ANALYSIS OF RAIN INDUCED SLOPE FAILURES USING COMBINED HYDROLOGICAL GEOTECHNICAL MODEL

Sabari Ramesh¹, Rakesh J Pillai², Anu Antony³

ABSTRACT

Landslide is a geological phenomenon which gets triggered by factors such as rainfall, earthquake and human activities such as deforestation, excavation, blasting etc. 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 this landslide hazards. In the present study, a methodology has been implemented to analyze rain induced slope failures by taking a landslide prone area in Western Ghats, 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 combined hydrological geotechnical model has been set up to evaluate rain induced slope failures in a deterministic framework using Microsoft Excel and it is used to back evaluate a slope failure which occurred in the study area during 2007 monsoon. Rainfall data, hydrologic properties and geotechnical properties of the study area is 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 equation for variably saturated flow and change in pore water pressure and moisture content as a result of a rainfall event is obtained. Top boundary condition is either flux controlled or head controlled. At each time step, top compartment of soil is checked for its saturation. If it is saturated, suction or pressure head is taken as zero and it is head controlled. If it is not saturated then potential infiltration rate is compared with infiltration capacity of soil at each time step and minimum of these two values is taken as actual flux and top boundary is flux controlled. Bottom boundary is controlled by water table. If water table is of shallow depth, suction is taken as zero at this bottom boundary. If water table is deep, suction is assumed based on capillary forces and type of soil. As a result of rainfall, suction in soil is either reduced or eliminated. A reduction in suction can also initiate landslide. Thus change in pore water pressure (negative and positive) with respect to time and depth is obtained and this result from hydrological model is given to geotechnical (stability model) in the same spreadsheet.

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In stability model, Janbu’s Generalized Method of slices is applied by using cohesion, unit weight, angle of internal friction, slope angle and trial failure coordinates as inputs. Factor of Safety (FOS) for the trial failure surface is obtained by circular iteration technique in Microsoft Excel. This may not be the actual critical failure surface. Critical failure surface is obtained by optimization using SOLVER tool in excel. Final result can be plotted as a graph between FOS and time. Thus by using this model whether the slope will remain stable as a result of particular rainfall can be determined, time to failure from start of the rainfall can be obtained and critical failure surface can be located. The result obtained shows good agreement with actual failure during previous landslide event in the study area and it can be applied in practice for evaluation of landslide hazards.

Keywords: Landslides, Rainfall, Hydrological, Geotechnical, Finite difference, Stability
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ABSTRACT: Landslide is a geological phenomenon which gets triggered by factors such as rainfall, earthquake, blasting etc. 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 landslides result in large casualties and huge economic loss during monsoon season. Therefore there is a need to precisely assess and manage this landslide hazards. A combined hydrological stability model has been set up to analyze rain induced slope failures in a deterministic framework. In this paper, a landslide event which occurred during 2007 monsoon in Upper Tikoy Basin, Kottayam district, Kerala, India is back evaluated to validate the model. The results obtained are in good agreement with the actual event and hence can be applied in practice for evaluation of landslide hazards.

INTRODUCTION
Landslide is a detrimental geological hazard that causes damage to natural and social environment. Varnes and IAEG (1984) defined landslides as ‘almost all varieties of mass movements on slope including some such as rock falls, topples and debris flow that involve little or no true sliding’ [2]. A recent definition by Courture R (2011) simply states that ‘landslide is a movement of mass of soil (earth or debris) or rock down a slope’ [3]. Landslides occur in almost all regions of the world in response to 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 [4]. According to the International Landslide Centre at University of Durham, recorded landslide occurrences in 2007 shows that India was the third most seriously affected country with 352 landslide-induced deaths after China (695) and Indonesia (465) [4]. The four identified regions in India which are prone to landslides are -[5]

1. The Western Himalayas (Uttar Pradesh, Himachal Pradesh and Jammu & Kashmir)
2. Eastern and North Eastern Himalayas and plateau margins (West Bengal, Sikkim, and Arunachal Pradesh)
3. Naga-Arakkan Mountain belt (Nagaland, Manipur, Mizoram, Tripura)
4. Plateau margins of the Western Ghats and some parts of Eastern Ghats (Kerala, Tamil Nadu, Karnataka and Maharashtra)

Large volumes and high intensity rainfall and the consequent pore water pressure development are considered as the principal trigger of landslides in the Himalayas and the Western Ghats. Earthquakes are also a trigger of landslides in the Himalayas but are not known to have directly triggered landslides in the Western Ghats [5]. Numerous studies have been conducted in Himalayan regions whereas only few studies were conducted in Western Ghats region. As reported by the Centre for Earth Science Studies (CESS), Kerala, the area with degraded vegetation together with intensive rain water have maximum slide intensity. Studies conducted in the
state indicate that prolonged and intense rainfall or more particularly a combination of the two and the resultant pore pressure variations are the most important trigger of landslides [5]. In Kerala 13 out of 14 districts are prone to landslides. Because of its topography and climatic conditions, Kerala is prone to landslides frequently and in every rainy season landslides causes severe damages to the state. A survey of post-landslide investigation and newspaper reports enabled the identification of 29 major landslide events in the state [5].

About 90% of all landslides are triggered by rainfall and different rainfall patterns produce different types of landslides [6]. Rain induced landslides are triggered by rise in ground water level which leads to increase in pore water pressure on the potential slip plane due to which frictional forces between soil particle decreases and ultimately reduces effective shearing resistance and leads to slope failure [7]. Rainfall-induced landslides have increasingly posed serious threats to infrastructure and people’s lives around the world. On an average, landslides are responsible for 17% of all fatalities from natural hazards worldwide [8]. This problem is expected to be even more serious in near future due to changes in climate which would result in more intense rainfall, longer drought period and possible subsequent change in vegetation cover [9]. Landslides or slope failures can be deep seated or shallow landslides and in the presented study, shallow landslides are our subject of interest. In case of shallow landslides, transient pore pressure in response to rainfall combined with water washing or soil erosion dominates stability [10] [11]. Assessment of hill slope hydrology shows that rainfall contributes to instability of slopes by means of infiltration which results in decrease of matric suction by a moving wetting front or increase of pore water pressure by a rising water table [12].

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 [13]. 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.[14] [15] [16] [17] [18] [19] [9].

In this paper a combined hydrological-geotechnical model is being setup using spreadsheet technique and it is used to back evaluate failed landslide in Upper Tikoy River Basin, Kottayam district, Kerala which occurred during 2007 monsoon. The main objectives of this study is

1. To implement an infiltration model to obtain pore pressure variations with depth below ground surface and time.
2. To implement a geotechnical model to obtain Factor of Safety of a slope.
3. To implement a combined hydrological geotechnical model to analyze rain induced slope failures with Upper Tikoy River Basin, Kerala as a case study.

**STUDY AREA**

The study area is selected from Western Ghats region which comes under moderate landslide hazard zone. Upper Tikoy River basin is administratively part of Kottayam and Idukki districts in Kerala, the Western Ghats region of India which is prone to large number of landslides every year. Aruvikkal catchment is a sub basin of Tikoy River, tributary of Meenachil River situated in Kottayam district. The physiographic classification of Kerala reveals that the study area has highlands, including within it the plateau, its steep plateau margins, midlands and lowlands, with elevation ranging from 1195 to 40 m. Every year landslide causes huge loss of life and property in this area as a result of heavy rainfall. As a part of study conducted by Kuriakose et al, at this area, a detailed Geotechnical survey was carried out at 12 locations in the study area and confirmed that the area has shallow sandy soil with low cohesion resting over hard crystalline Precambrian Charnockites [5].

The oldest known landslide event in the study area occurred on 4th October 1882 near Meladukkam. A partial landslide inventory of Upper Tikoy river basin created by Thampi et al. contained 33
landsides [20]. A total of 31 landslides were additionally included based on data derived from newspaper reports, village administration records, interview with local residents and the data base prepared by Vijith and Madhu [21]. A list of landslide events which occurred in the study area is shown in the Table 1. The study area experienced landslides on 22nd June 2007 as a result of 997mm of rainfall from 28th May to 22nd June. As a result of heavy rainfall there is a reduction in negative pore water pressure which triggered the failure. This event is taken as case study in this thesis. The location map of study area is shown in Figure 2.

Table 1 Year wise distribution of landslide events in the study area [5]

<table>
<thead>
<tr>
<th>Date</th>
<th>Number of Landslide events</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upper Tikoy River Basin</td>
</tr>
<tr>
<td>25 June 1985</td>
<td>1</td>
</tr>
<tr>
<td>2 Sep 1988</td>
<td>1</td>
</tr>
<tr>
<td>3 Nov 1990</td>
<td>1</td>
</tr>
<tr>
<td>27 Jul 1992</td>
<td>2</td>
</tr>
<tr>
<td>6 Oct 1993</td>
<td>33</td>
</tr>
<tr>
<td>8 Nov 1997</td>
<td>2</td>
</tr>
<tr>
<td>24 May 1999</td>
<td>1</td>
</tr>
<tr>
<td>24 Aug 2000</td>
<td>1</td>
</tr>
<tr>
<td>8 Jul 2001</td>
<td>11</td>
</tr>
<tr>
<td>3 Oct 2004</td>
<td>3</td>
</tr>
<tr>
<td>23 Oct 2005</td>
<td>4</td>
</tr>
<tr>
<td>22 Jun 2007</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>64</td>
</tr>
</tbody>
</table>

After the selection of study area, rainfall data and geotechnical data of the area is collected. The required main data are collected from CESS (Centre for Earth Science Studies) and ILDM (Institute of Land and Disaster Management), Kerala. The list of geotechnical and hydrological data obtained for study area are given in Table 2.

Table 2 Geotechnical and Hydrologic properties of Upper Tikoy River Basin

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope angle</td>
<td>27.2</td>
<td>Degrees</td>
</tr>
<tr>
<td>Soil depth to bed rock</td>
<td>4</td>
<td>Metre</td>
</tr>
<tr>
<td>Angle of internal friction</td>
<td>32</td>
<td>degrees</td>
</tr>
<tr>
<td>Cohesion</td>
<td>0.1</td>
<td>kilopascal</td>
</tr>
<tr>
<td>Saturated unit weight</td>
<td>17</td>
<td>kilopascal</td>
</tr>
<tr>
<td>Saturated Hydraulic conductivity</td>
<td>$4.02 \times 10^{-6}$</td>
<td>metre/second</td>
</tr>
<tr>
<td>Saturated moisture content</td>
<td>0.39</td>
<td>m$^3$/m$^3$</td>
</tr>
<tr>
<td>Residual moisture content</td>
<td>0.0387</td>
<td>m$^3$/m$^3$</td>
</tr>
<tr>
<td>van Genuchten parameter $\delta$</td>
<td>0.45</td>
<td>per kilopascal</td>
</tr>
<tr>
<td>van Genuchten parameter $n$</td>
<td>1.23</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig.2 Location map of Study Area- Upper Tikoy River Basin, Kerala, India [5]
METHODOLOGY

The methodology implemented here is largely based on Karim S Karam and Low and Tang [22][23]. Hydrological model is set up first which gives pore pressure variations with depth and time and then Stability model giving Factor of Safety (FoS) of the slope is implemented and finally output obtained from hydrological model is given as input to stability model and thereby a combined model which gives FoS as a function of time is obtained.

Hydrological Model

When a rainfall event occurs some rainwater infiltrate 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). Therefore hydrological model is required to assess the hydrologic response of slope. Landslide analyses, 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 increase 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 [24]. 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 Varibly saturated flow and Boundary Conditions

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

\[ S_s a(\phi) \left( \frac{\partial \phi}{\partial t} \right) + \frac{\partial \phi}{\partial z} - \frac{\partial u}{\partial z} = 0 \]  (1)

Darcy’s law in one dimension is expressed as

\[ q = K(\phi) \frac{\partial h}{\partial z} \]  (2)

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

\[ \frac{\partial \phi}{\partial t} = \frac{1}{(S_s a(\phi) + C(\phi))} \frac{\partial}{\partial z} \left[ K(\phi) \left( \frac{\partial \phi}{\partial z} + 1 \right) \right] \]  (3)

S_s - Specific storage coefficient

\( t \) - 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 conditions is determined by its degree of saturation, input flux and infiltration capacity of soil whereas bottom boundary condition is applied based on the location of ground water table. (whether it is located deep or shallow)
c. Numerical solution of flow equation and its spreadsheet implementation
Numerical methods are used to obtain solutions for partial differential flow equation. 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’ equation (Equation 3) as shown in Figure 3. The time index is denoted by \(i\) and the space index by \(j\).

\[
A_j \varphi_{j+1}^i + B_j \varphi_{j}^{i+1} + D_j \varphi_{j-1}^i = E_j
\]

A spreadsheet is used to implement the above method. For instance from Figure 3 hydraulic conductivity and pore pressure variations for time ‘\(i+1\)’ is obtained corresponding to the values at time ‘\(i\)’. The steps are repeated and hence pore pressure variations corresponding to entire time of rainfall (\(i, i+1, \ldots, i_n\)) and depth (\(j, j+1, \ldots, j_n\)) 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 homogenous soils. However, the model provides a powerful tool for estimating subsurface pore pressures that are generated during a rainfall event.

Geotechnical Model
In stability model, strength model is combined with geometric and equilibrium representations. Stability models based on limit equilibrium methods are extensively used in geotechnical engineering over the years. In this paper Janbu’s Generalized Method of Slices (1973) is used for assessing the slope stability by applying spreadsheet technique. The FoS of the slope is determined by using set of equations proposed by Janbu (1973). The procedure is outlined below

1. Divide the slope into any desired number of slices
2. Set up a spreadsheet(in MICROSOFT EXCEL) and specify the input parameters such as slope angle, soil parameters and horizontal and vertical coordinates of failure surface.(External forces and boundary forces on slope are assumed zero)
3. Janbu’s (1973) proposed equations are entered and using spreadsheet circular iteration technique FOS for a specified failure surface is found out.
(This may not be the critical failure surface. Therefore search for critical failure surface is required).

4. Critical failure surface (minimum FOS) is located by optimization (minimization) using spreadsheet’s optimization tool (Solver in Microsoft Excel).

**Combined Model**

In this part the infiltration model is combined with geotechnical model. The output from infiltration model (variation of pore water pressure with time) is given as input to stability model and FoS of slope as a function of time can be determined. Thus spatial and temporal hazards of landsliding can be assessed. Combined modeling is also done in the same spreadsheet environment as above. The procedure is outlined as follows

1. Using LOOKUP function in excel, pore pressure for various depth is extracted from infiltration model to stability model and FoS is determined. This is the initial state of stability at time \( t = t_0 \).
2. Then pore pressure is extracted for the next time increment \( t = t_0 + \Delta t \) and FoS for that time step is calculated.
3. Step 2 is repeated for different time intervals till the final chosen time for analysis
4. At each step FoS obtained is optimized (minimized) by invoking spreadsheet’s optimization tool and thus minimum FoS (critical failure surface) is obtained after each time step.

The result obtained is a plot between FoS and time and thus from this model one can determine whether the slope will remain stable as a result of particular rainfall. If failure takes place failure surface can be located and time to failure from the onset of rain can be ascertained.

**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 previous section. Hydrological model is prepared by inputting hydrologic properties, rainfall intensity and by applying finite difference method. Stability model is obtained by inputting geotechnical properties and applying Janbu’s generalized procedure of slices. By giving the results obtained from hydrological model to stability model, combined model is obtained.

The soil present is generally sandy soil with very low clay content. The rainfall intensity taken for the study is 280.8 millimetre/day for a period of 13 hours which was the rainfall which study area received during the actual day of landslide occurrence in 2007. Slope stability study in this thesis work is carried out based on that event by inputting all parameters such as slope geometry, soil properties etc. The geotechnical and hydrologic properties of soil are summarized in Table 2.

**Hydrological Model Results**

The soil is divided into 8 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 are shown in Figure 4 and Figure 5. Pore water pressure values have negative values in the Figures 4 and 5. From SWCC, hydraulic conductivities and pore water pressures (referred to as matric suction, if values are negative) corresponding to initial moisture content distribution are obtained. These are values at the initial state of stability of slope.

**Fig.4 Soil Water Characteristic Curve (K vs \( \phi \))**
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 6.

From the Figure 6, it can be clearly understood that initially matric suction value was -0.9240 kilopascal (in top compartment) and as the rainfall occurs value of suction decreases and gets eliminated and a positive value of 0.1486 kilopascal (in top compartment) at time t= 12 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. The failure of slope can be ascertained by setting up a stability and combined hydrological stability model which are explained in sections below.

**Geotechnical Model Results**

To implement geotechnical model, Janbu’s generalized procedure of slices and spreadsheet technique are applied by inputting the geotechnical properties given in Table 2. Initially slope is sectioned into 7 slices. Equations given by Janbu are entered in spreadsheet and a circular iteration is initiated and value for FoS is obtained. A FoS of 1.47 is obtained for trial failure surface at time t= 0. Then optimization tool in Excel (Solver) is activated and FoS for critical failure surface at time t=0 is obtained as 1.41. In this method, FoS is the objective function which is to be minimized by changing the trial failure surface coordinates. Since the FoS for critical initial failure surface is greater than unity, the slope is initially stable. Now the stability of slope with the progress of rainfall is evaluated by using combined hydrological geotechnical model.

**Combined Model Results**

In combined model pore water pressure values obtained from hydrological model are extracted and given as input to stability model. At each time step, factor of safety for critical failure surface is obtained by using solver tool in excel. The initial trial failure surface and critical failure are shown in Figure 7. The variation of FoS with time is shown in Figure 8. For every time steps suction values goes on decreasing and at time t =12 where suction gets eliminated (positive pore water pressure), the FoS obtained is 0.9918 which is less than unity and therefore slope becomes unstable and failure occurs.
After failure, there is a slight increase in FoS because the rainfall stopped after 13 hours and pressure redistribution occurred. Thus from combined model final critical failure surface is obtained and also the variation of FoS with time is obtained. From this model it can be concluded that a rainfall with an intensity 280.8 millimetre/day and duration 12 hours can trigger a landslide in the study area.

In the actual landslide event that occurred in 2007 as a result of rainfall intensity of 280.8 millimetre per day, slope failure occurred after 13 hours from the start of rainfall event [5]. According to our study, from Figure 8, failure occurred after 12 hours and it is almost in good agreement with the actual event.

**CONCLUSIONS**

In this study, a specific slope is analyzed in engineering terms and properties of the site are applied to a mathematical model and safety of slope is evaluated. The combined hydrological stability model is applied for the study area (Upper Tikoy River Basin) in Western Ghats, Kerala. During monsoon period of 2007, large number of landslides occurred all over Kerala and the study area also witnessed landslides. These landslides are taken as case study and assessed by applying the model. The following conclusions can be drawn after applying model in the study areas:

Hydrological model for study area shows that a positive pore pressure develops as a result of rainfall event. As a result of development of positive pressure, suction is eliminated and shear strength is reduced. Matric suction is eliminated at a time \( t = 12 \) hours. The result obtained from stability model indicates that slope at study area is initially stable before the start of rainfall. Combined model indicates that the slope failure occurred at time \( t = 12 \) hours for Tikoy River Basin when the FoS is less than unity. The result obtained indicates that both hydrological and stability models are in good agreement because the time at which positive pore pressures developed in hydrology model is same as that at which FoS reduced below unity in Stability model.

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. Reliability analysis and GIS can be incorporated in the study to set up a run out model which can predict the velocity and dimensions of flow thereby developing a probabilistic landslide hazard assessment model.
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, hydrological model can be used as a powerful tool for obtaining the pore pressure variations during a rainfall and when combined with stability model most critical failure surface and time at which failure occurs is obtained. 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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