Chapter 13
Effect of Antecedent Uniform Rainfall Pattern on the Stability of a Typical Northeastern Slope

Sreeram Shruthija and Sudheer Kumar Yamsani

Introduction

The Indian Himalayan region is greatly affected by the frequent occurrence of landslides, particularly rain-induced landslides. Out of all the landslides that happen around the world, 30% of them occur in the Himalayan region (GSI Report, 2016) leading to a loss of one billion USD, and there is a human life lost every year which is about 200 people per year. According to the NDMA report (2011), it is estimated that there is land loss of 120 m/km/yr, leading to a loss of 2500 tons/km^2 per year because of landslides. 0.49 million km^2 is affected by landslides which are around 15% of India's land area. Most of the landslides are because of rainfall and earthquakes.

Rain-induced landslides are seen in many parts of the world particularly in the tropical regions having hot and humid climates [4]. Rain-induced slope failures are seen in natural slopes, cut slopes, and embankments. Most of the rain-induced slope failures are shallow with the depth of failure less than 3 m, and the orientation of the slip surface is parallel to the surface of the slope. Tropical climatic conditions lead to the formation of residual soils which are usually in partially saturated conditions [5]. In tropical regions, depth of the water table is greater and hence will have greater suction. It is observed by many researchers that matric suction has a greater role in rain-induced slope failures [6]. Most of the rain-induced slope failures occur due to the wetting front and decrease in matric suction rather than an increase in the ground water table. Variation of matric suction is affected by climatic conditions like the intensity of rainfall, duration of rainfall, rainfall pattern, evaporation, and evapotranspiration.

S. Shruthija (✉) · S. K. Yamsani
National Institute of Technology, Warangal 506004, India
e-mail: srrmshruthi@gmail.com

S. K. Yamsani
e-mail: skyamsani@nitw.ac.in

K. Muthukumara et al. (eds.), *Earth Retaining Structures and Stability Analysis*,
Lecture Notes in Civil Engineering 303,
https://doi.org/10.1007/978-981-19-7245-4_13

As the rainfall infiltrates into the unsaturated soil, the matric suction or the negative pore water pressure starts decreasing; as a result, the shear strength of the soil is reduced leading to the failure of the slope. Northeast India has residual soils with their ground water levels at very greater depths and hence will have large initial suction values. The shear strength contributed by matric suction is also greater. Pore water pressures in the soil start changing as the rainfall gets infiltrated; this leads to variation in the ground water table, variation in pore pressures, and thereby, the strength contributed by matric suction is also lost. Loss of strength contributed by suction will result in failure of slope, and hence, the landslides occur. A lot of research has been done by the researchers in the area of various factors affecting rain-induced landslides like pore water pressures, properties of soil, the intensity of rainfall, duration of rainfall, antecedent rainfall (rainfall that occurs before the failure or it is the rainfall that is experienced by the slope in before), lithology, ground water table position, hysteresis, matric suction, land use and land cover, improper road constructions, drainage characteristics, the inclination of slope (angle), the elevation of slope (height of the slope), and the morphology of the area. There is limited work that is done in the area of antecedent rainfall and its patterns. The work that is presented in this paper focuses on one of the identified patterns from northeastern rainfall data (rainfall of Guwahati in the year 2018 is taken), and its impact on the stability of slope with varying soil properties and slope angle is discussed.

Background

Lim et al. [8] studied the effect of matric suction on the stability of residual soil slope and observed that canvas covered section shows less effect when compared with grassed covered and bare land slope sections with change in matric suction. Rahardjo et al. [11] studied the significance of antecedent rainfall on the distribution of pore water pressure in slopes with residual soils and concluded that antecedent rainfall, initial pore water pressures before the occurrence of significant rainfall, and magnitude of antecedent rainfall play a major role in developing the worst pore-water conditions. The significance of this antecedent rainfall is observed to be greater in low-conductivity soils when compared with high-conductivity soils. Once the slope reaches the highest pore water pressure profile, its contribution to subsequent rainfall is observed to be nil.

Rahardjo et al. [10] studied the significance of ground water table location, soil properties on slope stability during rainfall and observed that the slopes with the ground water table at greater depth at driest period will have a rapid reduction in factor of safety (FoS) of the slope. And also, that the soils which have a higher % of fine particles will have a high air entry value of the soil–water characteristic curve (SWCC), the permeability function will be gentle, and the saturated permeability will be less. Minimum FoS may not occur immediately after the rainfall ends, but few hours after rainfall ends.

Rahimi et al. [12] studied the significance of antecedent rainfall patterns on slope stability and found that the rate of decrease in FoS, the time corresponding to the occurrence of minimum FoS, and its value are controlled by antecedent rainfall patterns. The significance of the antecedent rainfall pattern is observed to be more on low-permeable soil slopes when compared with high-permeable soil slopes. Kim et al. [7] worked on the instability of unsaturated soil slopes with variation in rainfall and concluded that climate change influences shallow landslides.

Wu et al. [14] experimentally analyzed rain-induced slope failures and found that lesser rainfall intensity for a longer duration leads to a larger scale landslide. Failure patterns are observed to be related to the intensity of rainfall, slope gradient, and the initial conditions of matric suction. Zhang et al. [15] studied the delay phenomenon in slope instability due to rainfall and observed that the soils with a low water entry value and a lesser rate of rainwater infiltration had a greater probability of generating a delayed phenomenon. The influence of initial ground water table depth on the delay phenomenon is observed to be related to soil properties. The most obvious delay phenomenon is seen for soils with an anisotropic ratio $k_y/k_x = 0.5$ and also when saturated hydraulic conductivity is the same as the intensity of rainfall.

Bhardwaj et al. [1] did a case study on rain-induced landslides in the Indian Himalayan region. It is observed that slopes having slope angles 20–30° and elevation from 1000 to 2000 m are more susceptible to rain-induced landslides (R.I.L), and the landslides are found to be more susceptible in places having garnet ferrous gneiss, schist, migmatite rock. Dikshit et al. [3] wrote a review paper on RIL in the Himalayan region in which hazard monitoring, forecasting, and susceptibility analysis are focused.

The numerous factors that are used to analyze landslides are also studied. The study admits that there are numerous fields in which research work is required like including climatic change or the use of high-quality primary data as input data for computational models.

Soil Properties

Guwahati is a city in Assam, having hill slopes with residual soils of varied stratification. These are formed due to residual weathering. After geological investigation, it is identified that these soils comprise weathered basal rock, decomposed granite, core stones, lateritic and saprolitic residual soils. Isovolumetric weathering of bedrock leads to the formation of a residual soil layer called saprolite. These are dense and resemble parent rock fabric and structure. These are found to be very compact although being porous due to the leaching of fine particles. Once they are disturbed, they lead to landslides. Most of the landslides in Guwahati are found to be RIL, so it is very much essential to have the data of soil properties both physical and engineering properties for the analysis of slopes. Physical and engineering properties are collected from Sarma et al. [13] (See Fig. 13.1).

Fig. 13.1 Picture showing soils of a slope in Guwahati (site: cut slope in IIT Guwahati, Sarma et al. [13])

Table 13.1 Properties of soils in slopes of Guwahati

Property	Silty sand	Silty clay
Specific gravity	2.44	2.7
Liquid limit (%)	39	41.5
Plastic limit (%)	Non-plastic	23.2
USCS classification	SM	CL
ϒ (KN/m^3)	16.8	19
c^l (Kpa)	0	25
$Ø^l$ (degrees)	36	18
$Ø^b$ (degrees)	36	18
Saturated permeability (m/s)	6.6×10^{-5}	8.3×10^{-7}

USCS: Unified soil classification system
c^l: Effective cohesion
$Ø^l$: Effective angle of internal friction
ϒ: Unit weight
$Ø^b$: Angle of internal friction with respect to matric suction
SM: Silty sand; CL: Low compressible clay

Soils in Guwahati have two layers of soil; top layer is silty clay, and the bottom layer is silty sand. It is found that Guwahati slopes have unsaturated soils with the ground water table at greater depths, so it is very much important to have SWCC of these soils which are taken from literature review [2, 9] (See Table 13.1).

SWCC of the two soils is collected from a literature review [2] (See Figs. 13.2 and 13.3).

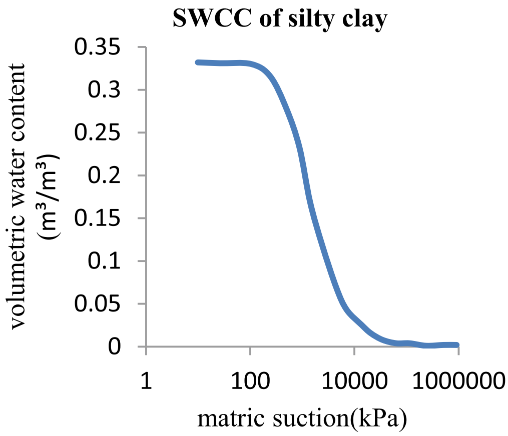


Fig. 13.2 SWCC for silty clay

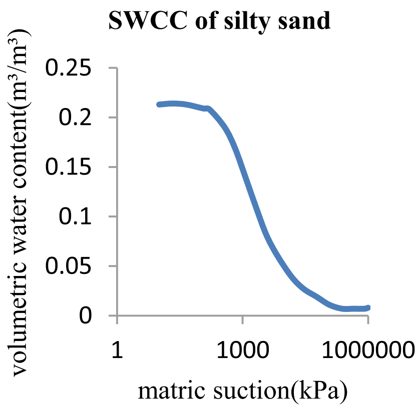


Fig. 13.3 SWCC for silty sand

The SWCCs are given as input in Geostudio software as volumetric data point functions. From the defined volumetric data point function, the hydraulic conductivity of soils is further estimated using the van Genuchten model. This defined SWCC and hydraulic conductivity function is assigned for the slope to perform seepage analysis.

Slope Geometry

See Fig. 13.4.

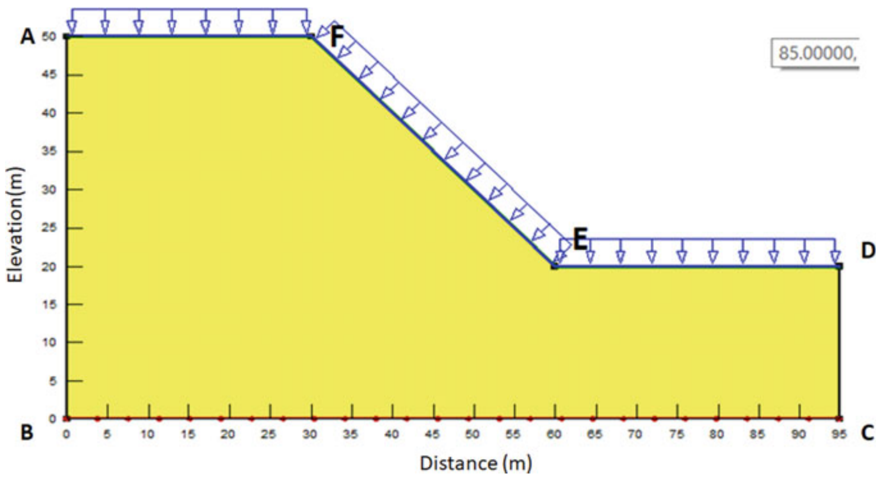


Fig. 13.4 Slope geometry

Boundary Conditions

AB, DC: No flow condition is assigned.
BC: Zero pressure line or datum line (free drainage).
AF, FE, ED: Rainfall is given; it is also the potential seepage face (Excess rainfall flows as runoff).
The slope angle is 45°, and the slope height is 50 m.

Methodology

The seepage analysis is performed using seep/*w* (module in Geostudio 2012). Pore water pressure data from seepage analysis are taken for slope stability analysis using slope/*w* (module in Geostudio 2012). Slope stability analysis is done by using the Mohr–Coulomb material model, and the suction contribution from shear strength is taken based on defined volumetric water content data point function.

Morgenstern price limit equilibrium method is used to find the FoS of slope using slope/w. This method is used because it satisfies all the conditions of equilibrium like moment equilibrium, force equilibrium, and can also be used for both circular and non-circular failure surfaces. This method also considers normal and shear forces acting on the sides of slices. Limit equilibrium method is used in the analysis because it is more conventional. One can also perform finite element analysis for slope stability using Geostudio by coupling with sigma/*w* analysis.

Designing Rainfall Patterns

Rainfall patterns are designed based on the methodology given by Rahimi et al. [12]. Rainfall data of Guwahati in the year 2018 are taken for evaluating most repeated patterns. Five patterns are identified as the most repeated patterns. Out of five patterns, a uniform rainfall pattern is considered and analyzed in this study. Maximum rainfall of 350 mm is taken in the present study. The maximum daily rainfall from the collected data is 71 mm. The maximum rainfall intensity calculated is 8.11E−7 m/s. The analysis is carried out for 10 days with 5 days of uniform rainfall, and after five days, rainfall is kept zero till the 10th day. Now, another analysis is carried out with initial 5 days uniform rainfall pattern followed by a major rainfall for 8 h (i.e., on the 6th day). The results are checked for 10 days keeping the rainfall as zero after 8 h of rainfall on 6th day till 10th day. This analysis is done to know how the antecedent rainfall is making the slope's initial condition worst. The major rainfall intensity given is the calculated maximum rainfall intensity. Gradually, the intensity of major rainfall is increased and observed.

Rainfall is assigned as a boundary condition in seep/*w*. Rainfall intensity and its duration values are given as boundary conditions by defining a new boundary condition. Rainfall intensity values are given as a step data point function.

Results and Discussions

Pore water pressure variations and infiltration values for uniform rainfall patterns are taken from results of seep/*w*. FoS variations with time are taken from slope/*w* results. Normalized FoS is the ratio of the FoS at a particular instant of time to the initial FoS. Normalized FoS is used for comparing results of uniform rainfall patterns because initial FoS for different soil types will be different as they have a wide range of pore water pressure distributions (Fig. 13.5).

It is observed that there is a 20% reduction of normalized FoS for low-conductive soil (silty clay) and a reduction of 10% for high-conductive soil (silty sand). To

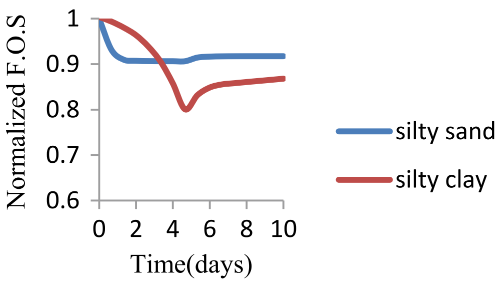


Fig. 13.5 Effect of antecedent uniform rainfall for 5 days with varying soil types

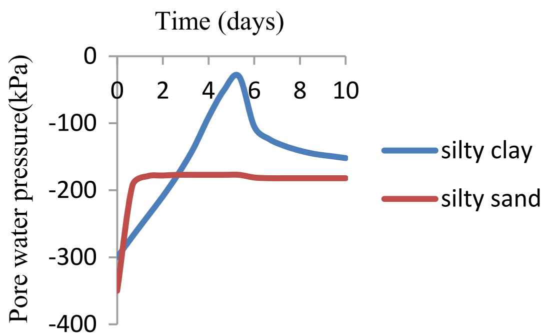


Fig. 13.6 Pore water pressure variation at depth 2 m below the toe of the slope

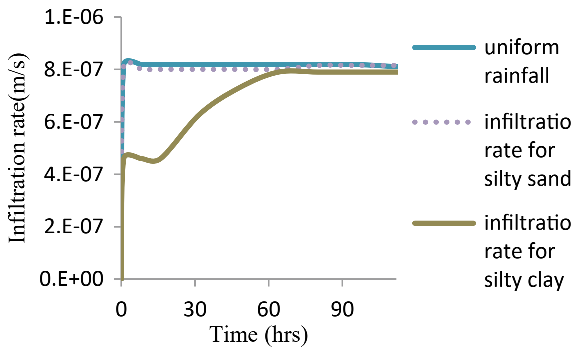


Fig. 13.7 Infiltration rate with varying soil type under 5 days antecedent uniform rainfall pattern

understand the above results, pore water pressure variations and also the infiltration rates are observed for slopes with both the soil types.

From Fig. 13.6, it is clear that the pore water pressure variations are greater for slope with low-conductive soil than high-conductive soil, and also that the trend in which the pore water pressures are varying is the same as the trend in which the normalized FoS is varying with time.

From Fig. 13.7, it is seen that the rainfall intensity and the infiltration rate are the same for slope with silty sand. This can be because of greater permeability all the rainwater infiltrates into the slope. For a slope with silty clay initially, the rainfall intensity and infiltration rate are not the same. This can be because for a low-conductive soil, the permeability will be less thereby the amount of water that gets infiltrated is very less. The unsaturated pores will saturate gradually with time, and hence, with time, as the saturated permeability is greater than the unsaturated permeability of the soil, the infiltration rate also gets increased (Fig. 13.8).

It is observed that a slope that experienced antecedent rainfall for 5 days when subjected to a major rainfall of intensity 8.11E−7 m/s for 8 h has undergone a reduction of normalized FoS of 26% for a slope with silty clay and a reduction of approximately close to 10% for a slope with silty sand. Without antecedent rainfall, the slope with major rainfall for 8 h has a reduction in normalized FoS of 1% for

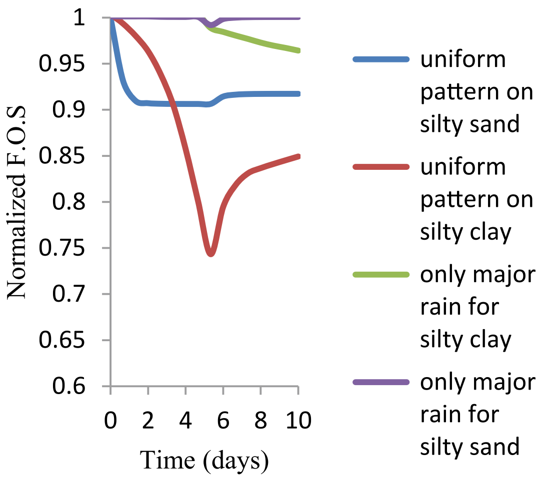


Fig. 13.8 Effect of major rainfall with and without antecedent rainfall

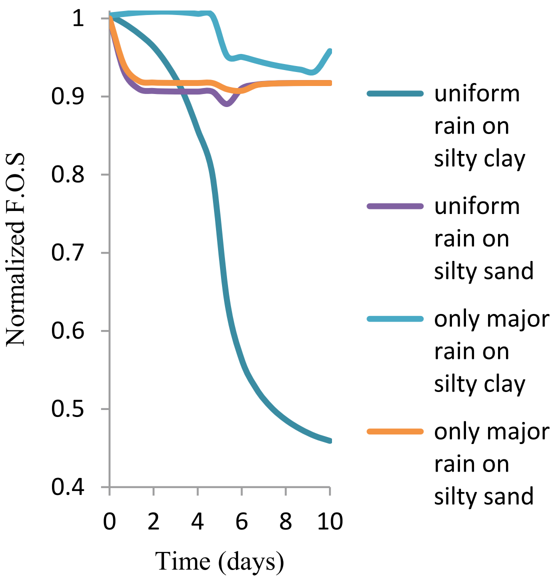
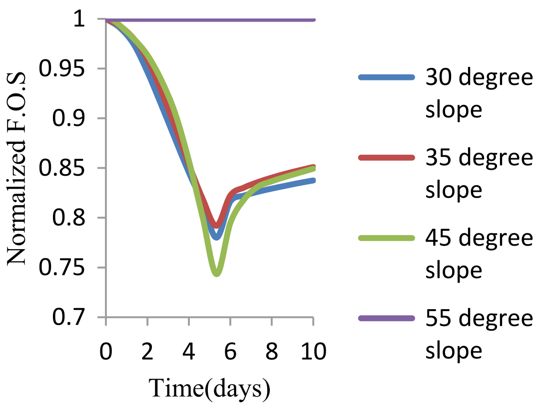


Fig. 13.9 Effect of increased major rainfall with and without antecedent rainfall

silty sand and 4% for silty clay. This clearly shows the significance of antecedent rainfall. Antecedent rainfall affected both slopes with silty sand and silty clay, but its significance is greater for low-conductive soil slope similar to findings of Rahardjo et al. [10] (Fig. 13.9).

When the magnitude of major rainfall is tripled, the low-conductive soil slope with antecedent rainfall followed by major rainfall has failed. This clearly indicates the significance of antecedent rainfall which is creating the worst initial conditions for low-conductive soil slopes (Fig. 13.10).

Fig. 13.10 Effect of antecedent rainfall with varying slope angle on low-conductive soil slope



Slope angle is changed for low-conductive soil slope. It is observed that the shallow slopes are significantly affected than the steep slopes. This is contradicting to our general understanding in soil mechanics that shallow slopes are more stable than steep slopes. This is because shallow slopes have more infiltration of rainwater, whereas in steep slopes infiltration is very less (more of the rainwater goes in runoff). In Fig. 13.8, it is observed that 45 degree slope is affected greatly because of the effect of both geometry and infiltration.

Conclusion

From this limited study, the following understandings are made.

- Antecedent rainfall before the occurrence of major rainfall affected both low-conductive and high-conductive soil slopes, and the effect is more significant in low-conductive soil slope.
- Pore water pressure variations are greater for low-conductive soil slope.
- The trend in which the pore water pressure is changing is the same as the trend in which the normalized factor of safety is changing.
- The infiltration rate and rainfall rate are the same for high-conductive soil slope.
- For low-conductive soil slope, the infiltration rate is less than the rainfall rate.
- The value of the minimum FoS is governed by the amount of infiltrated water.
- The time at which the minimum FoS occurs is the time at which the pore water pressure is minimum.
- Shallow slopes with low-conductive soils are more significantly affected by antecedent rainfall because the possibility for infiltration is more in the case of shallow slopes.

References

1. Bhardwaj A, Wasson RJ, Ziegler AD, Chow WT, Sundriyal YP (2019) Characteristics of rain-induced landslides in the Indian Himalaya: a case study of the Mandakini catchment during the 2013 flood. Geomorphology 330:100–115
2. Chatterjee D, Krishna AM (2019) Effect of slope angle on the stability of a slope under rainfall infiltration. Indian Geotech J 49(6):708–717
3. Dikshit A, Sarkar R, Pradhan B, Segoni S, Alamri AM (2020) Rainfall induced landslide studies in Indian Himalayan region: a critical review. Appl Sci 10(7):2466
4. Frattini P, Crosta G, Sosio R (2009) Approaches for defining thresholds and return periods for rainfall-triggered shallow landslides. Hydrol Process: Int J 23(10):1444–1460
5. Han KK, Rahardjo H, Broms BB (1995). Effect of hysteresis on the shear strength of a residual soil. In: proceedings of the first international conference on unsaturated Soils/unsat'95/paris/france/6-8 september 1995. Vol. 2
6. Indrawan IGB, Rahardjo H, Leong EC (2006) Effects of coarse-grained materials on properties of Residual soil. Eng Geol 82(3):154–164
7. Kim J, Jeong S, Regueiro RA (2012) Instability of partially saturated soil slopes due to alteration of rainfall pattern. Eng Geol 147:28–36
8. Lim TT, Rahardjo H, Chang MF, Fredlund DG (1996) Effect of rainfall on matric suctions in a residual soil slope. Can Geotech J 33:618-628
9. Malaya C, Sreedeep S (2013) A study on unsaturated hydraulic conductivity of hill soil of north-east India. ISH J Hydraulic Eng 19(3):276–281
10. Rahardjo H, Nio AS, Leong EC, Song NY (2010) Effects of groundwater table position and soil properties on stability of slope during rainfall. J Geotech Geoenviron Eng 136(11):1555–1564
11. Rahardjo H, Ong TH, Rezaur RB, Leong EC (2007) Factors controlling instability of homogeneous soil slopes under rainfall. J Geotech Geoenviron Eng 133(12):1532–1543
12. Rahimi A, Rahardjo H, Leong EC (2011) Effect of antecedent rainfall patterns on rainfall-induced slope failure. J Geotech Geoenviron Eng 137(5):483–491
13. Sarma CP, Krishna AM, Dey A (2019) Geotechnical characterization of hillslope soils of Guwahati region. In: Geotechnical characterisation and geoenvironmental engineering. Springer, Singapore, pp 103–110
14. Wu LZ, Huang RQ, Xu Q, Zhang LM, Li HL (2015) Analysis of physical testing of rainfall-induced soil slope failures. Environ Earth Sci 73(12):8519–8531
15. Zhang J, Li J, Lin H (2018) Models and influencing factors of the delay phenomenon for rainfall on slope stability. Eur J Environ Civ Eng 22(1):122–136