A STUDY ON EFFECT OF PERMEABILITY AND WATER TABLE ON STABILITY OF HILL SLOPES UNDER RAINFALL CONDITION

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ABSTRACT

The Himalayan foothills of the north eastern part of India are location of frequent rain-induced landslides. Literature study has shown that stability of these residual soil slopes is greatly affected by the loss of suction due to rainwater infiltration during monsoon season (Das et al, 2012). Depth of ground water table and permeability of the slope soil control the suction profile and water infiltration into the slope soil. This study investigates the variation of FOS of these hill slopes under a range of water table depth and permeability of the slope soil.

The geotechnical properties of the soil were obtained through laboratory testing of sample collected from Jorabat hills near Guwahati, the capital city of Assam state of India. The Soil Water Characteristic Curve (SWCC) was determined and based on the SWCC the variation of unsaturated co-efficient of permeability of the slope soil with matric suction was estimated by finite difference method. On the basis of the permeability curve the suction at different depths were estimated for particular rainfall intensity and gound water table depth assuming one dimensional steady state infiltration of rainwater into slope soil. The stability of the slopes were analysed for different saturated coefficient of permeability and ground water table depth under a range of rainfall intensities, whose values were assumed based on field observations of the study area.

It was observed that the stability of the slope, measured in terms of factor of safety, decreased with the increase in the rainfall intensity. The stability decreased with the increase in elevation of the water table. It was also observed that the factor of safety got reduced non-linearly with the decease in saturated coefficient of permeability of the slope soil.

Keywords: *Landslides, Rainfall, Permeability, Water-table, Matric Suction.*

1. INTRODUCTION

Assam the Northeastern state of India is surrounded by hills and its climate is typically tropical monsoon rainfall type with high humidity and heavy rainfall. The monsoon seasons starts from May and last till September. Within this period Assam receives a lot of rains causing many landslides all over the hilly region of the state.

According to Assam State Disaster Management Authority (ASDMA), 1000 events of rain induced landslides took placed in Assam during 2016-2022. Assam at an average receives 2,239.4 mm rain annually. According to several newspapers report, in June 2022 Assam and Meghalaya received 858.1mm rainfall which broke all the previous records. Due to the excessive rain, many landslides took place all over the states damaging many roads, infrastructures and human lives.

Guwahati, the capital city of Assam is located at the bank of river Brahmaputra. The city is surrounded by hills that are under threat due to unplanned urban development. The city contains 366 landslide prone zones across 18 hills according to the district administration. In June 2022, the city recorded 72 rainfall induced landslides in just 5 days which resulted in disruption of many roads, infrastructure and rail transportations.

Landslides occur when mass of rocks; debris or earth of a slope becomes weak and moves down the slope. It can occur due to various reasons like deforestation, earthquake, volcano eruption, heavy rains, change in ground water level, human activities etc.

Some soil parameters like pore water pressure, water table level and soil permeability gets changed with rain which makes the slope vulnerable to landslides. Many researchers (Thapa,2015; Pradhan et al,2020; Kankanamge et al,2018; Ering et al,2015; Paul et al,2000; Islam et al,2014; Lu et al,2004; and Gofar et al,2008) have studied different landslides and found that that slopes of residual soil that are high and steep remained stable during dry spells. The only time these slopes failed was when it rained.

This fact is related to the unsaturated zone above the groundwater table which have increased the shear strength in residual soil slope. As a result, the slope has a high factor of safety and is stable during dry seasons. The increased shear strength within the unsaturated zone is reduced by the infiltration of rainwater during rainfall. Hence during rainy seasons, the slope is prone to failing.

Loss of pore water suction due to rainwater infiltration during monsoon season has negative impact on the stability of residal soil hill slopes (Das et al, 2012). Depth of ground water table and permeability of the slope soil control the suction profile and water infiltration into the slope soil (Fredlund et al, 1993). This study investigates the variation of FOS of these hill slopes under a range of water table depth and permeability of the slope soil.

2. METHODOLOGY

Guwahati region was selected to analyze the slope stability and to understand the mechanism behind rain induced landslides. Soil samples were collected from Jorabat hills in the form of boulder size lumps. The lumps were carried to the Civil Engineering Department, Tezpur University for determination of the geotechnical properties in the geotechnical engineering laboratory.

Table1: Soil properties.

SOIL PROPERTIES	
Dry density, ρ_d	15.98 KN/m^3.
Specific Gravity, G	2.63

From grain size distribution curve shown below the Coefficient of uniformity (C_u) was 3.27 and Coefficient of curvature (C_c) was found to be 0.79. According to the Unified Soil Classification the sample collected from Jorabat is categorized as poorly graded sand (SP).

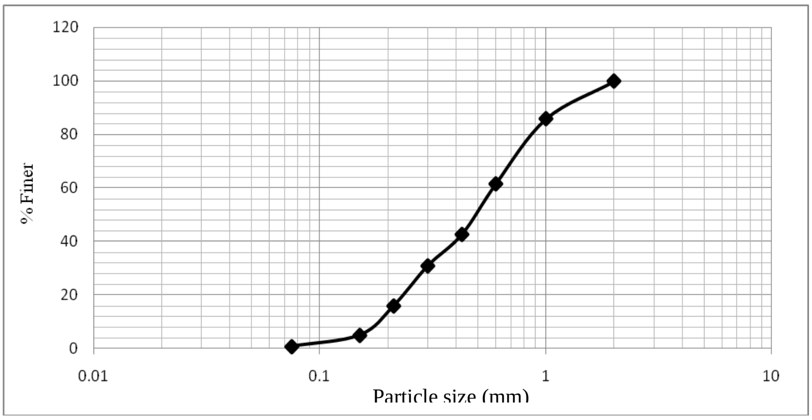

Figure 1: Grain size distribution curve.

2.1 Determination of strength parameters

Values of cohesion (c) and angle of internal friction (φ) are found out using Triaxial apparatus shown below. C-U testing was carried out under confining pressure of 1.0 kg/cm^2, 1.5 kg/cm^2 and 2.0 kg/cm^2.

Figure 2: Triaxial apparatus used.

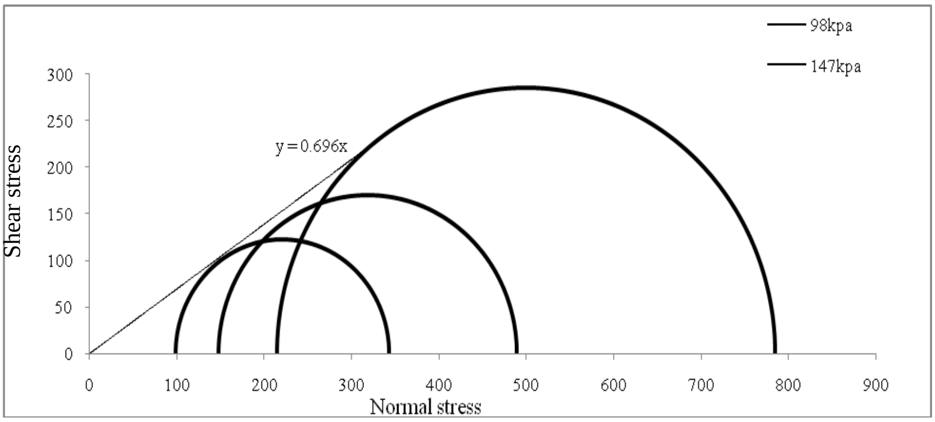

Figure 3 - Mohr circle.

From the above Mohr circle the value of cohesion (c) was found to be 0 and friction angle (φ) was found to be 34.83°

2.2 Soil slope profile

This study is carried out to investigate the effect of rainfall intensities, water table depths and soil permeability on the stability of a typical hill slope made of the soil collected from site. The effect of these three parameters on slope stability will be studied by evaluating the factors of safety of a typical slope under variable values of the three parameters i.e. rainfall intensities, water table depths and soil permeability. A typical slope is considered based on field observations of the Jorabat hill sites as shown below.

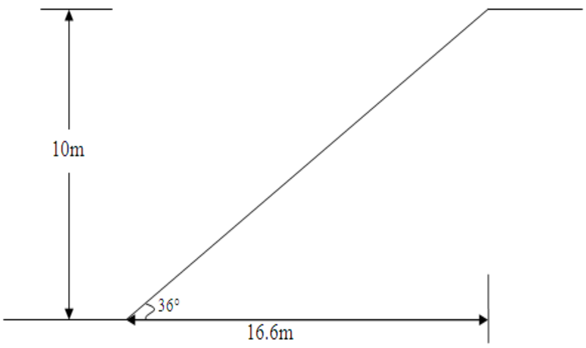

Figure 4: Soil slope profile

2.3 Stability Analysis of Slope

The stability analysis was carried out using **Swedish Circle method**. Factor of safety equation (1) was used to find the stability of the slope. (Ranjan,2005)

$$F = \frac{CL + tan\varphi \sum (N' = N)}{\sum T} \tag{1}$$

Here, N = Normal component, T = Tangent component, N' = Effective normal force acting against the slice base, C = Cohesion, φ = Friction angle and L = Length of failure surface.

2.4 Stability Analysis of Slope under Unsaturated Condition

Unsaturated soil has more than two phases and the pore-water pressure is lower than the pore-air pressure. In a situation where the water table lies below the ground surface, the soil nearer to the surface will be subject to negative pore-water pressures and possibly less saturation.

In other words, unsaturated soils regularly experience the instability of slopes during rainfall, particularly in tropical regions with frequent heavy rainfall events. Rain water gradually infiltrates and accumulates in the slope, inducing increase in pore water pressure which ultimately triggered slope failure. Rainfall intensity, soil permeability and depth of ground water table are some of the major parameters which have a significant impact on the fluctuations in pore-water pressures and the stability of residual soil slopes.

2.5. Determination of Hydraulic head in the slope

The pore water pressure head is not always linear. Changes in the environment causes a change in the negative pore-water pressure head profile. The pore-water pressures would decrease due to steady-state evaporation and increase due to infiltration (Fredlund,2012).

The non-linear distribution of pore water pressure due to infiltration can be calculated with the help of finite difference equation (3) by considering a column of unsaturated soil (Fredlund,2012).

$$h_{w(i)}=h_{w(i-1)}-\left\{\frac{4k_{wy(i)}+k_{wy(i+1)}-k_{wy(i-1)}}{8k_{wy(i)}^{2}}\right\}\times\frac{2\Delta y}{A}\times q_{wy} \quad (3)$$

Here, A is cross sectional area, h_w is hydraulic head, k_{wy} is water coefficient of permeability, q_{wy} is water flux and y is nodal point distance.

The hydraulic head distribution can be calculated by using finite difference equation (3) and by considering a soil column of unsaturated soil which is divided into n nodal points with equal spacing (Δy). It is assumed that the hydraulic head boundary condition at water table is zero and at the ground surface is unknown. However, the water flux (q_{wy}) is known and consistent throughout the soil column. The finite difference equation can be solved from known boundary conditions directly i.e. from water table.

The hydraulic head is calculated point by point from water table upto the ground surface. The coefficient of permeability (k_{wy}) is taken as constant for each iteration. For the first iteration the coefficient of permeability (k_{wy}) is taken as saturated coefficient of permeability (k_s). The hydraulic head (h_w) at every point is calculated from the finite difference equation. This iteration is repeated as long as the hydraulic heads do not have any significant change. Once hydraulic head (h_w) is know, pore water pressure head can be calculated by using equation (4) (Fredlund et al,1993).

$$h_w=h_g+h_p \quad (4)$$

Here, h_w is hydraulic head, h_g is gravitational head and h_p is pore water pressure head.

2.6 Determination of Coefficient of Permeability (k_{wy})

Soil Water Characteristics Curve (SWCC) of the soil is required to find the coefficient of permeability **(k_{wy})** but to determine SWCC is time consuming and expensive.

Hence to find the SWCC for my soil following paper was used: Lu, N.; Griffiths, D.V**. Profiles of Steady-State Suction Stress in Unsaturated Soils** [7].

Here, van Genuchten (vG) model which is very popular is used to describe the SWCC of unsaturated soils. The objective of the paper was to develop a method to determine the vG model parameter n and α (pore size parameter) to determine SWCC. To find out the pore size parameters n and α for the selected soil sample, residual degree of saturation was found out which was found out to be almost **5%.** For 5% Residual degree of saturation (S_r), the pore size parameter α was chosen as α = 0.1 (Lu, 2004).

A pre determined SWCC curve was selected for α = 0.1. After selecting a suitable SWCC , matric suction values are substituted from midpoint along the selected SWCC. With the help of **Childs and Collis-George (1950)** model, the coefficient of permeability based on random variation of pore size was found out by using equation (5) (Fredlund et al,1993).

$$k_w(\theta_i)=\frac{k_s}{k_{sc}}\times A_d\sum_{j=i}^{m}[(2j+1-2i)(u_a-u_w)^{-2}] \tag{5}$$

Here k_s is saturated coefficient of permeability, k_{sc} is calculated saturated coefficient of permeability, A_d is adjustment factor, m is total intervals and (u_a-u_w) is matric suction.

After finding the coefficient of permeability, finite difference equation was used to find the non linear distribution of pore water pressure.

2.7 Determination of water flux (q_{wy})

The climate of Guwahati is typically ‘tropical monsoon rainfall’ type, with high levels of humidity and heavy rainfall. Guwahati receives about 1600 mm annual rainfall (https://www.wunderground.com/weather/in/guwahati). A lot of rain (rainy season) falls in the months from April to October. Few rainfall data were collected from internet source and based on the rainfall data the study is carried out for the following rainfall intensities: 2.71mm/day, 10 mm/day, 20 mm/day, 30 mm/day, 50 mm/day, 100 mm/day, 150 mm/day, 200 mm/day and 300 mm/day.

This study assumes one dimensional steady state flow of the entire rainfall to the ground water table. As such the rainfall intensities are taken as intensity of water flux.

2.8 Saturated coefficient of permeability

The saturated coefficient of permeability (k_s) values for this study was assumed on the basis of permeability values of Guwahati hill soil in published literatures. The assumed saturated coefficients of permeability (ks) values are $3x10^{-4}$ m/sec, $3x10^{-5}$ m/sec and $3x10^{-6}$ m/sec (https://www.geotechdata.info/parameter/permeability).

2.9 Depth of water table

The maximum depth of water table was taken at 10m from ground surface which is at the base of the considered soil column to generate unsaturated condition. After that the depth was decreased from 10m to 7m to generate saturated condition from unsaturated condition.

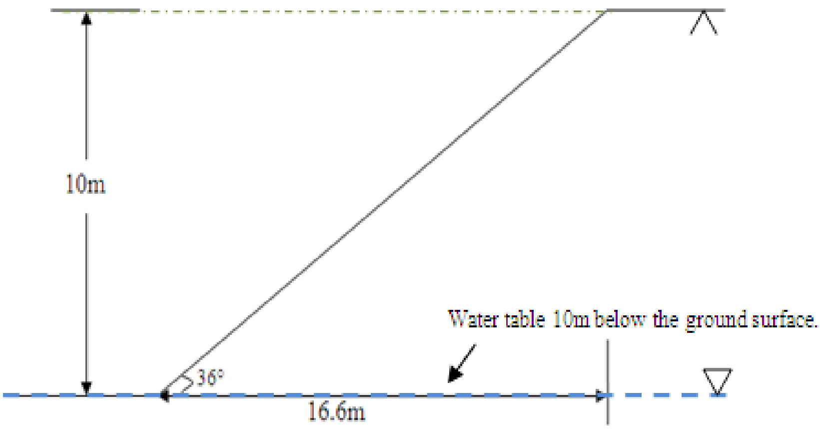

Figure 5: Soil slope profile with water table.

3. RESULTS

3.1 The coefficient of permeability (k_w) vs. Matric suction plots for different values of saturated coefficient of permeability (k_s):

3.2 The SWCC curve for different coefficient of permeability (k_w) was found out with the help of Childs and Collis-George (1950) model and the results are shown below.

3.1.1 The Coefficient of permeability (k_w) vs. Matric suction plots for the saturated coefficient of permeability (k_s) value of $3x10^{-4}$ m/sec is shown:

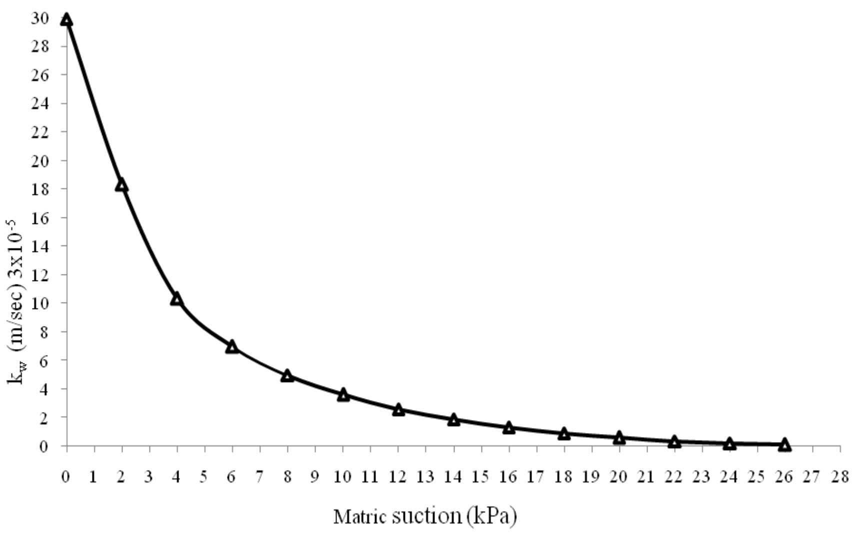

Figure 6 - Coefficient of permeability vs. Matric suction for saturated coefficient of permeability $3x10^{-4}$ m/sec.

Similarly, Coefficient of permeability (k_w) vs. Matric suction plots for other saturated coefficient of permeability (k_s) were found out. After plotting the curve the values of coefficient of permeability were used in further calculations.

3.2 Pore water pressure head distribution for different rain intensities:

The non-linear distribution of pore water pressure due to infiltration was calculated with the help of finite difference equation by considering a column of unsaturated soil. Various rain intensities (2.71mm/day, 20 mm/day, 30 mm/day, 50 mm/day, 100 mm/day, 150 mm/day, 200 mm/day and 300 mm/day) were considered to find the non-linear pore water pressure head distribution.

3.2.1 Pore water pressure head distribution with saturated coefficient of permeability $3x10^{-4}$ m/sec:

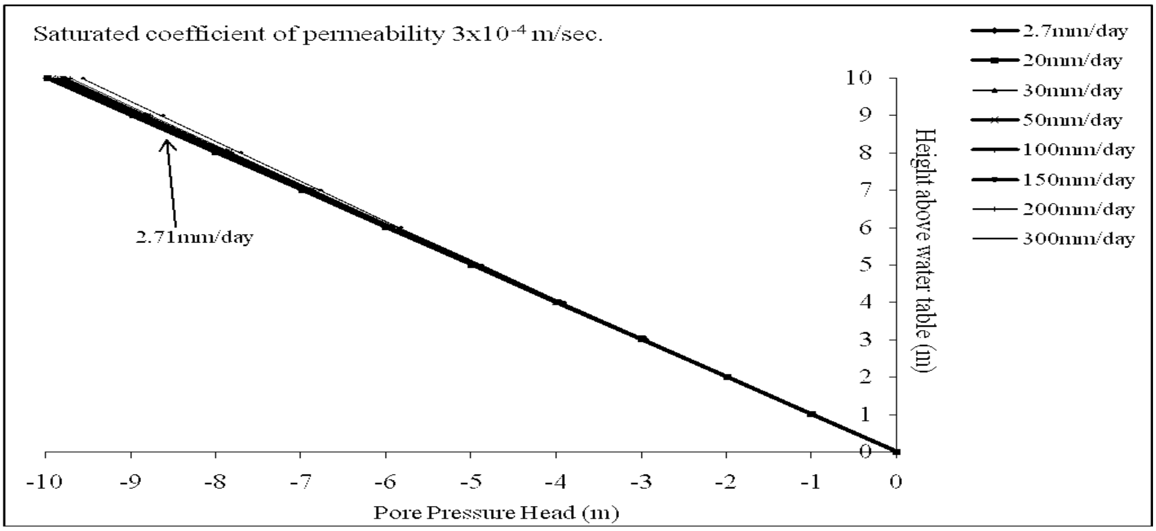

Figure 7: Pore pressure distribution head for different rain intensities for saturated coefficient of permeability $3x10^{-4}$ m/sec.

It is observed that the pore water pressure head increases towards a more negative pore pressure head from the water table to the ground surface. This means that with high intensity rains the soil loses its matric suction i.e. the additional strength diminishes.
It was also seen that rain with low intensities does not have much effect on the negative pore water pressure. This means that at low intensities the slopes will not loss its stability.

3.2.2 Pore water pressure head distribution with saturated coefficient of permeability $3x10^{-5}$ m/sec:

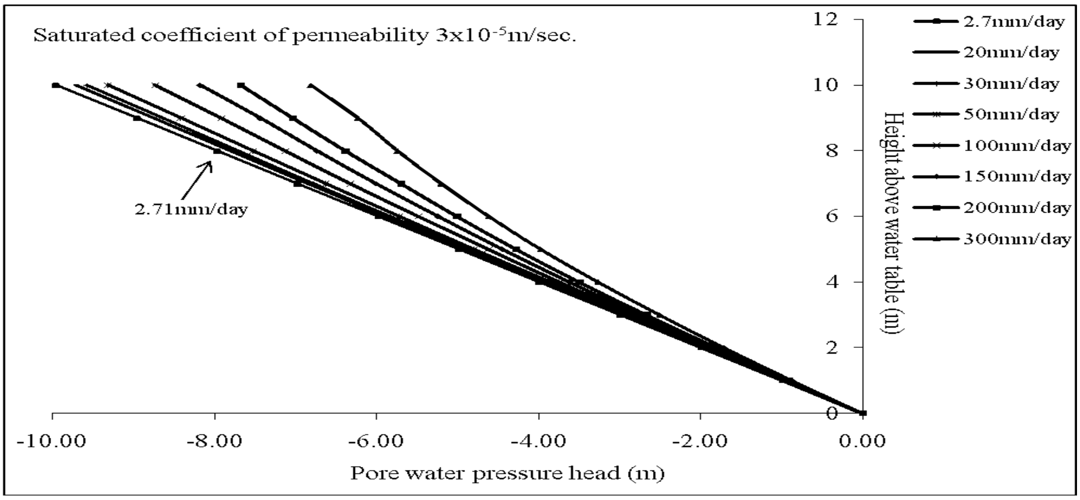

Figure 8: Pore pressure distribution head for different rain intensities for saturated coefficient of permeability $3x10^{-5}$ m/sec.

Here also similar things were observed that is the pore water pressure head increases towards a more negative pore pressure head from the water table to the ground surface. This means that with high intensity rains the soil loses its matric suction i.e. the additional strength diminishes. It was also seen that rain with low intensities does not have much effect on the negative pore water pressure. Moreover it was also observed that the reduction of pore water pressure was more than coefficient of permeability $3x10^{-4}$ m/sec.

3.2.3 Pore water pressure head distribution with saturated coefficient of permeability $3x10^{-6}$ m/sec:

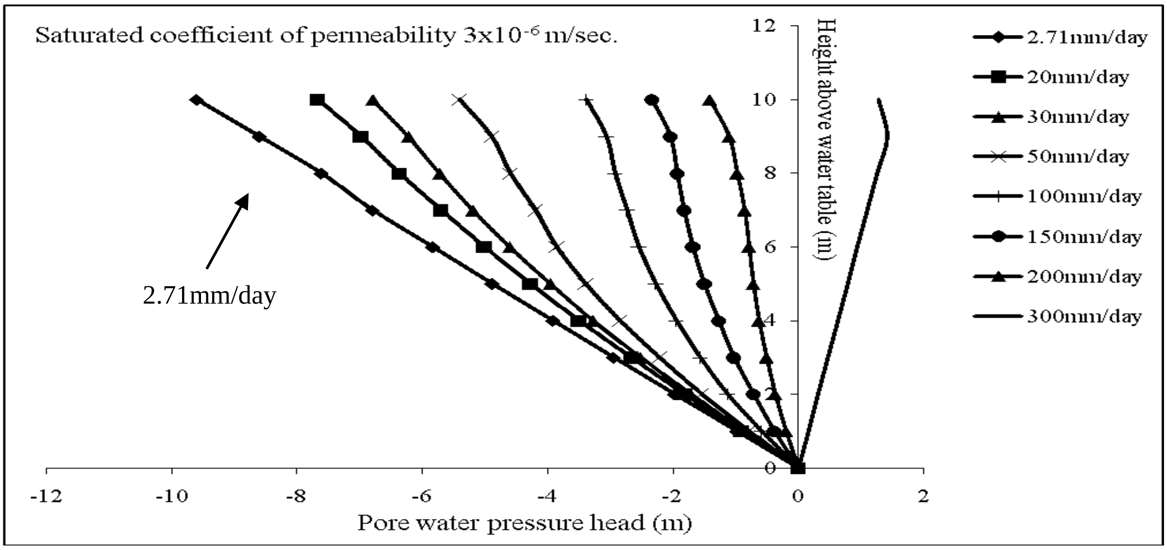

Figure 9: Pore pressure distribution head for different rain intensities for saturated coefficient of permeability $3x10^{-6}$ m/sec.

Here also similar things were observed that is the pore water pressure head increases towards a more negative pore pressure head from the water table to the ground surface. This means that with high intensity rains the soil loses its matric suction i.e. the additional strength diminishes. It was also seen that rain with low intensities does not have much effect on the negative pore water pressure. Moreover it was also observed that the reduction of pore water pressure was more than coefficient of permeability $3x10^{-4}$ m/sec and $3x10^{-5}$ m/sec.

3.2.3 Discussion:

When the saturated coefficient of permeability was high (i.e. $3x10^{-4}$ m/sec), the pore water pressure head decreased very slowly with increase in rain intensity. This happened because excess pore water pressure got dissipated and soil strength was maintained and hence the pore pressure distribution head curves were almost similar for each rainfall intensities.

With less saturated coefficient of permeability (i.e. $3x10^{-6}$ m/sec) the pressure head dropped very rapidly with increase in rain intensities. This happened because the excess pore water pressure was unable to dissipate due to low permeability which reduced the soil strength.

3.3 FOS vs. Rainfall intensities at various water table depths:

Slope with different water table depths were analyzed for different rainfall conditions. The results are shown below.

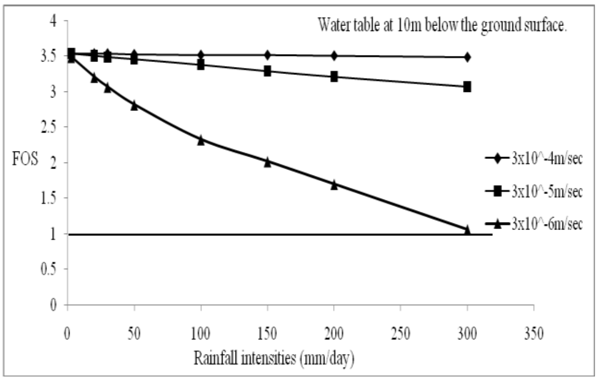

Figure 10: FOS vs. rainfall intensities when water table is at 10m below the ground surface.

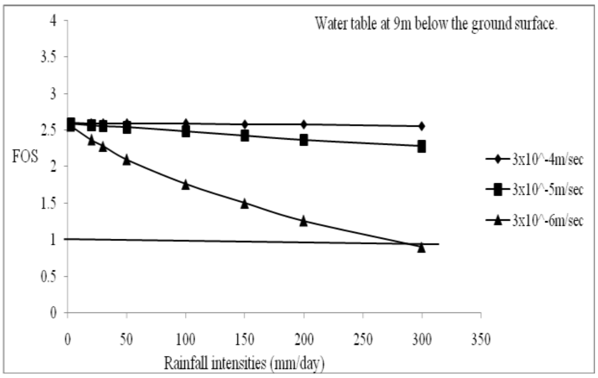

Figure 11: FOS vs. rainfall intensities when water table is at 9m below the ground surface.

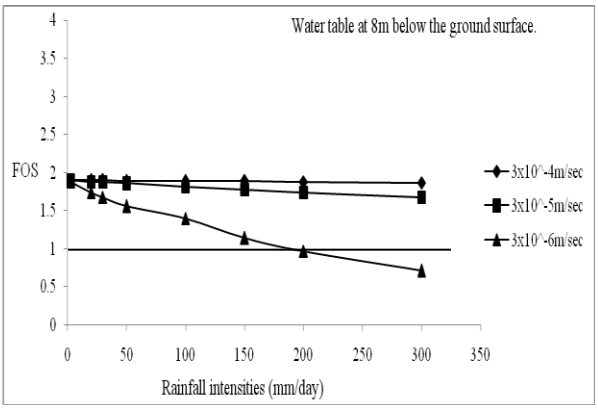

Figure 12: FOS vs. rainfall intensities when water table is at 8m below the ground surface.

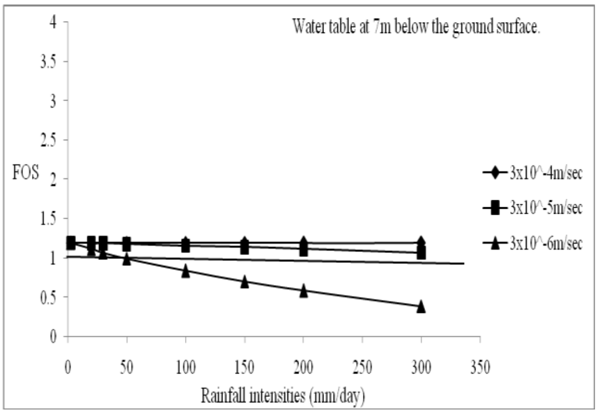

Figure 13: FOS vs. rainfall intensities when water table is at 7m below the ground surface

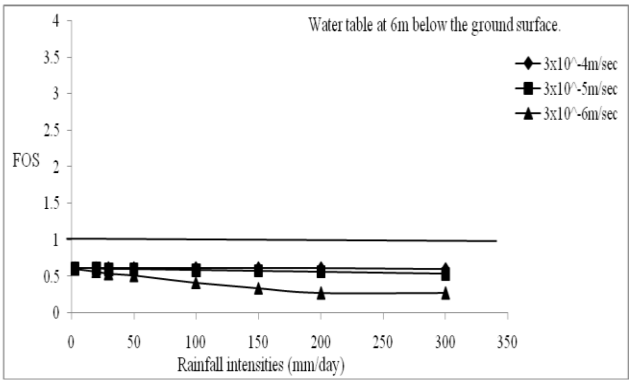

Figure 14: FOS vs. rainfall intensities when water table is at 6m below the ground surface.

Discussion:

From all the graphs it is observed that with increase in rain intensities the FOS gets reduced. This means that at higher rain intensities the negative pore water pressure (suction) gets reduced due to infiltration of rainwater into the slope which makes the slope unstable.

Also, at 6m water table depth the slope with saturated coefficient of permeability $3x10^{-6}$m/sec, $3x10^{-5}$m/sec and $3x10^{-4}$m/sec failed even at 0 rain intensities i.e. the slope was completely saturated when 6m water table depth was considered.

3.4 FOS vs. Water Table Depths at various Rain Intensities:

Slope with different coefficient of permeability were analyzed for different water table depths. The results are shown below:

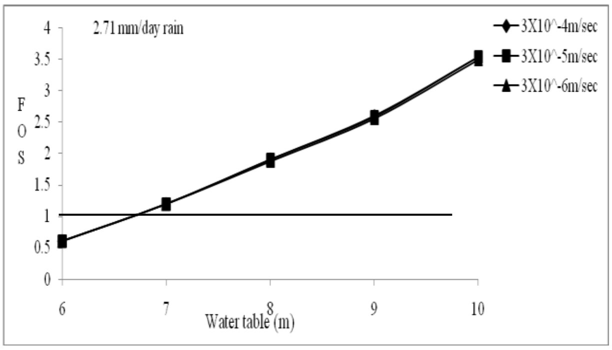

Figure 15: FOS vs. water table depth considering 2.71mm/day rain.

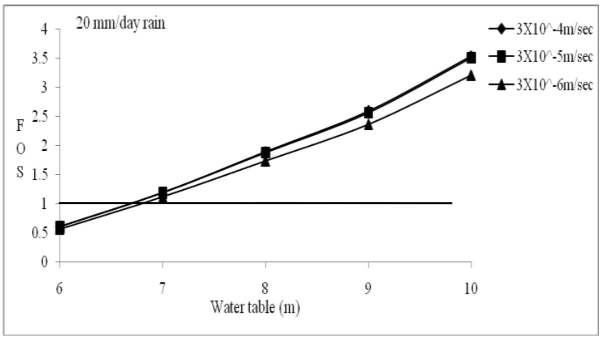

Figure 16: FOS vs. water table depth considering 20mm/day rain.

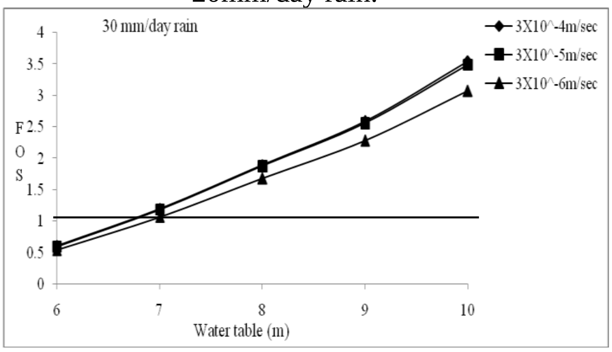

Figure 17: FOS vs. water table depth considering 30mm/day rain.

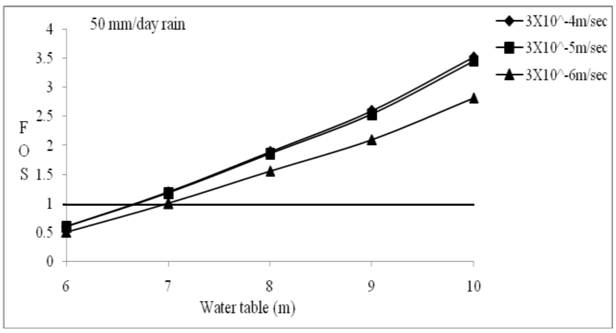

Figure 18: FOS vs. water table depth considering 50mm/day rain.

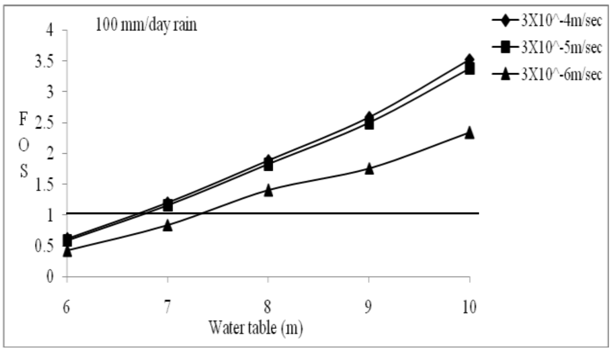

Figure 19: FOS vs. water table depth considering 100mm/day rain.

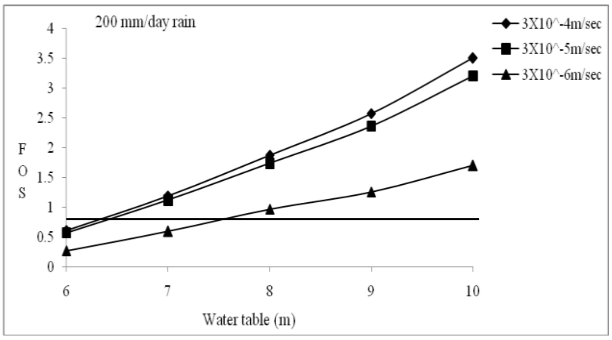

Figure 21: FOS vs. water table depth considering 200mm/day rain.

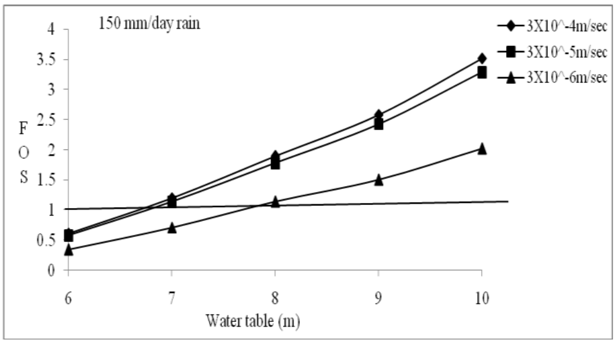

Figure 20: FOS vs. water table depth considering 150mm/day rain.

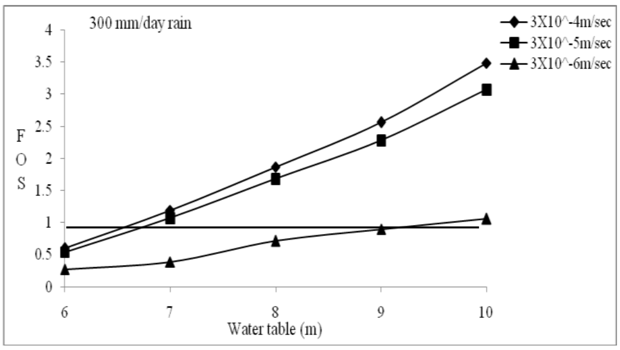

Figure 22: FOS vs. water table depth considering 300mm/day rain.

Discussion:

As water table depth from ground surface was decreased, the factor of safety got reduced to some extend for all the soil type. When water table depth is reduced, the thickness of unsaturated soil above the water table reduces which reduces the additional shear strength (due to suction) and ultimately leads to slope failure. It was also seen that with a sufficient depth of water table the slope remains stable even at higher rain intensities.

4. CONCLUSIONS:

The major key findings of the research work are listed below:-

It was found that as water table depth was decreased, the factor of safety got reduced for all the soil type, the effect being more prominent in case of soil with lower permeability. The slopes were found to be critical at a water table depth of about 70% of slope height.

Also, with the increase in the intensity of rainfall the FOS of all slopes are found to have decreased. The decrease in FOS with increase of rainfall intensity is relatively low for more permeable soil, with FOS falling by maximum of 12% when rainfall was increased from 2.7mm/day to 300mm/day intensity. But for soil with low permeability the FOS dropped by about 60% with increase in rainfall from 2.7mm/day to 300mm/day.

The stability condition of the slope under steady state infiltration of rainwater was found have worsened with the decrease in coefficient of permeability of the slope soil. At a 7.0m depth of water table, as the rainfall was increased from 2.7mm/day to 300mm/day, the FOS was found to have decreased non-linearly by 1%, 11% and 65% respectively with increase in rain intensities.

The soil slope is observed losing its shear strength with increase in rain intensities. This is the reason why landslide occurs during heavy rainy days.

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