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Analysis of rainfall induced landslides using hydrological model

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Abstract: *Landslides are a major type of geological disaster, commonly triggered by heavy or prolonged rainfall that increases the water content of slopes, leading to instability and movement of soil and rock. India is a country which has witnessed the deleterious effect of many disastrous landslides. North eastern parts (Himalayan Region) and Western Ghats of India are more prone to landslides every year mainly due to heavy rainfall and thus resulting in large casualties and huge economic loss. Therefore there is a need to precisely assess and manage these landslide hazards.*

In the present study, a methodology has been implemented to analyze rain induced slope failures by taking a landslide prone area in Wayanad, Kerala as a case study. Many previous landslides are reported in this region due to heavy rainfall during monsoon and steep slopes of the area. A hydrological model has been set up to evaluate rain induced slope failures in a deterministic framework using Microsoft Excel. Rainfall data, hydrologic properties and geotechnical properties of the study area are collected. Rainfall data and the infiltration capacity at the site is an important input to the model.

Initial moisture content distribution, saturated moisture content, residual moisture content and saturated conductivity of the soil deposits are used to obtain soil water characteristic curves (SWCC).Pore water pressure and hydraulic conductivity of soil is estimated from SWCC for the initial state of stability. An implicit finite difference backward solution is used to solve partial differential equations for variably saturated flow and change in pore water pressure and moisture content as a result of a rainfall event is obtained. Thus change in pore water pressure (negative and positive) with respect to time and depth is obtained and this results from the hydrological model.

Key Word: *Soil water characteristic curves (SWCC), Pore water pressure, hydrological model.*

I.INTRODUCTION

Landslides are a detrimental geological hazard that causes damage to the natural and social environment. Landslides occur in almost all regions of the world in response to a wide variety of natural processes and triggering factors such as rainfall, earthquakes and human activities. Asia is identified as the continent in which landslides have caused the greatest number of fatalities. This is due to development of large cities, large changes in the size and distribution of the population as well as land-use, and of course changes in climate

Recent studies revealed that the best approaches for spatial prediction of landslide is the application of deterministic slope stability models, combined with steady state or transient infiltration models for hill slope hydrology. Several researchers have proposed different deterministic approaches based on an infinite slope stability model with rainfall infiltration models by using softwares such as Seep/W, Slope/W, Shetran, Flac-Tp-Flow etc. In this paper a hydrological model is being set up using spreadsheet technique. The main objectives of this study are to implement an infiltration model to obtain pore pressure variations with depth below ground surface and time.

II.STUDY AREA

The study area is administratively in Erumakolli area, a part of Kottapadi village in Vythiri taluk of Wayanad district.It is well connected by road. Calicut- Vythiri-Gudalur road passes close to the study area.Around forty landslides had been recorded in this area.Major part of the study area is covered by soil with tea plantations and other agricultural activities.

The general slope of the study area is 30º and the slope is covered with unconsolidated boulders of different sizes which were deposited as a result of palaeo- landslides. As the major part of the slope is made up of loose colluvium, it is more prone to landslides.

III. METHODOLOGY

The methodology implemented here is largely based on Karim S Karam and Low and Tang Hydrological model is set up first which gives pore pressure variations with depth. When a rainfall event occurs some rainwater infiltrates into soil and some will go as run off at surface. Rainfall distribution will depend upon the characteristics of rainfall (intensity and duration) and hydrologic properties of soil (hydraulic conductivity and degree of saturation). Since the soil near surface is unsaturated, it involves flow of water through unsaturated zone which makes the infiltration process very complex as the unsaturated soil exhibits changes in properties with time of rainfall and depth of soil and also flow through unsaturated soil reduces matric suction (negative pore pressure).There fore hydrological model is required to assess the hydrologic response of slope. Landslide analysis and stability models in particular, require the determination of pore water pressure variations with time. Unsaturated soil properties are found out using soil water characteristic curves initially. The governing equation for variably saturated flow is derived and solved by one dimensional implicit finite difference method for obtaining the pore water pressure variations with respect to depth and time.

The different steps for implementing hydrological model includes

a) Estimation of Unsaturated soil properties using Soil water characteristic curve (SWCC)

Unsaturated soil has four phases- solid, water, air and contractile skin (air-water interface). The contractile skin in an unsaturated soil is subjected to an air pressure (u_a) which is greater than water pressure (u_w). The pressure difference u_a-u_w is called matric suction in a soil. Increase in matric suction increases the shear strength and vice versa. The unsaturated soil properties volumetric moisture content (θ) and hydraulic conductivity (K) are functions of matric suction (φ). In this study, the initial moisture content distribution at different depths below ground surface before the start of rainfall, saturated hydraulic conductivity, saturated moisture content and residual moisture content are obtained. Based on this, SWCC (θ Vs φ and K Vs φ) are drawn by applying the set of equations proposed by van Genuchten. Soil is divided into 'n' number of compartments throughout the depth to be analyzed. The hydraulic conductivities (K(φ)) and matric suction (φ(θ)) at different depths are obtained using SWCC.

b) Equation for Variably saturated flow and Boundary Conditions

Assuming soil as homogeneous and isotropic, and flow is one-dimensional (vertical), the conservation of mass of water equation is given by

$$SsSa(\varphi) \left(\partial\varphi\ \partial t \right) + \partial\theta\ \partial t - \partial q\ \partial z = 0 \qquad (1)$$

Darcy's law in one dimension is expressed as

$$q = K(\varphi)\ \partial h\ \partial z \qquad (2)$$

By combining these two equations a variably saturated flow equation known as Richards' equation is obtained as

$$\partial\varphi\ \partial t = 1\ (SsSa(\varphi)+C(\varphi))\ \partial\ \partial z\ [K(\varphi)\ (\ \partial\varphi\ \partial z + 1)] \qquad (3)$$

Ss - Specific storage coefficient

Sa - Degree of saturation t - Time

q - Soil moisture flux (water flux through the soil)

z - Vertical coordinate with origin at the soil surface; taken to be positive downwards

C(φ) - specific moisture capacity (slope of θ(φ) characteristic curve)

To obtain the solution of this equation, boundary conditions are applied. Boundary conditions refer to the known conditions at the top and bottom compartments of soil at different stages of rainfall which are to be applied to solve the problem. The top boundary condition is determined by its degree of saturation, input flux and infiltration capacity of soil whereas the bottom boundary condition is applied based on the location of ground water table, whether it is located deep or shallow.

a) Numerical solution of flow equation and its spreadsheet implementation

Numerical methods are used to obtain solutions for partial differential flow equations. The variably saturated flow equation obtained is solved by applying implicit finite difference method to determine the pore pressure variations with respect to time and depth. In finite difference method, the problem is divided into small time steps and the values corresponding to next time steps are predicted using finite difference formulations such as forward, backward and central difference method. This method gives better accuracy for dynamic problems which depend upon time. In this method, a finite difference grid for the implicit scheme is formulated to solve Richards's equation

Finite difference grid is applied and solution for the Richards' equation is obtained as a simple algebraic equation as shown below

$$A_j\varphi_{j+1}^{i+1} + B_j\,\varphi_j^{i+1} + D_j\,\varphi^{i+1} = E_{j-1} \qquad (4)$$

A spreadsheet is used to implement the above method. For instance hydraulic conductivity and pore pressure variations for time 'i+1' are obtained corresponding to the values at time 'i'. The steps are repeated and hence pore pressure variations corresponding to the entire time of rainfall (i,i+1,..i_n) and depth (j,j+1…j_n) are obtained. The model solves simultaneously for saturated and unsaturated flow within a spreadsheet environment. One of the biggest drawbacks of the model is that it assumes that rainwater infiltrates into soil as a stable wetting front, and neglects the possibility of fingering and preferential flow that may develop in both heterogeneous and homogeneous soils. However, the model provides a powerful tool for estimating subsurface pore pressures that are generated during a rainfall event

IV.RESULTS AND DISCUSSIONS

The geotechnical and hydrologic data of the study area collected are given to the model, which is implemented by applying the method explained in the previous section. Hydrological model is prepared by inputting hydrologic properties, rainfall intensity and by applying a finite difference method.

The soil is divided into 12 compartments with each compartment having a depth of 0.5m. Using van Genuchten equations, initial moisture content distribution, saturated moisture content, residual moisture content and saturated conductivity, Soil Water Characteristic Curves (SWCC) are prepared. Initial moisture content is assumed based on antecedent rainfall. SWCC drawn using above data is shown in Fig.1 and Fig.2. From SWCC,hydraulic conductivities and pore water pressures corresponding to initial moisture content distribution are obtained. These are values at the initial state of stability of slope.

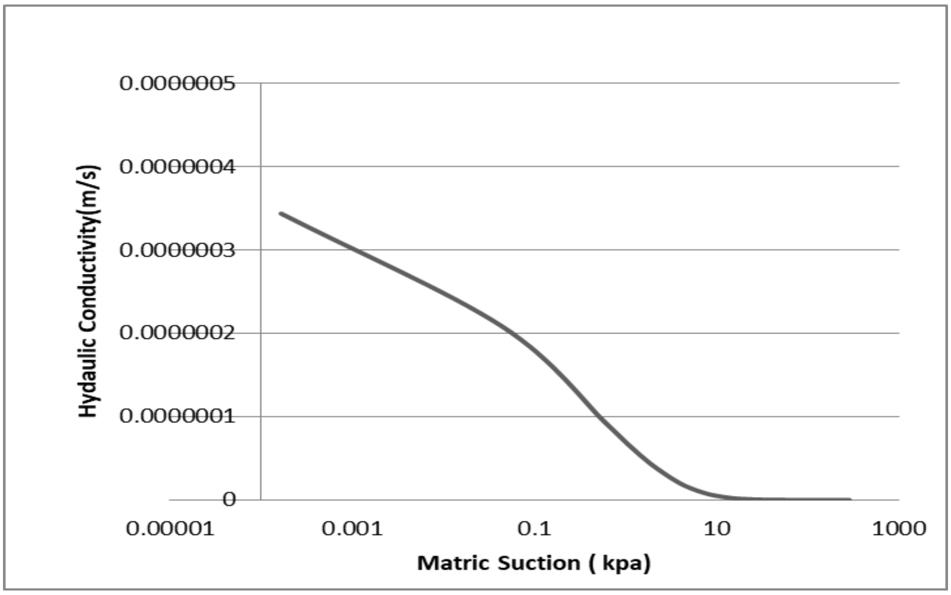

Fig. 1. Soil Water Characteristic Curve (K vs φ)

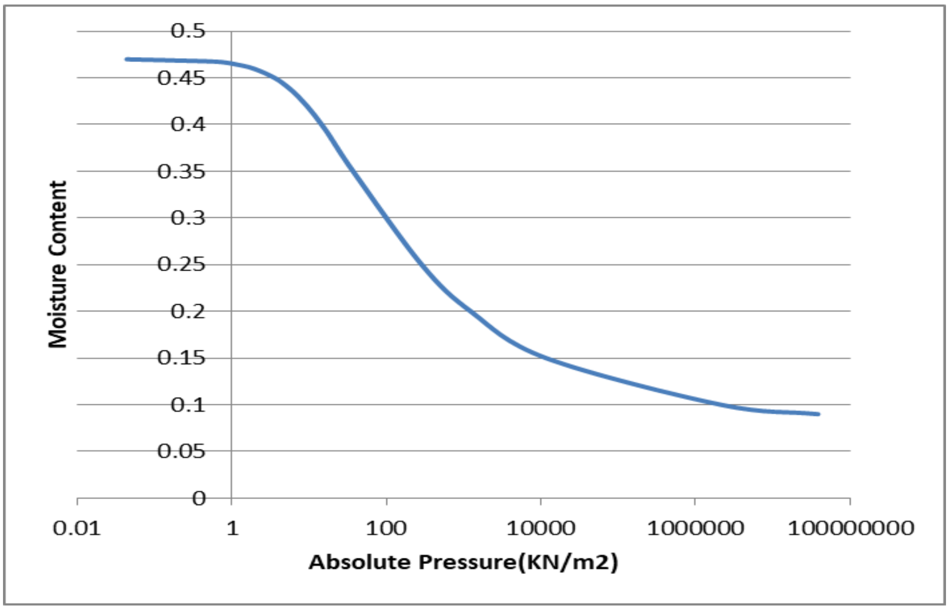

Fig. 2. Soil Water Characteristic Curve (θ vs φ)

To obtain the values of pore water pressures at different time intervals from the start of rainfall, implicit finite difference method is used as explained in the methodology. The hydrological model gives variation of pore water pressures for different time periods and depth below ground surface as shown in Figure 3.

From the Figure 3, it can be clearly understood that initially matric suction value was -3.05 kilopascal (in top compartment) and as the rainfall occurs value of suction decreases and gets eliminated and a positive value of 0.146 kilopascal (in top compartment) at time t= 5 hours is obtained. As a result of generation of positive pore pressure and elimination of suction there will be reduction in shear strength of soil and slope may fail.

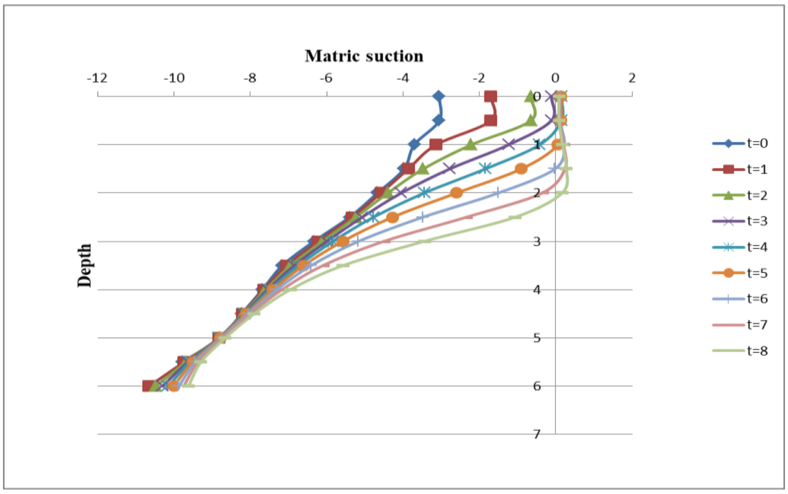

Fig. 3. Change in pore water pressure with depth for various time intervals

V.CONCLUSIONS

Hydrological model for the study area shows that a positive pore pressure develops as a result of rainfall events. As a result of development of positive pressure, suction is eliminated and shear strength is reduced. Matric suction is eliminated at a time t = 5 hours. From our study it is clear that failure occurs at study area due to generation of excess pore water pressure as a result of heavy rainfall which was the actual reason for slope failures that occurred in the study area. Thus the model can be applied in practice for deterministic stability analysis of slopes. Since the work is implemented in Microsoft Excel, it is relatively easy and we can modify it in our own ways.

The model has some limitations such as heterogeneity and stratification of soil is not considered, variations in slope angles are not taken, rainfall intensity is considered constant throughout the study and flow in vertical direction is only considered. In spite of all these limitations, the hydrological model can be used as a powerful tool for obtaining the pore pressure variations during a rainfall. If the study is carried out for different intensities and duration of rainfall, a rainfall threshold can be prepared with which slope failures can be predicted.

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