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Failure Mechanism Of An Unsaturated Slope In The Nilgiris District, Tamil Nadu, India

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ABSTRACT: Landslides are one of the natural disasters that cause an enormous amount of loss to both the individual and society. The Nilgiris in the Western Ghats are highly vulnerable to landslides where the triggering factor is rainfall. Around 76% of landslides occur due to rainfall. The failure mechanism of an unsaturated soil slope is presented in this article. The soil samples were collected from the Nilgiris location, where a landslide already occurred in 2009. Direct shear tests were performed to attain the shear strength parameters of the silty sand. The effect of infiltration on the unsaturated slope was analysed using coupled stress/ pore water pressure analysis from SIGMA/W. The stability of the slope was analysed using SLOPE/W software. The results show that the safety factor is not constant throughout rainfall period, as done in conventional methods and it varies depending on the period of infiltration and the matric suction of the soil. This analysis provides a realistic approach to calculating the factor of safety when compared with the other conservative methods.

Keywords: landslides, unsaturated slope stability, matric suction, rainfall, failure mechanism

1) Introduction

Landslides are defined as the forth and down motion of a mass made up of rocks and soils as a result of natural or artificial causes. The major reasons for the cause of landslides in India are rainfall and earthquake. Especially in the Western Ghats, rainfall is the main triggering factor that induces flow-type landslides. Residual soil slopes with steep angles which have a higher factor of safety (FoS) during dry periods fail during monsoon seasons [11]. Generally, an unsaturated condition state is created when the stratum is above the water table or due to infiltration due to gravity [1]. Since it is above the water table level, the pore water pressure developed is negative and varies into positive below it. The negative pore pressure developed is also called as suction [15] which is one of the reasons for the increase in shear strength of the soil.

The soil system has three phases namely, solids, water, and air, in addition to this, in unsaturated soil, the air-water interface was introduced by [6]. Due to surface tension acting on the soil, they are held together enhancing the cohesion and resulting in an increase in shear strength [11]. Each soil has a different response to the behaviour of unsaturation, for example Sand does not undergo much of a change due to its high permeability, whereas high plastic clay which swells when saturated shrinks during the dry period posing a severe issue. In the same way, loose silt crumble when saturated will behave differently when unsaturated. This kind of soil is at high risk for failure during intense rainfall as they tend to lose strength and collapse.

When analysing the slope stability under saturated conditions, the FoS is considered constant throughout the time. But in reality, it is not constant and it varies with time due to matric suction and increase in Ground Water Level (GWL), which changes the soil stratum from unsaturated to saturated condition [7] [8] [16] .[7] conducted numerical analysis on a slope for sand and clay by varying the angle as 45° and 70° for both saturated and unsaturated conditions. It was found that while the FoS remained constant for saturated conditions, it reduced in unsaturated conditions. In the same way [12] used FEM and FDM to study the stability of slopes during dry and wet periods, it was found that while the slope was stable during the dry period became less stable during the monsoon season. The unsaturated behaviour of sea clay was done by [10] and it was found that the FoS reduced considerably and became constant at 48hours. It is because, during the dry period the GWL lowers which makes the soil at shallow depth increase in the shear strength, which in turn increases the FoS, but during monsoon season, the GWL rises near the ground surface (GS) and decreases the shear strength of the soil and makes the slope unstable. Hence there is a need to study the unsaturated behaviour of the slope which varies with the time of rainfall and type of soil.

Even though there are many studies to calculate the variation of stability of the slope in unsaturated behaviour, most of them are hypothetical slopes. Here we are going to consider an actual slope that failed previously during extreme rainfall. This study presents the results of unsaturated and saturated behaviour of a slope in The Nilgiris district in Tamil Nadu which underwent failure at the toe area during 2009 rainfall. The Geostudio software was used to determine the disparity between the stress and stability of the slope under unsaturated and saturated conditions. The change of FoS with respect to the time was analysed for the soil that was collected from the site and analysed in the laboratory.

2) Study area

The analysis of the stability of an unsaturated slope was performed on a particular hill in The Nilgiris district in Tamil Nadu, India. This district is at the border of Tamil Nadu surrounded by Karnataka in the North and Kerala in the west. The Nilgiris hills are a highland that rises above the Coimbatore uplands. It slopes sharply into the Mysore plateau to the north and gradually merges with the Western Ghats to the north-west, west, and south[14]. Over the entire stretch of the road network, Mettupalayam-Conoor-Ooty and Ooty-Kothagiri roads are more prone to landslides [13]. Our study area falls in the former stretch in Ootacamund (Ooty), where the slopes are gentle and has soil cover of a predominant thickness due to weathering [14]. This area consists of Charnokite Gneiss complex overlain by lateritic soil up to a considerable depth.

The Nilgiris are more susceptible to landslides in the entire Western Ghats range [4]. The casual factors for the occurrence of landslides are rainfall and many anthropogenic activities that disturb the stability of the slope. The district receives rainfall during both north-east and south-west monsoons from July to December. The average annual peak rainfall received in the past 40 years was 2007 of intensity 2332mm. The study area Elk hill which is present in Manjur underwent earth flow at the toe of the slope during the intense rainfall in November 2009. This slope has been prone to landslide even before that (Fig 1) The irregular slope cutting for the cultivation of tea led to this disaster where many houses were buried and human lives were lost [13]. There are chances that this slope could fail in the future event of heavy rainfall. Hence there is a need for analysing this particular hill for its stability over the period of time during and after the rainfall.

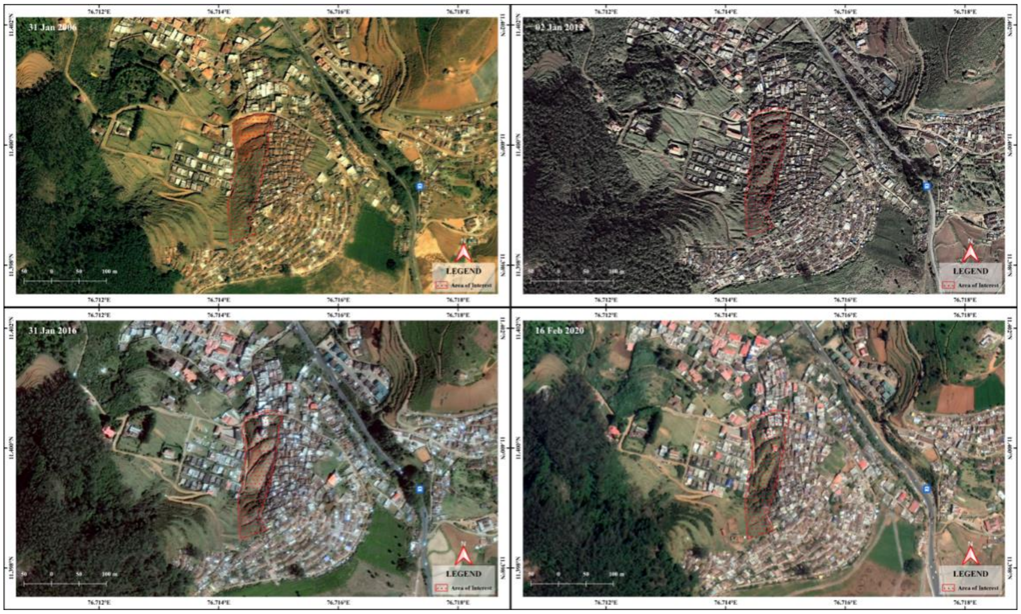


Fig. 1. Historical image of our study area (Elk hill)

3) Methodology

The slope instability which occurs due to rainfall is due to the following process (i) When the rainfall occurs the GWL increases (ii) The pores are filled with water which increases the pore water pressure (iii) The shear strength of the soil which is the governing parameter for the stability of the slope decreases failing the slope. The FoS is used to find whether the slope is stable or unstable and it is defined as available shear strength to required shear strength. While considering the saturated soil mechanics, the FoS is derived considering the effects of pore water pressure alone, the unsaturated soil mechanics considers both pore water and air pressure. The FoS (Eq 1) for saturated slope is obtained after Coulomb's equation for shear strength as follows

$$FoS = \frac{C + \sigma' tan\varphi}{C_m + \sigma' tan\varphi_m} \quad (1)$$

C is the cohesion and φ is the angle of internal friction, whereas C_m and φ_m are the mobilized cohesion and internal friction of the soil.
σ' is the effective normal stress which is (σ-u_w) for saturated soil, replace $\sigma' tan\varphi$, with (σ-u_a)tanϕ +(u_a-u_w)tanϕ^b for unsaturated soils.
σ is the total normal stress.
u_w is the pore water pressure and u_a is the pore air pressure which is responsible for matric suction.
The increase in the shear strength can be considered as the cohesion parameter; hence the shear strength can be rewritten as

$$S_m = C + (\sigma - u_a tan\varphi') \quad (2)$$

C is the cohesion parameter than includes the matric suction (i.e: c'+(u_a-u_w)tanϕ^b)

It is to be noted that the stability of the slope is not constant throughout the period of rainfall. Before the monsoon season or after a certain period of rainfall the soil becomes unsaturated near the ground surface. The variation in the suction of soil depends on the environmental changes, GWL, vegetation, and permeability of the soil [5]. The change of suction with respect to water is presented using the Soil Water characteristic Curve (SWCC). This curve represents how the suction reduces with an increase in the water content in the soil. This can be used to calculate the reduction in the shear strength relating to the matric suction.

There are many software used to analyse the unsaturated behaviour of the slope. Eg, Plaxis, Geostudio, Abaqus etc.. Here in this article, a combination of two packages in the Geostudio software has been used to analyse the strength variation in soil. The detailed procedure is provided in [7] where the unsaturated behaviour of the sand and clay was studied using Finite Element Analysis. Here the in-situ stress was analysed using SIGMA/W followed by the variation of pore water pressure with respect to time and rainfall infiltration was obtained by coupled stress/ pore water pressure analysis in SIGMA/W. Lastly, the stability of the slope was calculated using Morgenstern–Price in SLOPE/W.

4) Results and Discussion

The slope of our interest which is present in south-west of The Nilgiris failed during the extremely intense rain in November 2009. The study area Elk Hill which became unstable during the episode of continuous rainfall for three days destroyed human lives and properties. The fact to be noted is that the failure occurred at the toe of the slope, where the angle of the slope was around 15°. When the reduction in matric suction is very rapid, it could result in shallow failure at the toe of the slope [9]. This indicated that even a gentle slope can undergo landslides.

The slopes are always considered completely saturated while analysing the stability when rainfall is the triggering factor. But that is not the case for the real-time analyses. The variation of climate overall the year plays an important role in the stability of the slope. The GWL which rises to the surface during the monsoon season lowers to a certain depth after a certain period of time due to matric suction. Following that during the dry period, the GWL lowers even further increasing the shear strength which in turn increases the stability of the slope.

This section provides the details of the results obtained from laboratory tests for analysing the FoS. Initially, soil samples were collected from the study area and basic tests were performed to classify the soil using [2]. The basic properties of the soil are shown in Table 1. Followed by that, direct shear (DST) was conducted under the consolidated drained (CD) condition to obtain the strength parameters of the soil according to [3].

Table 1 Basic and engineering properties of silty sand

Layer	**Soil type**	**C(kPa)**	**ϕ**	**ϕ^b**	**E(kPa)**	**μ**
1	Silty sand (from laboratory investigation)	21	21	10.5	183000	0.334
2	Sand with silt (from laboratory investigation)	40	30	0	1022000	0.3
3	Weathered Charnockite (from MASW test)	80	34	0	1015000	0.28

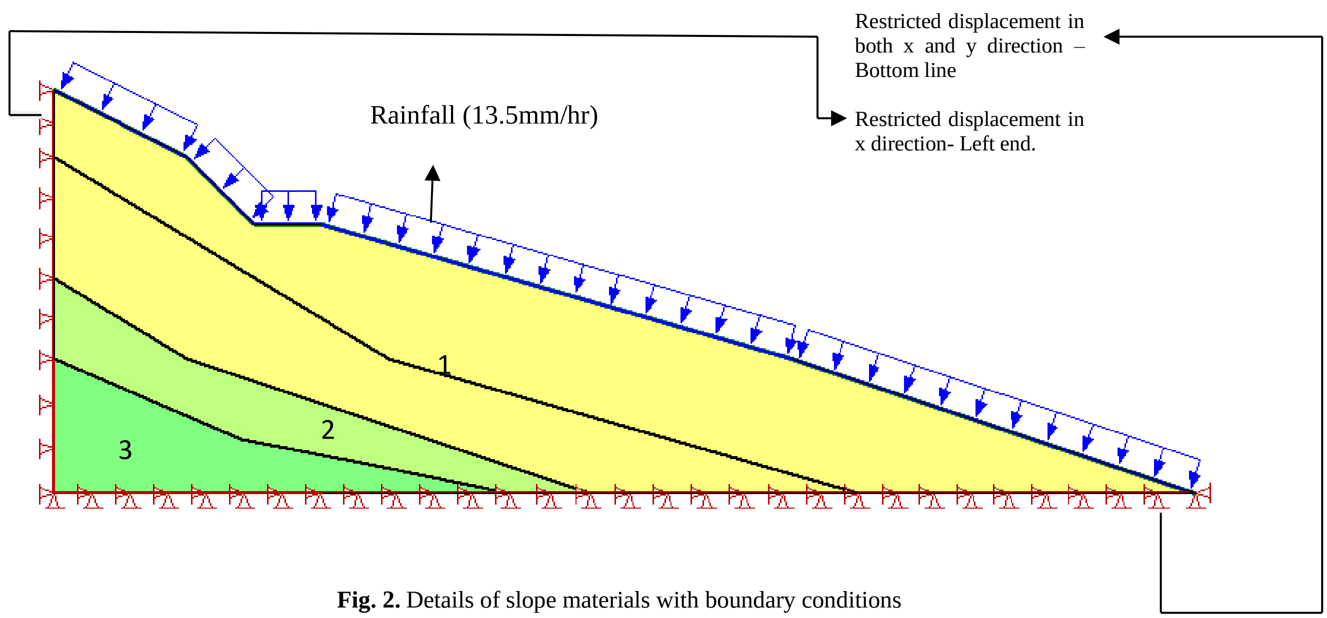
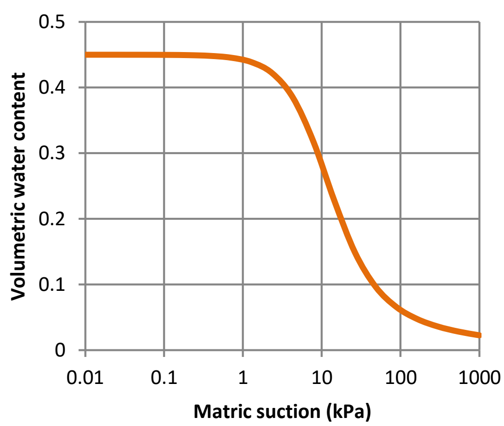
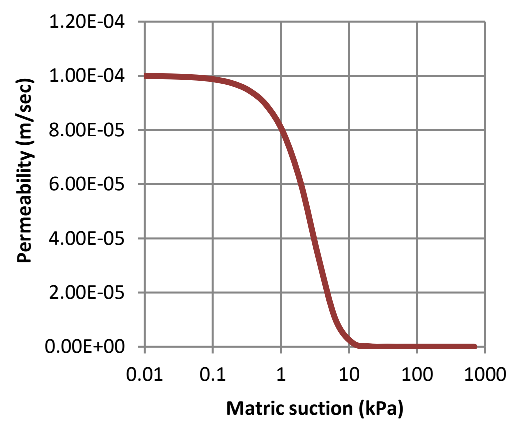


Fig. 2. Details of slope materials with boundary conditions

The stability of the slope which failed at the toe area alone is considered here. The average angle of the slope is considered between 15-20°. The shallow silty sand layer was alone considered as unsaturated (Fig. 2). The details of the deeper layers were obtained from the results of Multichannel Analysis of Surface Waves (MASW). The initial in-situ stress was obtained using In-situ stress analysis from SIGMA/W, where the initial water table was provided at 5m from the ground level. This serves as the parent analysis for further calculations. Followed by that to know the variation of the pore water pressure in the required period of time, Coupled stress/PWP change analysis was performed using SIGMA/W. The rainfall intensity was provided as 13.5mm/hr based on the rainfall received during the year 2009. It is to be noted that the rainfall was provided as a hydraulic boundary condition created using water flux, which can be considered either constant or varying over a different time interval. The SWCC (Fig. 3(a)) and permeability (Fig 3(b)) of the soil were estimated from the functions provided in SIGMA/W (Fig. 3).



(a)



(b)

Fig. 3. (a) SWCC curve (b) Permeability curve for silty sand

The cohesion and angle of internal friction of the silty sand were obtained using the direct shear test in the consolidated drained environment (Fig. 4). For saturated conditions the GWL raised to the ground surface and ϕ^b was considered zero. For the unsaturated condition, the variation of PWP with respect to time was obtained from the rainfall intensity provided. Finally, the stability of the slope was calculated using the SLOPE/W, Limit Equilibrium method (Morgenstern Price Method). The surcharge load was used to incorporate the load from buildings present in our study area. It is noted that for fully saturated conditions, the FoS was constant all over the period of rainfall whereas, it reduced from 1.016 to 1.009 during the period of rainfall as shown in Fig. 5.

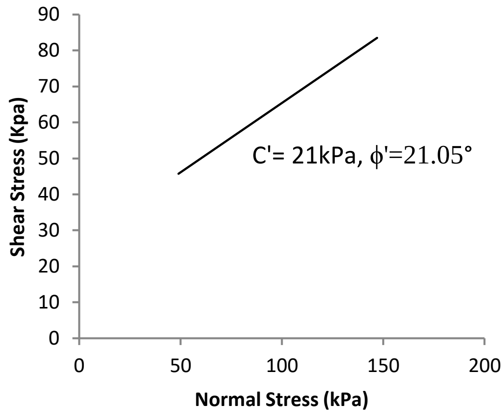


Fig. 4. Shear strength parameters obtained from the direct shear test

The results for unsaturated soil obtained agree well with the results obtained by [7], in which stability decreased during the rainfall and increased after the event for sandy soil and remained constant for clayey soil. Since our soil is silty sand, the FoS decreased considerably up to 10 hours and still continued to decrease up to 48hours but at a very less rate. The reduction of stability agrees to some extent with the sandy soil, because the critical FoS was observed around 10 hours which is the same in our case too (Fig 5). But it does not increase post the episode of rainfall but rather decreases further. It is to be noted that the stability calculation was done only for two days it may increase post this period of consideration. Whereas the stability remained constant for the saturated condition for both initial GWL and when the water table raised to 1m below the GS. This shows how in real time the stability is not constant over time and varies with respect to time.

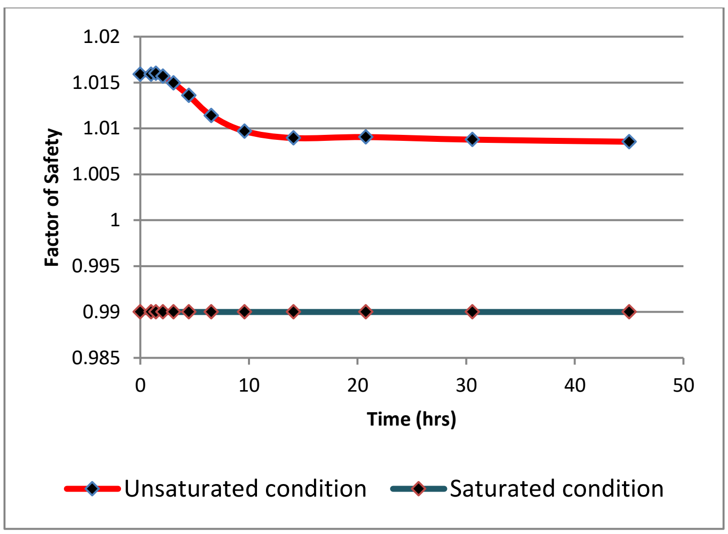


Fig. 5. Variation of FoS with time for saturated and unsaturated condition

5) Conclusion

The unsaturated and saturated behaviour of silty sand on a gentle slope of Elk hill was analysed using Geostudio software. The variation of FoS under saturated and unsaturated conditions were studied with respect to time. For saturated conditions, as the GWL elevated near the GS (1m below GS), the shear strength of the soil reduced which resulted in the reduction of stability of the slope to 0.99. On the other hand, for unsaturated soil analysis, the additional parameter matric suction played an important role in calculating the shear strength. Due to this, there was variation in the FoS at the beginning, during and after the rainfall period providing the real-time behaviour of the slope instability. Before the rainfall, the GWL was at 5m below the GS and had FoS of 1.016 and reduced during the rainfall and reached critical instability at 10 hours to FoS of 1.009 which is at the verge of failure. The failure of this slope occurred after continuous precipitation for three consecutive days. With this analysis we can conclude that the slope was on the verge of failure on the second day itself. It has to be noted that the slope had an angle of 15°, which is very gentle. Generally, gentle slopes are mostly stable, but this slope failed during the event of extreme rainfall due to reduction of matric suction. Thus the behaviour of unsaturated soil analysis provides more realistic results than considering the soil as completely saturated. The unsaturated slope analysis can be used appropriately in real-time applications such as early warning systems, reactivation of landslides, etc.

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