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Stability Analysis of Rainfall-InducedLandslide Using Numerical Modelling

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Abstract. Landslides triggered by rainfall are very frequent in India, especially in the Himalayanregion. despite various attempts, they are still occurring and causing heavy loss of life and civilization. As it is known that natural calamities are inexorable but the reduction in damage caused by them is possible., through preventive measures. For the prevention of landslides, we need to adopt various mitigation techniques but before that, an analysis of a slope's stability is required to find a critical surface. In this study, a failed slope is considered in the Shimla districtof Himachal Pradesh, and its stability before and after rainfalls of different intensities (throughoutthe year) was studied using numerical modelling. The repeated slope failure necessitates a numerical approach to comprehend the instability components because there have been no previous stability investigations of this slope failure. According to the results, the failure of this slope was primarily caused by rain during the monsoon. Before rainfall, the slope's F.O.S. was more than 1, indicating that it was stable; but, following rainfall, it drops to 0.801,0.578, and 0.576, respectively. This study further in the future can be used in designing a landslide early warning system.

Keywords: Slope stability, rainfall-induced landslides, GeoStudio, Slope/W, Seep/W.

1 Introduction

The Himalayas is one of India's most prone areas to landslides, making it the ideal location to research all types of mass movements and slope failures that occur in nature. The Himalayas Mountain belt is geologically younger and comprises tectonically unstable geological formations. Himalayan province alone contributes to nearly 30% of the world's total loss due to landslides (Li, 1990; Dahal et al, 2009). Rainfall-induced landslides are most common in the Himalayan region, especially in the monsoon season which results in heavy loss of life and property. The principle behind rainfall catalysing landslide is that when rainfall water infiltrates via pores present in the soil, it leads to the generation of positive pore water pressure which leads to decrement in effective stress thus resulting in a reduction of soil's strength and ultimately leading to slope failure or landslide. Himachal Pradesh is one of the most landslide-prone states in India, mostly because of the deadly combination of (Unstable Himalayan formation and heavy rainfall). To prevent the loss due to rainfall-induced landslides, we have to study the stability criterion for which numerical techniques have been proven a reliable tool to study the stability of slopes and the effect of rainfall on them.

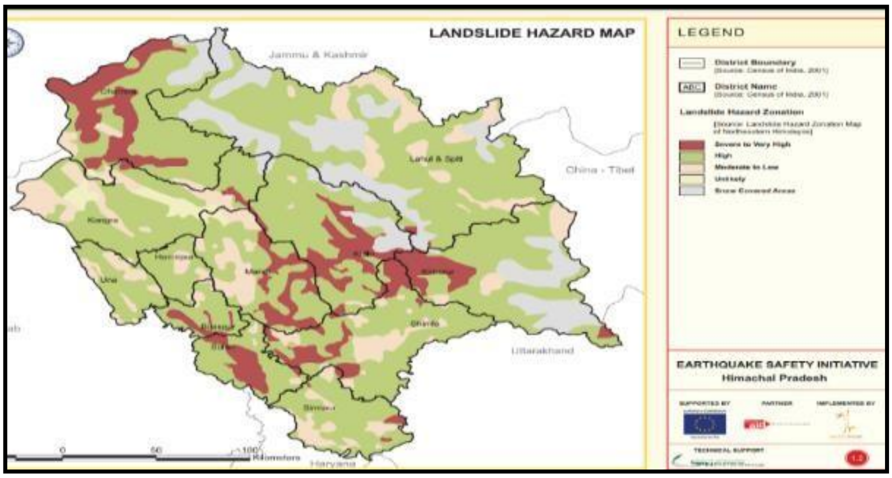

Fig. 1. Landslide Hazard Map of Himachal Pradesh (Source: HPSDMA)

[1] Kotropi soil is tested chemically and geotechnically as part of the preliminary investigation. Helical soil nails with a diameter of 20 mm and a length of 6 m are used to stabilise the failed slope in the presence of favourable prevailing soil conditions. Determining the factor of safety using the limit equilibrium approach, which is additionally checked by numerical modelling using a finite element subroutine PLAXIS 2D. [2] The inherent qualities of soil materials that affect the stability of the current slope have been identified through the geotechnical study. To measure the connection between precipitation and slope collapse, an event-specific antecedent rainfall threshold has been proposed. To show the situation of pre- and post-failure stability of the slope,a two-dimensional limit equilibrium method has also been used. [3]A tiny catchment in Niihama city on Shikoku Island in western Japan was chosen because it had a historyof seven slope failures brought on by severe rainfall brought on by a storm in October 2004. Following extensive fieldwork and a series of laboratory experiments to calculate hydro-mechanical parameters in saturated and unsaturated conditions, seepage and slope stability modelling of these slope failures were carried out in the GeoStudio environment using the precipitation data of 1920 October 2004. In silty sand, the pore water pressure was quickly changing, according to the seepage modelling results, and larger topographic hollows were shown to have greater maximum pore water pressures.[4] has carried out an examination of slope stability using the Mohr-Coulomb and Hoek-Brown failure criteria. The comparable traits for the slope stability analysis are identified in this work. It is established that employing an inadequate approximation of the confining stress causes major mistakes in the present conversion relationships.[5] The coupled model is established between internal erosion and unsaturated flow. It investigates how internal erosion affects slope stability and pore water pressure profiles. There is parametric research on hydraulic and erosion parameters. The findings of the numerical example demonstrate that internal erosion occurs mostly in the area inside the wetting front, which speeds up the wetting front's advance and reduces slope stability.[6] investigates rain-soaked soil-related landslides that occurred in Seoul, Korea. Used laboratory, field, and numerical methods to study landslides brought on by rainfall. The utilised approach is suited for simulating landslides, according to a

significant correlation between the numerical results and the analysed data.[7] Even in coarse-grained soils, pore pressure builds up because the movement does not allow for volume change, which results in the liquefaction of the soil mass. This results in a reduction in soil shear strength, making the slope unstable.[8] The main flaw of limit equilibrium approaches, which only satisfy statics equations, is that they fail to take strain and displacement compatibility into account. This has two detrimental effects. One is that it is unable to account for local differences in safety factors, and the second is that computed stress distributions are frequently erroneous.

As there have been very few studies conducted in this area, more research is required to demonstrate the viability and applicability of numerical modelling in this Himalayan Mountain belt region, which is particularly vulnerable to rainfall-induced landslides. To minimise the limitations of limit equilibrium analyses, the Morgenstern–Price method is used in this study which satisfies both force and moment equilibrium. The goal of this study is to determine whether numerical modelling can accurately simulate landslides in the Himalayan region under consideration, where rainfall is the primary cause of landslides. This study explains the role of rainfall in slope instability, which can be used to develop a rainfall-intensity duration model.

2 Study Location

The research area is close to Mishnu road near Bhajawa village of Shimla district of Himachal Pradesh, India (Fig.2). The place is shown in the satellite image retrieved below by Google Earth. The area is vulnerable to landslides brought on by rains.

Fig. 2. Showing the location of the research area

2.1 Description of Study Area

To conduct the study of stability analysis a failed slope's data is taken from the Bhukosh Portal of the Geological Survey of India which is 30-33 m (on a 1/3 scale) in height with a slope angle of 43° (Fig.3). This slope has already failed during the monsoon season of the year 2016. Loose and heavily worn quartz mica schist and gneiss were found on the slope. The grain size distribution of slope matter is nonuniform and contains rock pieces embedded in the soil.

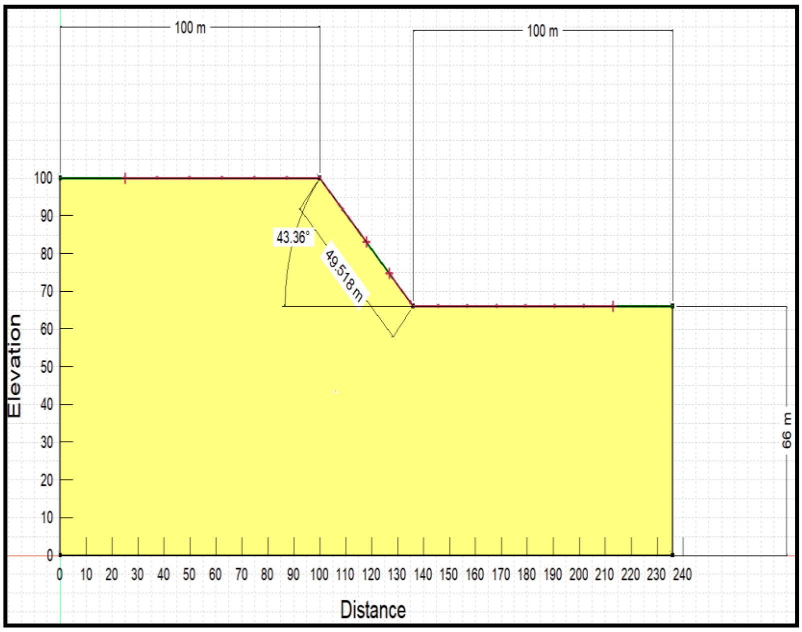

Fig. 3. Geometry of Study Slope

2.2 Material Properties and Tests

The landslide was separated into three equal portions along the landslide slope to collect samples from the site: the higher, middle, and lower sections. At various depths of 0.5 m, 1 m, and 1.5 m, soil samples are taken from each area using the core cutter method in open pits. Compaction, direct shear test as per IS 2720(Part 13):1986, and consolidometer tests are only a few examples of experiments that are carried out. Modelling in Finite Element analysis is based on the outcomes of these parameters. Results of these tests give the value of the Natural moisture content as 12%, Saturated unit weight of soil as 16 kn/m^3, Cohesion as 12 kn/m^2, and Angle of internal friction 32° under UU Condition of the triaxial test as per IS 2720(Part 12):1981, and Coefficient of permeability as 0.0026 m/hr.

2.3 Rainfall Characteristics

The southwest monsoon, which is a result of the orographic precipitation conditions, is primarily responsible for the rainfall in this research area. The southwest monsoon occurs from June through September, with the heaviest rainfall occurring in July. The Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) provided data on the study's monthly precipitation variation (Fig.4). For the simulation of slope conditions during the monsoon period, rainfalls of three different intensities are considered. The reason for considering 6.6 mm/day,33 mm/day, and 100 mm/day rainfall intensities is that 6.6 mm/day is the highest monthly rainfall intensity value for the monsoon period, and 100 mm/day is the maximum daily rainfall in July and 33mm/day is rainfall intensity over which there is no significant change in F.O.S of slope indicating complete failure.

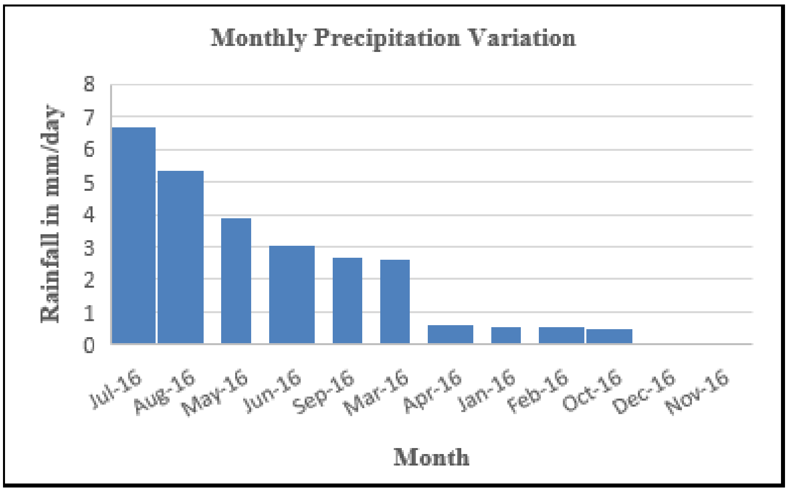

Fig. 4. Showing monthly precipitation variation of the year 2016 (Source: CHIRPS)

3 Methodology

3.1 Numerical Modelling

In this study to examine the soil slope, GeoStudio 2020 Software is used. Complete numerical modelling is performed in three phases. In the first step Slope/W tool which is a method based on the limit equilibrium approach was used to examine slope stability before the rainfall then using the finite element approach, Seep/W was used to model the rainfall, and the results were obtained from Seep/W again used in Slope/W to examine the stability of saturated slope following heavy rainfall.

3.2 Seepage Analysis During Rainfall

Based on the 2D finite element approach using SEEP/W, we can obtain Pore water pressure generated by rainfall of appropriate intensity concerning stated material property, slope geometry, and corresponding starting and boundary conditions. The mechanism behind its work is that it solves Darcy’s equation for a given slope condition by using a numerical discretization technique and executes water flow governing equations for the calculation of 2D seepage (Paswan & Shrivastava,2022).

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial H}{\partial y}\right) + q = m_w^2 \, Y_w \frac{\partial H}{\partial t} \qquad (1)$$

3.3 Stability Analysis

The slope’s stability is examined using the GeoStudio software's Slope/W tool and is based on the limit equilibrium approach. Although there are other ways to calculate a slope's factor of safety, the Morgenstern-Price approach is what we'll be using in this research. This approach is used because it has the benefit of taking into account both force and moment equilibrium.

3.4 Geometry Modelling

The study used numerical analysis to create four geometry models. The first model is for slope stability study before rainfall, while the other three models are for investigation of slope stability following rainfalls with intensities of 6.6mm/day, 33mm/day, and 100mm/day, respectively. The reason behind choosing these intensities of rainfall is to consider all three possibilities of minimum, moderate and maximum rainfall. Two boundary conditional models are presented for demonstration.

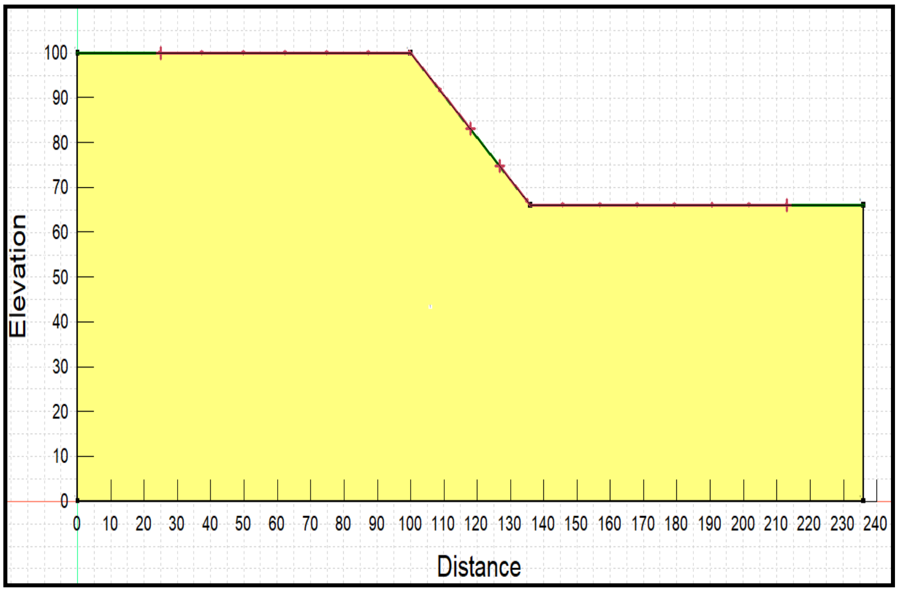

Fig. 5. Showing model of the unsaturated slope before rainfall

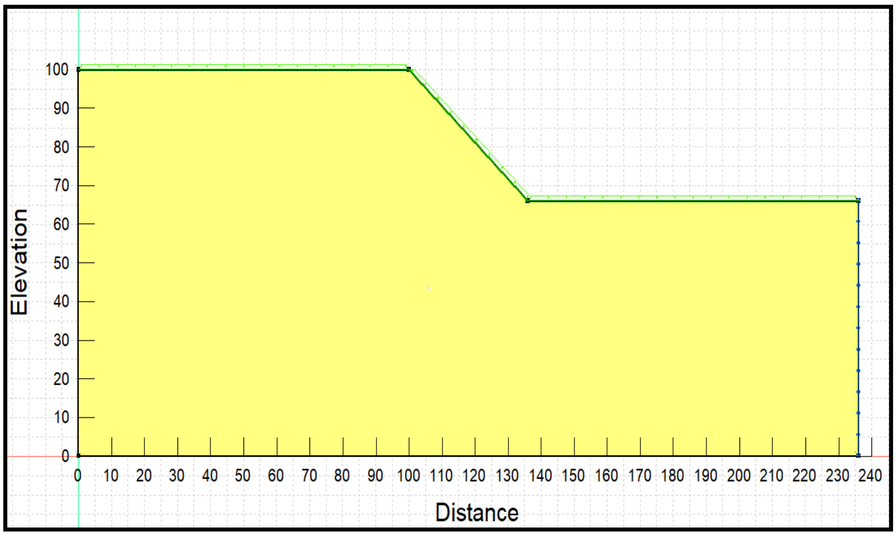

Fig.6. Showing model of the saturated slope after rainfall

4 Results and Discussion

4.1 Before Rainfall

This section deals with the outcomes of numerical modelling. To study the effect of rainfall on the stability of the slope, a factor of safety for the slope before rainfall is examined and it is found to be more than 1 (Fig.7). which justifies that the slope is stable when there is no rainfall. This analysis is also giving a critical slip surface on which factor of safety is minimum or we can say critical. Thus, information can be utilised for future mitigation purposes.

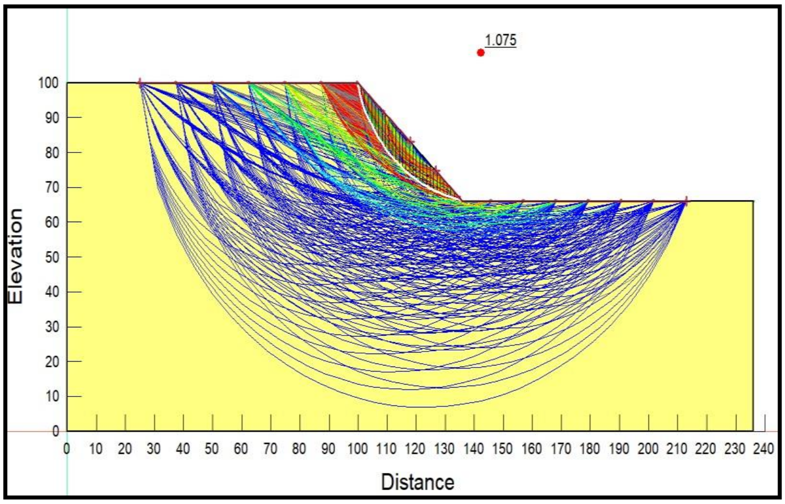

Fig. 7. Shows that the F.O.S of the slope is more than 1 before rainfall

4.2 After Rainfall

Now the analysis is carried out using different rainfall intensities and boundary conditions to observe the variation in factor of safety due to infiltration of the rainwater. is done in 2 parts, firstly seepage analysis is performed in the Seep/W tool, and then its results are used in Slope/W to find the stability of slopes. (Fig.8,9,10) Showing factor of safety for slopes with different rainfall intensities and it is very conclusive from them that F.O.S is decreasing with an increase in rainfall intensity. The factor of safety is 0.801 for rainfall intensity of 6.6mm/day and further decreasing to 0.578 for rainfall intensity of 33mm/day which is understandable as more infiltration of rainfall water causes the development of more pore water pressure resulting in a decrease in value of effective stress and ultimately leads to decrease in value of F.O.S but after rainfall intensity of 33mm/day, it is found that there is no significant change in values of F.O.S and possible reason of this is that slope is completely failed at rainfall intensity of 33mm/day and any further increase in rainfall intensity is not causing any difference in the value of F.O.S that’s why F.O.S safety at 100mm/day rainfall intensity is also coming out to be 0.576.

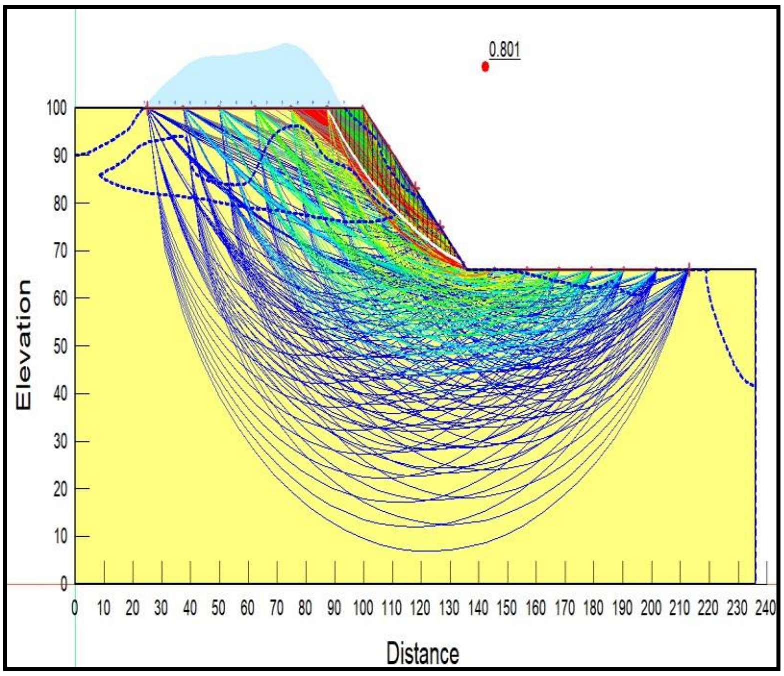

Fig. 8. Shows that the F.O.S of the slope is 0.801 for rainfall intensity of 6.6mm/day

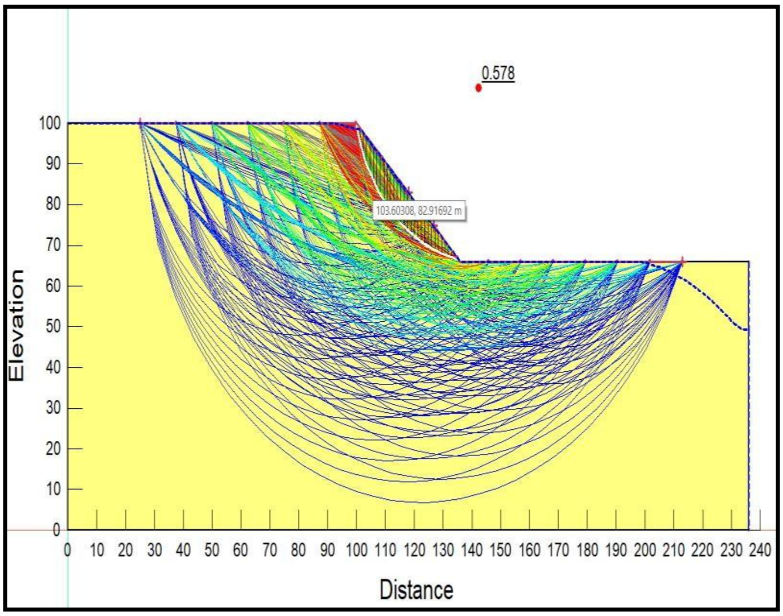

Fig. 9. Shows that the F.O.S of the slope is 0.578 for rainfall intensity of 33mm/day

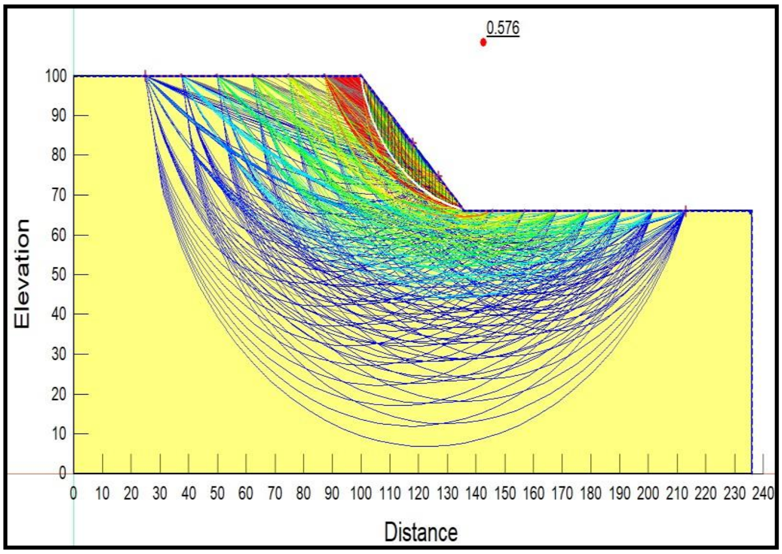

Fig. 10. Shows that the F.O.S of the slope is 0.576 for rainfall intensity of 100mm/day

Figure 11 is showing a plot of shear mobilisation and shear resistance before implementing rainfall intensity on the slope model. As we can see the value of shear resistance is more than shear mobilisation, which indicates that the value of forces that participate in slope failure is less than forces that are contributing to the stability of the slope, hence our slope is stable before rainfall.

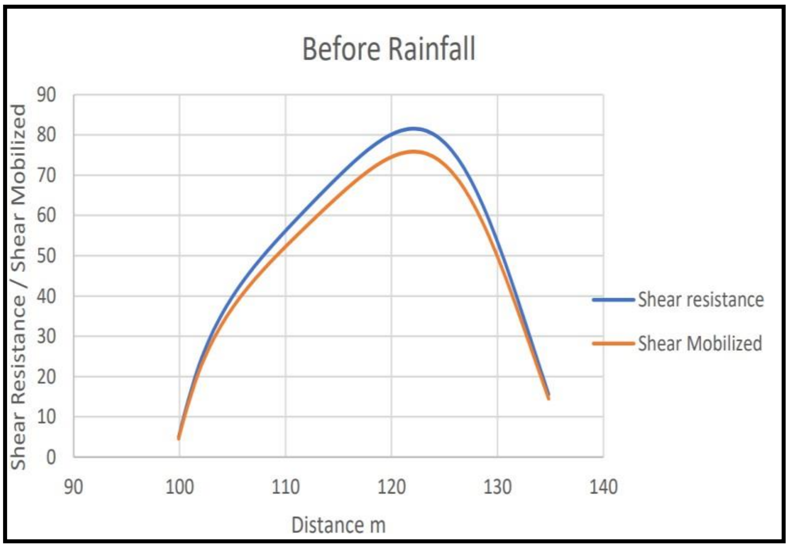

Fig. 11. Showing Shear Mobilised vs Shear Resistance comparison before rainfall

Figure 12 is showing a plot of shear mobilised and shear resistance after implementing rainfall intensity of 6.6mm/day on the slope model. As we can see, the value of shear mobilisation is more than shear resistance now, which indicates that the value of forces that participate in slope failure is more than forces that are contributing to the stability of the slope, ultimately failing the slope.

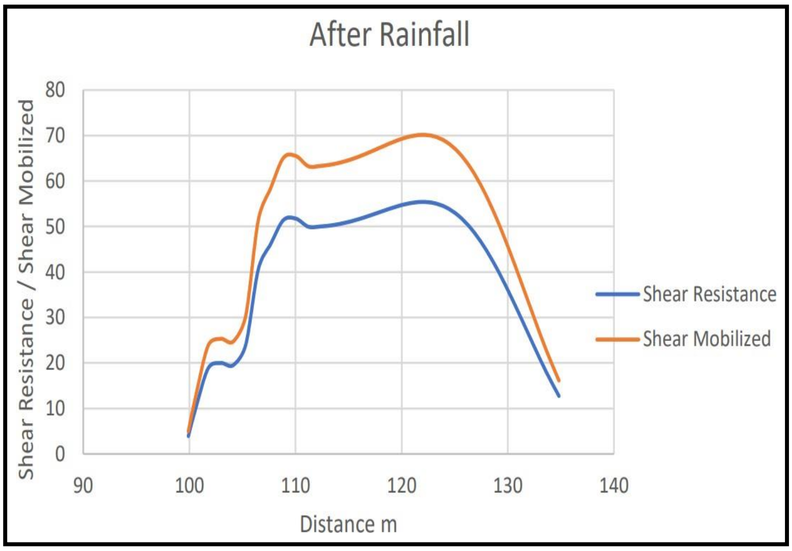

Fig. 12. Showing Shear Mobilised vs Shear Resistance comparison after rainfall

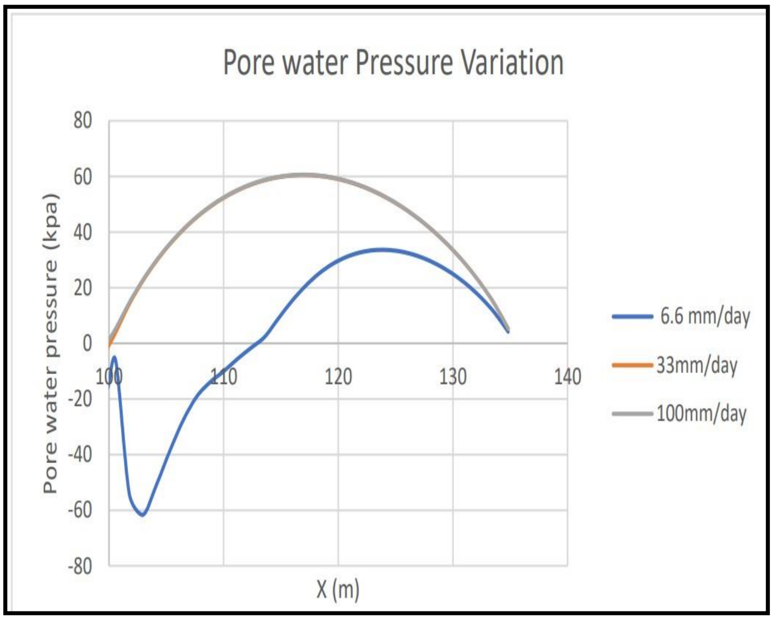

Fig. 13. Shows an increase in pore water pressure with an increase in rainfall intensity and hence causing slope instability

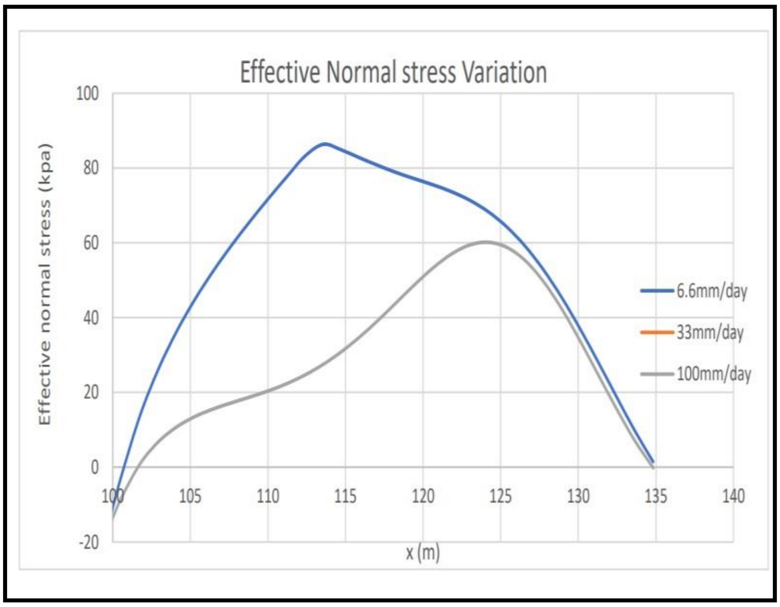

Fig. 14. Shows a decrease in effective normal stress with an increase in rainfall intensity and hence causing slope instability

5 Conclusions

In this study, an investigation is carried out to study the effect of rainfall intensity on a soil slope. The major findings of this study are:

(1) Factor of safety before rainfall or pre-monsoon was greater than 1, indicating a stable slope.
(2) Factor of safety for the slope after rainfall of intensity of 6.6mm/day was 0.801 which is less than 1 and hence indicates an unstable slope.
(3) Factor of safety for the slope after rainfall of intensity of 33mm/day was 0.578 which is very less than 1 and hence shows the critical failure condition.
(4) Factor of safety for the rainfall intensity of 100mm/day is 0.576, indicating that the slope has already completely failed before the such high intensity of rainfall, hence showing no significant reduction in the safety factor value.
(5) As this study confirms that rainfall is the main culprit behind landslides and slope instability in this area, this study can be used as a base to determine a rainfall intensity–duration threshold model which can be further used as a landslide early warning system for this location.

Future Scope and Limitation

There is a need for more studies for the validation and comparison of results obtained from numerical simulation with actual physical modelling results. This study only talks about the effect of rainfall intensities on slope stability but not about any remedial technique.

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