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Effect of Rainfall on Stability of Soil Slope

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Abstract
Slope failure caused by rain is a frequent geotechnical hazard that occurs all over the world. Infiltration of rainwater into the soil raises porewater pressure and lowers matric suction as well as shear strength, resulting in slope failure. The present study investigates the effect of different rainfall events on a natural slope of Paima area in Bajura district using numerical modeling. GeoStudio software was used to analyze seepage and slope stability. Transient seepage finite element analysis through unsaturated-saturated soils was used to calculate the porewater pressure in the slope during rainfall and slope stability analysis was done by limit equilibrium method using Morgenstern-Price formula. The results obtained from the analysis show that the rainwater infiltration reduces the safety factor and the rate of reduction increases as the rainfall intensity increases. The stable slope prior to rainfall event becomes unstable after rainfall events. Parametric studies on slopes with two distinct permeabilities show that slopes with high permeability soil become critical in a short time, while slopes with low permeability sustain relatively a long duration.

Keywords
Landslides, Rainfall, Seepage analysis, Slope stability, Unsaturated soil

1. Introduction

Rainfall-induced slope failure is a frequent geotechnical hazard that occurs all over the world. Nepal being a mountainous country cannot avoid severe tragedies related to slope failure due to its steep topography, fragile geology and climatic conditions. Landslides and slope failure difficulties are common during the monsoon season. Rainfall is one of the most prominent stimulate factor triggering landslide [1, 2, 3, 4, 5]. Rainwater infiltrating the unsaturated zone of soil increases the pore water pressure thereby lowering shear strength of the soil which leads to reduction in safety factor [6, 7, 8]. In the slope with coarse grained soil the main causes of failure is due to the development of positive porewater pressure, while in the fine grained soil slopes the reduction in matric suction is cause of failure [1]. The porewater pressure fluctuations in unsaturated soils are significantly affected by pattern of rainfall, intensity, duration and its return period. Therefore, under different rainfall conditions their effect on different soil types should be identified and recognized in order to mitigate these issues and thereby eliminate maximum possible losses. Seepage modelling are required to assess the change in porewater pressure due to rainfall infiltration. The stability condition due to porewater pressure change is analysed by slope stability modelling. Hence, both the seepage as well as slope stability analyses are requisite for modelling rainfall induced slope failure.

1.1 Seepage Analysis

The seepage analysis is used to explore how groundwater will flow in the slope under rainfall infiltration. For seepage analysis SEEP/W module in the Geostudio software was used. Two-dimensional transient seepage analysis was carried out to obtain positive and negative porewater pressure distribution using Richard's equation. The two-dimensional transient water flow governing equation is as follow:

$$\frac{\partial}{\partial x}(k_x\frac{\partial H}{\partial x})+\frac{\partial}{\partial y}(k_y\frac{\partial H}{\partial y})+q=m_w^2\gamma_w\frac{\partial H}{\partial t}$$

where, k_x and k_y = coefficients of permeability in x and y directions; H = hydraulic head or total head;
q = applied boundary flux; γ_w = unit weight of water; t = time; m_w = the slope of volumetric water content curve.

1.2 Slope Stability Analysis

The slope stability analysis is used to examine the effect of different seepage conditions on stability conditions of slope. The stability condition of the slope is determined by calculating safety factor. The safety factor in the process of rainfall infiltration is calculated using SLOPE/W. The pore water pressures at various points, calculated by SEEP/W can be directly imported in SLOPE/W as input. The shear strength equation by the extended Mohr-Coulomb criteria is as follow [9]:

$$\tau = c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b$$

Where τ = shear strength of unsaturated soil;
c' = effective cohesion; $(\sigma_n - u_a)$ = net normal stress; σ_n = total normal stress; $(u_a - u_w)$ = matric suction; u_w = porewater pressure; u_a = pore air pressure; ϕ' = internal friction angle; and ϕ^b = angle indicating the rate of increase in shear strength relative to the change in matric suction. The angle ϕ^b commences at a value equal to ϕ' at low matric suction (under saturated condition) and is decreasing with matric suction.

2. Description of Study area

The study area is Paima landslide which falls in Triveni Municipality-9, Bajura District in Sudur Paschim province of Nepal as shown in Figure 1.

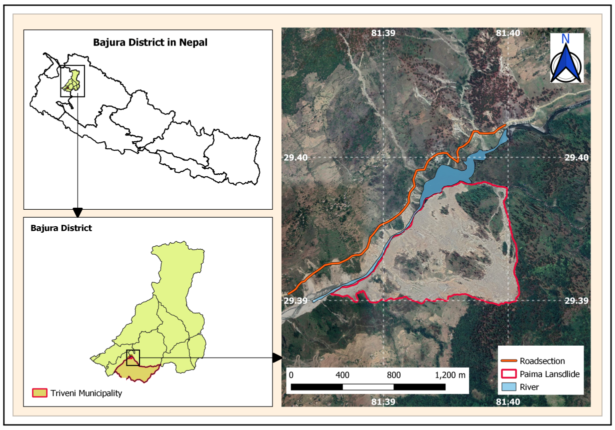

Figure 1: Location map and landslide

Geographically, Paima landslide lies at 29°23'30" N, 81° 23' 57" E at an altitude of 1048 to 1735 m. Geologically, the landslide area lies in the Lesser Himalaya of Sudur Paschim province of Nepal. Climate is tropical to subtropical. The annual average precipitation is 1860 mm, with 70 % of that falling during the rainy season, which runs from mid-June to mid-September. During the rainy season, landslides do have a frequent occurrence in this area. On 3rd July 2019, a landslide had occurred in the area as a result of rainfall. The length of landslide is estimated to be 400 m, with width of the slide ranging from 81 m to 440 m. The slide material was dumped on the lower part, blocking the Budhiganga river partially. The area affected by landslide is approximately 0.83 km^2. The Paima landslide was first occurred in 2074 B.S. and has remained active since then. Several episodes of landslide occur each year, especially during the rainy season. The landslides have destroyed several residences and agricultural lands. But fortunately, no human lives were lost to date. The landslide is still active and is expanding on the crown area and the left flanks as there is a settlement at the left flank.

3. Materials and Methods

3.1 Material Properties

Properties of soil samples obtained from the study area are presented in Table 1. These properties were obtained from the laboratory tests.

Table 1: Geotechnical parameters used in numerical analysis

Material properties	Values
Gravel	33 %
Sand	64 %
Fines	3 %
Soil type	SP
Saturated volumetric water content, θ_s	0.4
Saturated coefficient of permeability, k_s	36,360 mm/h
Unit Weight, γ	20 kN/m^3
Cohesion, c	5 kN/m^2
Angle of friction, ϕ	31 °
Angle of friction with respect to matric suction, ϕ^b	15 °

The particle size analysis was done as per ASTM D 6913, atterberg limits were determined as per ASTM D 4318-17. The soil sample found in the study area were classified as SP (poorly graded sands) material referring to USCS. The shear strength parameters (c, ϕ) of soil were determined from shear box test of disturbed but representative soil samples as per IS 2720 (Part 15)-1986. The angle of friction with respect to matric suction, ϕ^b can be taken in the range of one-half to two-third of ϕ. In this study is is taken as 0.5ϕ. At saturated condition ϕ^b becomes equal to ϕ. Properties mentioned in Table 1 were used in the numerical analysis. Despite the fact that soil parameters, including hydraulic conductivity, are not uniform in the field, parametric analyses were carried out for slopes with saturated coefficients of permeability of 36 and 360 mm/h, respectively.

Volumetric water content function was estimated using sample function method, as presented in Figure 2.

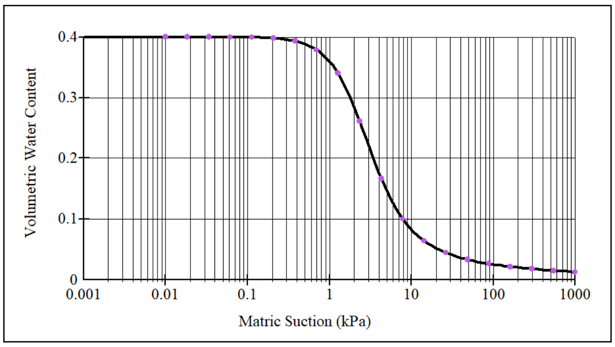

Figure 2: Volumetric water content function

Hydraulic conductivity function was estimated using Fredlund and Xing's method [10], as presented in Figure 3.

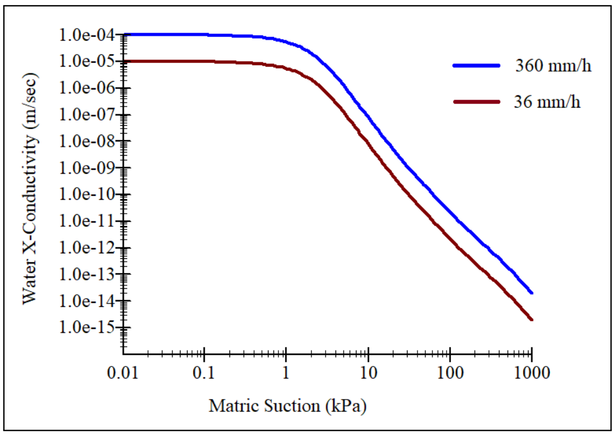

Figure 3: Hydraulic conductivity function

3.2 Slope Geometry

In this study, a two-dimensional slope domain is used for modelling. The ground of the site consists of a surficial layer of coarse grain soil that sits over bedrock. The surface soil is considered to be uniform throughout its depth. The ERT survey demonstrate that the depth of soil varies from 3 m to 24 m and groundwater table is located at 8 m from surface. The measurements from Google Earth image demonstrate that the slope angle is 25° and length of failure surface is about 400 m. Hence, for geometrical model length of slope 400 m, angle of slope 25°, depth of soil 10 m and groundwater table position 8 m from surface is adopted.

3.3 Boundary Condition

The water table was drawn at a depth 8 m below the ground surface which is inclined parallel to the bedrock to establish an initial pore pressure distribution condition. To avoid excessive porewater pressure in the analysis the maximum negative porewater pressure was set at 10 kPa. The rainfall was applied as a unit flux hydraulic boundary condition with potential seepage face review. So, the rainfall in excess of infiltration will be drained from model as runoff and no ponding of water above the soil surface will occur. The base of the soil slope and upstream vertical face was specified as zero flux boundary,assuming no flow occurs beyond this point. A zero flux boundary with the potential seepage face review was applied on the downstream vertical face. The corresponding geometry and boundary conditions of the slope are given in Figure 4.

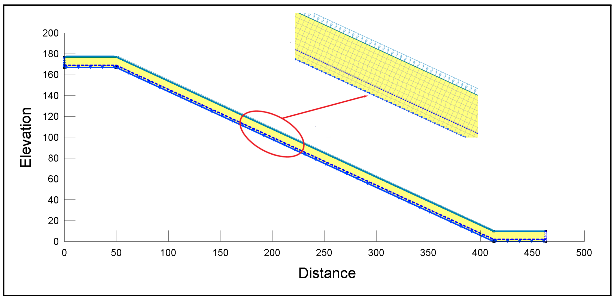

Figure 4: Geometrical model of slope and boundary condition used in numerical modelling

4. Results and Discussion

Parametric studies were performed by using constant rainfall intensity values ranged between 4 and 50 mm/h and two different soil types to reflect the site's high- and low-conductivity soils (k_s = 36 and 360 mm/h). Seepage and slope stability analysis were performed to find out the time of the rainfall that is necessary to trigger slope failure. The results obtained from analysis are presented in the following.

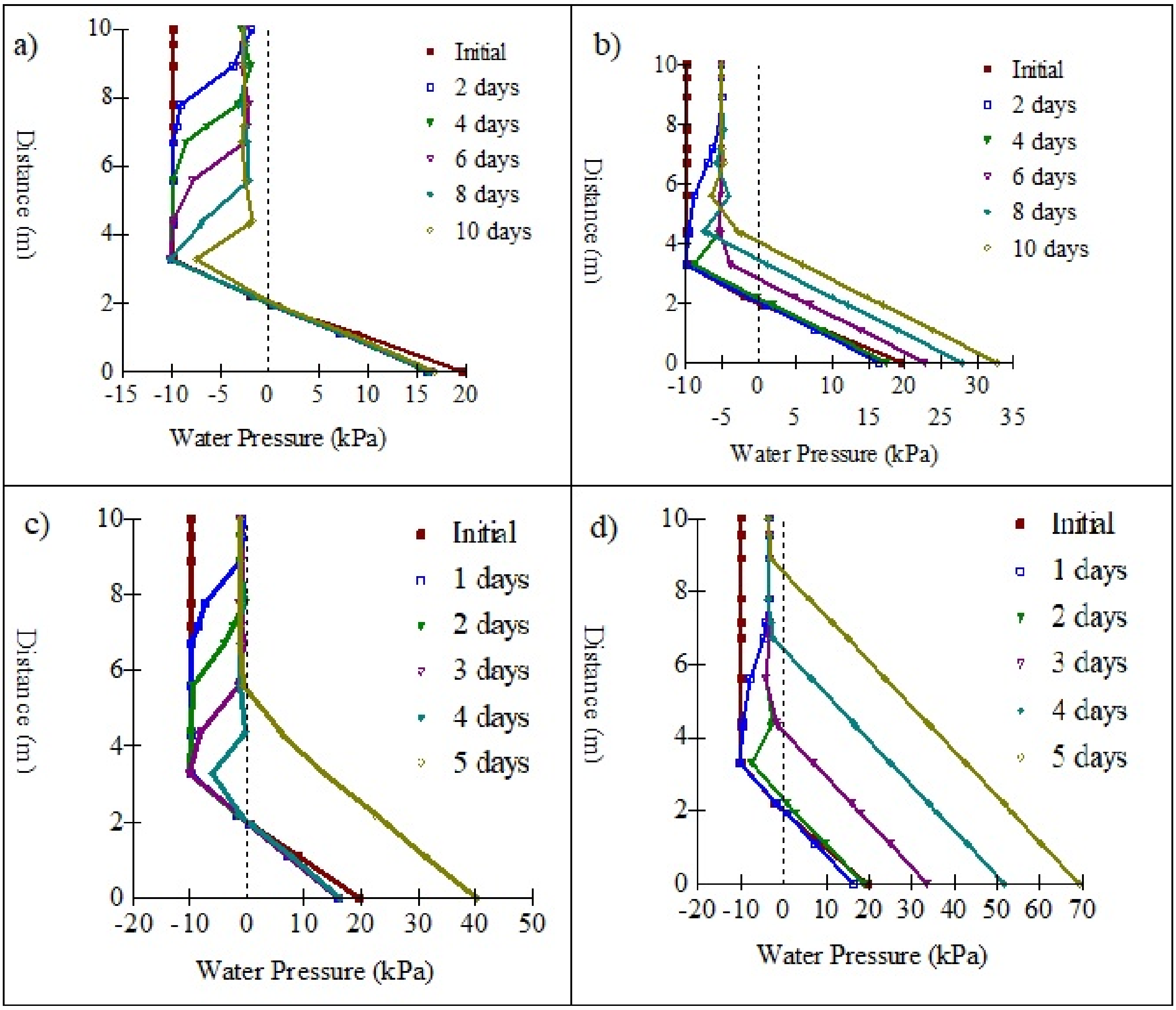

Figure 5: Relationship between porewater pressure at various depths and rainfall duration for a) I= 4 mm/h, k_s= 36 mm/h; b) I= 4 mm/h, k_s= 360 mm/h; c) I= 16 mm/h, k_s= 36 mm/h; d) I= 16 mm/h, k_s= 360 mm/h

4.1 Seepage analysis result

Figure 5 presents the relationship between porewater pressure at various depths within the slope with respect to rainfall duration. To depict the porewater pressure profile, a vertical section was taken in the middle of the slope. The distance zero corresponds to the bedrock level and 10 is top surface of the slope.

The Figures 5 a,b show that light rainfall requires very long duration (up to 10 days) to change pore water pressure distribution. However figures 5 c,d indicate pore water pressure changes in short duration (by 5 days) with increasing the rainfall intensity. Figures 5 a,c illustrate that for low conductive soil (k_s =36 mm/h) wetting front expanded in the unsaturated zone and matric suction decreased almost completely as rainfall duration increased. For high conductive soil (k_s =360 mm/h) the water percolates down to the groundwater level without causing too much decrease in suctions in the unsaturated zone, as seen in the Figures 5 b,d. As a result, the groundwater level rose and positive pore pressure developed in the bottom section.

4.2 Slope stability analysis result

Figures 6,7 show the decrease in factor of safety with increasing duration of rainfall for varied rainfall intensities. The results indicate that as rainfall intensity increases, the time necessary for slope failure decreases. In another words, higher intensity requires short duration to trigger landslides. The comparison between two figure shows that for given rainfall intensity, slope with higher permeability failed earlier than slope with lower permeability. This is because slope with higher permeability soil becomes saturated faster than low permeability soil.

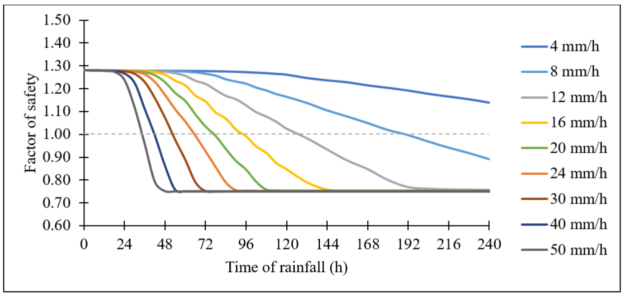

Figure 6: Factor of safety versus rainfall duration under different rainfall intensities for k_s = 360 mm/h

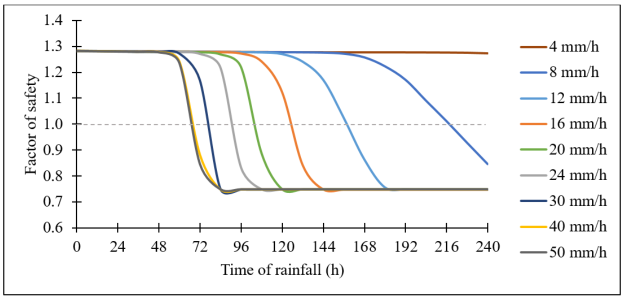

Figure 7: Factor of safety versus rainfall duration under various rainfall intensities for k_s = 36 mm/h

5. Conclusion

In this study, the distribution of porewater pressure in the slope under infiltration of rainwater was calculated by 2D finite element transient seepage analysis through unsaturated-saturated soil media, and the slope stability analysis was conducted by limit equilibrium method using Morgenstern-Price formula. Parametric study was carried out to assess the effect of rainwater infiltration on the soil slope stability. The study's findings lead to the following conclusions:

1. The slope stability is depended on rainfall intensity, duration, hydraulic characteristics as well as the soil shear strength.
2. The rainwater infiltration reduces the matric suction while increasing the wetting front (moisture content) in the unsaturated zone. The reduction in matric suction is aided by the length of rainfall.
3. Soil with higher permeability shows increase in ground water table rather than reduction in matric suction.
4. For same rainfall intensity, slope with high permeability soil become critical in short duration as compared to slope with low permeability soil.

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