Early Warning System for Rainfall-Induced Landslides along NH-5, Using Rainfall Threshold and Slope Stability Analysis

A DISSERTATION
SUBMITTED IN PARTIAL FULFILLMENT
FOR REQUIREMENT OF THE DEGREE OF
MASTER OF TECHNOLOGY
IN
CIVIL ENGINEERING
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Submitted By
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CANDIDATE'S DECLARATION

I, Akash Bhardwaj, 2K21/GTE/04, student of M. Tech (Civil Engineering), hereby declare that the project dissertation titled "**Early Warning System for Rainfall-Induced Landslides along NH-5, Using Rainfall Threshold and Slope Stability Analysis**" is submitted to the Department of Civil Engineering, Delhi Technological University, Delhi, by me in partial fulfillment of requirement for the award of degree of **Master of Technology (Geotechnical Engineering)**. This thesis is original work done by me and not obtained from any source without proper citation. This project work has not previously formed the basis for award of any degree, diploma, fellowship, or other similar title or recognition.

Place: Delhi
Date: 31/05/2023

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CERTIFICATE

I hereby certify that project dissertation titled "**Early Warning System for Rainfall-Induced Landslides along NH-5, Using Rainfall Threshold and Slope Stability Analysis**" submitted by Akash Bhardwaj, 2K21/GTE/04, Department of Civil Engineering, Delhi Technological University, Delhi, in partial fulfillment for the award of degree of Master of Technology, is a project work carried out by the student under my supervision. To the best of my knowledge, this work has not been submitted in part or full for any degree or diploma to this university or elsewhere.

Place: Delhi
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ABSTRACT

The regular occurrence of landslides along National Highway 5 during the monsoon season is a cause for concern as they lead to substantial damage and traffic congestion. An integrated empirical and numerical modelling approach is required to mitigate the damage because there has never been an empirical rainfall threshold established, particularly for this section. This study is an effort to determine the local thresholds for rainfall that cause landslides based on the amount and timing of precipitation before a landslide event occurs along the hilly section of NH5 in Himachal Pradesh, India. To determine the threshold for rainfall, statistics on about 80 landslide episodes are gathered with their dates of occurrence. However, rainfall episodes involving 68 of the 80 landslides were examined to determine an empirical intensity-duration threshold for landslide occurrences. A frequentist approach is utilized to calculate the power law curve's slope ‘β’ and intercept ‘α', which serve as indicators of the rainfall threshold. The relationship between rainfall intensity and duration that was fitted to the lower boundary of rainfall events that caused landslides is $I=0.8046\ D^{0.9111}$ (I=rainfall intensity in millimeters per day and D=duration in days). For the validation of the threshold, numerical modelling is carried out on a slope that had previously failed, considering the rainfall event that preceded it, which had a mean rainfall intensity of 1.8 mm/day. After that, the effect of rainfall on the slope's Factor of Safety is assessed both before and after rainfall. From the obtained threshold equation, it can be concluded that a continuous rainfall of 1.513 mm/day for the minimum duration of 2 days can trigger landslides. The slope failure and validation of the threshold equation are confirmed by the reduction of the factor of safety to a value of 0.623, which was larger than 1 before the rainfall event.

Keywords: Rainfall Threshold; Landslides; National Highway; Numerical Modelling

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AKASH BHARDWAJ
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LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviation	Definition
NH	National Highway
ID	Intensity-Duration
FOS	Factor of Safety
LEM	Limit Equilibrium Method
FEM	Finite Element Modelling
EWS	Early Warning System
COOLR	Cooperative Open Online Landslide Repository
CHRS	Center for Hydrometeorology and Remote Sensing at the University of California
TWI	Topographic Wetness Index
AHP	Analytic Hierarchy Process
α, β	Empirical Parameters
δ	Deviation from Best Fit Line

CHAPTER 1- INTRODUCTION

1.1 GENERAL BACKGROUND

1.1.1 Landslides

A natural disaster that denotes the downward displacement of soil and rock under the action of gravity is termed as landslide. Five types of slope movement are called "landslides": falls, topples, slides, spreads, and flows. When forces acting downwards under the action of gravity exceed the forces providing stability to the earth components that make up the slope, slope movement occurs.

Fig 1.1: Showing a downward movement of debris (Source: https://www.indiaspend.com)

1.1.2 Problem Statement

The Himalayan Mountain range is geologically very new and hence uncertain, due to this reason it is extremely prone to landslides. This natural calamity becomes very troublesome and deadly, especially for road networks. Landslides along the highways result in traffic chaos such as route blockage and are also blameworthy for the casualties. National Highway 5 (Himachal) in India is very majorly affected by landslides every year and the main reasons for this are unpredictable Himalayan geology and Heavy rainfall conditions. The region of the lower Himalayas is prone to slope failures due to the frangible nature of soil strata, which is accompanied by rainfall conditions and much anthropogenic activity (Singh et al., 2017).

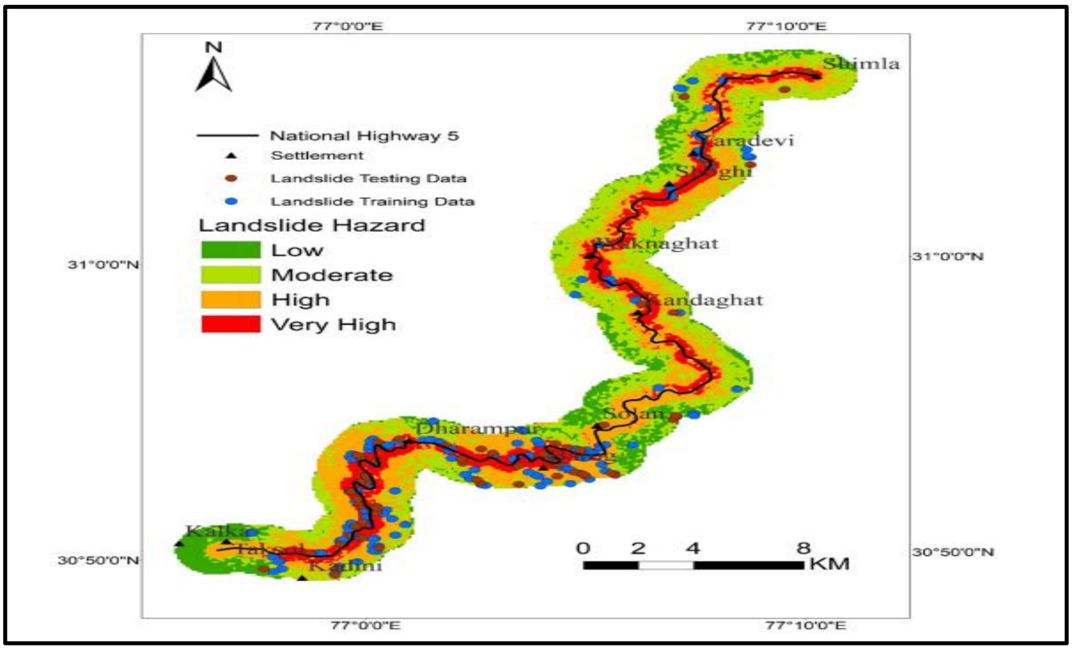


Fig 1.2: Showing Landslide Affected National Highway 5 (Panchal and Shrivastava., 2022)

1.1.3 Rainfall – Induced Landslides

The theory underlying rainfall-caused landslides is that, as rainwater infiltrates via soil pores, it develops positive pore water pressure, which in turn causes a decrement in effective stress, which reduces soil strength and ultimately causes slope failure or landslides.

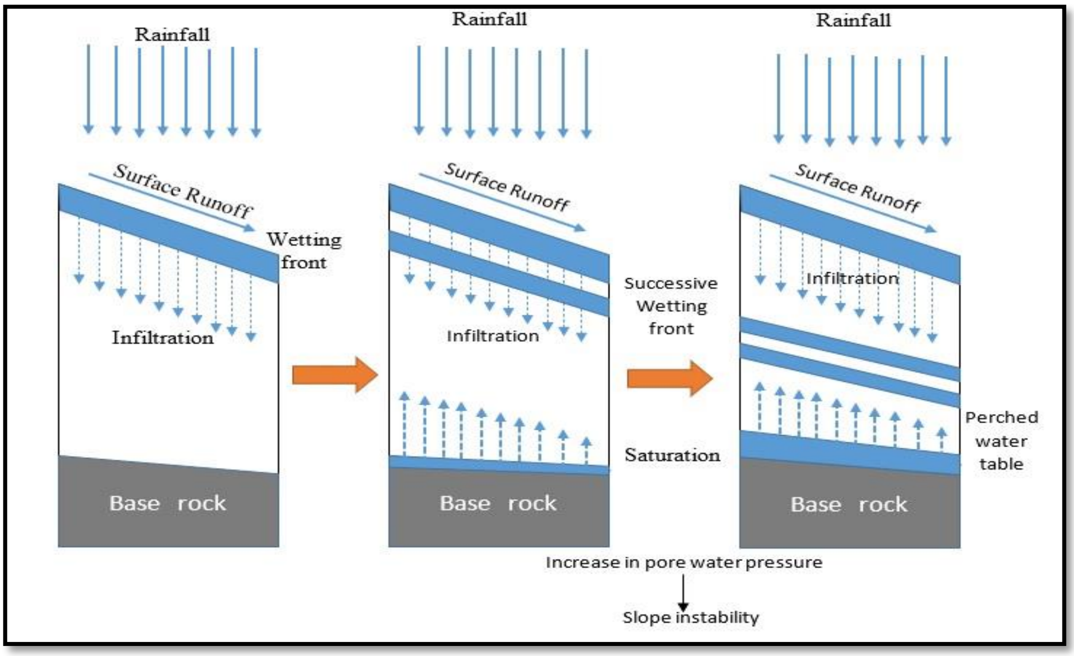


Fig 1.3: Shows sequential rainfall-induced landslide initiation (Paswan and Shrivastava., 2022)

1.1.4 Rainfall Thresholds

The least amount necessary for a process or phenomenon to occur or to result in a change in its condition is how thresholds are commonly defined. Correspondingly, the rainfall intensity-density threshold for landslides refers to the minimum value of intensity/duration of rainfall required to initiate a landslide. Additionally, a threshold could be used to specify hydrological conditions such as the amount of rainfall, and moisture content present in the soil that, if attained or exceeded, are likely to result in a landslide.

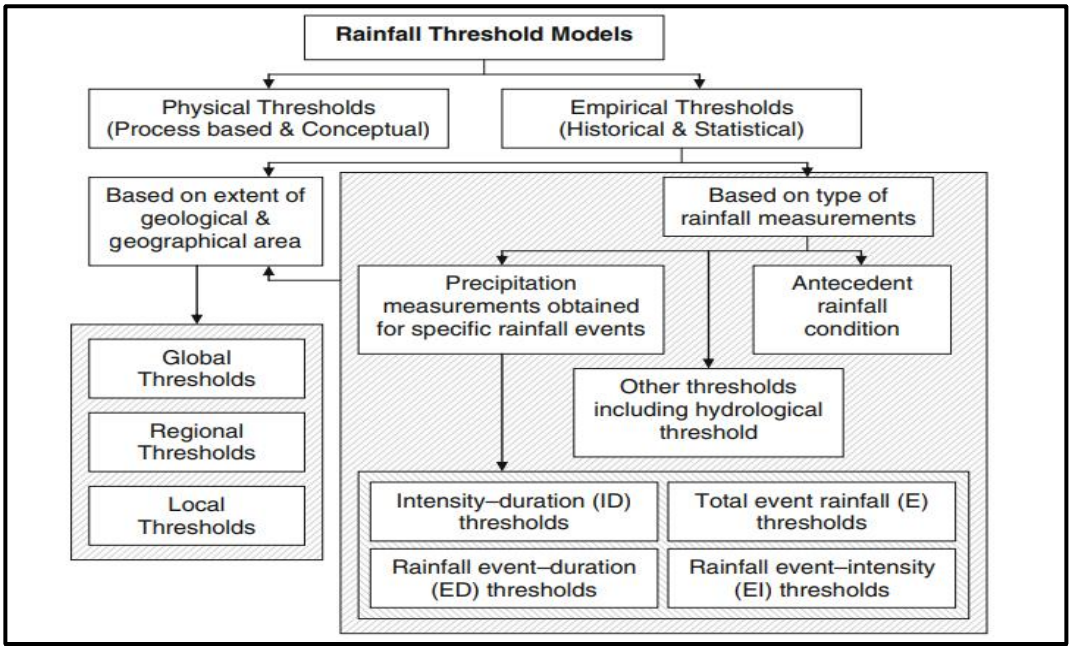


Fig 1.4: Showing different rainfall threshold models (Kanungo and Sharma., 2013)

1.2 NEED OF PRESENT STUDY

Himalayan province alone contributes to nearly 30% of the global loss owing to landslides. National Highway 5 despite being a very important route and vulnerable to landslide events does not have any previous study regarding rainfall threshold or dedicated early warning system.

There is a need for more studies based on numerical modelling to prove its suitability for the region which can be further utilized for the verification of rainfall thresholds.

1.3 OBJECTIVES OF STUDY

(1) To collect landslide events with date and their corresponding rainfall data for the study location.
(2) To derive local rainfall Intensity-Duration threshold for landslides based on rainfall's intensity and duration before the occurrence of a landslide event along the Hilly region of NH5 in Himachal Pradesh, India.
(3) To select and determine input parameters for numerical modelling.
(4) To validate the obtained rainfall threshold using numerical modelling.

1.4 ORGANIZATION OF THESIS

Chapter 1 introduces the study. Chapter 2 showcases the literature review performed relevant to the present study. Chapter 3 describes the study area, triggering factors causing landslides, and data collection which is an important part of this study. Chapter 4 deals with the methodology adopted, which is further explained in 3 parts: rainfall threshold development, experimental study, and numerical modelling. Chapter 5 deals with results and discussions and is also explained in 3 parts as divided into the methodology. Chapter 6 is a conclusion summary discussing major outcomes and Chapter 7 states some limitations of this study which can be used to guide future research.

CHAPTER 2 - LITERATURE REVIEW

2.1 RAINFALL THRESHOLD

Paswan and Shrivastava., (2022) carried out a study to investigate the sliding mechanism, and physical model tests on very similar kind of material were carried out. Furthermore, GeoStudio was used for numerical modelling to verify and compare the results and assess the suitability of this study by studying the seepage and slope stability parameters. An imitation of rainfall was done to simulate the amount and rate of rain to investigate the mechanism underlying the least amount of precipitation required to cause slope instability. As per the results, the model slope failed at a fixed intensity of 30 mm/h and a threshold rainfall depth of 80 mm.

Mondal and Sarkar., (2020) developed a rainfall threshold model for the area along National Highway-10. 288 rainstorm events have been observed, causing 681 landslides along this stretch of road. $I= (20.10 \pm 1.84)\ D^{(-0.45 \pm 0.05)}$ has been estimated as the threshold equation for the entire NH-10. Rainfall event on the day of landslide occurrence is responsible for triggering 17-18% more landslides as compared to a cumulative threshold of 3-5 days.

Abraham et al., (2019) carried out a detailed study to define a regional threshold for landslide occurrence in the Idukki district of Kerala. This study applies the frequentist approach of determining the intensity-duration thresholds. The investigation relied on data from 225 landslides collected over nine years. Records for the final day of precipitation at failure are contrasted with records for the 3, 10, 20, 30, and 40 days before the failure. The results showed that antecedent rainfall circumstances influenced the initiation of landslip occurrences more than the rainfall events on the day of the occurrence. For the Idukki district ID threshold is determined as $I = 0.9\ D^{-0.16}$. As per the results on the increment of the period before the landslide, landslide events distribution shifts towards circumstances related to antecedent rainfall.

Harilal et al., (2019) established the rainfall threshold for the area of Sikkim by using daily rainfall data and landslip initiation in this area between 1990 and 2017. The author examines how antecedent rainfall affects landslip initiation by examining the cumulative rainfall values linked with landslides on a daily, 3-day, 5-day, 7-day, and 20-day basis.

The study sheds light on the impact of cumulative precipitation days before the landslide event on slope stability, the regional rainfall threshold is derived as $I = 43.26\ D^{-0.78}$.

Teja et al., (2019) Study involves the application of an algorithm-based model which overcomes the limitations and drawbacks of the conventional statistical approach. The analysis was conducted for the Kalimpong Region of the Darjeeling Himalayas using rainfall and landslip data from 2010 to 2016. Results obtained from this study conclude that landslides can be initiated by a 48-hour rainfall event with a total event rainfall of 36.7 mm. The rainfall thresholds are reconstructed using the Calculation of Thresholds for Rainfall-Induced Landslides-Tool (CTRL-T). This tool uses an algorithm to automatically extract precipitation events from daily rainfall data., reproduce the triggering rainfall circumstances that cause landslides, and establish rainfall thresholds for various values of landslide occurrence probabilities.

Dikshit and Satyam., (2018) deal with the formation of rainfall thresholds for the Kalimpong area. The study's main goal is to determine local rainfall thresholds for landslip occurrences in this region utilizing daily rainfall and landslip data from 2010 to 2016. The power law equation was employed to determine an intensity-duration threshold for landslide occurrences. The results show that when 24 hours of rainfall with an intensity of 0.95 mm/h occurs, there is a statistically significant likelihood that a slide will begin in this area. Obtained threshold relationship for the study area is $I = 3.52\ D^{-0.41}$. One of the drawbacks of employing an empirical rainfall threshold is the lack of readily available, verified landslide events and rainfall information, including recording time. According to research on rainfall thresholds using antecedent rainfall, an antecedent rainfall of 3 days to 4 months is significant in comprehending landslip occurrences.

Naidu et al., (2018) integrated cluster and regression analysis were used to find the rainfall threshold that causes landslides in Amboori, Kerala, India. With a threshold equation of $80.7 - 0.1981x$, the 5-day antecedent vs. daily rainfall provided the best fit to the data. In the slope stability analysis, the places where previous landslides occurred had lower Factors of Safety. As a result, rainfall threshold analysis combined with slope stability analysis can result in the development of a straightforward, affordable, and thorough early-warning system for shallow landslides in Amboori and surrounding areas.

Kanungo and Sharma., (2013) based on information about the amount of rain that falls each day in the Chamoli-Joshimath area of the Garhwal Himalayan range, India, this paper attempts to form local rainfall thresholds for landslides. Around 81 landslides were analyzed out of 128 landslides to produce an equation that defines the lower limit of rainfall intensity and duration for landslide occurrences. A long-duration rainfall event lasting about 5 days with an average precipitation of 0.6 mm/h appears to be sufficient to trigger landslides, according to the study. It indicates that rainfall events lasting up to 24 hours with a rainfall intensity of 0.87 mm/h can cause landslides in this section of the terrain. The threshold relationship fitted for the study region causing landslides is $I=1.82\ D^{-0.23.}$

Dahal and Hasegawa., (2008) examined 193 of the 677 landslides related to rainfall data to determine a rainfall ID threshold relationship for the onset of landslides. The study found that while landslides in the Himalayas can occur with rainfall durations of 100 hours or more with an average intensity of 2 mm/h, rainfall durations of 10 hours or less with an intensity of more than 12 mm/h are also capable of doing so. Additionally, there is always a chance of landslides occurring on Himalayan slopes when daily rainfall hits 144 mm.

2.2 SLOPE STABILITY ANALYSIS

Paswan and Shrivastava., (2022) utilized numerical modelling to investigate the effect of rainfall on the slope's stability. The research location is in the Shimla District of Himachal Pradesh, near the town of Jhakri. The safety factor is computed before and after rainfall, and it is discovered that rainfall is the primary triggering factor for landslip events in the region. The current study supports the use of numerical Modelling for analysis and prediction in the Indian Himalayan region.

Table 2.1 Properties of soil sample considered in the study

Parameters	**Values**
Natural Water Content %	6.7
Bulk unit weight (kN/m^3)	14
Coefficient of Permeability (m/h)	0.0023
Angle of Internal Friction (φ) °	32
Cohesion (kPa)	9.5

Panchal and Shrivastava., (2022) carried out a thorough investigation utilizing the analytic hierarchy process (AHP) methodology to create a map of the landslip hazards along National Highway 5. The various causes of landslides examined in this study include slope, aspect, curvature, relative relief, fault density, drainage density, geology, topographic wetness index (TWI), distance from the road, and lithology. The analytical hierarchy process (AHP) is used to break up the causative components and assign weights to each one. It has been demonstrated that as the slope gradient increases, so does slope instability. If the slope angle is less than 30, there are no landslides. Slopes with a slope angle of less than 60 degrees make up only 20% of the research area. 80 percent of the research region is made up of slopes more than 60 degrees, and 57% of all landslides take place there. 15% of the study area is made up of slopes with slope angles ranging from 45 to 60, and 28% of all landslides occur in these areas. There are no landslides in the region where slopes range from 0 to 15 degrees.

Dhanai et al., (2022) carried out an analysis of transient seepage and stability of soil slopes in three regions of India, as well as the effect of climate change due to global warming on slope stability. carried out a parametric study based on data found by different researchers, followed by seepage and stability analysis in Geo Studio Software's Seep/W and Slope/W programs. The author discovered that the factor of safety decrease is greater on steeper slopes and in soils with high permeability and that the slope saturation rate depends on the initial matric suction present in the soil.

Dikshit et al., (2020) utilized many factors to assess landslides for distinct landslide zones in the area. The analysis indicates that several areas need thorough investigation including climate change or the data accumulation of the paramount quality that can be utilized in the form of input for computational models. The review also shows that, even though the entire area is very susceptible to landslides, most studies have only concentrated on a small number of places while neglecting many larger ones. To address the problem of a severe lack of ground-based rainfall data in broad portions of the Himalayan region, begin evaluating and determining the best dataset to use for various areas of the Himalayan region using remote sensing data (e.g., satellite radar rainfall predictions).

Sarma et al., (2020) studied rainfall-induced landslides on the hill slopes of India's Guwahati region. Soil geotechnical characterization was performed, followed by pore pressure variation in SEEP/W and stability analysis in Slope/W in Geo Studio software.

It was discovered that in the absence of rainfall, the soil slopes are stable and that rainwater infiltration causes a decrement in FOS due to a rise in pore water pressure. The three models utilized in the study were capable of producing consistent results with actual field conditions and identifying areas prone to landslides.

Sharma et al., (2018) carried out a detailed study to mitigate recurring kotropi slope failure with the help of soil nailing technique. Helical soil nails of length 6 m and diameter 20 mm each are chosen for mitigation purposes. The study involves geotechnical and chemical testing of the soil at the site. The safety factor is obtained after applying soil nails using the LEM and then by using FEM in PLAXIS 2D software validation is done. The fact that LEM focuses largely on the equilibrium of forces acting on the soil wedge and FEM addresses the elastoplastic deformation of nodes may be the cause of the disparity between the LEM factor of safety and the FEM factor of safety. The latter is more realistic as it takes into account the interaction between helical soil nails and the soil, whereas nails in LEM are only taken into account as a stabilizing force.

Dey and Sengupta., (2018) studied the rainfall-induced failure at Malin, Maharashtra. In GeoStudio Software, a 2-dimensional slope model was made for analysis. A parametric analysis of the influence of varied rainfall intensities on slope stability was conducted. The Seep/W and Slope/W programs were used to calculate pore pressure variation and FOS for the slopes associated with various rainfall intensities. The author discovered that during low-intensity rainfall, the slope remained steady. Before rainfall, a FOS of 1.6 was measured, which drops to less than one for high-intensity rainfall conditions. Unceasing rainfall infiltration created a perched water table near the surface of the slope, resulting in saturation of ground and positive pore water pressure build-up at a short depth within the slope.

Singh et al., (2017) performed a geotechnical investigation to find out the intrinsic properties of soil materials that affect slope stability. An event-specific antecedent rainfall threshold has been proposed to measure the connection between precipitation and slope collapse. To show the situation of pre- and post-failure stability of the slope, a two-dimensional LEM has also been used. In Slide v.7.0 software, LEMs such as Bishop Simplified (BS) and Morgenstern-Price (MP) were used to study the slope, and analysis was performed for both pre-and post-failure scenarios of the slope. Based on the results of the limit equilibrium analysis, it has been determined that slope geometry is a significant influencing parameter that determines the failure pattern.

Table 2.2 Physical and Geotechnical properties of soil sample considered in the study

Parameters	**Values**
Unit Weight (kN/m^3)	13.30
Saturated Unit Weight (kN/m^3)	17.14
Bulk density (kN/m^3)	14
Coefficient of Permeability	0.0026
Cohesion (kPa)	9.81
Angle of Internal Friction (φ) °	32

Jeong et al., (2017) investigated landslides due to the infiltration of rainfall water in Seoul, Korea. Rainfall-caused landslides were studied using laboratory, field, and numerical methods. Matric suction, which is important in unsaturated soils, influences the mechanism of rainfall-induced landslides. In this regard, commercial programs SEEP/W and SLOPE/W are used to undertake a series of transient seepage and limit equilibrium evaluations. The method used is suitable for simulating landslides as it is an integration of both experimental and numerical modeling. There is a significant correlation between the numerical results and the data examined which acts as validation.

Rahardjo et al., (2007) conducted a parametric study by selecting various factors affecting slope stability, followed by seepage analysis in the SEEP/W module and stability analysis in the SLOPE/W module of GeoStudio software to determine the relative importance of soil properties, rainfall intensity, initial depth of water table, and slope geometry in assessing the instability of a homogeneous soil slope under different rainfall conditions. It was discovered that cumulative rainfall days before landslide events play a dominating role in slope stability in slopes with soils with a low saturated coefficient of permeability. The starting value of the factor of safety is determined by the depth of the water table, but the reduction in FOS is mostly determined by the severity of rainfall.

Krahn., (2003) explained the shortcoming of the LEM that solely satisfies statics equations is that they do not account for strain and displacement compatibility. This has two negative consequences. The first is that it is incapable of accounting for local differences in safety factors, and the second is that calculated stress distributions are frequently wrong.

2.3 RESEARCH GAPS

After completing a detailed research review of studies based on rainfall intensity duration threshold and slope stability analysis based on numerical modelling, the following research gaps are observed:

- Not enough studies to validate the application of numerical modelling techniques in the Indian Himalayan region for analysis purposes.
- Ineffectiveness of regional and global thresholds.
- No study regarding the empirical rainfall ID threshold for the landslide-prone stretch of National Highway 5.
- Absence of threshold validation in most of the studies.

CHAPTER 3 – LOCATION AND DATA COLLECTION

3.1 STUDY AREA

The area for research is a stretch of National Highway 5 which is around 165 km in length from Solan to Rampur Bushahr.NH5 is a very important route as it links the isolated places of the mountainous highlands and demonstrates the relationship between Tibet and India. This stretch of NH5 inhibits a long history of landslide events every year due to unstable geology and heavy rainfall conditions. “The research area is covered with sediments from the Miocene, Neoproterozoic, and Eocene eras. Numerous rock types, including siltstone, limestone, sandstone, dolomite, and quartzite, are present in the region” (Panchal and Shrivastava., 2022). Most of the limestone deposits are in the Shimla area.

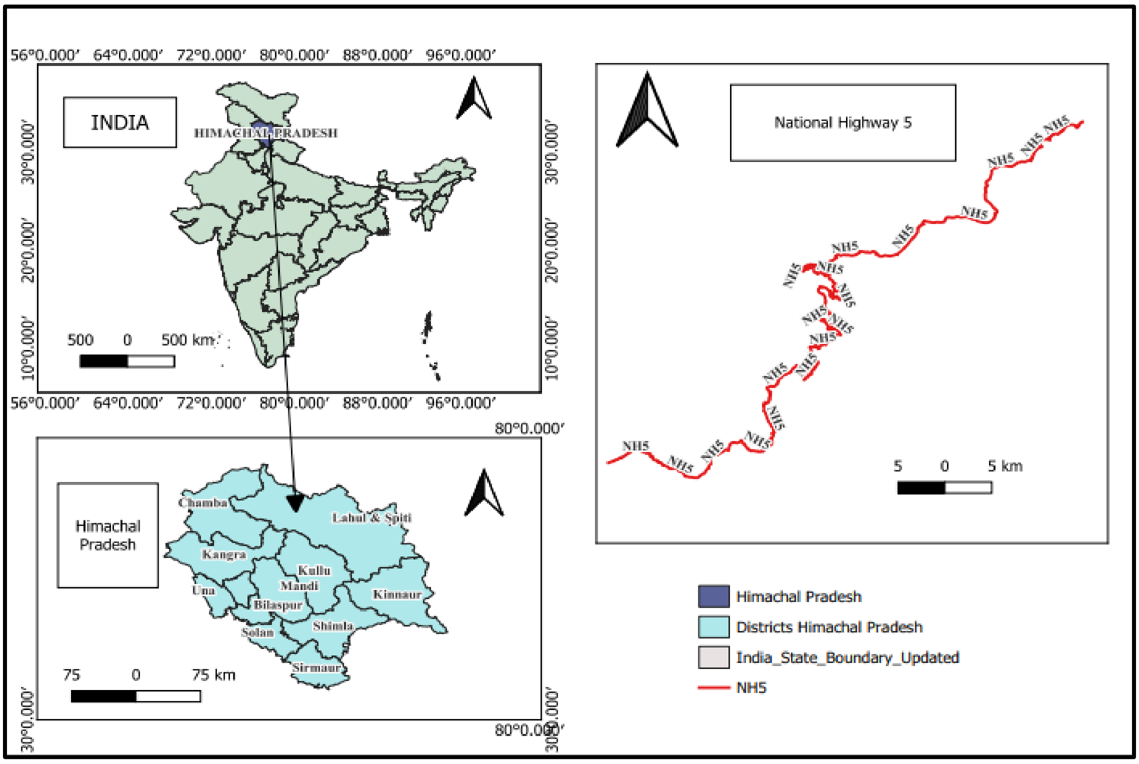


Fig 3.1: Study Area

3.2 TRIGGERING FACTORS

The southwest monsoon, which develops as a result of the orographic precipitation conditions, has historically brought about yearly rainfall in the Shimla region of the state of Himachal Pradesh of about 1000 mm. The large intensity of rainfall decreases the stability of roads constructed on hilly slopes by increasing pore pressure in the soil strata thus decreasing effective stress. As per the record of local authorities, NH5 has seen a large increase in traffic in previous years due to the increase in tourist activities, and construction activities across the highway are taking place in large numbers including many government projects.

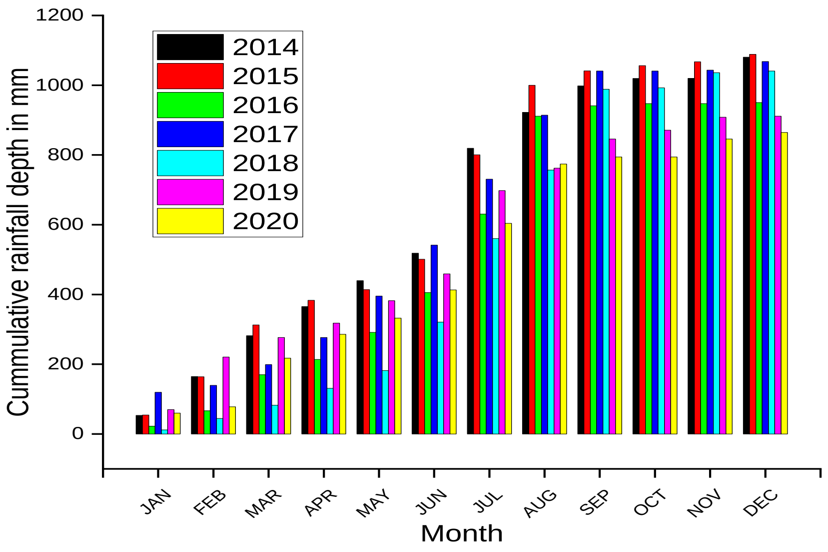
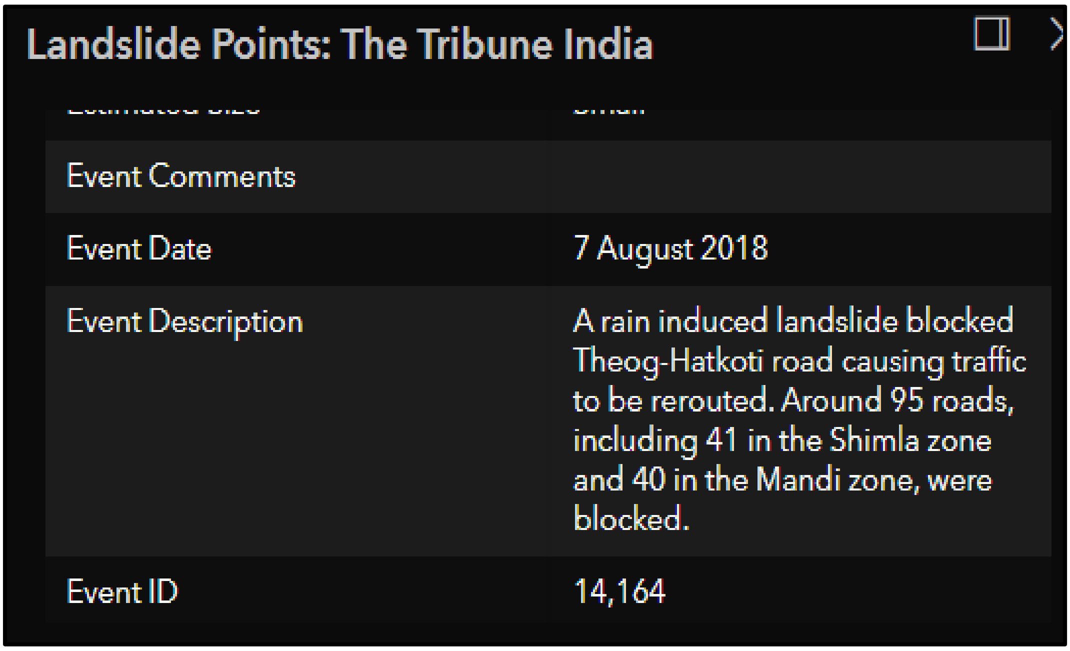


Fig 3.2: Shows cumulative rainfall over the years for the Shimla district (Source: IMD)

3.3 LANDSLIDE DATA

The main challenge in the collection of landslide data was to determine their exact date of occurrence as most of the government-maintained landslide inventory does not contain dates of landslide. Landslide data is collected manually from news articles, websites, and local newspapers and using The Cooperative Open Online Landslide Repository (COOLR). Fig 3.3 shows sample landslide COOLR data. Statistics of around 80 landslide events with their date of occurrence are collected to attain rainfall threshold. Among 80 landslide data points, rainfall events of about 68 landslide events were analyzed to get an empirical ID threshold equation for landslide initiation.



Landslide Points: The Tribune India

Event Comments	
Event Date	7 August 2018
Event Description	A rain induced landslide blocked Theog-Hatkoti road causing traffic to be rerouted. Around 95 roads, including 41 in the Shimla zone and 40 in the Mandi zone, were blocked.
Event ID	14,164

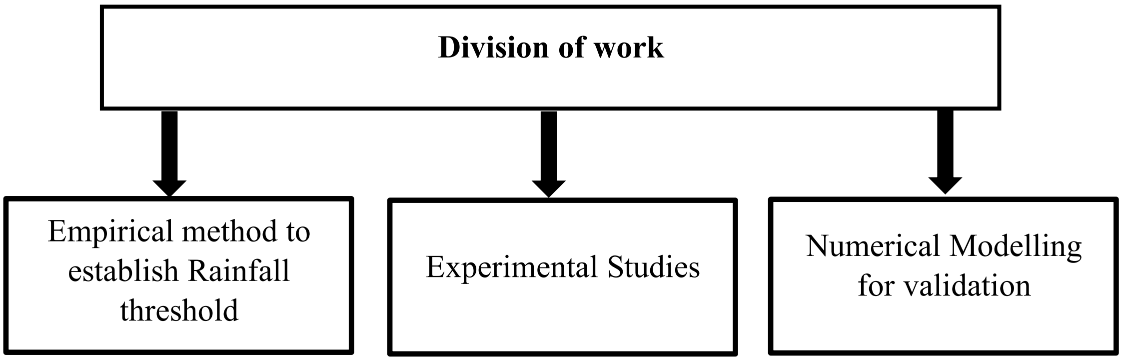
Fig 3.3: Sample Landslide viewer data showing landslide event details by COOLR

3.4 RAINFALL DATA

“The Persiann-cloud classification system is used to get rainfall data corresponding to each landslide event. It is a real-time, global, resolution (4km x 4km,) satellite rainfall product created by the University of California's Center for Hydrometeorology and Remote Sensing” (CHRS Data Portal,2023).

CHAPTER 4 – METHODOLOGY

The methodology for this study comprises three parts (i) empirical methods are used to get an association between the Intensity and duration of Rainfall events that contributed to landslide initiation, (ii) Experimental work to get input parameters for numerical modelling, (iii) Numerical Modelling in which GeoStudio software is used to model a slope on which we will apply rainfall more than threshold for the validation of our rainfall ID threshold.



4.1 EMPIRICAL METHOD

The empirical method of developing rainfall threshold deals with historical data and statistics of landslides and rainfall events. Following are the steps involved in it:

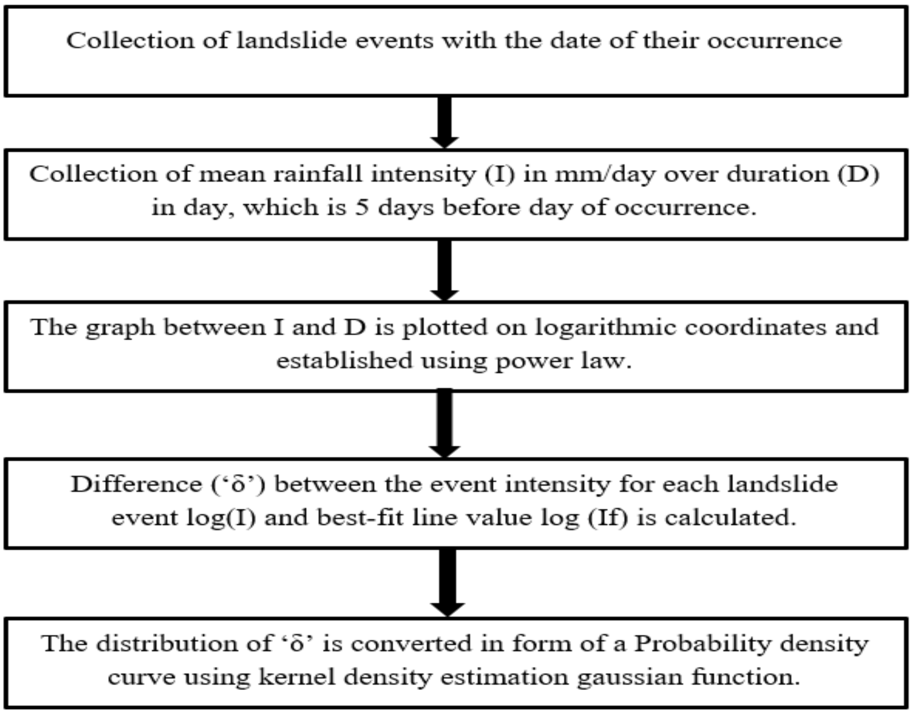


Fig 4.1: Showing stepwise development of the rainfall ID threshold

For the development of the rainfall ID threshold, the most challenging part is the collection of landslide data with the date especially for the regions like this where there is no organized landslide inventory with the accurate date of occurrence, so landslide events are collected with the help of the Cooperative Open Online Landslide Repository (COOLR).and local media are used to manually collect data on landslides. The rainfall information relating to each landslide incident is obtained using the Persiann-cloud categorization technique. It is a global, real-time, high-resolution (4km x 4km), satellite precipitation tool made by the Center for Hydrometeorology and Remote Sensing at the University of California (CHRS). The daily rainfall intensities of all precipitation events related to the occurrence of landslides were studied and shown on a logarithmic scale vs the number of days the events lasted. The power-law distribution is used to fit the distribution of the events:

$$I = \alpha D \beta \tag{1}$$

Where,

α and β are curve fitting parameters

I is rainfall intensity in mm/day

D is the duration of rainfall in days

Two presumptions underlie the use of the power law equation in the prediction of landslides. First off, the likelihood of landslides rises nonlinearly as rainfall intensity rises. According to this supposition, the likelihood of a landslide occurring is low below the threshold value and rises nonlinearly above it. According to the second premise, a decrease in slide initiation occurs as rainfall duration lengthens. 'δ' values are collected as the difference between the individual intensity values of rainfall events and the value of intensity at the best-fit line, obtained series is used to form a probability distribution curve in which Kernel density estimation (with help of Python program) method is used to transform δ values in from of Probability Density curve. From the probability density curve, the standard deviation is calculated and this value of standard deviation is the difference between the best-fit line and the threshold line.

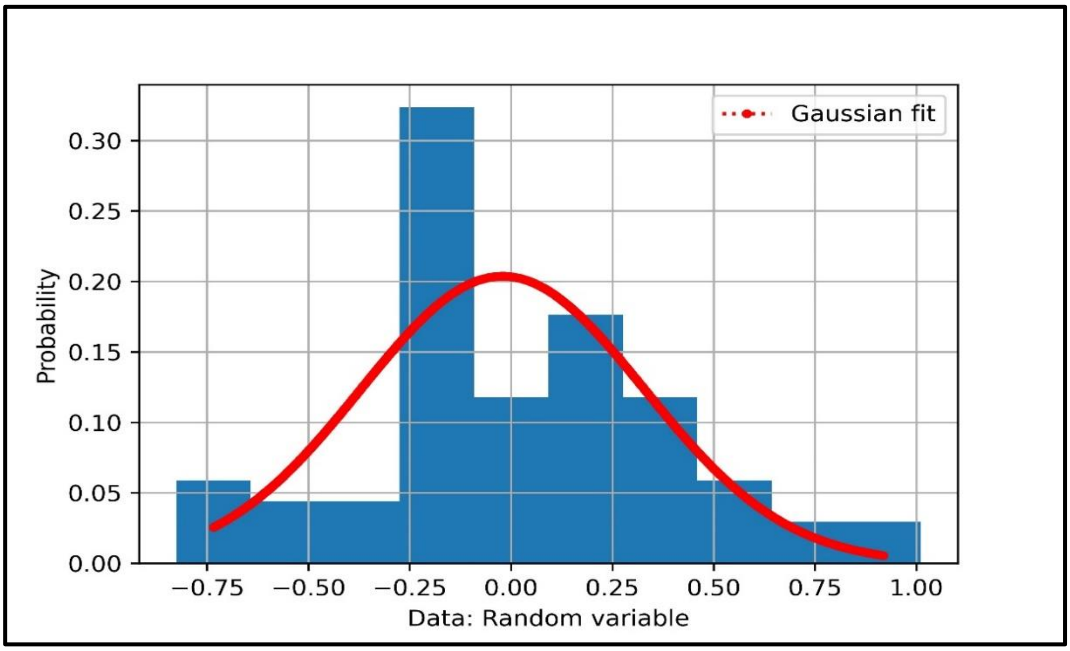


Fig 4.2: Showing Probability distribution curve of δ distribution using Python code

4.2 EXPERIMENTAL STUDIES

4.2.1 Grain Size Analysis

Sieve analysis was performed taking reference from IS:2720 (Part 4)-1985 by putting sieves of diameters 4.75mm,2.36mm,1.18mm,0.6mm,0.3mm,0.15mm, and 0.075mm on the pan and placing a top lid. A mechanical shaker is used to pass 1000 grams of oven-dried material through this series of sieves. Soil retained on each sieve is weighted and with the help of its percentage retained and percentage finer is calculated. In this case, the percentage finer than the 75-micron sieve is between 5 and 12 so it is a borderline case that requires a dual symbol and there is a need for Atterberg limits to categorize the soil as per IS:1498. Values of Cu and Cd are calculated with the help of sieve analysis.

Fig 4.3: Sieve arrangement placed on a sieve shaker

4.2.2 Atterberg Limits

As per IS:2720 (Part 5)-1985, experiments are performed for liquid limit and plastic limit. 120 gm of soil sample passed from the 425-micron sieve was used for the testing. Soil paste is formed by mixing water thoroughly and then it is placed in Casagrande's apparatus and then leveled to get a uniform depth of 1 cm. A grove is made in the soil and then the handle given in the apparatus is rotated with a uniform speed of 2 rotations per second. The number of blows is noted which led to the connection between two edges of grooves joining for 12 mm and blows should be in the range of 15 – 35. A portion of the soil from Casagrande's cup is taken and dried in an oven to obtain the water content of the soil. This step is repeated 4-5 times and a graph is plotted between the log of the number of blows and respective water content.

A 50-gm soil sample passed through a 425-micron sieve is mixed with adequate water and rubbed between fingers and a glass plate to form a thread-like shape of roughly 3mm diameter for the plastic limit test. The water content of the soil is then measured using a portion of the produced soil thread. A plastic limit is the value of moisture content present in the soil at which the soil crumbles just after creating the shape of a 3 mm diameter thread.

Fig 4.4: Shows Casagrande's apparatus for liquid limit determination

4.2.3 Specific Gravity and Natural Moisture Content

IS:2720 (Part 3, Section 1)-1980 is used to perform a specific gravity test using a pycnometer, and natural moisture content was measured using a moisture sensor. The formula used for the calculation of specific gravity is stated below.

$$\text{Specific Gravity (G)} = W_2 - W_1 / ((W_2 - W_1) - (W_3 - W_4)) \tag{2}$$

Where,

W_1 = Weight of empty pycnometer

W_2 = Weight of pycnometer+ oven dry soil

W_3 = Weight of pycnometer+ oven dry soil + water

W_4 = Weight of pycnometer+ water

Fig 4.5: Shows a pycnometer

4.2.4 Proctor Compaction test for Unit Weight of Soil

The compaction test is carried out following IS:2720 (Part 7)-1974. The used proctor mould had an inner diameter of 10 cm, a height of about 12 cm, and a capacity of 938 cc. A metal rammer with a face diameter of 5.08 cm and a weight of 2.5 kg was used to execute the compaction procedure. The rammer was additionally outfitted with an arrangement that limited the drop's height to a free fall of 30 cm.

Fig 4.6: Shows Compaction Apparatus

4.2.5 Shear Strength

The Parameters like cohesion (c) and angle of internal friction (φ) of soil sample shear strength characteristics have been evaluated using the direct shear test (DST) as per IS:2720 (Part 13)-1986. The shear strength of a soil mass refers to the highest amount of shear stress that may be mobilized within it (Ranjan and Rao., 1991). In the shear box, plain gride plates are positioned at the top and bottom of the soil sample. On the top grid plate, a loading pad is put in position, and a standard load is then applied. Between the upper and bottom halves of the shear box, a 1 mm space is kept. Until a shear displacement of 12 mm (or 20% of the longitudinal dimension), a shear load is applied. The shear loads are provided by the proving ring assembly, and the equivalent horizontal displacement is provided by the horizontal dial gauge. Three times the test was run with standard loads of (0.5 kg/cm^2, 1.5 kg/cm^2, and 2.0 kg/cm^2). For each test, the strain rate of 1.25 mm/min was maintained.

Fig 4.7: Shows the Direct Shear Test Assembly

4.3 NUMERICAL MODELLING

A previously failed soil slope from the study region is taken from a is taken from the Bhukosh Portal of the Geological Survey of India and examined using GeoStudio 2020 software in this study for validation. Slope/W, a method based on the limit equilibrium approach, is initially used to estimate the stability of an unsaturated slope to determine the slope's stability following rainfall. The rainfall was modeled using the FEM in Seep/W, and the results from Seep/W were then input in Slope/W to assess the stability of a saturated slope after a strong downpour. The Morgenstern-Price technique has been chosen for the factor of safety analysis utilizing the modified Mohr-Coulomb shear strength parameter, whereas Seep/W employs the Darcy theory using equation (3).

4.3.1 Seepage Analysis

Based on the mentioned material property, slope geometry, and pertinent starting and boundary conditions, we may determine the Pore pressure developed by rainfall events of the suitable intensity using the 2D finite element method utilizing SEEP/W. The method by which it operates is that it applies water flow regulating equations to calculate 2D seepage while also solving Darcy's equation for a given slope condition using a numerical discretization methodology.

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial H}{\partial \gamma}\right) + q = m_w^2\, Y_w \frac{\partial H}{\partial t} \tag{3}$$

4.3.2 Geometry Modelling

The slope model is prepared in GeoStudio software, maintaining an angle of around 43 degrees. It was very difficult to develop actual geometry for the failed slope, the slope is taken into consideration concerning numerous prior studies to get an unambiguous conclusion.

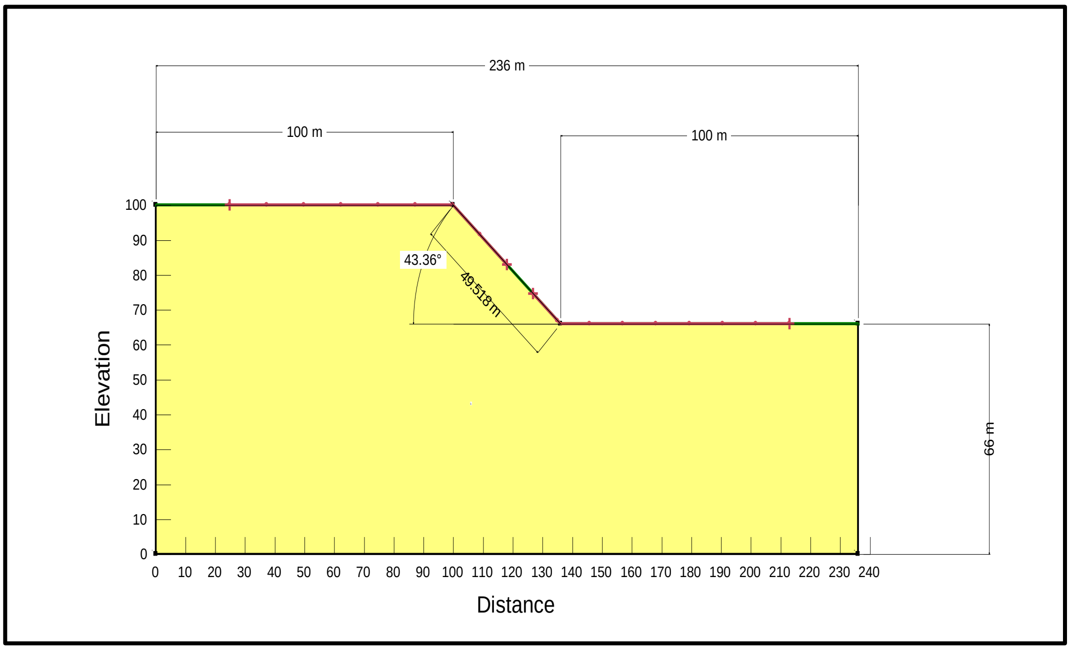


Fig 4.8: Showing model of slope considered for validation

CHAPTER 5 – RESULTS AND DISCUSSION

5.1 EMPIRICAL METHOD RESULTS (RAINFALL INTENSITY-DENSITY THRESHOLD)

The spread of the data distribution from the mean value is quantified using a statistical method, and the threshold is set by the lower boundary value of the points indicating landslide-catalyzing rainfall events to determine the lower boundary of the points. The 3 σ value is subtracted from the regression line's ordinate to get the data points' lower bound.

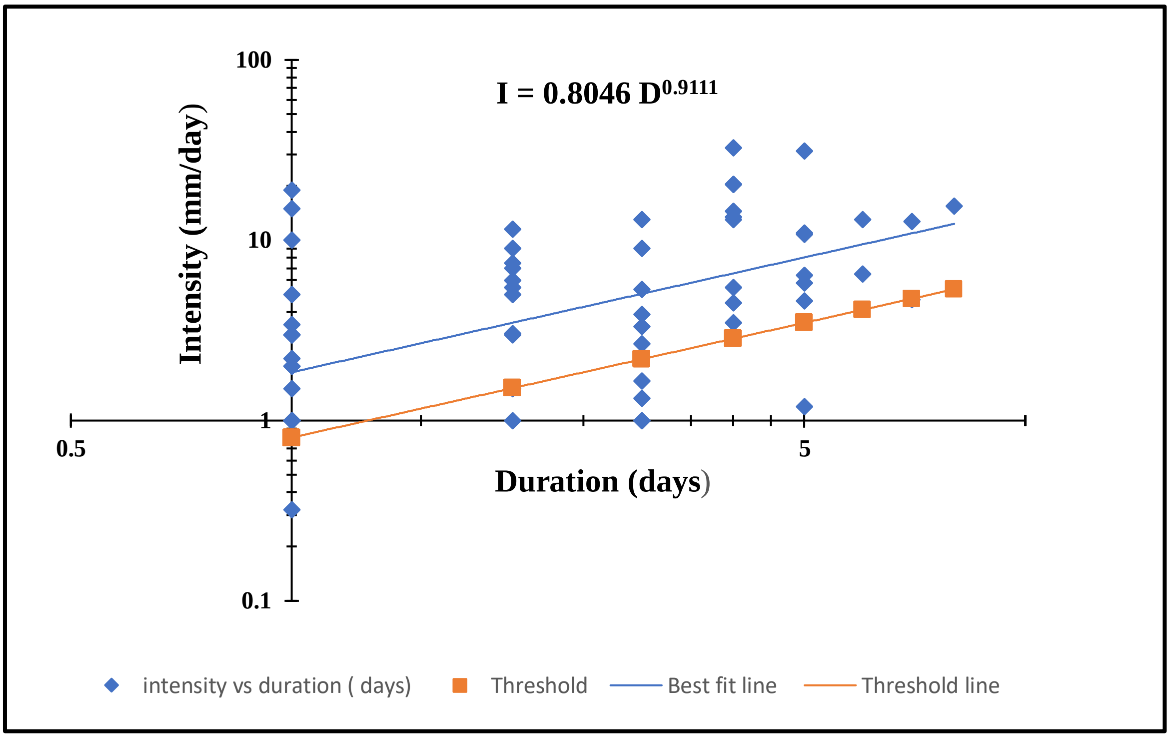


Fig 5.1: Showing best-fit line and threshold line

The threshold is created using the value of standard deviation discovered from the curve fitting factors and is written as:

$$I = 0.8046\ D^{0.9111} \quad (4)$$

Where 'I' stands for intensity of rainfall in millimeters per day and 'D' for rainfall event duration in days.

5.2 EXPERIMENTAL RESULTS

5.2.1 Grain Size Analysis

From the fine sieving, it was found that soil comprises majorly coarse grains and there is a slight portion of fine particles. Values of Cu and Cd come out to be 6.7 and 1.6 respectively which states that it is a case of Dual classification where the majority part is Well graded Sand with either silt or clay for which Atterberg limits are required.

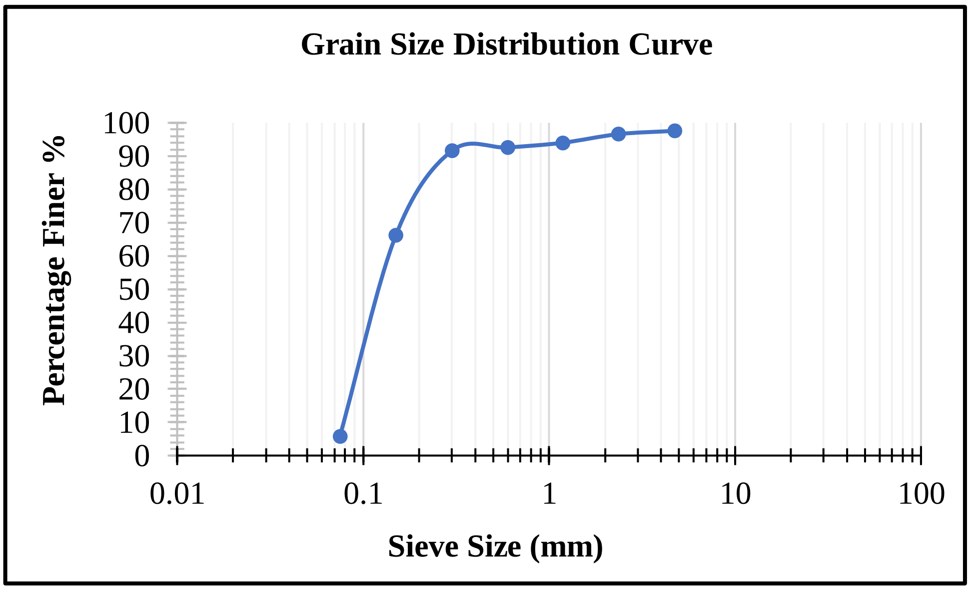


Fig 5.2: Showing plot of Grain Size Distribution

5.2.2 Atterberg Limits

Table 5.1 Laboratory results for various Atterberg Limit Tests

Parameters	Values
Liquid Limit %	28
Plastic Limit %	19.38
Plasticity Index %	8.62

The liquid limit comes out to be 28, whereas the plastic limit is 19.38 with a plasticity index of 8.62. The values of the liquid limit and plastic limit of the soil imply low to medium plastic soil or minor to moderate plastic inorganic silt. The Atterberg limits results suggest inorganic clay that is only weakly plastic.

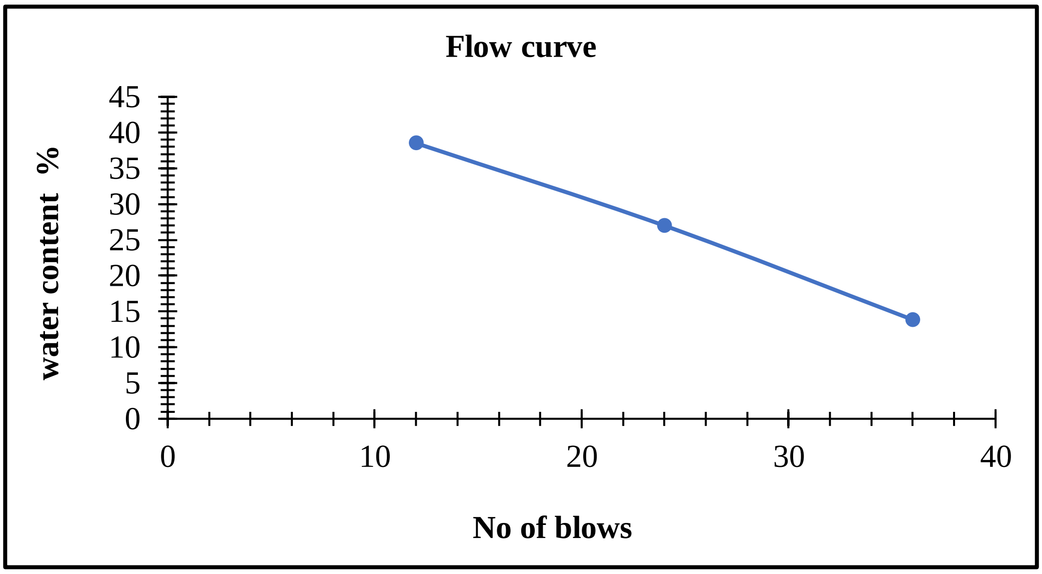


Fig 5.3: Showing plot obtained from Casagrande's Liquid Limit Experiment

5.2.3 Natural Moisture Content, Specific Gravity, and Bulk Density

Table 5.2 Laboratory results for various parameters

Parameters	Value
Natural Moisture content %	6.2
Specific Gravity	2.58
Bulk Density in kN/m^3	14.2
Coefficient of Permeability (m/hr)	0.0026

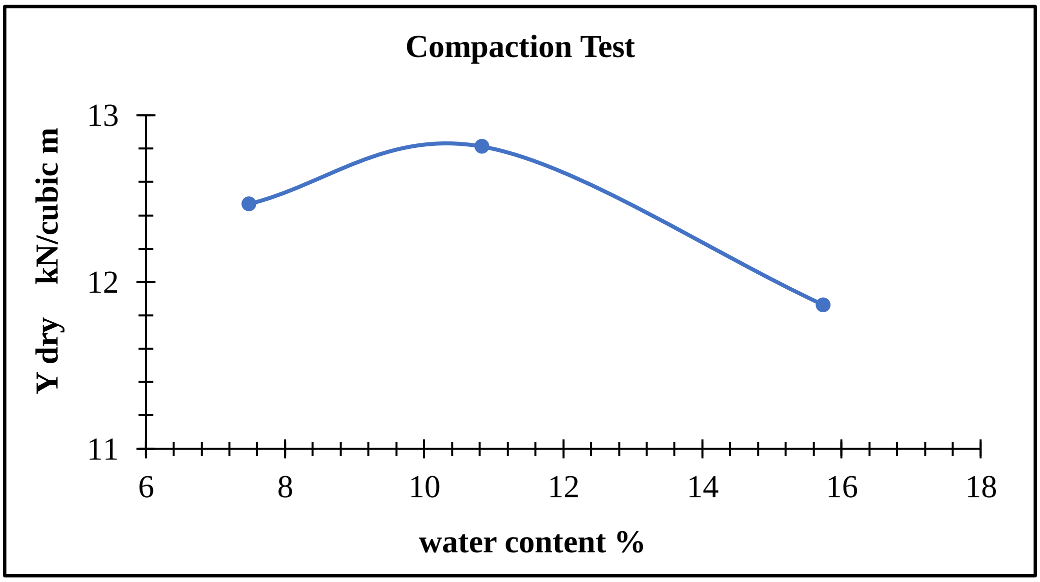


Fig 5.4: Showing plot obtained from Proctor Compaction Test

5.2.4 Direct Shear Test Result

The high value of the (ϕ) is due to the high proportion of sand (coarse grain soil), and the presence of silt may be responsible for the considerable cohesion values. Because the behavior of non-plastic silt is more like sand and plastic silt is more like clay, the presence of plastic silt may be attributed to the cohesion parameter.

Table 5.3 Laboratory results for Direct Shear Test

Parameter	Value
Angle of internal friction (ϕ) °	32.44
Cohesion (c) (kN/m^2)	10

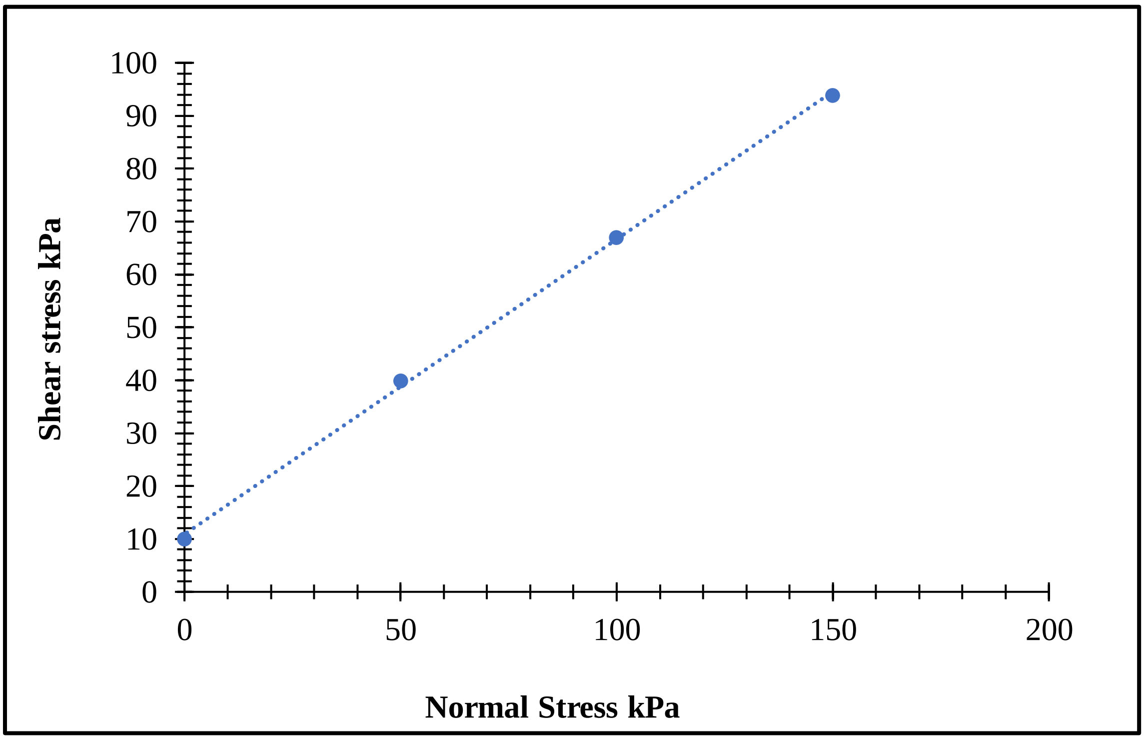


Fig 5.5: Showing plot obtained from Direct Shear Test

5.3 NUMERICAL MODELLING RESULTS

5.3.1 Before Rainfall

The slope's safety factor is evaluated before the rain, it is discovered to be more than 1 (Fig 5.6). which justifies that the slope is stable when there is no rainfall. The shear resistance is larger than the shear mobilized before rainfall, indicating that stabilizing forces outweigh those attempting to produce instability.

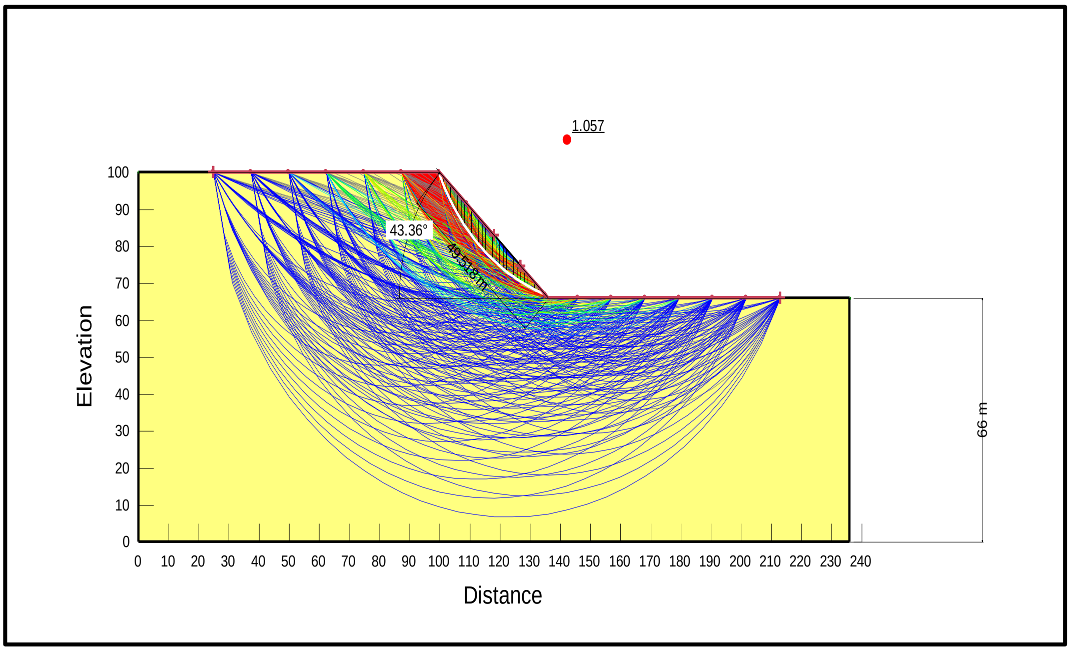


Fig 5.6: Factor of Safety before rainfall

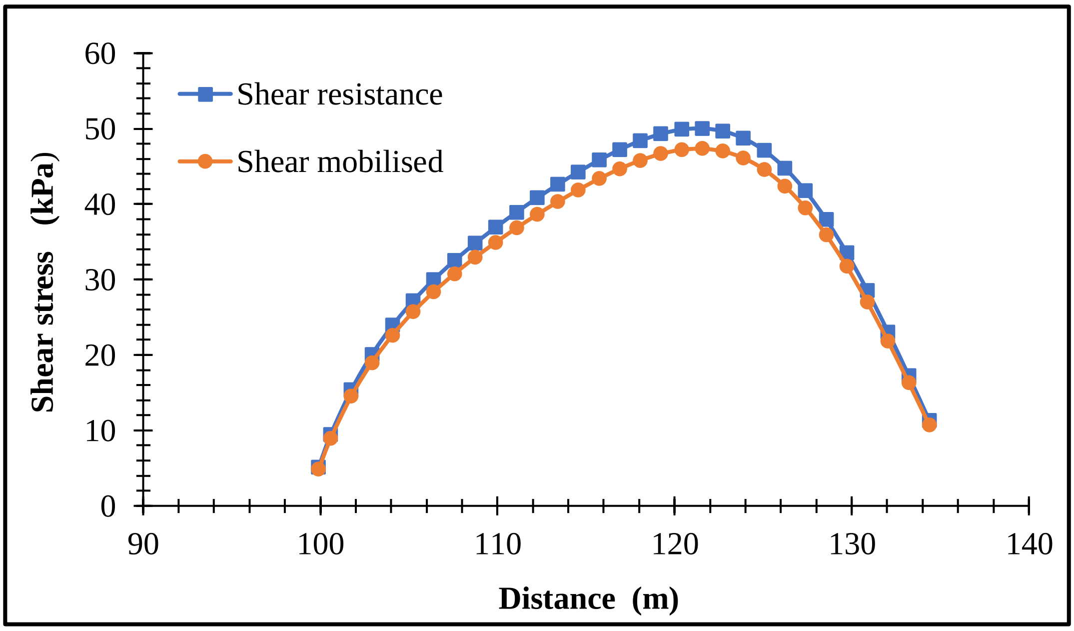


Fig 5.7: Shear resistance and Shear mobilized comparison before rainfall

5.3.2 After Rainfall

It was found that the landslide was induced by a rainfall event of a 2-day duration with a mean intensity of 1.8 mm /day. This intensity is applied to the slope model to determine the safety factor after rainfall, which turned out to be less than 1 (Fig 5.8), showing an extremely unstable soil slope. Rain caused a significant increase in pressures that were attempting to make the slope unstable and overcome the shear resistance.

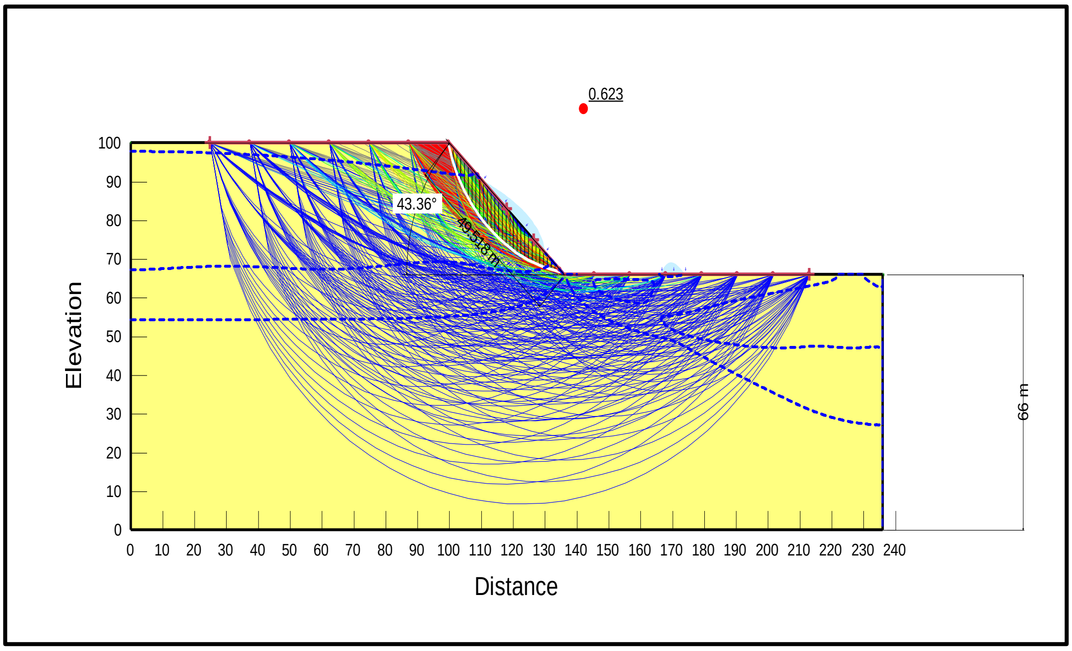


Fig 5.8: Factor of Safety After Rainfall

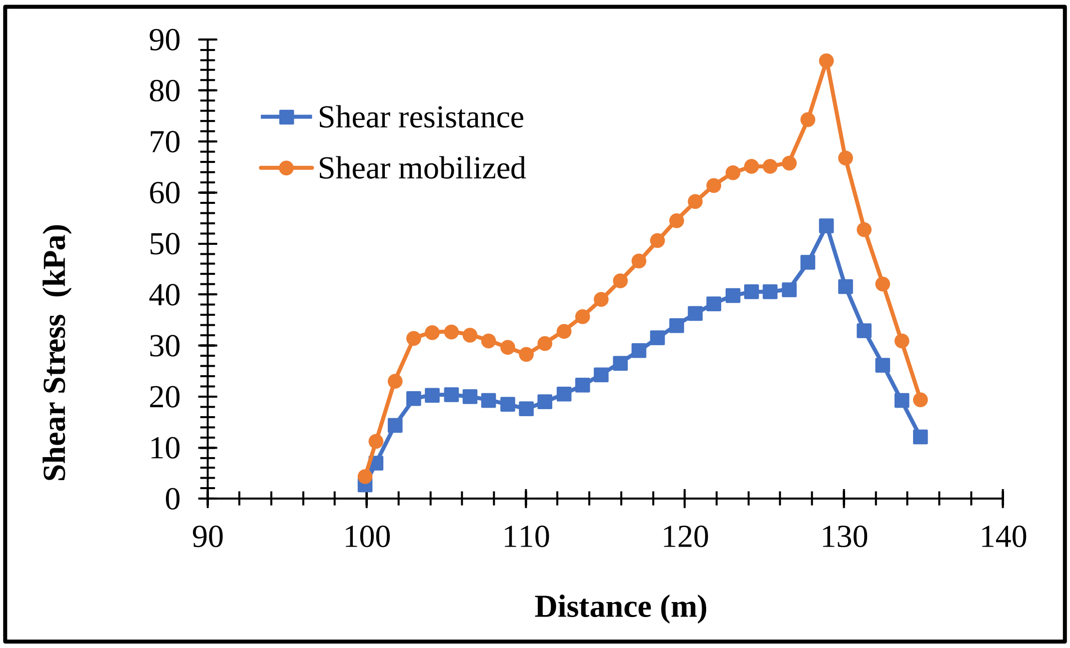


Fig 5.9: Shear resistance and Shear mobilized comparison after rainfall

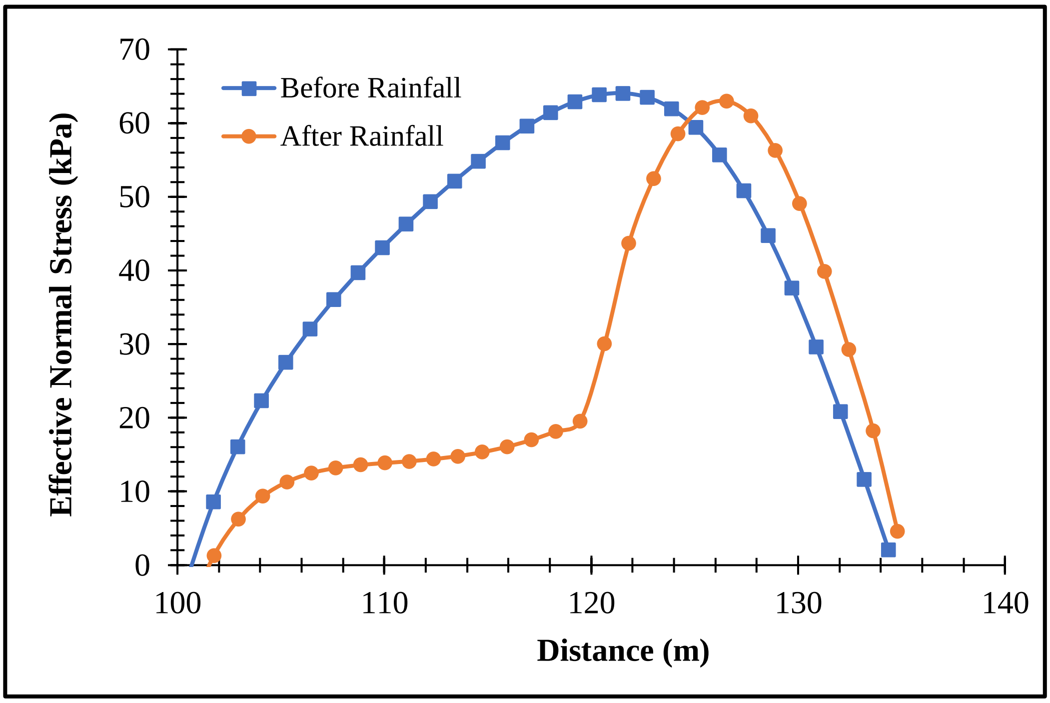


Fig 5.10: Effective Normal stress comparison before and after the rainfall

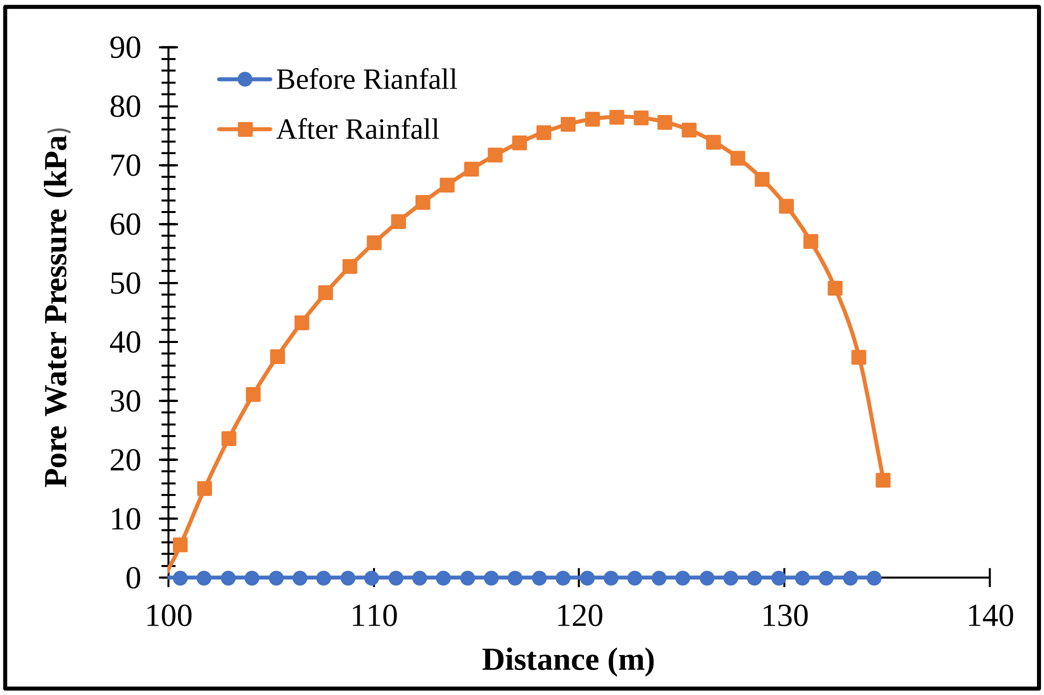


Fig 5.11: Showing buildup of pore water pressure after rainfall

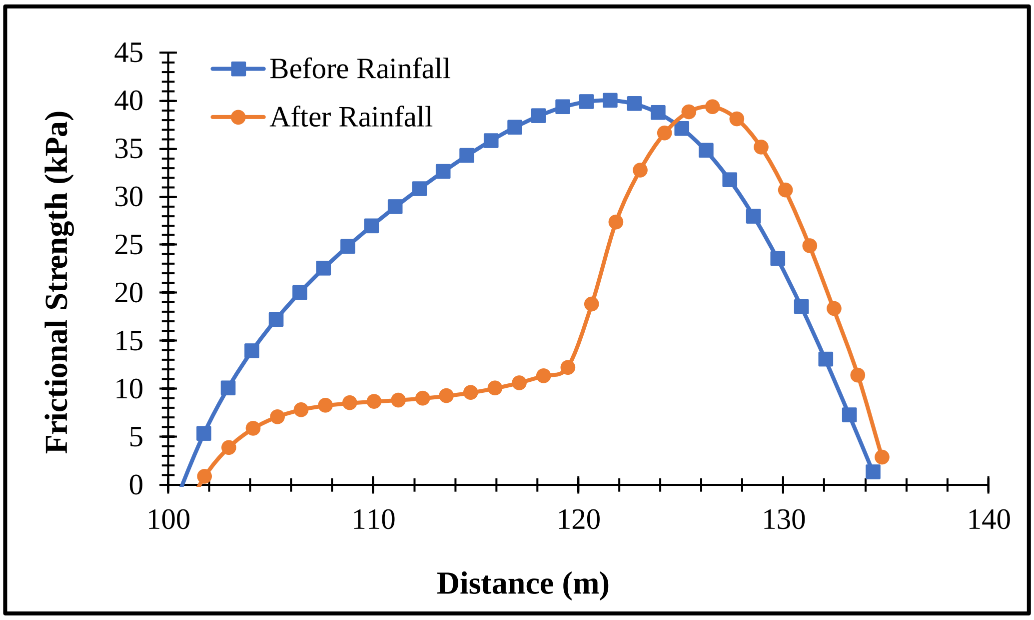


Fig 5.12: Frictional Strength comparison before and after the rainfall

In previous studies, there is research done on physical modeling and Landslide Hazard zonation maps for a landslide-prone stretch of National Highway 5 but there is no study dealing with the Rainfall ID threshold for the same region. There are studies based on developing rainfall thresholds for other regions in India and over the world, but they lack validation by any other technique. There are separate studies based on numerical modeling for slopes in the NH5 region to research how rainfall affects their stability. In this study, first, there is the development of equation (4) using empirical methods then this threshold is validated using numerical modelling. It was found that a rainfall event of 2-day duration caused the failure of our considered slope which was of mean intensity 1.8 mm/day. As per our derived threshold that is equation (4) if we put duration D equals 2, it states that rainfall above the intensity of 1.513 mm/day can trigger a landslide, with the help of numerical modeling slope model is designed and rainfall of 1.8 mm/day is applied on it which is more than the threshold for the validation. It was observed that the FOS of the slope reduced to 0.623 which was over 1 before the rainfall. 0.623 FOS indicates the slope failure due to the rainfall. Fig 5.7 and Fig 5.9 are showing how Shear mobilized took over Shear resistance after the rainfall which indicates forces trying to fail the slope becomes greater than forces acting to stabilize it which ultimately leads to failure.

To comprehend the mechanism of slope failure brought on by rainfall, numerous additional factors can be considered, such as Effective Normal Stress and Pore Water

Pressure. The plots shown in Fig 5.10 indicate the reduction in the value of effective normal stress after the rainfall and the reason behind this decrement is shown in Fig 5.11, which indicates the development and increase in the value of pore water pressure inside the soil layer. To understand the term Pore Water Pressure, we can relate it to the blood pressure inside the human body as a low value of it can cause a collapse of the body, and a high value creates hypertension, similarly, a high value of Pore Water Pressure creates uplift pressure inside the soil layer which contributes in slope failure. As effective normal stress is the result of the subtraction of Pore Water Pressure from Total Normal Stress, an increment in Pore Water Pressure causes a reduction in Effective Normal Stress. A reduced value of Effective Normal Stress is a direct indicator of a reduction in Frictional Strength as shown in Fig 5.12, which further results in a landslide.

The results obtained in this study lead to the development of an integrated approach, which includes both an Empirical approach and Numerical Modelling. The threshold for rainfall intensity and duration set here establishes a minimum bar below which there are very few chances that rain will cause a landslide. Beyond these points, the probability of occurrence increases exponentially, although false alarms are still a possibility and must be considered. Rainfall is the dominant factor for slope instability among other physical factors. A reliable Landslide Early Warning System should combine the rainfall thresholds with other indicators, such as soil moisture content, movement of soil strata, etc. Rainfall criteria have been developed and are regularly updated to help anticipate landslide incidents around the world. This study is a step towards creating a reliable early warning system for landslides that can lessen the damage caused by an incident along National Highway 5.

CHAPTER 6 – CONCLUSIONS

- This study established a rainfall ID threshold based on a frequentist approach for a landslide-prone stretch of National Highway 5. This is the first of its kind for the studied area.
- The rainfall threshold relationship fitted to the lower value of the landslide triggering rainfall events is developed and validated in this study. The resulting threshold equation is $I = 0.8046\ D^{0.9111}$ and it leads to the conclusion that a continuous rainfall of 1.513 mm/day can cause landslides for at least two days.
- For validation of this obtained threshold numerical modeling is used where rainfall more than the threshold is applied on the slope and it was observed that the Factor of Safety reduced to 0.623 which indicates slope failure.
- This initial attempt to establish empirical rainfall thresholds for the outbreak of landslides along National Highway 5 will spur additional research with finer accuracy of rainfall events and more landslide points to strengthen the rainfall intensity-duration threshold models locally and eventually develop an early warning, especially for slope failures caused by rainfall.

CHAPTER 7 – LIMITATIONS AND FUTURE SCOPE

- A major limitation of this study is that there is no organized record of the date of landslide events in the studied region and no availability of rainfall ground data that's why landslide data was collected manually and remote sensing data is used for rainfall events. In the future availability of more precise landslide and rainfall data can cause a major improvement in this work.
- Reliability on rainfall threshold alone can result in false alarm sometimes as despite rainfall being a major triggered factor of landslides, there are other factors too.
- To increase the accuracy of a landslide-based EWS, it is necessary to include other characteristics such as soil moisture, pore water pressure, and soil movement. Consequently, numerous sensors that record variables like pore pressure, moisture, and movement are used in addition to rain gauges.
- Further for the improvement of this study stretch of National Highway 5 can be divided into various parts of the same kind of geological strata, so that separate studies can be carried out for more accurate EWS development. Integration of different techniques such as Physical threshold, landslide zonation map, and rainfall intensity–duration threshold is desirable and can be a game changer in the battle against this natural hazard.

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LIST OF PUBLICATIONS

S.no	Paper Title	Presented at	Publishing in	Current Status
1.	Rainfall Threshold for Prediction of Landslides around National Highway 5, Himachal Pradesh, India	International Conference on Advancement in Civil Engineering (ICACE)	AIP Conference Proceedings Journal Indexing Status	Accepted and under publication
2.	Stability analysis of rainfall-induced landslide using numerical modelling	Indian Geotechnical Conference 2022	Will be published by Springer as a proceedings book volume Indexing Status	Accepted and available at Google Scholar

PAPER NAME	AUTHOR
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