Implementation of infinite slope stability rain infiltration model for landslide predictions in Chamoli district, Uttarakhand

Pattanaik, Amitansu
Mishra, Brijendra K.
Defence Terrain Research Laboratory (DTRL), Metcalfe House, Delhi-110054
Gaur, Anuvrata
Jabil Global Services India Pvt Ltd, Manesar, Gurgaon
E-mail:amitansu@yahoo.com

Abstract

Landslides involve the movement of debris, rocks and earth surfaces under the influence of gravity. It is a catastrophic phenomenon which causes extensive damage to both life and property. The Himalayan region has a fragile ecosystem which has often been associated with recurring landslides. The Chamoli district in Uttarakhand comprises of steep slopes and narrow valleys. This district holds special religious relevance for Hindus. Due to frequently recurring landslides huge economic and loss of lives of tourists and local people takes place each year. This district receives heavy rainfall during the monsoonal months which leads to slope instability and triggers landslides
.
Depending on the characteristics property of the soil found here such as its porosity, saturated hydraulic conductivity it is influenced to landslide triggering factors particularly rain infiltration and the stability of these slopes gets affected in terms of the height of the potentially unstable plane, increase in matric suction leading to reduction in factor of safety on the ground surface. External factors such as slope angle, depth of the water table below the ground also play a significant role in influencing slope stability. The changes in factors such as suction stress, effective saturation and factor of safety at varying heights above water table with different steady infiltration rate as determined from annual rainfall data for Chamoli district have been studied by implementation and verification of Infinite slope stability under steady unsaturated seepage conditions from various literatures and by using MATLAB. MATLAB provides an interactive environment helps in visualizing and effectively solving extensive numerical computations which have been carried out in this literature. In this literature shallow landslides and their depth of occurrence below the ground surface has been effectively programmed and analyzed. With predictive analysis of slope stability parameters, landslides can be forecasted and mitigation steps can be taken on time to reduce the extent of damage.

Key words- Factor of safety, infiltration rate, matric suction, suction stress, effective saturation, MATLAB.

1. Introduction:

Landslides is a phenomena associated with mountainous terrain which involves mass movement of hill slopes comprising of rocks, artificial fills, soils in downward and outwards direction under gravitational influence[1]. Landslides can be attributed to both natural and human induced factors. The natural causative factors of landslides include rainfall, geology, weather conditions, depth of water table from the ground surface while human causative factors includes deforestation, modification of slopes by construction of roads and buildings besides excavations, mining and other quarrying activities. The duration of occurrence of landslides can vary ranging from a few minutes in case of rapid landslides and few hours, days, weeks or months to trigger slow landslides. Various landslides can be characterized according to the movement of the soil material ranging from toppling, creeps, debris flow, mudflow, debris avalanche, falls, Lahar and lateral spreads [2]. The Himalayan region which consists of younger mountains is tectonically sensitive region prone to earthquakes. Being situated within this sensitive region where stress release occurs frequently besides heavy infiltration especially during monsoonal months makes Uttarakhand state vulnerable to landslides [3]. With unchecked expansion and development mostly due to human activities have modified slopes and with increasing deforestation, exposed the soil to factors triggering landslides.

Landslides rapid or slow mostly occur in the monsoonal months extending from July to September wherein high humidity exceeding 70% and high rainfall can be observed. Rainfall induced shallow landslides render destruction to thousands of lives besides economic damage [4]. During initially dry conditions the soil has high matric suction (existence of pore-air and pore-water in unsaturated soils resulting in adhesive forces) and exhibits thus high shear strength. As a result of infiltration into the slope surface increases the soil-water content leading to reduction in matric suction and the shear strength of the soil triggering shallow landslides [5], [6]. Intensive soil erosion besides growing urbanization are another major culprit in occurrence of landslides in this region. Initially prediction of landslides triggered as a result of infiltration was based on identifying landslide prone terrains [7] and by identifying the duration and intensity of rainfall that causes slope failure [8], [9], [10].However these empirical methods failed to incorporate the importance of hydrological processes in triggering landslides. Physical based slope stability models combine hydrological models with infinite slope stability models for effectively forecasting spatial and temporal distributions of landslides [11], [12], [13], [14].

Classic methodology ignored conditions of partial saturation and only fully saturated soils would trigger landslides. However various studies concluded that various shallow slope failures take place in conditions of partial saturation [15], [16], [17]. Quantification of negative pore pressure above water table for slope stability analysis was also effectively performed [18], [19].Under conditions of partial saturation Terzaghi principle of effective stress was inacceptable since it ignored changes in suction stress or soil moisture[20]. The concept of suction stress affecting shear strength of the soil was then proposed [21].This concept was utilized for various slope stability analysis [22], [23].Alternatively the concept wherein changes in suction stress altering effective stress of the soil instead of the shear strength was proposed [24],[25],[26].

The Classic Infinite slope stability also assumes a planar slip surface on an infinitely extended planar slope whose depth is small compared to the length of the slope but failed to take into account changes in certain factors such as porosity, friction angle with depth besides considering fixed depth of sliding plane below the ground surface.

In our study the infinite slope stability model under steady unsaturated seepage conditions has been considered for hillslopes of different soils has been conducted wherein the influence of external factors such as slope angle, infiltration and internal factors of a particular soil such as cohesion, porosity, hydraulic conductivity have been analyzed. The failure slope is assumed to be parallel to the ground surface. For different infiltration rates prediction of slope stability at various depths below the ground surface has been made. For a depth below the ground surface where the Factor of safety is predicted to be less than 1 then the failure plane at that particular depth is predicted.

Various parameters such as pore water pressure, effective saturation and suction stress have also been calculated.

2. Study area:

Chamoli lies in the northwest part of Uttarakhand state and is the second largest district of the state. It is bounded by North Latitude 29º 55' 00" & 31º 03' 45" and East Longitude 79º 02' 39" & 80º 03' 29".

This district is surrounded by Uttarkashi in North West, Pithoragarh in Southwest, Almora in South East, Rudraprayag in South West and Garwal in West. It is also important from strategic point of view as it shares its northern boundary with Tibet (China). Chamoli is famous for its hill stations, picturesque areas and places of religious interests such as Badrinath, Kedarnath Hemkund Tungnath and Joshimath.

3. Methodology:

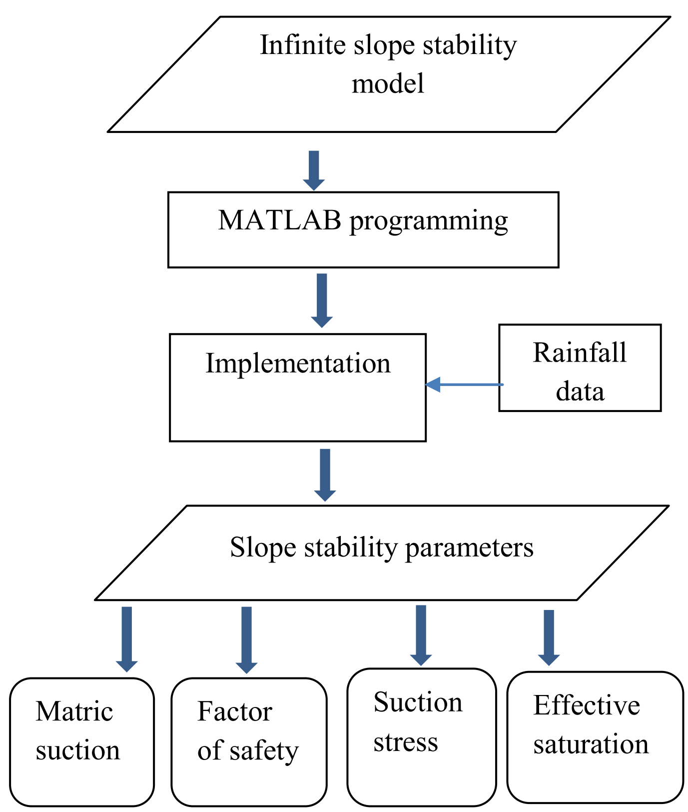

Figure 1 Flowchart depicting methodology used

A. Infinite slope stability model equations:

The Infinite slope stability model was programmed and analyzed based on the following generalized model equations which effectively calculates Factor of safety, suction stress, matric suction and effective saturation.
Matric suction for a soil is defined in terms of infiltration q, saturated hydraulic saturated conductivity k_s [27].

$$u_\alpha - u_w = \frac{-1 \ln[(1+q/k_s)e^{-\gamma_w \alpha z} - q/k_s]}{\alpha} \quad (1)$$

Where u_a represents pore air pressure, u_w represents pore water pressure, z represents the vertical coordinate in upward direction and γ_w is the unit weight of water.Suction stress for various degrees of saturation has been expressed by the following equations:

$$\sigma^s = -(u_\alpha - u_w) \qquad u_\alpha - u_w \leq 0 \quad (2)$$

$$\sigma^s = \frac{1}{\alpha} \frac{\ln[(1+q/k_s)e^{-\gamma_w \alpha z} - q/k_s]}{(1+\{-\ln[(1+q/k_s)e^{-\gamma_w \alpha z} - q/k_s]\}^n)^{(n-1)/n}} \qquad u_\alpha - u_w > 0 \quad (3)$$

By SWCC (Soil water characteristics curve), the degree of saturation can be expressed in terms of matric suction of the soil which is illustrated by the following equation.

$$\frac{S - Sr}{1 - Sr} = \left\{\frac{1}{1+[\alpha(u_\alpha - u_w)]^n}\right\}^{1-1/n} \quad (4)$$

Here S denotes the degree of saturation and S_r denotes the residual degree of saturation. Here n and α are empirical fitting parameters for partially saturated soils.
Another important factor for gauging out slope stability is the Factor of Safety which is the ratio of soil shear strength to the shear stress has been conceptualized as follows[34]:

$$F(z) = \frac{\tan\varphi'}{\tan\beta} + \frac{2c}{\gamma H_{ss} \sin 2\beta} - r_u (\tan\beta + \cot\beta)\tan\varphi' \quad (5)$$

$$\text{where } r_u = \frac{\sigma^s}{\gamma(H_{wt} - z)} \quad (6)$$

Here φ' represents the change in slope angle which has been expressed as a function of depth [28], [29].Also *β* represents slope angle and *c'* denotes soil cohesion. Factor of safety for stable slopes is 1.The first term in this expression denotes internal frictional resistance of the soil, while the second term represents cohesion among soil particles and the third term depicts the suction stress present in the soil.

B. Matlab:

MATLAB (Matrix Laboratory) is a numerical computing environment which was developed by MathWorks. It allows performing various functions such as matrix manipulations, effective computing of data, plotting of various functions and data, allows interfacing with external programs in C, C++, Java, Fortran etc [30]. MATLAB has been used in our study for implementation of the infinite slope stability model and calculation of various factors for predicting slope stability. Visualization tools in MATLAB help in generating plots which help in easy analysis and interpretations of the parameters of interest.

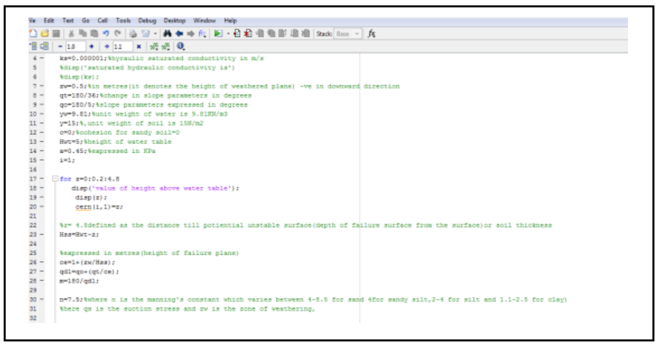

Figure 2 MATLAB editor

4. Discussions and results:

For the purpose of this literature the Chamoli district with fine sandy soils has been considered with an average slope of 30^0, the weathering zone z_w set as 0.5 meters and the water table assumed parallel to the slope. The characteristics slope stability parameters such as Matric suction, suction stress, effective saturation and factor of safety were calculated using the above rainfall data for four different months i.e. January, April, August and November were plotted as follows:

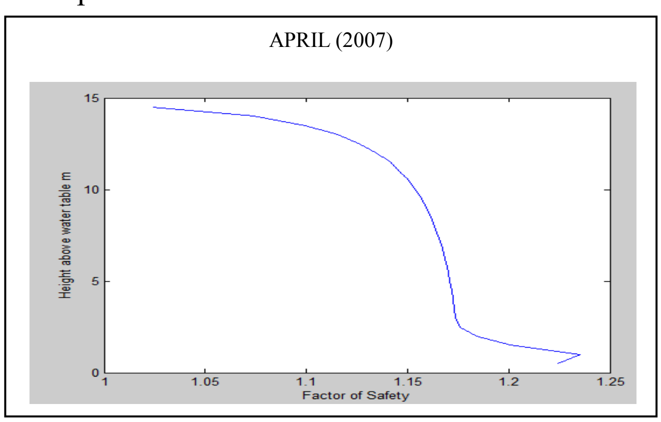

Figure 3 Graph depicting factor of safety vs height above water table (in m) in the month of April (2007)

In the month of April, as observed from the above figure the factor of safety of the soil is greater than one throughout the soil profile indicating stability of the slopes.

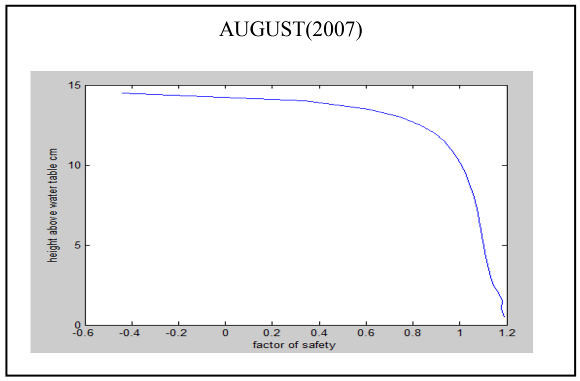

Figure 4 Graph depicting factor of safety vs Height above water table (in m) in the month of August (2007)

With heavy rainfall in monsoonal month of August the factor of safety <1 over the height of 8 meters above the water table thus rendering the slope instable. This can be attributed to wetting front or complete saturation zone penetrating deeper into the soil and susceptible to landslides.

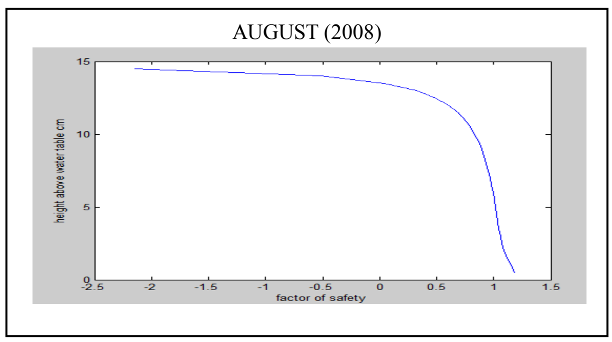

Figure 5 Graph depicting factor of safety vs Height above water table (in m) in the month of August (2008)

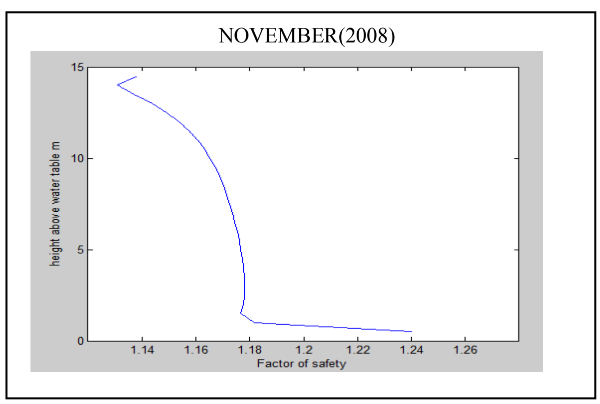

Figure 6 Graph depicting factor of Safety vs height above water table in the month of November (2008)

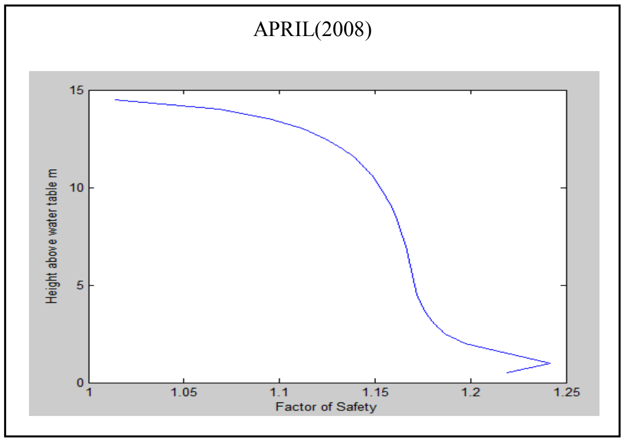

Figure 7 Graph depicting factor of safety vs height above water table (m) for the month of April (2008)

As observed in the above figures the factor of safety>1 in the month of November and April thus the slope is not susceptible to landslides in these months of 2008. With the factor of safety <1 at a height of 12 meters above water level, the slope becomes susceptible to slope failure.

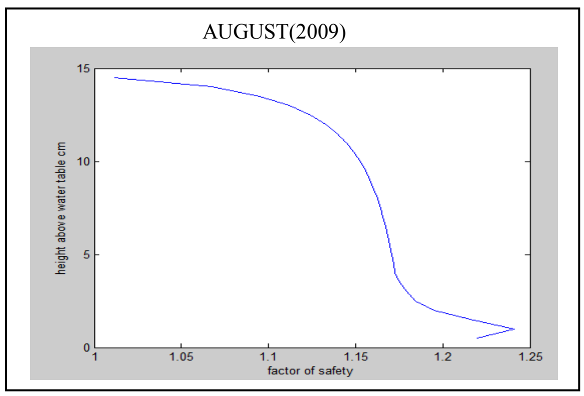

Figure 8 Graph depicting factor of safety vs Height above water table (in m) in the month of August (2009)

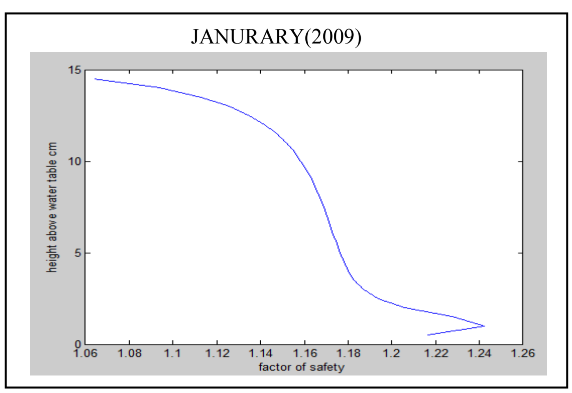

Figure 9 Graph depicting factor of safety vs Height above water table (in m) in the month of January (2009)

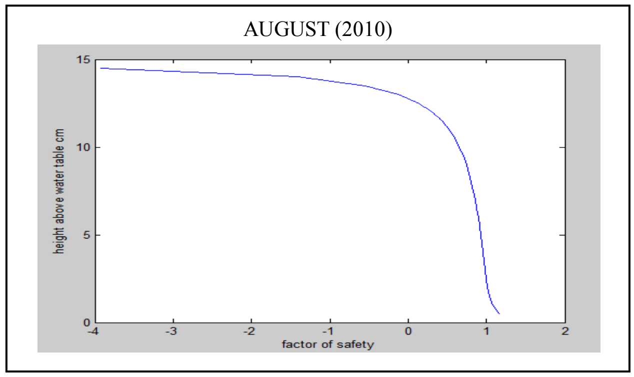

Figure 10 Graph depicting factor of safety vs height above water table (m) for the month of April (2008)

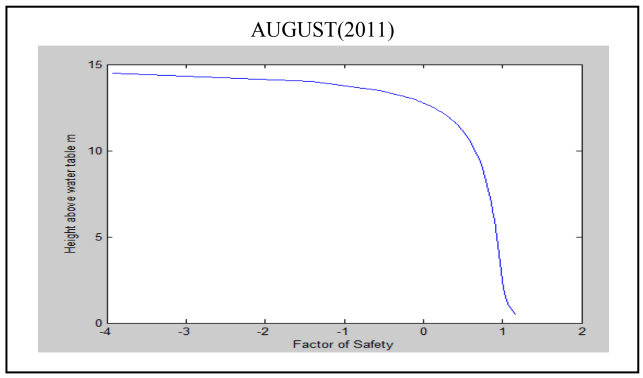

Figure 11 Graph depicting factor of safety vs Height above water table (in m) in the month of January (2011)

Considering average slope below the ground we observe from the graphs that when the infiltration in the month of August 2011 was the highest compared to the previous years, the depth of failure plan was less than 5 meters above the water table, demonstrating instability of the slope was maximum during this year. During rest of the year i.e. for winter season (January), Hot weather season (April) and Post monsoon season (November) the factor of safety >1 for all the five years depicting slope stability and no landslide occurrence.

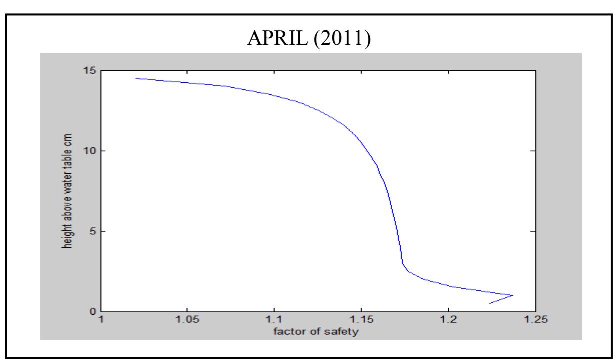

Figure 12 Graph depicting factor of safety vs Height above water table (in m) in the month of April (2011)

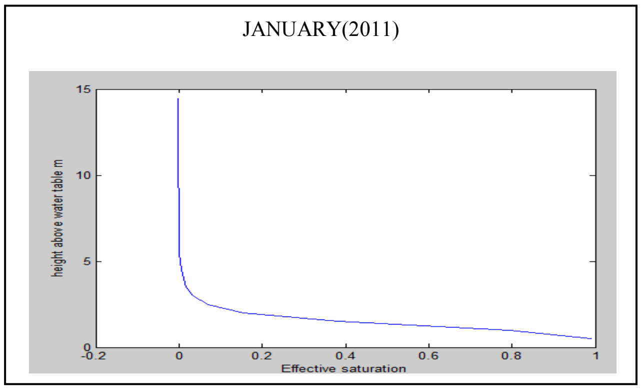

Figure 13 Graph depicting effective saturation vs Height above water table (in m) in the month of January (2011)

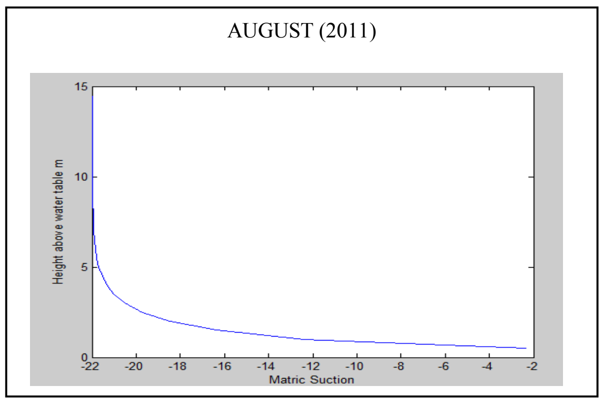

Figure 14 Graph depicting matric suction vs Height above water table (in m) in the month of January (2011)

The effective saturation in the month of January is below 1 at the ground surface indicating less or no landslides during the month of January.

As can be observed from figure 11, the matric suction or pore pressure in the month of August becomes negative since the soil gets completely saturated. The factor of safety in the same month as observed in the previous graphs falls below 1 indicating slope failure.

5. **Conclusions:**

This paper examined infinite slope stability model as an generalized yet effective method for assessing the stability of slopes at steady infiltration conditions considering such factors such as depth of water table below the ground, slope angle and using real time rainfall data and then at different heights above the water table the factors for slope stability such as matric suction, suction stress, effective saturation and factor of safety have been calculated. With increase in infiltration especially in the monsoonal months, the stability of the slope varies as the factor of safety reduces and so does matric suction of the soil. There is an increase in effective saturation to near saturation while suction stress is increases. The depth of the failure plane falls much below the ground and finally causing instability and thus landslides. This district is most prone to landslides in monsoonal months due to rapidly degrading factors of slope stability as observed during the course of this literature. Thus rainfall as an important triggering factor for landslides has been observed. By incorporating unsteady unsaturated flow and accounting for various other factors such effect of vegetation and tehsil specific rainfall data for this district a more precise real time study can be accounted which can help in effective and timely prediction of shallow landslides so that mitigation measures can be taken in advance to reduce the loss of property and lives.

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