NUMERICAL ASSESSMENT OF RAINFALL INDUCED SLOPE FAILURE

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Abstract

Rainfall is an extrinsic factor for the collapse of sloping terrain in Western Ghats of Kerala. Careful analysis of rainfall induced landslide is very important as people in the area have serious threat from landslides. In-depth assessments of variation of pore water pressure change in slopes during avalanche rainfalls are required for the purpose of mitigation. Soil water characteristic curve was prepared by field and laboratory tests so that various properties of unsaturated soil could be estimated. As suction distribution and rainfall infiltration were influenced by the ratio of rainfall intensity to saturated hydraulic conductivity, numerical models were analysed for various ratio of rainfall intensities. Variations of pore water pressure across different sections of the slope and reduction of factor of safety with respect to time and rainfall intensities were analysed. The results of the analyses can be applied in practice for determining the probability of landslide hazards in areas vulnerable to heavy rainfall and consequently damage from landslides.

Keywords: Rainfall induced landslide, water pressure, suction distribution, numerical assessments, slope failure

I. Introduction

Landslides are natural hazards which happen without any warning, causing huge loss of public property and lives across the globe. Landslide evaluation and mitigation planning has become a major concern for geologists in developing countries. According to geographical survey of India, it is estimated that developing countries are facing economic loss of 1-2% of their gross national product and it has
been reported that 80% of reported fatalities due to landslides occur in developing countries.

In India, more than 12.6% of total land area (excluding snow covered) is vulnerable to landslide. The Western Ghats of Kerala, which are thickly populated, are recognized as one of the major areas prone to frequent landslides. From June to August 2018, torrential rain lashed Kerala. More than 342 landslides were reported from 20 districts of the state and 433 persons lost their lives due to floods and landslides. Once landslide occurs, the hollow or depression created will be filled by materials from adjacent slopes due to surface wash, debris and the vegetation around the failed slope. This process of accumulation and heavy rainfall precipitation in monsoon make the slopes vulnerable to failure in future too.

The purpose of this study was to reproduce the physical process of rainfall infiltration and analyse slope stability based on the simulation. This helps in arriving at an understanding of the variation of suction and failure mechanism in unsaturated soil during rainfall. Rainfall induced landslide is a complex phenomenon. Researchers around the world have analysed and concluded that rainfall induced landslide involves analysis of seepage, infiltration of water from unsaturated regime to saturated regime and shear strength of the soil so that the phenomenon may be understood and remedial measures initiated to prevent the occurrence of landslides.

The increase in pore water pressure due to rainfall leads to decrease in effective shearing resistance and reduction in frictional forces between soil particles (Van Beek et al., 2002). A rise in water table or decrease in matric suction due to rainfall infiltration causes instabilities in slope (Dhakal and Sidle, 2004). The infiltration model was proposed by Green and Ampt in 1911. Then infiltration model was integrated along with slope stability analysis to predict the factor of safety and depth of failure by Chen and Young, 2006; Muntohar and Liao, 2010. This infiltration model correlates saturated hydraulic conductivity (ksat) and wetting front depth. Ng and Zhang concluded that coefficient of permeability is controlled by saturated hydraulic conductivity in lower suction range. De Campos and Menezes 1991, Rahardjo and Fredlund 1995 observed failure in slopes without formation of positive pore water pressure, due to loss of unsaturated shear strength.

Ng and Shi (1998), Rahardjo 2000 et al conducted various numerical analyses on rainfall induced slope failure mechanism. Many researchers from the past found that the response of suction to rainfall infiltration is mainly governed by the ratio of infiltration flux (q) to saturated hydraulic conductivity ksat and soil water characteristic curve (swcc). Since soil near the ground surface is usually unsaturated, the process of infiltration involves flow through the unsaturated zone. Unsaturated soil exhibits great spatial and temporal variation in properties with changes in moisture content. These can be analysed by Soil water characteristic curve (swcc). Gaffar et al 2008 showed that suction distribution for q/ksat <1 was highly influenced by rainfall intensities and vice versa. Rainfall intensities had no influence on suction distribution when q/ksat >1.
In this paper, Idukki district of Kerala was taken for the study. As per Indian Meteorological Department, shallow landslides and slope failures are major problems in tropical mountain cloud forests of Western Ghats. This paper reports analysis of slope failure in Adimali area of Idukki district in Kerala, India. The variation of pore water pressure with respect to depth and time was analyzed on different sections of slope. Factor of safety was evaluated with respect to time for different rainfall intensities.

II. Theoretical Consideration and Numerical Modelling

To investigate the effect of rainfall infiltration and stability of the slope, coupled Seep/W and Slope/W model have been used by most of the researchers (Anderson et al 2000; Rahardjo 2007). If flow condition changes with time, the flow is transient flow. Infiltration of rain water into unsaturated soil involves transient flow analysis. Seep/w follows Darcy’s law flow of water through unsaturated soil as well as saturated soil. The 2D seepage is expressed using the following partial differential water flow equation:

\[ \frac{\partial}{\partial x} \left( k_s \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_s \frac{\partial H}{\partial y} \right) + Q = \frac{\partial \theta}{\partial t} \]

Seep/w change in volumetric content is related to change in pore water pressure. In transient analysis, pore air pressure remains constant at atmospheric pressure. The relationship between pore water pressure and volumetric water content can be expressed in the form of SWC curve. One other unknown parameter in equation 1 is hydraulic conductivity, which is also a function of SWC curve. Transient analysis requires volumetric water content function and in Seep/w it can be developed using Fredlund and Xing (1994) equation. The governing Fredlund and Xing (1994) equation is:

\[ O_w = C_v \left\{ \frac{O_s}{\left[ 1 + \left( \frac{\psi'}{a} \right)^n \right]^m} \right\} \]

Where
\[ \theta_w = \text{Volumetric water content} \]
\[ C_v = \text{Correction factor} \]
\[ \theta_s = \text{Saturated volumetric water content} \]
\[ \psi' = \text{Negative pore water pressure} \]
\[ a, n, m = \text{curve fitting parameter} \]

Suction values for various water contents were measured in drying phase. The measured data were fitted into SWC curve with the help of Fredlund and Xing (1994) model using SWRC fit. Curve fitting parameter for SWC curve are n=0.37574, m=2.8335, a=1076 kPa. SWCC used for this study is shown in Fig: 1.

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Hydraulic conductivity function reflects the ability of the soil to conduct water. If negative pore water pressure (suction) increases in soil, more pores become filled with air and that will decrease hydraulic conductivity. Hydraulic conductivity function depends on the amount of water present in the soil. It can be generated with volumetric water content function and saturated hydraulic conductivity in Seep/w. hydraulic conductivity function, as shown in Fig: 2.

A huge amount of rain fell in Adimali, Idukki district region from August 8th to August 9th 2018. The three day cumulative rainfall from August 15 to August 17 was 818mm in Idukki district. It was approximately 0.2 to 0.3 times the hydraulic conductivity function used in seepage modelling.
saturated conductivity $k_{sat}$. For $q/k_{sat} < 1$, rainfall intensity exercises high influence in suction distribution. On the other hand, for $q/k_{sat} > 1$, rainfall intensity plays no role in suction distribution. Since the ratio of rainfall intensity to saturated hydraulic conductivity controls degree of infiltration, rainfall intensity from $0.2k_{sat}$ to $1k_{sat}$ was considered in this study. The antecedent rainfall of 1500 mm was applied to the slope before applying actual rainfall intensity. Soil properties and details for the study area are listed in Table 1.

**Table 1 Results of Laboratory and Field Investigation**

| Property                        | Value         |
|--------------------------------|--------------|
| Unit density                   | 16 kN/m³     |
| Cohesion                       | 1 kPa        |
| Angle of internal friction     | 36°          |
| Saturated hydraulic conductivity $k_{sat}$ | $1e-06$ m/s |
| Compressibility                | $1e-05$      |
| Soil layer thickness           | 5 m          |
| Slope angle                    | 45°          |

Slope geometry used in the study is shown in Fig: 3. The slope model has two layers. Bedrock and uniform thickness of 5m soil layer are the two layers. Boundary conditions are shown in Fig: 4. Infiltration flux with potential seepage face is applied over the slope and null flux boundary is applied between the soil layer and bedrock.

![Fig: 3 Slope geometry used in this study](image)
Slope stability analysis was carried out for slope/w. Simulated 2 dimensional seepage output can be linked directly to Slope/W. Strength of the soil layer is defined using Mohr-Coulomb's model. Bedrock model in slope/W is assigned to bedrock layer. It is an indication that failure will not enter the bedrock. To find the slip surface, entry and exit functions were used. Bishop method was employed to calculate the factor of safety for each time step.

### III. Results and Discussion

The rainfall intensities of $I=0.3\text{ksat}$, $I=0.6\text{ksat}$, $I=1\text{ksat}$ are applied on the soil slope. The variation of pore pressure in X-X, Y-Y, Z-Z section is shown in figures. Fig 5, 6, 7 show the variation of pore water pressure at sections X-X, Y-Y, Z-Z for rainfall intensity of $I=0.3\text{ksat}$, $I=0.6\text{ksat}$, $I=1\text{ksat}$ respectively. The factor of safety value with respect to rainfall duration for varying rainfall intensity is provided in Fig 8.

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**Fig: 4 Boundary conditions used in this study**

**Fig: 5.a Variation of pore water pressure at X-X for I=0.3\text{ksat}**
Fig: 5.b Variation of pore water pressure at Y-Y for I=0.3ksat

For I=0.3ksat, at 1m depth in X-X section, pore water pressure rises from -132.415 kPa at t=1 day to 4.03 kPa after 18 days. There is 103% increase in pore water pressure. Similarly there is an increase in pore water pressure of 62% and 127% for Y-Y and Z-Z section also at 1m from the top of the surface.

Fig: 5.c Variation of pore water pressure at Z-Z for I=0.3ksat

Fig: 6.a Variation of pore water pressure at X-X for I=0.6ksat
It is observed from fig:5 and fig:6 that pore water pressure distribution on different sections for 0.3ksat and 0.6ksat rainfall intensities are almost same. There is no significant difference in pore water pressure variation due to lower saturated hydraulic conductivity.
For rainfall intensity equal to hydraulic conductivity I=ksat, suction vanished at the top surface. But due to low hydraulic conductivity and high air entrain value, suction at deeper depth did not change much. Fig: 7.a to fig:7.c show that pore water pressure variation is high in Z-Z section.

Change in factor of safety of the slope with respect to rainfall duration is shown in Fig 8. The factor of safety for rainfall intensity of I=0.3ksat and I=0.6ksat does not differ much unlike the variation of pore water pressure. There is rapid change in factor of safety for rainfall intensity of I=ksat.
IV. Conclusions

Coupled transient and slope stability analyses were carried for rainfall intensities of 0.3ksat, 0.6ksat, and 1ksat respectively in the present study. The following conclusions can be made based on the study:

1. Saturated hydraulic conductivity plays a critical role in rainfall induced landslide. Slope failure is possibly found during the rainfall event when rainfall intensity is equal to or higher than the infiltration rate.
2. Pore water pressure variation is higher in the toe section.
3. Suction vanishes and leads to failure of slope if the soil has high permeability value. Highly permeable soil and high intensity rainfall might trigger slope failure even if the duration of rainfall be short.

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