh & Lu, 2015). A better alternative is to utilize integrated simulation models that simulate water flow through the unsaturated-saturated soil zones and carry out slope stability analysis by considering the change in pore water pressure due to the water flow dynamics. Simulation models can also assist in analyzing the spatio-temporal variation in the evolution of pore water pressure with the change in the hill slope geometry (due to natural or anthropogenic activities).

GeoStudio-Slope/W (Geo-Slope, 2012) is a widely used simulation model for slope stability analysis (Jalilzadeh et al., 2020; Bui et al., 2020; Mishal & Khayyun, 2018). It can simulate a variety of slip surface shapes, pore water pressure conditions, analysis methods, and loading conditions. Pore water pressures accounted in the stability analysis in GeoStudio-Slope/W can be defined using piezometric lines or spatial functions or from GeoStudio finite element analysis model (Seep/W). Since pore water greatly influences the stability of the slope, GeoStudio-Slope/W model should be provided with accurate pore water pressure information (D. Fredlund, 1987; Rahardjo et al., 2008a; Xu & Yang, 2018). Among various simulation models for water flow dynamics and pore water pressure estimation in unsaturated-saturated soil zones, HYDRUS-2D/3D has been extensively used to predict pore water pressure dynamics (Karandish & Šimůnek, 2019; Lehmann et al., 2013). An approach towards improving slope stability analysis using GeoStudio-Slope/W can be achieved by integrating the pore water pressure measurements from HYDRUS-2D/3D into GeoStudio-Slope/W. Jalilzadeh et al., 2020 studied that HYDRUS-1D has more database on soil/vegetation functions and offers less computational time than GeoStudio-Seep/W (commonly used finite element model for pore water estimation in GeoStudio-Slope/W). HYDRUS-2D/3D can consider root water uptake, hysteresis, and tortuosity in the soil. HYDRUS-based simulations programs are already integrated with other models like MODFLOW (Beegum et al., 2018, 2019), AQUACROP (Kanda et al., 2021), etc., due to its modeling capabilities compared to other existing models.

The objective of the study was to analyze the evolution of PWP and its relation to the hillslope stability using the integrated application of simulation models (HYDRUS-2D/3D and GeoStudio-Slope/W). As a case study, a hill slope in Kerala, India, that has undergone a modification in the natural hillslope was considered. Kerala Planning Board (KPB), 2019 reported 143 major landslides in this district, which was the highest recorded in the country in 2018. This study dictates the integrated application of the simulation models as a tool to understand and predict the landslide process. This study will help identify and predict future landslide-prone areas and design a subsequent mitigation approach to save human and property damages or warning before the incidence.

2. Materials and Methods

2.1. Study design

The study area considered was a hillslope in Munnar (10.087°N Latitude, 77.094°E Longitude) in the district of Idukki in Kerala, India. A massive slide occurred at this location on 16th August 2018 (Fig. 1).

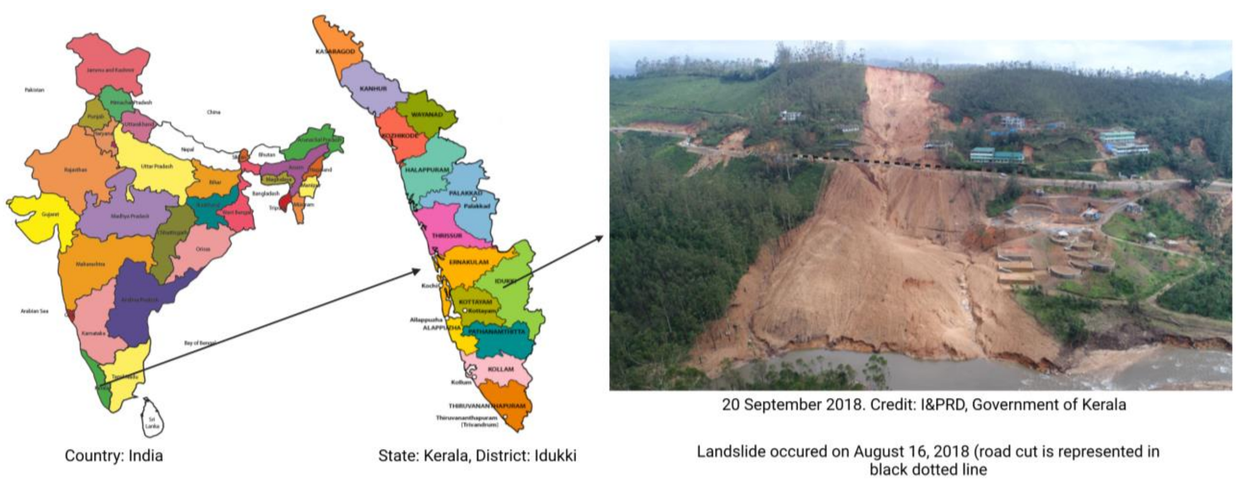


Fig. 1. The country India, Kerala state, Idukki district, and a photograph of the landslide occurred on 16th August 2018.

Specific objectives of the study were to analyze; (a) PWP evolution corresponding to the extreme rainfall event that occurred in August 2018 (which was the month with the highest recorded rainfall in the year) and (b) the impact of modification of the natural hill slope on slope stability. Two different cases were analyzed: Case 1: a case with road cut in the hill slope (hill slope after slope modification), and Case 2:

a case without road cut in the hill slope (natural hillslope). Case 1 corresponds to the prevailing slope in this area before the landslide occurred in 2018. Case 2 is an assumption made to analyze the potential impact of the extreme rainfall event if natural hillslope existed in this area (Fig. 2).

2.2. Simulation models and modeling approach

2.2.1. HYDRUS-2D/3D

HYDRUS-2D/3D (Šimůnek et al., 2016) is a physics-based model for simulating water, heat, and solute movement in two- and three-dimensional variably saturated media. The advantages of HYDRUS-2D/3D lie in its ability to simulate highly heterogeneous soil layers, variable boundary conditions, the automated time-stepping algorithm for simulation optimization, etc. Several studies have demonstrated the capabilities of HYDRUS-2D/3D in simulating the pressure head/PWP and moisture content variation in the unsaturated and saturated soil zones (Beegum et al., 2018, 2019; Simunek et al., 2018; Šimůnek et al., 2016). The modeling of water flow and transfer and transformation of the solute consider soil hydraulic properties, solute transport parameters, environmental factors (precipitation, evaporation rate, transpiration rate), plant water uptake, and various boundary conditions. The HYDRUS-2D/3D model solves water flow in the unsaturated zone using the modified two-dimensional Richards' equation:

$$\frac{\partial\theta(h)}{\partial t} = \frac{\partial}{\partial x_i}\left[K(h)\left(K_{ij}^A\frac{\partial h}{\partial z} + K_{iz}^A\right)\right] - S(h)$$

where θ is the volumetric water content (dimensionless), h is the soil water pressure head [L], t is time [T], z is the vertical coordinate [L], S is the sink term [T^{-1}], and K(h) is the unsaturated hydraulic conductivity [LT^{-1}]. K_{ij}^A is the components of dimensionless anisotropy tensor K^A, S(h) is the sink/ source term [$L^3L^{-3}T^{-1}$] and x_i is the spatial coordinate [L]. The unsaturated hydraulic conductivity, K(h), and water content, θ, depends on the soil water pressure head *(h).* This makes Richards' equation a highly nonlinear equation that needs to be solved numerically. HYDRUS-2D/3D permits using five different analytical models to describe the soil hydraulic properties (Brooks & Corey, 1964; Durner, 1994; Kosugi, 1996; Van Genuchten, 1980; Vogel & Cislerova, 1988).

2.2.2. GeoStudio-Slope/W model

GeoStudio-Slope/W model is developed based on the general limit equilibrium (GLE) formulation (Fredlund & Krahn, 1977). This formulation is based on two factors of safety equations; (a) the factor of safety with respect to moment equilibrium and (b) the factor of safety with respect to horizontal force equilibrium (Spencer, 1967). The interslice shear forces in the GLE formulation are based on the equation proposed by Morgenstern and Price (Morgenstern & Price, 1965):

$$X = E\lambda f(x)$$

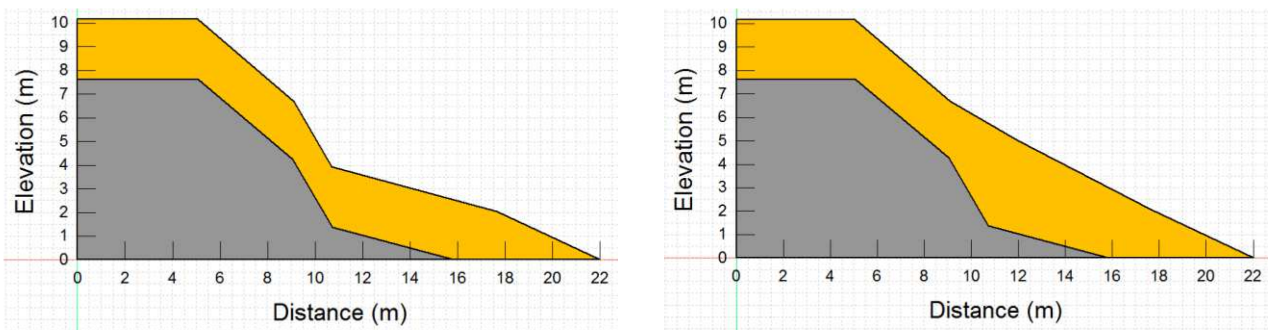
Where f(x) is the function describing the distribution of internal forces, λ is the percentage of the function used, E is the interslice normal force, and X is the interslice shear force.

2.2.3. Integration of HYDRUS-2D/3D with GeoStudio-Slope/W model

The integrated application of two different models was performed to utilize the advantages of HYDRUS-2D/3D in its accurate estimation of the pore water pressure with the stability analysis capabilities of the GeoStudio-Slope/W module. HYDRUS-2D/3D solves the water flow in the soil using a finite element formulation. A finite element mesh was generated in the soil domain of the hillslope by dividing the flow region into quadrilateral or triangular elements (Fig. 5). Once the water flow simulations were carried out using HYDRUS-2D/3D, the pore water pressure at the nodes that form the corners of the elements was extracted for discrete time intervals. The time variable pore water pressure distribution was mapped into the GeoStudio-Slope/W model corresponding to the discrete-time intervals and spatial locations. The slope stability analysis in the GeoStudio-Slope/W model was then carried out based on these pore pressure distributions.

2.3. Model setup

The input data required for simulations using HYDRUS-2D/3D and GeoStudio-Slope/W were (a) cross-sectional details of the hill slope, (b) soil physical and hydraulic properties, and (c) initial and boundary conditions. The cross-sectional details of the hill slope and soil properties in the study area were obtained based on the field investigation to examine the causes of repeated extreme heavy rainfall events, subsequent floods, and landslides in Kerala (Kerala Planning Board, 2019; Choudhury et al., 2019). The geometry of the hill slope in Case1 (with road cut) and Case 2 (without road cut) is shown in Fig. 2. The average angle of elevation is 24.8˚. The maximum depth of the soil (shown in yellow color in Fig. 2) above the rock (shown in grey color in Fig. 2) in Case 1 is 2.3 m, and for Case 2 is 4.4 m.



Case 1: With road cut   Case 2: Without road cut

Fig. 2. The geometry of the hill slope in Case1 and Case 2. The yellow-colored region represents the soil layer, and the grey-colored area represents the rock.

Table 1. Index and engineering properties of the soil in the hill slope

Moisture content (%)	**Bulk density (g/cc)**	**Shear strength parameters**		**Grain size distribution (%)**			**Consistency limits (%)**	
		c (kPa)	ϕ (degree)	Silt+clay	Sand	Gravel	Liquid limits	Plastic limits
4.26-18.8	1.34-1.76	2.0-74.0	22.29-36.69	20-76	21-54	1.0-40	34.5-63.1	22.9-35.31

Table 1 shows the index and engineering properties of the soil in the hill slope. The unit weight of the rock was considered as 29.4 KN/m^3. This corresponds to the rock type - Peninsular Gneissic Complex

(PGC) observed in the north region Idukki district represented by granite gneiss (District Survey Report of Minor Minerals, Idukki District, Department of Mining and Geology, 2016). The van Genuchten-Mualem analytical model (van Genuchten, 1980) was used to describe the hillslope soil hydraulic properties with the parameters given in table 2.

Table 2. van Genuchten-Mualem analytical model parameters

van Genuchten-Mualem analytical model parameters	Values
Residual water content, θ_r	0.077
Saturated water content, θ_s	0.425
Saturated hydraulic conductivity, K_s	1.5 m day^{-1}
Pore connectivity parameter, l	0.5
Shape parameters, α and n	α = 1.37 m^{-1}, n = 1.4027

These parameters were obtained using the neural network prediction of soil hydraulic properties using the Rosetta Lite V.1.1 (Schaap et al., 2001). The specific weight of water was considered as 10 KN/m^3.

2.3.1. Initial and boundary condition

In both cases (Case 1 and Case 2), a hydrostatic pressure head distribution was considered in the soil domain at the beginning of the simulation. The left boundary and the bottom of the soil layer (or the top of the rock layer) were considered to have a no-flow boundary. A seepage boundary was given at the extreme right slope of the domain for a depth of 2 m (Fig. 3). In the seepage boundary, when the node next to seepage face becomes saturated, water is immediately removed by overland flow, which in HYDRUS-2D/3D is considered to be removed from the system.

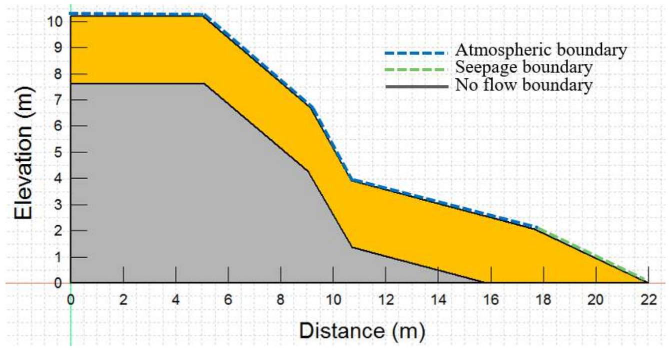


Fig. 3. Boundary conditions (atmospheric boundary, seepage boundary and no-flow boundary) considered in the study.

2.3.2. Surface boundary condition

To simulate the landslide event in August 2018 in Munnar, the daily rainfall data for this month was used as the atmospheric boundary condition on the slope surface. This data was obtained from the Indian Meteorological Department (IMD) for the weather station in Munnar. The maximum rainfall in August 2018 recorded in this station was 291.8 mm/day on 16th August 2018, followed by 253.6 mm/day on 9th August 2018. Transpiration from the surface of the soil was not considered in the analysis. Figure 4 shows the rainfall for August 2018 in Munnar.

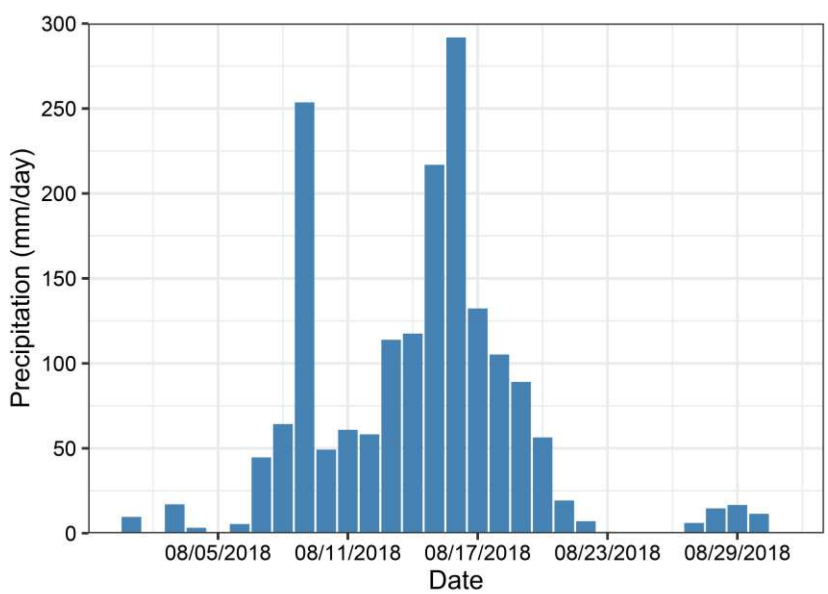
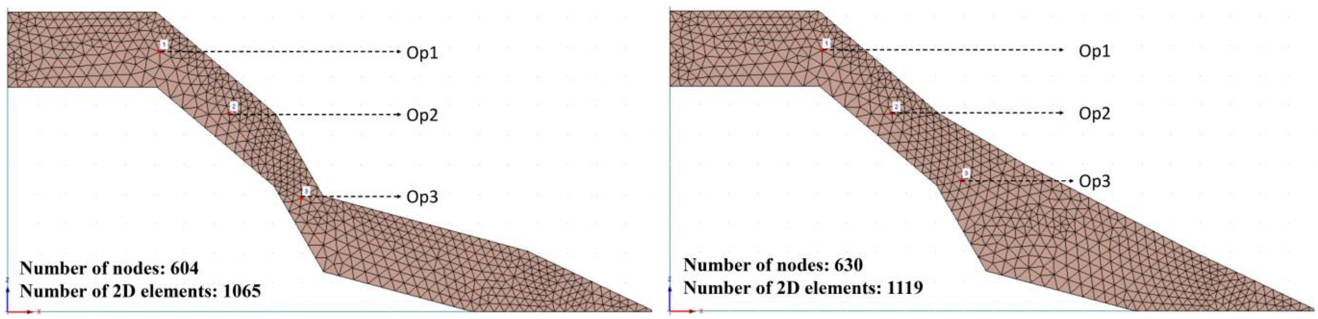


Fig. 4. Precipitation in mm/day in August 2018 in Munnar IMD station

The simulation was carried out for 31 days, corresponding to the number of days in August 2018. The model was simulated to analyze the pore water pressure on each day. A finite element unstructured triangular mesh was developed in the model with a finer resolution at the soil surface. Three observation points (Op1, Op2, and Op3) were specified in the soil domain (Fig. 5).



Case 1: With road cut Case 2: Without road cut

Fig. 5. The unstructured triangular mesh, observation points (Op1, Op2, Op3), and the number of finite elements and nodes considered in the study.

3. Results and Discussion

Model simulations for Case 1 and 2 were carried out based on the integration methodology discussed in section 2.2.3. The variation in the volume of the water in the hill slope domain, variation in the moisture content at different observation points, pore water pressure distribution, and the factor of safety were analyzed in the hill slope corresponding to the rainfall event in August 2018 and are discussed in the following sections.

3.1. Variation in the volume of water in the domain

The analysis of total volume of the water in the hillslope soil is important because of its correlation with landslide activity. Klose et al., 2012; Wicki et al., 2020 used soil moisture characteristics for determining the water content threshold for landslide predictions and early warning. The volume of water depends on soil hydraulic properties, rainfall, initial moisture content, and domain geometry. The total volume of water was more in Case 2 than in Case 1 because of the larger soil volume in Case 2 (56.44 m^3) compared to Case 1 (48.88 m^3). The volume of water for both cases increased from 6th August 2018, corresponding to the rainfall event on that day. On 9th August 2018, 253.6 mm/day rainfall was received in this area. A sudden increase in volume of water in the domain was observed from 8th to 9th August 2018 for both cases (Fig. 6). Though the rainfall on 10th, 11th, and 12th August was less than the rainfall on the 9th August, volume of water in soil did not show a considerable decrease. This indicates that the volume of water added to soil due to the rainfall on 9th August 2018 was drained at a slow rate in the hill slope. This was mainly because of lateritic soil in this region with clay and slit particles which retain water in the pores for a long time even after rainfall stops (Easton & Bock, 2016). Moisture content in soil reached its maximum on 16th August 2018 with 20.77 m^3 of water in Case 1 and 23.98 m^3 of water in Case 2. On this day, the hillslope received the maximum rainfall (291.8 mm/day).

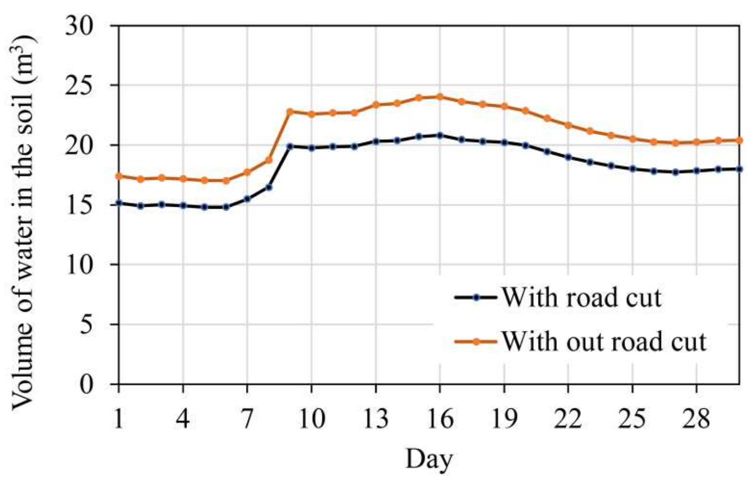


Fig. 6. The total volume of water in the domain for Case 1 (with road cut) and Case 2 (without road cut).

3.2. Variation in the moisture content at observation points

Water content in the soil's pores leads to pore water pressure (PWP). Changes in water content at three observation points (Op) (points 1, 2, 3 in Fig. 5) for Case 1 and Case 2 were analyzed. Water content increased at all the Op's and reached a saturated condition (water content = 0.425) at different times. The Op3 reached saturation earlier than the other two locations. This is because of the combined effect of rainfall and the initial hydrostatic pressure head distribution assumed in the domain. Op2 reached the saturated condition earlier than Op1 for both cases. A maximum pressure head/water content is observed in the soil in all the observation points, approximately 15 to 16.5 days. Water content value equal to 0.425 at any location and time corresponds to the saturated condition, and the water table will be at or above this point. Moisture variations at Op1 and Op2 were similar in both cases. The moisture content at Op3 in Case 1 reached the saturated condition earlier than Case 2. At Op3, Case 1 reached the saturated state in 12.15 days, and Case 2 reached the saturated condition in 13.5 days. It was also observed that moisture content remained in saturated condition for a longer time (from 12.15 to 19.85 days) at Op3 in Case 1 compared to Case 2 (which was from 13.50 to 18 days). The moisture content decreased slower (0.004/day after 20 days) for Case 1 compared to Case 2 (0.0084/day after 20 days). This shows that the specific hill slope geometry in Case 1 retained the moisture in the soil for more time with a low rate of its decrease compared to Case 2. Soil moisture status has a crucial role in landslide initiation since the increase in moisture content increases the pore water pressure and decreases the shear strength (Abraham et al., 2020; Marino et al., 2020).

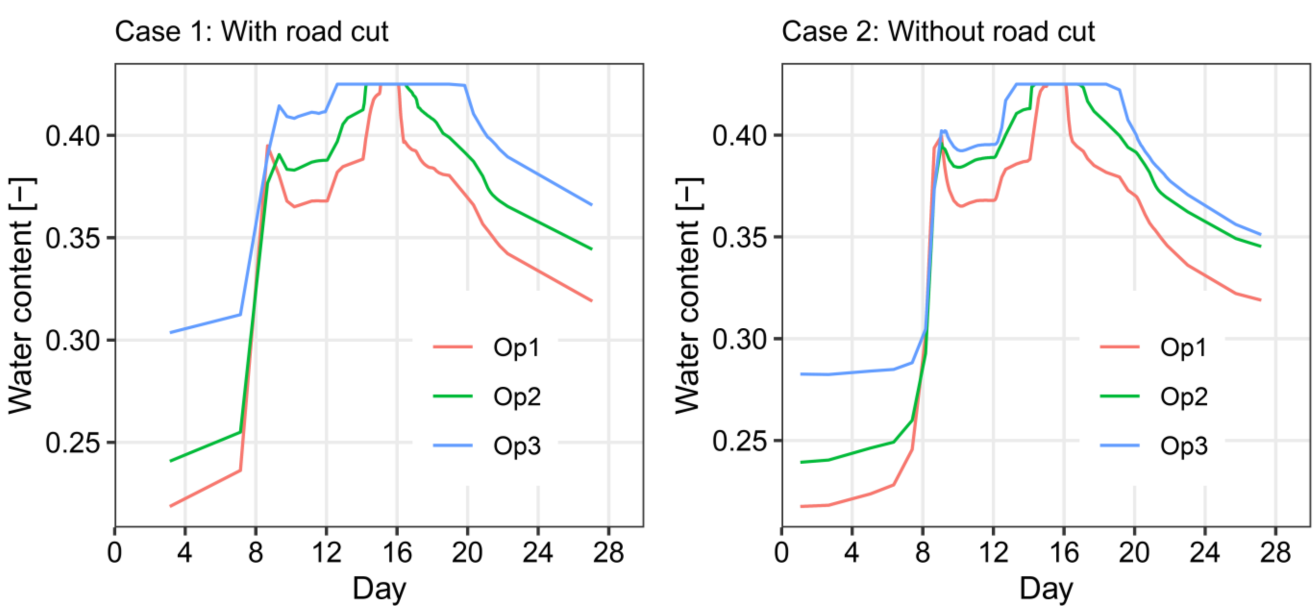


Fig. 7. Change in the water content in the soil at three observation points (Op1, Op2, Op3) in the domain for Case 1 and Case 2.

3.3. The factor of safety in the hill slope

The factor of safety (FoS) is a crucial indicator of slope stability and is defined as the ratio of the resisting force to the driving force along a failure surface. An FoS equal to or greater than one represents that the slope is stable, and a value less than one represents likely failure. The FoS of the hill slope corresponding to the pore water pressure distribution (determined using HYDRUS-2D/3D) in the soil in August 2018 was simulated using the GeoStudio- Slope/W.

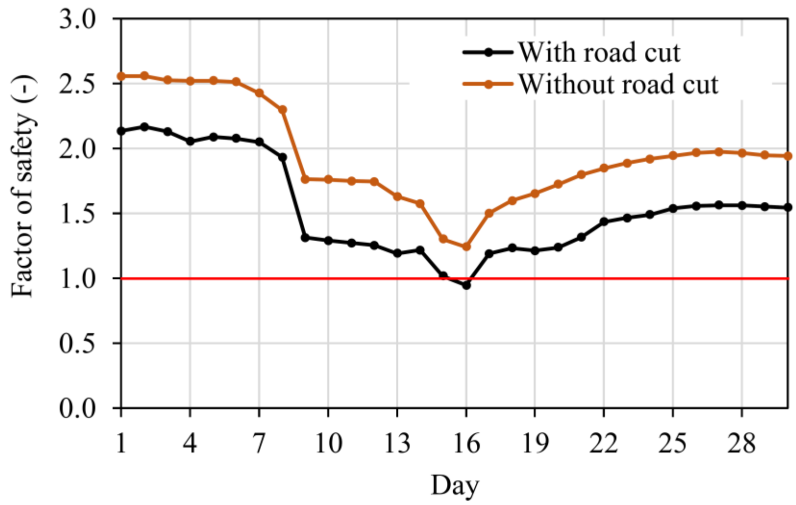
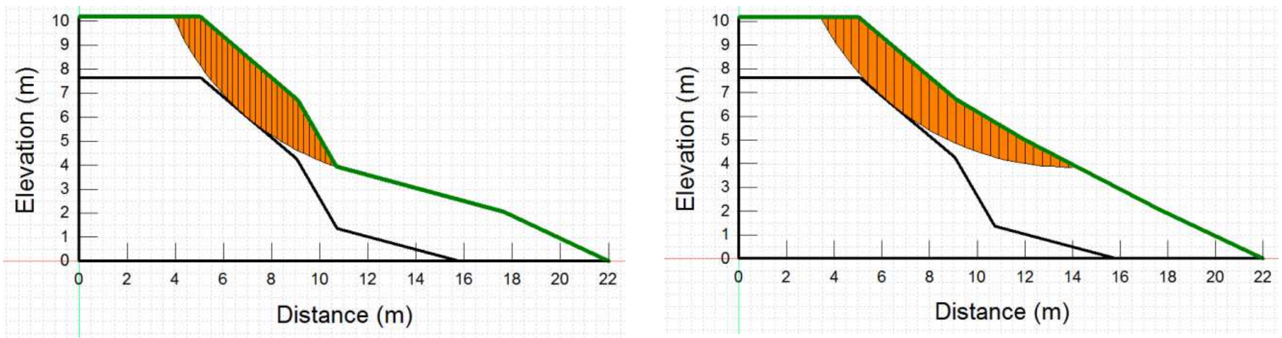


Fig. 8. The factor of safety of the slip surface for Case 1 (with road cut) and Case 2 (without road cut)

Figure 8 shows the minimum FoS of the slip surface each day in August 2018 for Case 1 (with road cut) and Case 2 (without road cut). The slope was found to be stable in Case 2 compared to Case 1. For both cases, the FoS showed a sudden decrease after 8th August 2018. This corresponds to the (a) increase in rainfall on the same day, (b) increase in moisture content, and (c) increase in pore pressure in the soil. A minimum FoS was observed on 16th August 2018 (0.946) for Case 1. This day corresponds with the day with maximum rainfall (291.8 mm/day), the maximum volume of water (23.98 m^3) in the domain, and a longer saturated soil condition in the hill slope (as discussed in sections 3.1 and 3.2). It was on this day the actual landslide occurred in this location (a picture of the landslide is shown in Fig. 1). The weight of the soil, geometry of the hill slope, and the moisture in the soil in Case 2 were such that the resisting moment in the slide was greater than the activating moments, which resulted in FoS>1. This shows that the natural slope of the hill was able to prevent rainfall-induced landslides in the study area. Figure 9 shows the slip surface with minimum FoS for Case 1 (FoS= 0.946) and Case 2 (FoS= 1.243) on 16th August 2018.

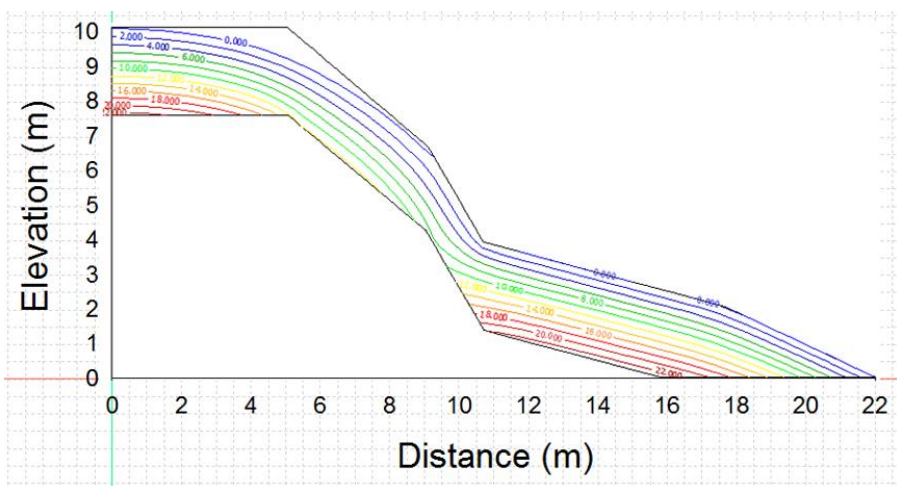


Case 1: With road cut

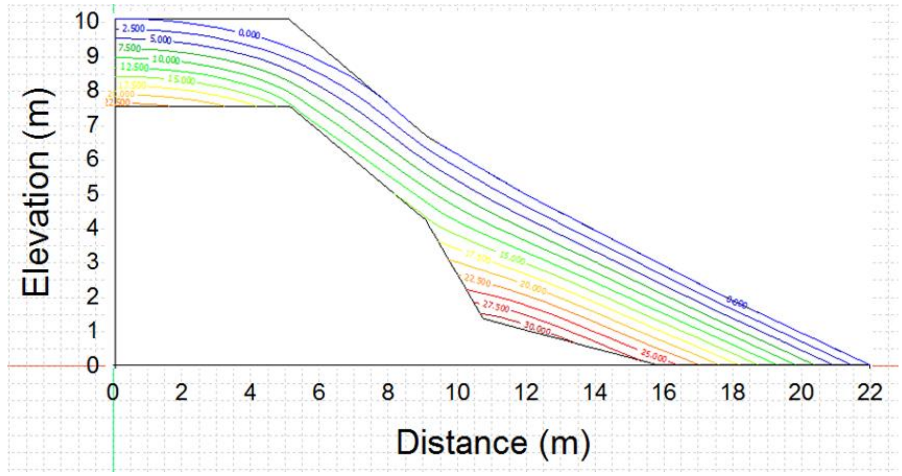
Case 2: Without road cut

Fig. 9. Slip surface with minimum Factor of Safety for Case 1 (with road cut) and Case 2 (without road cut)

3.4. Pore water pressure distribution

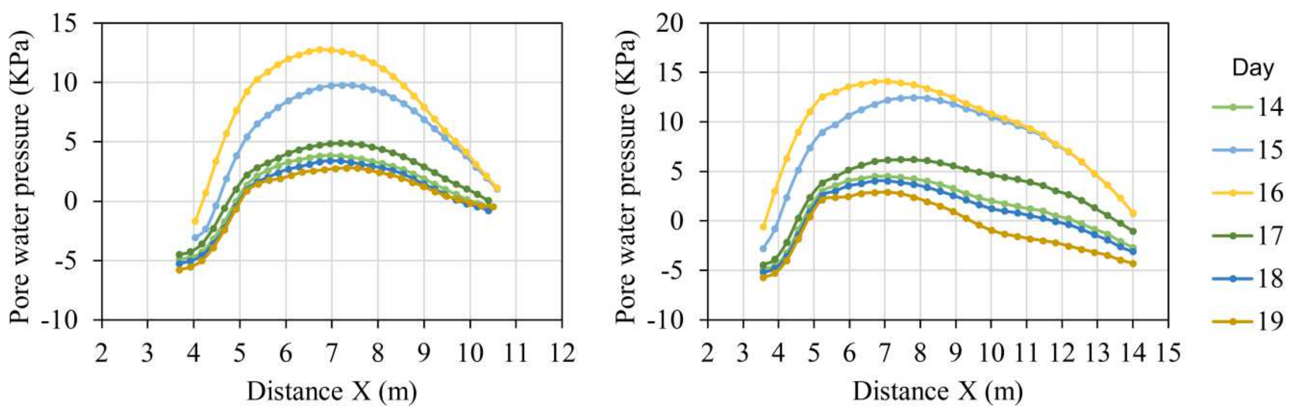


Case 1: With road cut



Case 2: Without road cut

Fig. 10. Pore water pressure distribution in the hill slope for Case 1 (with road cut) and Case 2 (without road cut) on 16th August.



Case 1: With road cut

Case 2: without road cut

Fig. 11. Pore water pressure along the slip surface from 14th August 2018 to 19th August 2018 for Case 1 and 2.

Figure 10 shows the pore water pressure distribution in the soil for Case 1 and 2 on 16th August 2018 simulated using HYDRUS-2D/3D. The hill slope in Case 2 was subjected to larger pore water pressure than Case 1, with a maximum of 23 KPa and 31 KPa for Case 1 and 2, respectively. Figure 11 shows the pore water pressure along the slip surface from 14th August 2018 to 19th August 2018 for Case 1 and 2. For both cases, pore water pressure increased from 14th to its maximum at 16th and then decreased. The pore water pressure is depended on the amount of saturation in the soil. Larger pore water pressure was observed in Case 2 (14.5 KPa at a distance of 7 m) compared to Case 1(12.8 KPa at 6.8 m). It was observed that Case 2 was more stable compared to Case 1 even when the pore water pressure along the slip surface was more in Case 2. This shows that the geometry of the hill slope plays a predominant role in keeping the slope stable. Glade, 2003; Jaboyedoff et al., 2016; Singh & Singh, 2013 also observed a decreased hill slope stability with land-use change and artificial topographic interventions in hill slopes.

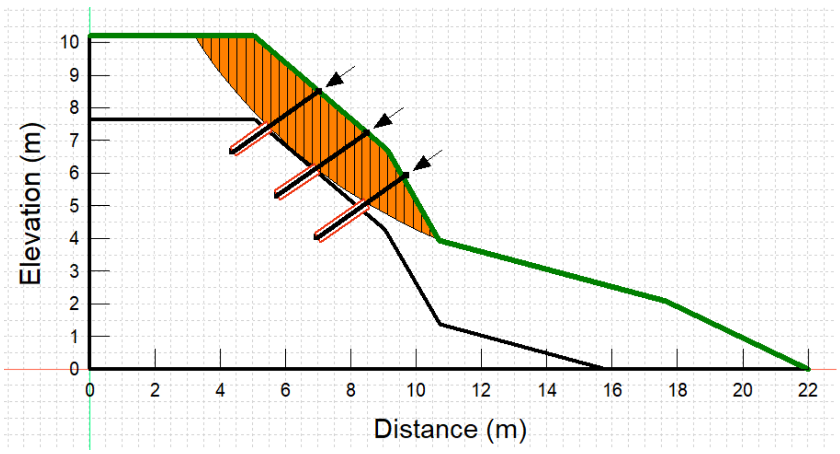


Fig. 12. Strengthening of the slope using nail reinforcement in Case 1 (hillslope with road cut). The black arrow marks represent the location of the nail reinforcement.

Several slope strengthening measures can be adopted to prevent the slope from failing (e.g., anchors and piles, geosynthetic reinforcement, sheet pile walls, etc.). In this study, one of the strengthening measures was studied to improve the slope stability in Case 1 (hillslope with road cut). Model simulations were carried out to analyze the slope stability using a nail reinforcement (Fig. 12). This method of reinforcement is generally used for strengthening the natural slope. Soil nails are included in GeoStudio-SLOPE/W by defining the pull-out resistance, representing the amount of stress mobilized per unit area at the interface between the nail and soil. Table 3 shows the nail specifications used in this case study.

Table 3. Specification of the nail reinforcement

Nail specifications	Value
The inclination of the nails	35°
Bond diameter: The diameter of the grouted section in contact with soil	0.3 m
Resistance reduction factor: This factor accounts for the nonlinear stress reduction over the embedded length	1.5
Pull-out resistance: This represents the amount of stress mobilized per unit area at the interface between the nail and soil	100 KPa
Tensile capacity	400 KN
Shear reduction factor: This accounts for the reduction of the tensile capacity due to physical processes such as installation damage, creep, and durability	1

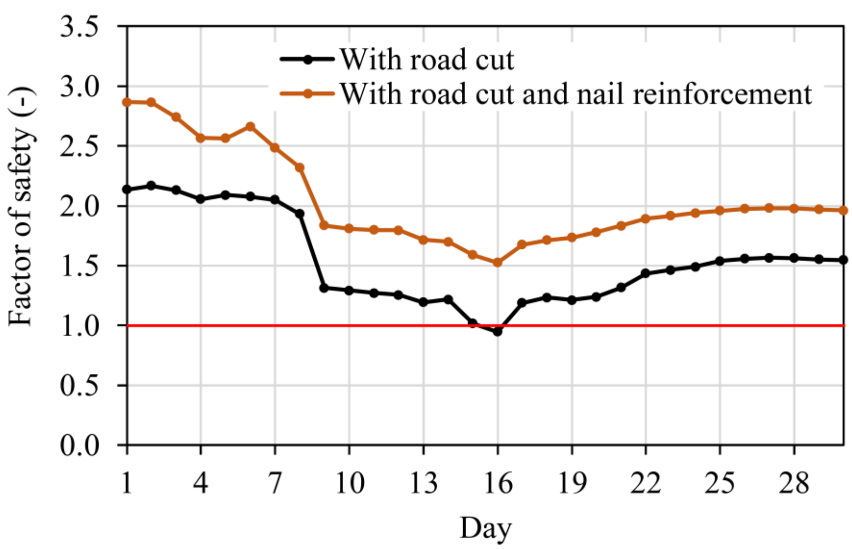


Fig. 13. The factor of safety of the slip surface for Case 1 (with road cut) and the case with road cut and nail reinforcement.

Figure 13 shows the FoS of the slip surface in Case 1 (with road cut) and the case with road cut and nail reinforcement corresponding to the rainfall in August 2018. It was observed that the FoS has improved after incorporating the nail reinforcement throughout the month. The lowest FoS when there is no reinforcement was observed as 0.946, and the lowest FoS after incorporation of the nail reinforcement was found to be 1.524 on 16th August 2018. This demonstrates that strengthening measures can be incorporated to improve the stability of this hillslope, and this can be analyzed using the integrated modeling approach. A detailed investigation can be carried out to optimize the strengthening measure, its design, and the related parameters.

4. Conclusions

In the context of a large number of landslides worldwide, it is essential to investigate the potential solutions for its mitigation. This requires analysis of the landslide triggering mechanisms. Though several triggering factors exist that independently and combinedly act upon a hill slope, the current study focuses on slope stability analysis based on rainfall-induced pore water pressure in the soil, which is one of the significant triggering mechanisms. A methodology for integrating existing models (HYDRUS-2D/3D and GeoStudio- Slope/W) for simulating pore water pressure-induced landslides was developed. As a case study to illustrate the methodology, a hill slope in Munnar, India, was investigated for its stability corresponding to the ERE during August 2018. The stability analysis considered the pore water pressure distribution in the soil corresponding to the daily variation in the rainfall in the hill slope. The volume of water in the hill slope, temporal and spatial evolution of pore water pressure and factor of safety were analyzed and correlated with the actual landslide that occurred in the study area. It was observed that the slope was stable (with FoS equal to 1.243) when there was no road cut in the natural slope of the hill, whereas the slope failed on 16th August 2018 in the case with road cut (with FoS equal to 0.946). The integrated application of the simulation models (HYDRUS-2D/3D and GeoStudio-Slope/W) effectively predicted the landslide that occurred in the study area on 16th August 2018. The integrated model application also helped analyze the importance of the hill slope geometry in resisting forces that drive the initiation of a slide. Though the pore water pressure was found to be more in Case 2 (without road cut) compared to Case 1 (with road cut), it was Case 1 that failed compared to Case 2. A similar simulation modeling approach can be utilized for predicting landslides by anticipating extreme rainfall conditions. The study also demonstrated the analysis of one of the strengthening measures (nail reinforcement) for improving slope stability in Case 1 (hillslope with road cut) using the integrated modeling approach.

Software availability

Simulation model: **HYDRUS-2D/3D**

Authors: M.Sejna and J.Simunek, Rien Van Genuchten

Copyright © 2006 - 2016:, PC-Progress s.r.o., Korunni 108a, Prague, Czech Republic

Contact details: hydrus@pc-progress.cz, admin@pc-progress.cz

Website: www.hydrus3D.com, www.pc-progress.com

Simulation model: **GeoStudio-Slope/W**

Developers: GEO-SLOPE International Ltd 1400, 633 – 6th Ave SW Calgary, Alberta, Canada T2P 2Y5

Contact details: info@geo-slope.com

Website: http://www.geo-slope.com

References

Abraham, M. T., Pothuraju, D., & Satyam, N. (2019). Rainfall thresholds for prediction of landslides in Idukki, India: An empirical approach. *Water (Switzerland)*. https://doi.org/10.3390/w11102113

Abraham, Satyam, N., Pradhan, B., & Alamri, A. (2020). Forecasting of Landslides Using Rainfall Severity and Soil Wetness: A Probabilistic Approach for Darjeeling Himalayas. *Water*, *12*, 804. https://doi.org/10.3390/w12030804

Beegum, S., Šimůnek, J., Szymkiewicz, A., Sudheer, K. P., & Nambi, I. M. (2018). Updating the Coupling Algorithm between HYDRUS and MODFLOW in the HYDRUS Package for MODFLOW. *Vadose Zone Journal*, *17*(1).

Beegum, S., Šimůnek, J., Szymkiewicz, A., Sudheer, K. P., & Nambi, I. M. (2019). Implementation of Solute Transport in the Vadose Zone into the "HYDRUS Package for MODFLOW." *Groundwater*, *57*(3), 392–408.

Brooks, R., & Corey, A. (1964). Hydraulic properties of porous media. *Hydrology Papers, Colorado State University*, *3*(March), 37 pp. https://doi.org/10.13031/2013.40684

Bui, X.-N., Nguyen, H., Choi, Y., Nguyen-Thoi, T., Zhou, J., & Dou, J. (2020). Prediction of slope failure in open-pit mines using a novel hybrid artificial intelligence model based on decision tree and evolution algorithm. *Scientific Reports*, *10*(1), 9939. https://doi.org/10.1038/s41598-020-66904-y

Carey, J. M., Massey, C. I., Lyndsell, B., & Petley, D. N. (2019). Displacement mechanisms of slow-moving landslides in response to changes in porewater pressure and dynamic stress. *Earth Surface Dynamics*, *7*(3), 707–722. https://doi.org/10.5194/ESURF-7-707-2019

Choudhury, D., Pain, A., & Rao, V. D. (2019). *Landslide investigations, kerala*.

District Survey Report of Minor Minerals, Idukki district, Department of Mining and geology, www.dmg.kerala.gov.in. (2016).

Durner, W. (1994). Hydraulic Conductivity Estimation for Soils with Heterogeneus pore Structure. In *Water Resources Research* (Vol. 30, Issue 2, p. 211;223). https://doi.org/10.1029/93WR02676

Easton, Z. M., & Bock, E. (2016). *Soil and soil water relationships*.

Fannin, R. J., & Jaakkola, J. (1999). Hydrological response of hillslope soils above a debris-slide headscarp. *Canadian Geotechnical Journal*, *36*(6), 1111–1122. https://doi.org/10.1139/t99-074

Fredlund, D. (1987). *Slope Stability Chapter 4 Slope Stability Analysis Incorporating the Effect of Soil Suction*.

Fredlund, D. G., & Krahn, J. (1977). COMPARISON OF SLOPE STABILITY METHODS OF ANALYSIS. *Canadian Geotechnical Journal*, *14*(3), 429–439. https://doi.org/10.1139/T77-045

Geo-Slope. (2012). *Stability Modeling with SLOPE/W, an engineering methodology*.

Glade, T. (2003). Vulnerability assessment in landslide risk analysis. *Erde*, *134*(2), 123–146.

Hopkins, T. C., Allen, D. L., & Deen, R. C. (1975). *Effects of Water on Slope Stability*. 44.

Huang, A. Bin, Lee, J. T., Ho, Y. Te, Chiu, Y. F., & Cheng, S. Y. (2012). Stability monitoring of rainfall-induced deep landslides through pore pressure profile measurements. *Soils and Foundations*, *52*(4), 737–747. https://doi.org/10.1016/J.SANDF.2012.07.013

Jaboyedoff, M., Michoud, C., Derron, M.-H., Voumard, J., Leibundgut, G., Sudmeier-Rieux, K., Michoud, C., Nadim, F., & Leroi, E. (2016). Human-Induced Landslides: Toward the analysis of anthropogenic changes of the slope environment. In *Landslides and Engineered Slopes. Experience, Theory and Practice*. CRC Press.

Jalilzadeh, H., Hettiaratchi, J., Fleming, I., & Pokhrel, D. (2020). Effect of Soil Type and Vegetation on the Performance of Evapotranspirative Landfill Biocovers: Field Investigations and Water Balance Modeling. *Journal of Hazardous, Toxic, and Radioactive Waste*, *24*. https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000535

Johnson, K. A., & Sitar, N. (1990). Hydrologic conditions leading to debris-flow initiation. *Canadian Geotechnical Journal*, *27*(6), 789–801. https://doi.org/10.1139/t90-092

Jones, S., Kasthurba, A. K., Bhagyanathan, A., & Binoy, B. V. (2021). Landslide susceptibility investigation for Idukki district of Kerala using regression analysis and machine learning.

Arabian Journal of Geosciences 2021 14:10, *14*(10), 1–17. https://doi.org/10.1007/S12517-021-07156-6

Kanda, E. K., Senzanje, A., & Mabhaudhi, T. (2021). Coupling Hydrus 2D/3D and AquaCrop Models for Simulation of Water Use in Cowpea (Vigna Unguiculata (L.) Walp). In D. S.-K. Ting & A. Vasel-Be-Hagh (Eds.), *Sustaining Tomorrow* (pp. 53–63). Springer International Publishing. https://doi.org/10.1007/978-3-030-64715-5_4

Karandish, F., & Šimůnek, J. (2019). A comparison of the HYDRUS (2D/3D) and SALTMED models to investigate the influence of various water-saving irrigation strategies on the maize water footprint. *Agricultural Water Management*, *213*, 809–820. https://doi.org/10.1016/j.agwat.2018.11.023

Kim, J., Kim, Y., Jeong, S., & Hong, M. (2017). Rainfall-induced landslides by deficit field matric suction in unsaturated soil slopes. *Environmental Earth Sciences 2017 76:23*, *76*(23), 1–17. https://doi.org/10.1007/S12665-017-7127-2

Klose, M., Damm, B., & Gerold, G. (2012). Analysis of Landslide Activity and Soil Moisture in Hillslope Sediments Using Landslide Database and Soil Water Balance Model. *Geo-Öko*, *33*, 204–231.

Kosugi, K. (1996). Lognormal Distribution Model for Unsaturated Soil Hydraulic Properties. *Water Resources Research*, *32*(9), 2697–2703. https://doi.org/10.1029/96WR01776

Kuriakose, S. L., Jetten, V. G., van Westen, C. J., Sankar, G., & van Beek, L. P. H. (2008). Pore water pressure as a trigger of shallow landslides in the Western Ghats of Kerala, India: Some preliminary observations from an experimental catchment. *Physical Geography*, *29*(4), 374–386. https://doi.org/10.2747/0272-3646.29.4.374

Lehmann, P., Gambazzi, F., Suski, B., Baron, L., Askarinejad, A., Springman, S. M., Holliger, K., & Or, D. (2013). Evolution of soil wetting patterns preceding a hydrologically induced landslide inferred from electrical resistivity survey and point measurements of volumetric water content and pore water pressure. *Water Resources Research*, *49*(12), 7992–8004. https://doi.org/10.1002/2013WR014560

Liang, W. L. (2020). Dynamics of pore water pressure at the soil–bedrock interface recorded during a rainfall-induced shallow landslide in a steep natural forested headwater catchment, Taiwan. *Journal of Hydrology*, *587*, 125003. https://doi.org/10.1016/J.JHYDROL.2020.125003

Marc, O., Stumpf, A., Malet, J.-P., Gosset, M., Uchida, T., & Chiang, S.-H. (2018). Towards a global database of rainfall-induced landslide inventories: First insights from past and new events. *Earth Surface Dynamics Discussions*, 1–28. https://doi.org/10.5194/ESURF-2018-20

Marino, P., Peres, D. J., Cancelliere, A., Greco, R., & Bogaard, T. A. (2020). Soil moisture information can improve shallow landslide forecasting using the hydrometeorological threshold approach. *Landslides*, *17*(9), 2041–2054. https://doi.org/10.1007/s10346-020-01420-8

Matsuura, S., Asano, S., & Okamoto, T. (2008). Relationship between rain and/or meltwater, pore-water pressure and displacement of a reactivated landslide. *Engineering Geology*, *101*(1–2), 49–59. https://doi.org/10.1016/J.ENGGEO.2008.03.007

Mishal, U., & Khayyun, T. (2018). *Stability Analysis of an Earth Dam Using GEO-SLOPE Model Under Different Soil Conditions*. *36*, 523–532. https://doi.org/10.30684/etj.36.5A.8

Morgenstern, N. R., & Price, V. E. (1965). The analysis of the stability of general slip surfaces. *Geotechnique*, *15*(1), 79–93. https://doi.org/10.1680/GEOT.1965.15.1.79

Oh, S., & Lu, N. (2015). Slope stability analysis under unsaturated conditions: Case studies of rainfall-induced failure of cut slopes. *Engineering Geology*, *184*, 96–103. https://doi.org/10.1016/j.enggeo.2014.11.007

Petley, D. (2012). Global patterns of loss of life from landslides. *Geology*, *40*(10), 927–930. https://doi.org/10.1130/G33217.1

Rahardjo, H., Leong, E. C., & Rezaur, R. B. (2008a). Effect of antecedent rainfall on pore-water pressure distribution characteristics in residual soil slopes under tropical rainfall. *Hydrological Processes*, *22*(4), 506–523. https://doi.org/10.1002/HYP.6880

Rahardjo, H., Leong, E. C., & Rezaur, R. B. (2008b). Effect of antecedent rainfall on pore-water pressure distribution characteristics in residual soil slopes under tropical rainfall. *Hydrological Processes*, *22*(4), 506–523. https://doi.org/10.1002/HYP.6880

Rahimi, A., Rahardjo, H., & Leong, E. C. (2010). Effect of hydraulic properties of soil on rainfall-induced slope failure. *Engineering Geology*, *114*(3–4), 135–143. https://doi.org/10.1016/J.ENGGEO.2010.04.010

Schaap, M. G., Leij, F. J., Van Genuchten, M. T., & Brown, G. E. (2001). Rosetta: A computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. *Journal of Hydrology*, *251*, 163–176.

Simunek, J., Sejna, M., & van Genuchten, M. T. (2018). New features of version 3 of the HYDRUS (2D/3D) computer software package. *JOURNAL OF HYDROLOGY AND HYDROMECHANICS*, *66*(2), 133–142. https://doi.org/10.1515/johh-2017-0050

Šimůnek, J., van Genuchten, M. Th., & Šejna, M. (2016). Recent Developments and Applications of the HYDRUS Computer Software Packages. *Vadose Zone Journal*, *15*(7), 0–0. https://doi.org/10.2136/vzj2016.04.0033

Singh, C. D., & Singh, J. (2013). Landslides caused due to ignorance—Case studies from northeast India. *Journal of the Geological Society of India*, *82*(1), 91–94.

Spencer, E. (1967). A method of analysis of the stability of embankments assuming parallel inter-slice forces. *Geotechnique*, *17*(1), 11–26. https://doi.org/10.1680/GEOT.1967.17.1.11

Talebi, A., Uijlenhoet, R., & Troch, P. A. (2007). Soil moisture storage and hillslope stability. *Natural Hazards and Earth System Sciences*, *7*(5), 523–534. https://doi.org/10.5194/nhess-7-523-2007

Van Genuchten, M. T. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils 1. *Soil Science Society of America Journal*, *44*(5), 892–898.

Vogel, T., & Cislerova, M. (1988). On the reliability of unsaturated hydraulic conductivity calculated from the moisture retention curve. *Transport in Porous Media*, *3*(1), 1–15. https://doi.org/10.1007/BF00222683

Wasowski, J. (1998). Understanding rainfall-landslide relationships in man-modified environments: A case-history from Caramanico Terme, Italy. *Environmental Geology*, *35*(2), 197–209. https://doi.org/10.1007/s002540050306

WHO. (2018). *United Nations Office for Disaster Risk Reduction (UNISDR) and the Centre for Research on the Epidemiology of Disasters (CRED), part of the Institute of Health and Society (Université catholique de Louvain)*.

Wicki, A., Lehmann, P., Hauck, C., Seneviratne, S. I., Waldner, P., & Stähli, M. (2020). Assessing the potential of soil moisture measurements for regional landslide early warning. *Landslides*, *17*(8), 1881–1896. https://doi.org/10.1007/s10346-020-01400-y

Xu, J., & Yang, X. (2018). Effects of Seismic Force and Pore Water Pressure on Three Dimensional Slope Stability in Nonhomogeneous and Anisotropic Soil. *KSCE Journal of Civil Engineering*, *22*(5), 1720–1729. https://doi.org/10.1007/s12205-017-1958-y

Statements and Declarations

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Acknowledgments

The authors would like to acknowledge the Kerala State Council for Science Technology and Environment (KSCSTE) for involving them in the field investigation and analysis carried out by the

committee to examine the causes of repeated heavy rainfall events, subsequent floods, and landslides in Kerala, 2020.

Competing Interests

The authors declare that there is no conflict of interest

Author Contributions

All authors contributed to the study's conception and design. Sahila Beegum, Jainet P J, Dawn Emil, K P Sudheer, and Saurav Das performed material preparation, data collection, and analysis. Sahila Beegum wrote the first draft of the manuscript. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.