Original Research Article

Stability analysis of rainfall-induced landslides: A case study of a hilly area in Bangladesh

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Abstract: Rainfall-induced landslides stand as the prevailing geohazard in tropical and subtropical regions. The ongoing global climatic changes have introduced a wave of anomalous rainfall events across the world. These abnormal weather patterns have triggered numerous landslide incidents, resulting in significant loss of life and property. To develop early warning systems for such threats to people in mountainous areas of Chittagong, Bangladesh, it requires an in-depth understanding of the geo-environmental properties of soil slopes under heavy rainfall. Historical records reveal that rainfall in total exceeding 150–250 mm has resulted in both localized slope collapses and debris floods. When it rains heavily, rainwater infiltrates initially unsaturated slopes, elevating the degree of saturation while decreasing soil suction. Consequently, the reduced shear strength along the critical slip surface diminishes the factor of safety (FoS), and slope failure occurs. As a result, studies of soil-water characteristics have been conducted, followed by laboratory testing at the impacted sites, and the study found that rainfall and soil type (fine-grained silt) were the most critical factors behind landslides. The mechanism of slope failure is also demonstrated using a simple numerical infiltration model and a slope stability equation. The soil characteristics, the saturated volumetric water content (θ_s), closely match the field water holding capacity (θ_f), with a minor difference of 4-8%, and the drainage condition at the bottom of the slope appear to be important factors. Application of these test results to an early warning system for landslides and flash floods is finally demonstrated based on some simplifying assumptions.

Keywords: Antecedent rainfall, landslide, slope stability, suction, seepage, unsaturated soil.

1. Introduction

Rain-induced landslides and slope instabilities are prominent geohazards in tropical and subtropical regions due to steep topography and adverse geological features such as relict joints, differential weathering, high infiltration rates, a lack of a proper drainage system, and reductions in matric suction, resulting in a lower factor of safety against landslides[1–5]. As can be seen in Table 1, the number of landslides, debris flows, and mudflows caused by rainfall in Bangladesh's Chattagram Hilly Districts (CHD) has increased during the past few decades. The economic losses and casualties caused by landslides are often underestimated, with annual losses in countries like Japan, the USA, Italy, Taiwan, Hongkok, India and Banladesh[27,28]. In recent years, landslide disasters in Bangladesh's Chattagram Hilly Districts have resulted in significant loss of life and harm to vital infrastructure, ecosystems, way of life, and the local economy[6-8, 25]. About 725 people died in CHD landslides between 2000 and 2023[14,26,27]. In June 2017, monsoon rainfall-triggered landslides killed 160 people and impacted 80,000, UNOCHA,2017[12].

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Table-1 The major fatal landslide events in Chittagong, Bangladesh, 2000 to 2023.

Date of Landslide Incidence	Total No. of Landslides in a single date	Total of Districts affected duet to each event	Total No. Upazila Affected due to each event	Total No. of Deaths	Total No. of Injuries
23-Jun-00	1	1	1	13	20
26-Jun-03	16	2	3	23	9
26-Jul-03	4	1	3	0	0
11-Jun-07	100	1	5	127	125
12-Jun-07	5	1	1	0	0
3-Jul-08	3	1	2	10	8
6-Jul-08	3	1	2	8	20
18-Aug-08	1	1	1	11	7
30-Jul-09	4	1	1	10	9
15-Jun-10	14	2	4	57	100
1-Jul-11	1	1	1	16	3
9-Aug-11	1	1	1	2	4
26-Jun-12	3	2	2	15	7
27-Jun-12	22	3	13	96	446
26-Jun-15	9	2	6	14	16
13-Jun-17	35	5	11	164	187
11-Jun-18	37	1	1	1	2
12-Jun-18	7	2	3	13	3
25-Jul-18	3	1	3	5	3
8-Jul-19	8	3	5	13	10
10-Jun-21	1	1	1	1	0
26-Jul-21	5	2	4	8	5
28-Jul-21	2	1	1	5	2
17-Jun-22	5	2	4	4	6
7-Dec-22	1	1	2	4	0
7-Apr-23	1	1	1	1	2

The vulnerability of slopes in hilly regions and the increasing population and development demands, the construction of roads, buildings, other infrastructure in these areas is inevitable as well as hill cutting, deforestation (Figure 1), and lack of cultural understanding have made landslide tragedies a national concern[9-11]. With the arrival of about one million Rohingya refugees from Myanmar in August 2017, the area's landslide dynamics have worsened, UNHCR, 2020[12]. Cox's Bazar District cut over 6000 acres of reserved hilly woodland to house refugees[7]. Almost 3 million people—including urbanized Bengali groups, indigenous tribal populations, and Rohingya refugees—live in the CHD with significant landslide hazards as shown in figure 2.

Figure-1. (a) The degradation of forest resources in Chattogram Hill Tracts (CHT) (b) Hill cutting soil is being transported as raw materials in the brickfields (c) settlements in foothill. Source: Department of Environment, Chittagong, 2014 and Ahmed, 2017.

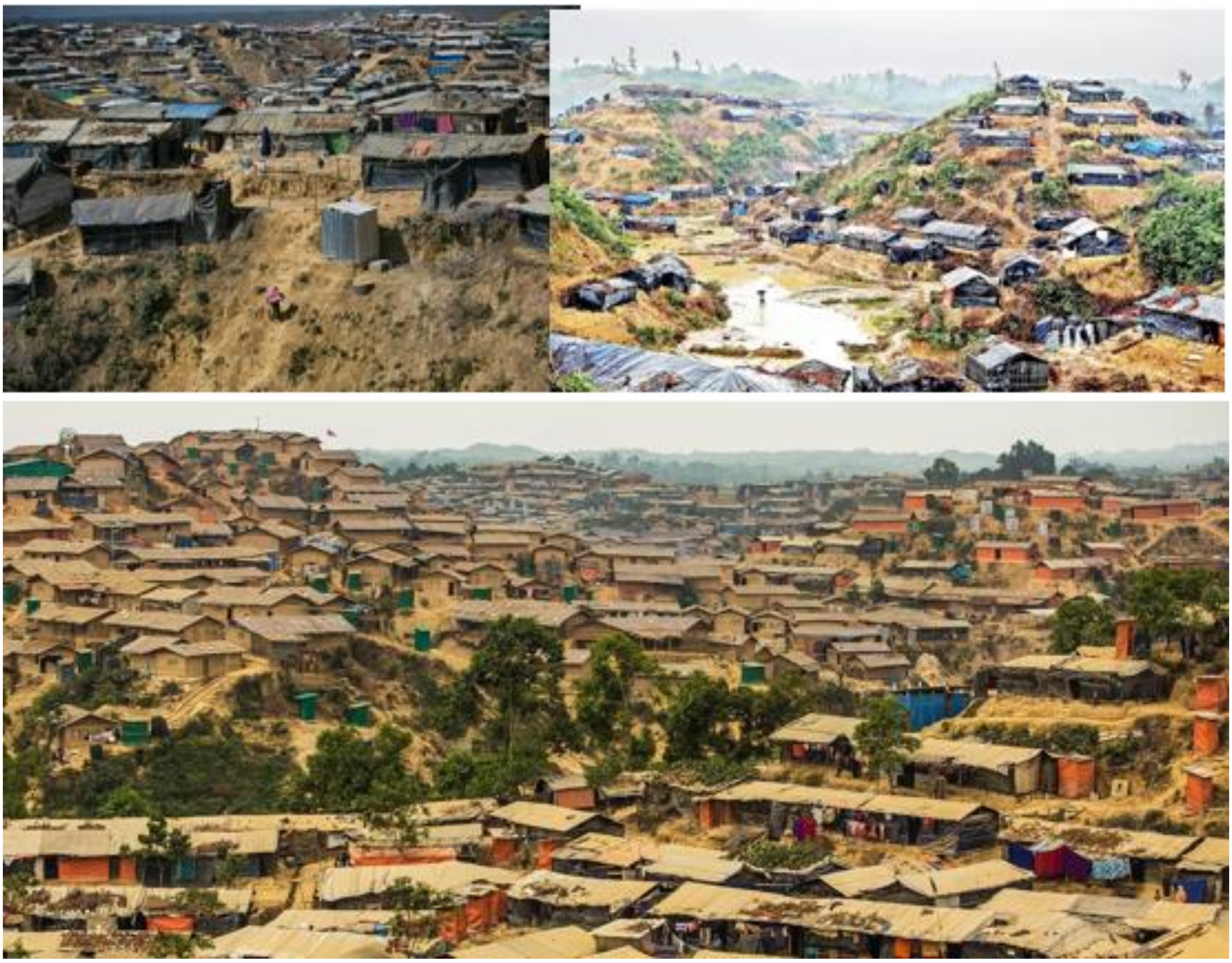


Figure 2 Cox's Bazar District cut over 6000 acres of reserved hilly woodland to house Rohingya refugees (Daily Star, 2018).

The importance of antecedent rainfalls and soil water characteristics on slopes in developing an early warning system for landslides has been highlighted by various researchers. Studies by Jotisankasa et al., (2010, 2023), Ng & Shi (2003) and Rahardjo et al. (2007, 2016), Baum et al. (2008), Bao & Ng (2000), and Mairaing et al. (2009) underscore the critical role of these factors. Additional research, such as that conducted by Smith et al. (2002), Alonso et al. (2003), and Sasahara et al. (2008), further supports this perspective. Understanding the historical rainfall patterns and the soil's moisture behavior, often monitored through techniques like tensiometers and soil-water characteristic curves, enables the establishment of a comprehensive framework for landslide prediction and prevention.

The main objective of this research is to develop a early warning system to predict landslides and slope failures, with a primary geographical focus on the Chittagong region of Bangladesh. This goal is pursued through a multifaceted approach, which involves an extensive analysis of precipitation data spanning from 2000 to 2022. Furthermore, the study encompasses numerical assessments to evaluate the susceptibility of slope failures. To enhance the accuracy of the early warning system, the research places particular emphasis on utilizing field water-holding capacity (θ_f) data derived from soil-water characteristic curves, with specific attention to a suction level of 33 kPa. Beyond this, the research conducts a comprehensive exploration of geotechnical characteristics and seeks to identify the underlying causative factors contributing to landslide and slope failure occurrences in the region.

2. Antecedent Rainfall

Climate change has led to a worrying increase in the frequency of heavy one-day or multi-day precipitation events around the world (Cities and climate change: global report on human settlements, 2011). It is, therefore, essential to develop an early warning system for the hilly areas of Chattagram incorporating local knowledge to reduce the loss of lives and property. If the daily rainfall in Chittagong is expected to be greater than 150-250 mm, early warnings will be sent to populations that are close to hill slopes and are at risk. The amount of precipitation for which a warning is issued will depend on local factors like slope, vegetation, and geology[15,16,21,22]. In Chittagong, the criteria for rainfall-related landslide warnings are often derived from statistical studies (from 2000 to 2022, figure 3) and practical knowledge. Figure 4 shows the rainfall occurrences that were seen in Chittagong, Bangladesh, prior to landslides and multiple cut slope failures in 2017.

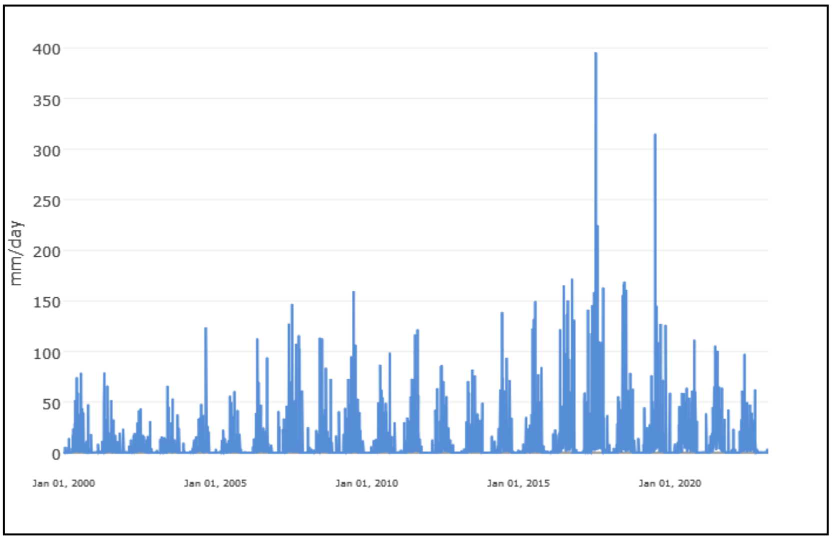


Figure 3 Yearly variation of maximum-minimum rainfall in Chittagong, Bangladesh.

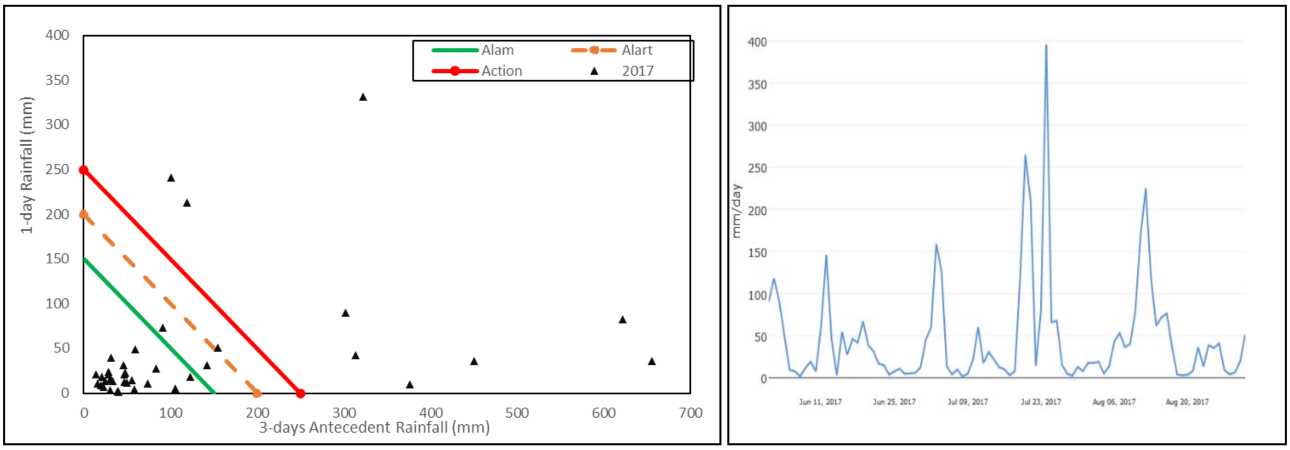


Figure 4 Rainfall events observed before landslides including debris flows and several cut slopes failure in Chittagong, Bangladesh in 2017.

Numerous studies have revealed a significant correlation between landslides, antecedent rainfall, and soil moisture[17–20]. This connection underscores how excessive rainfall can elevate soil water content and pore water pressure, rendering the soil more susceptible to landslides. Chittagong, Bangladesh, serves as a compelling case study where specific rainfall patterns, notably 3-day antecedent rainfall, have been identified as potential triggers for localized collapses, possibly attributed to delayed infiltration. A critical range of cumulative rainfall, typically around 150–250 mm over a four-day period, has been shown to predict landslides (Figure 5), with limited influence from evaporation and deep percolation.

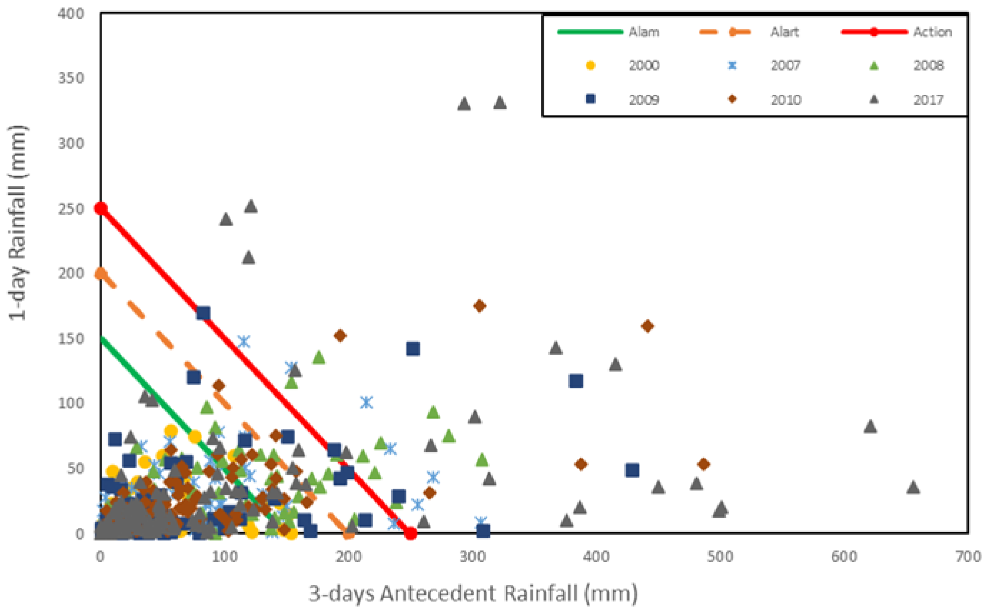


Figure 5 Rainfall events observed before major & medium landslides, including debris flows and several cut slopes failure in Chittagong, Bangladesh (from 2000 to 2023).

3. Soil suction measurement

Antecedent rainfall and soil moisture conditions play a pivotal role in predicting landslides. To monitor soil moisture in the field, various techniques such as tensiometers, TDR, gypsum blocks, and resistivity probes are employed, each requiring specific calibration for soil type accuracy. Tensiometers, for instance, gauge soil matric suction, a vital parameter for assessing soil moisture. The soil-water characteristic curve (SWCC), establishing the relationship between volumetric water content and soil suction, is essential for estimating soil moisture conditions. Studies by Johnson & Sitar (1990) and Jotisankasa et al. (2008,2023) have demonstrated correlations between soil suction and debris flow initiation. Moreover, it is the high positive pore water pressure that triggers slope movement and debris flow, as indicated by past research like Vaughan (1985) and Wang & Sassa (2003). The SWCC, in conjunction with field water holding capacity measurements, enables the estimation of rainfall required to saturate a slope, serving as an early warning system when combined with rainfall measurements. In this study, laboratory data obtained from the SWCC, using KU tensiometers as depicted in Figure 6, is utilized to further our understanding of the relationships between soil moisture and landslide risk.

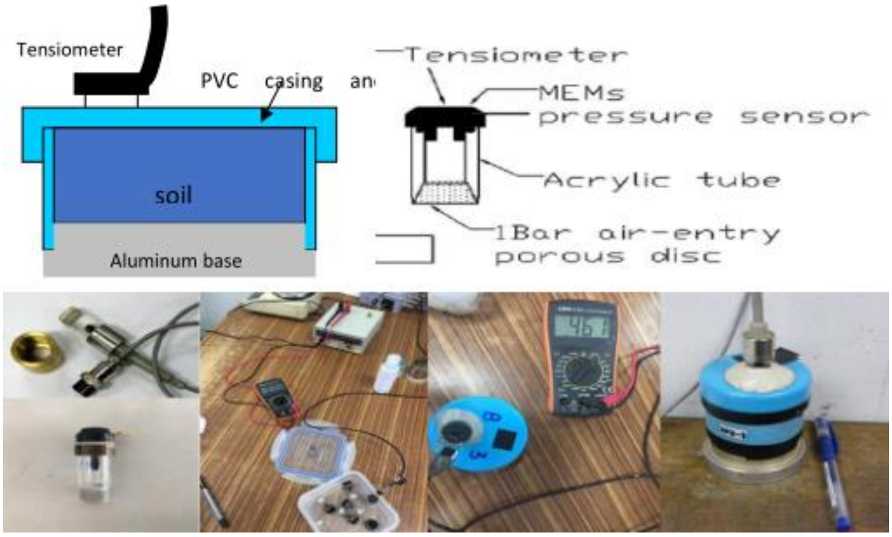


Figure 6 The suction testing procedure and necessary equipment's

4. Material and location of the study

The experimental program involved the collection of soil samples from Chattogram's landslide-prone locations and the conducting of various experiments on the samples. Following the experimental investigation, input soil parameters for numerical modeling were obtained using the study's findings. Five distinct areas in Rangamati where the landslides happened were chosen. The failing slopes next to the landslide were sampled for both disturbed and undisturbed samples. The sample collection was done shortly after the disastrous landslide. Figure 7 and Table 2 show the locations of Rangamati, Chattogram Hill Tracts, and sample collecting locations.

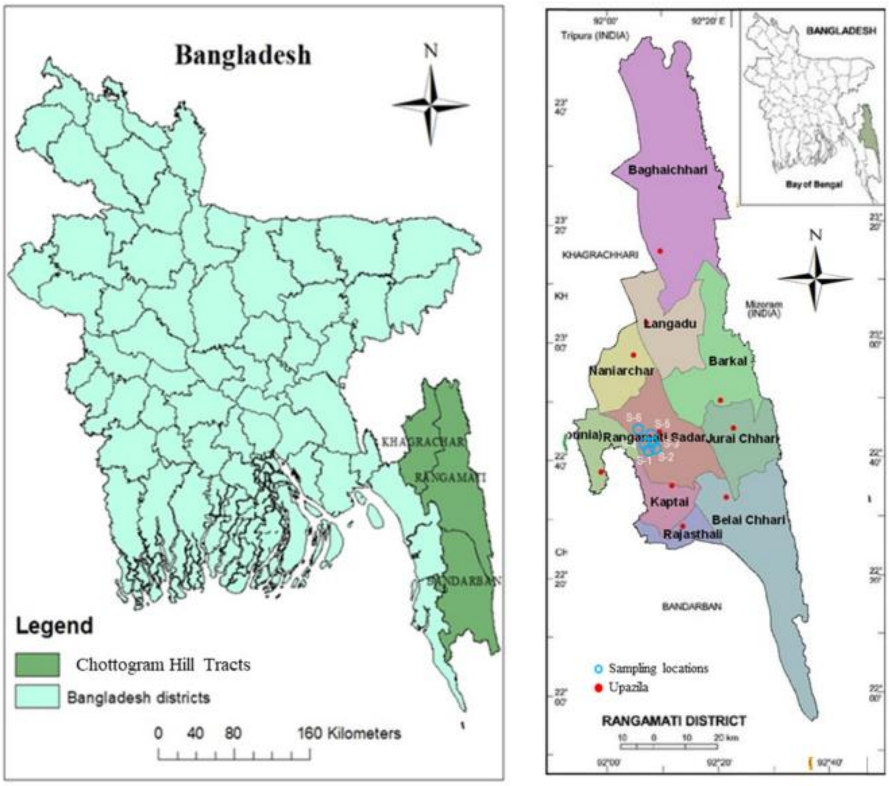


Figure 7 The Locations of soil samples collection in Rangamati, Chittagong, Bangladesh

Table 2 Some basic soil properties and locations of the sites

Location	Slope Angle	Soil Type (USCS)	Liquid Limit	Plasticity Index	Cohesion, C (kPa)	Friction Angle, ϕ(°)
22°38055.8492” N 92°8 015.7956” E	65°	SM	28	4	1.3	39.7
22°38041.7948” N 92°8 018.5316” E	50°	CL	33	13	18.1	10.5
22°38038.9184” N 92°8 035.9544” E	70°	CL-ML	24	6	9.4	27.4
22°38046.5684” N 92°8 045.9984” E	45°	CL	26	14	12.9	32.7
22°41032.2008” N 92°6 020.7684” E	50°	SM-SC	24	9	1.8	30.2

The samples were obtained without damaging the surrounding environment by digging a test pit close to the landslide source and then driving a thin wall cylindrical tube with a sharpened edge (with a diameter of about 63 mm) to the ground at the required depths (between 0 and 1.5 meters). Additionally, bag samples were collected for tests such as the grain size distribution curve, liquid limit, and plastic limit, which are crucial for classifying soils. Grain size distribution and general characteristics of the studied soils are depicted in Figures 8 and Figures 9.

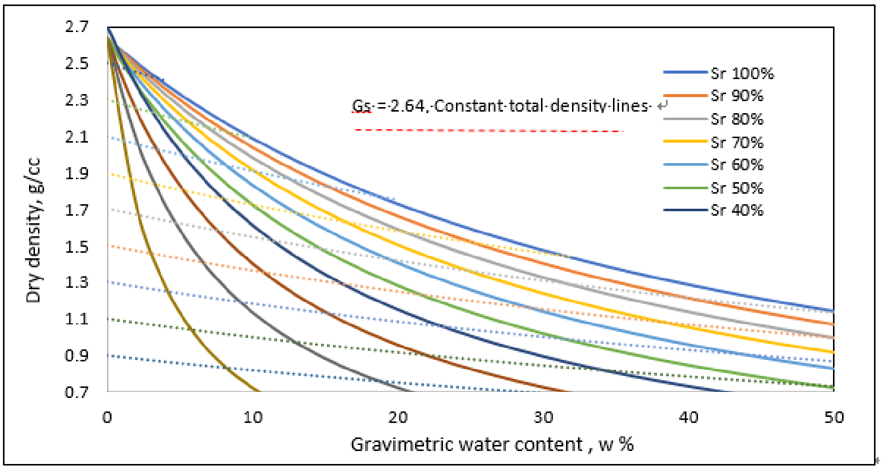


Figure 8 Gravimetric water content versus dry density with constant total density for specific gravity

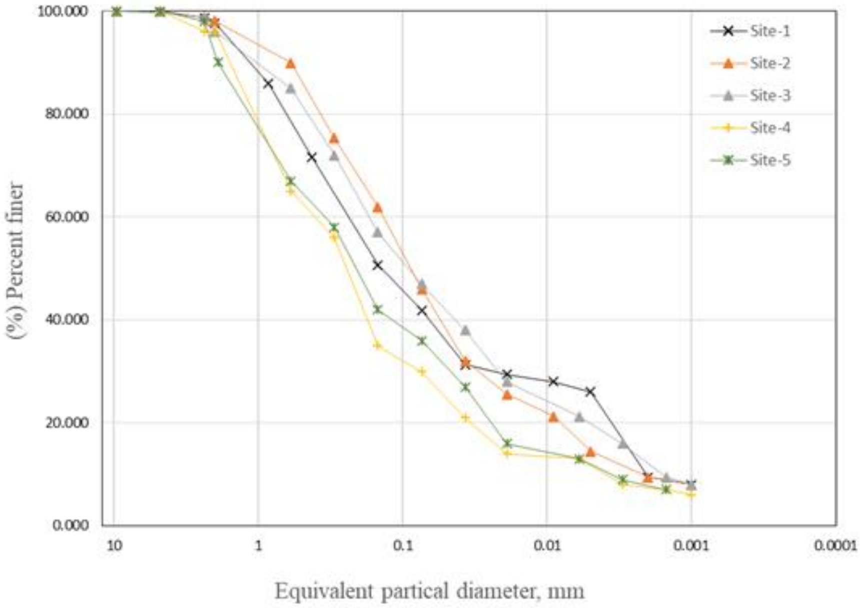


Figure 9 The equivalent particle diameter and percent finer of collected soil curves

It is noteworthy that the soils obtained from five landslide/debris flow locations in Chittagong exhibit characteristics of silty soils with low plasticity, as classified under the SM, ML, and CL categories. Prior studies[21] indicate that such materials are prone to displaying brittle undrained behavior while undergoing shearing and may be vulnerable to static liquefaction. According to Wang and Sassa's (2003)[24] findings, sand containing a higher proportion of fine particles, such as loess, exhibits increased mobility and elevated pour water pressure when subjected to landslides. The materials observed within the debris flow regions of Chittagong, Bangladesh were seemingly classified within this particular category.

5. Soil-Water Characteristic Curve (SWCC)

The soil-water characteristic curve for landslide area soils is used to convert tensiometric measurements to water content. Furthermore, the water content-suction relationship can be utilized to predict other mechanical properties of soil at various levels of saturation, such as shear strength change with suction and the permeability function[4,17]. These features are essential for any numerical investigation of rainwater seepage down a slope. As shown in Figure 6, simple wetting/drying experiments were conducted on the undisturbed materials.

In order to test the sample, we add 1–2% more water to it over the course of the test, and then measure it suctions after each addition. Samples are wetted by spraying or fogging them with water. In order to ensure that the suction measured at the upper surface of the sample was representative of the entire sample, it was necessary to wait for the suction measurement to reach equilibrium (which typically took about three days). To ensure complete soaking, the sample was submerged in water for 5–7 days while the overburden pressure was held at a notional 1kPa. This was done after the soil suction was lowered to less than 1kPa. After air drying the sample slowly, we tested its suction in the same progressive manner. The test was carried out in a room maintained at 20±0.5℃. Figure 10 shows the characteristic curves of the tested materials.

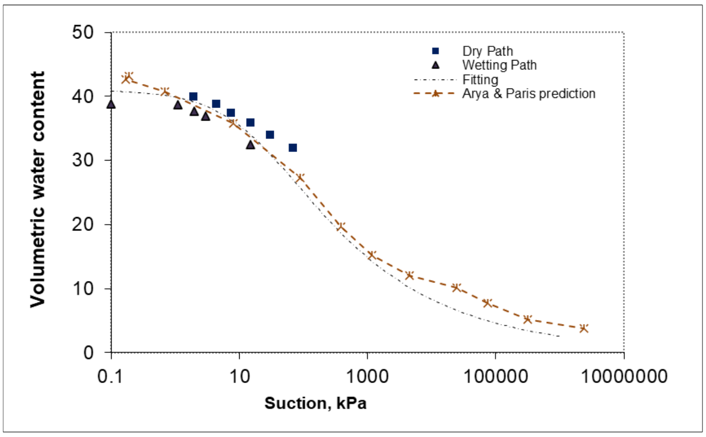


Figure 10 Soil-water characteristic shapes of soils from a landslide-prone area of Chittagong

6. Unsaturated soil and landslide

Unsaturated soil shear strength values are also required for assessing the stability of a slope under rain infiltration. Unsaturated soil strength can be determined using a variety of equations that have been presented[4]. The degree of saturation, S_r, is equal to Bishop's factor (χ), therefore we may apply a straightforward and accurate stress estimate (see equation 1 below).

$$\tau = C' + (\sigma_n - u_a).tan\phi' + (u_a - u_w).s_r.tan\phi' \quad \text{(Eq.1)}$$

Alternatively, Equation 2, Fredlund & Rahardjo, 1993, can also be used, and the shearing angle concerning suction ϕ^b, can be determined experimentally using direct shear or triaxial shearing tests with soil suction measurement.

$$\tau = C' + (\sigma_n - u_a).tan\phi' + (u_a - u_w).tan\phi^b \quad \text{(Eq.2)}$$

The effective cohesion, C', and effective angle of shearing resistance, ϕ', are determined using slow drained direct shear tests in this study. The pore air pressure ua value is zero, uw is pure water pressure or negative suction, and σn is the usual stress.

$$F_S = \frac{C' + (\gamma.z\cos^2\beta).\tan\phi' - u_w.\tan\phi^b}{\gamma.z\sin\beta.\cos\beta} \quad \text{(Eq.3)}$$

Based on Equation 2, the factor of safety for a simple infinite slope model can be derived as in Equation 3 with slope gradient, β, depth of failure, z, and soil total unit weight, γ (the values of ϕ^b being equal to ϕ' once u_w > 0).

7. Results and discussion

The study was conducted to investigate the impact of under-drainage conditions on slope stability during a rainfall event with an intensity of 40 mm/hr. The factor of safety (Fs), calculated using Equation 3, the parameters used, the soil-water characteristics (Figure 8), the strength parameters using (C' = 14 kPa, ϕ' = 30° and, ϕ^b =

20°), and saturated permeability, k_s, (10^{-7} m/sec). The permeability function was estimated using Jackson's (1982) theory, as the key parameter for assessing slope stability. The mesh of finite elements is shown in Figure 11.

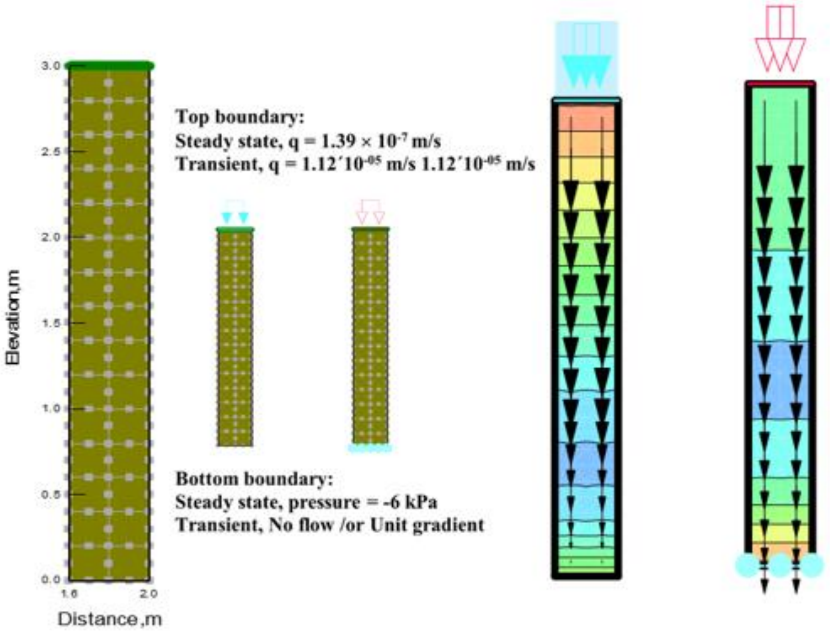


Figure 11 Finite Element Mesh and result for the infiltration analysis for both case free draining and no flow boundary

As illustrated in Figures 12(a) and 13(b), the distribution of pore water pressure within the soil profile during the simulated rainfall event is a key factor in understanding slope behavior. In slopes without a bottom flow barrier (Figure 12a), it is evident that once the wetting front reaches the impermeable rock bottom, there is a rapid buildup of pore water pressure. This surge in pore water pressure causes the factor of safety to drop below one, indicating slope instability and potential failure. This phenomenon clearly underscores the significance of the wetting front's interaction with impermeable layers as a critical trigger for slope destabilization.

In contrast, Figure 12(b) represents the scenario in which a unit gradient bottom boundary (free-draining condition) was applied. Even when the wetting front reaches the bottom of the soil profile, pore water pressure remains consistently at zero. This intriguing observation suggests that under these conditions, seepage continues without causing a significant increase in pore water pressure. This implies that slope stability is maintained. Thus, the study underscores the pivotal role of under-drainage conditions in controlling pore water pressure, which is a key determinant of slope stability.

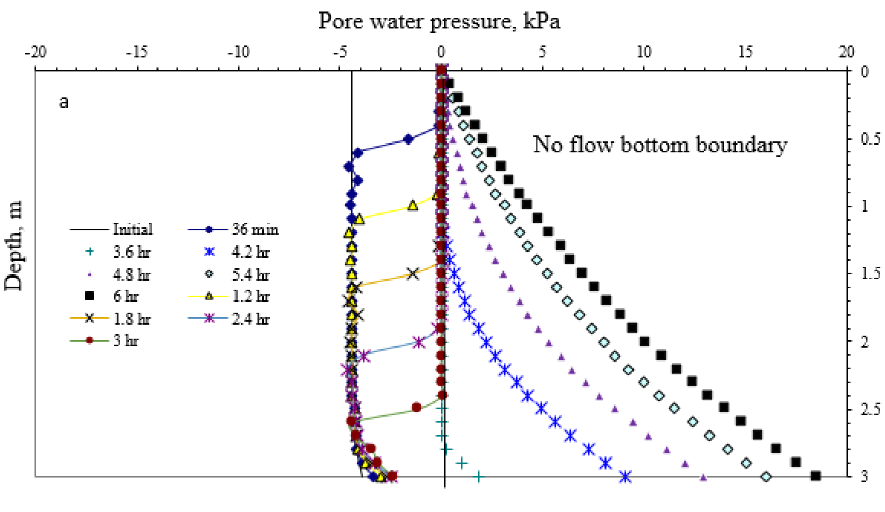


Figure12(a) Pore water pressure during rainfall intensity of 40 mm/hr. for both cases

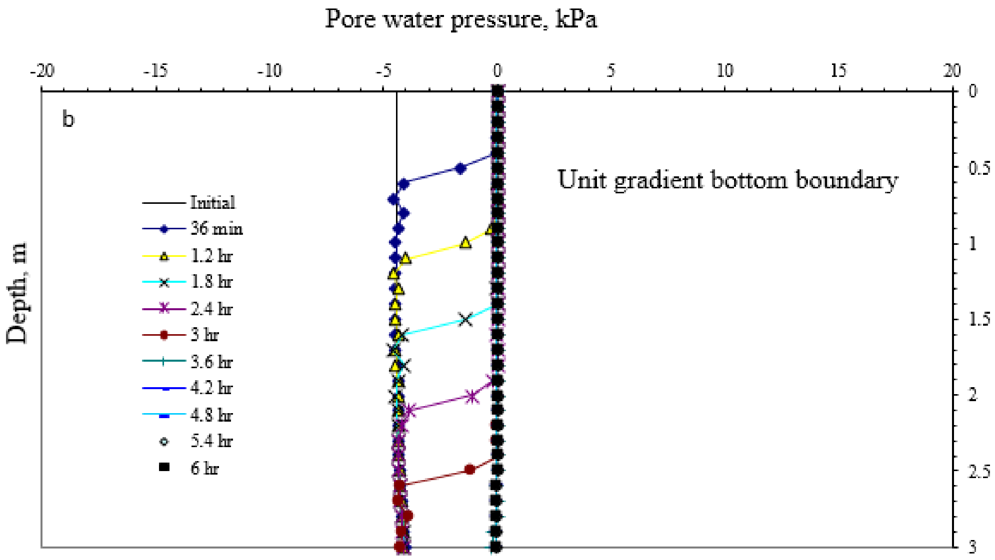
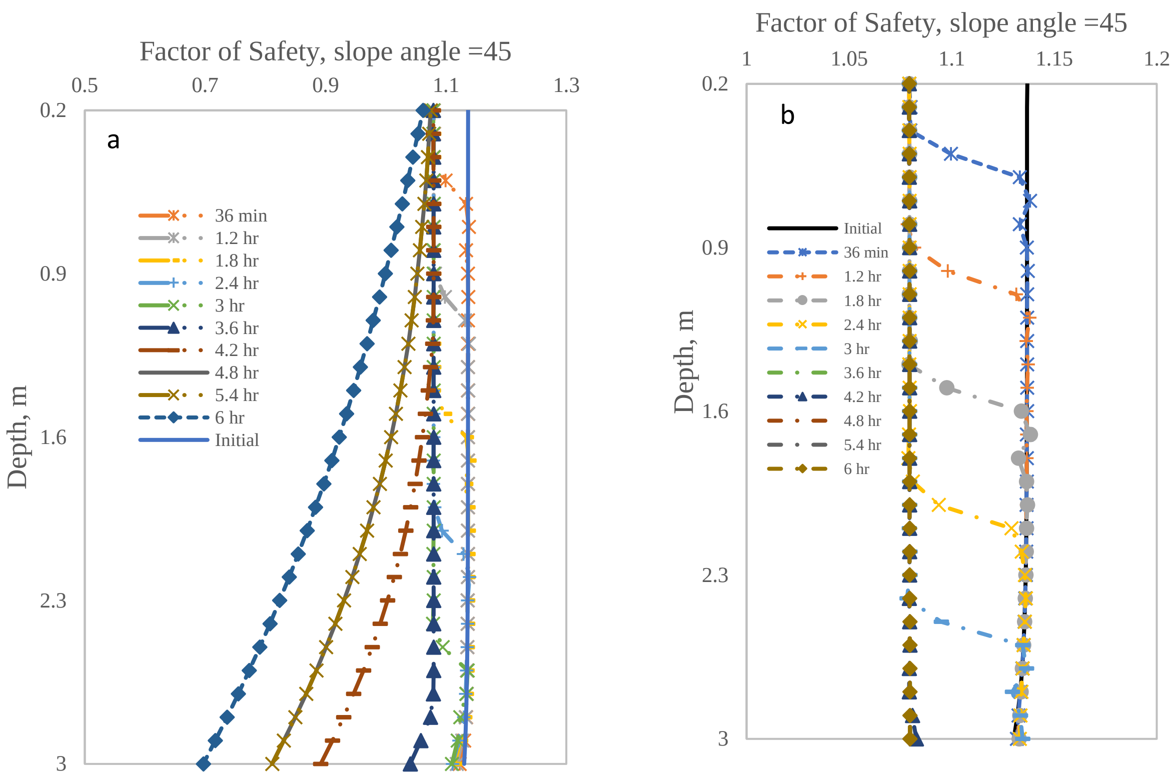


Figure12(b) Pore water pressure during rainfall intensity of 40 mm/hr. for both cases

Figures 13 and 14 further elucidate the role of under-drainage conditions in slope stability assessment. In slopes without a bottom flow barrier (Figure 13), the rapid increase in pore water pressure once the wetting front arrives results in an F_s value less than one, signifying slope instability and potential failure. This emphasizes the importance of impermeable rock bottoms as critical thresholds for evaluating slope stability.Conversely, in the case of the unit gradient bottom boundary (Figure 14), the factor of safety remains above one even after the wetting front reaches the bottom of the free-draining layer. This demonstrates that, under this under-drainage condition, slope stability is maintained.



a) no flow bottom boundary

b) unit gradient bottom boundary

Figure 13 Factor of safety during rainfall intensity of 40 mm/hr.

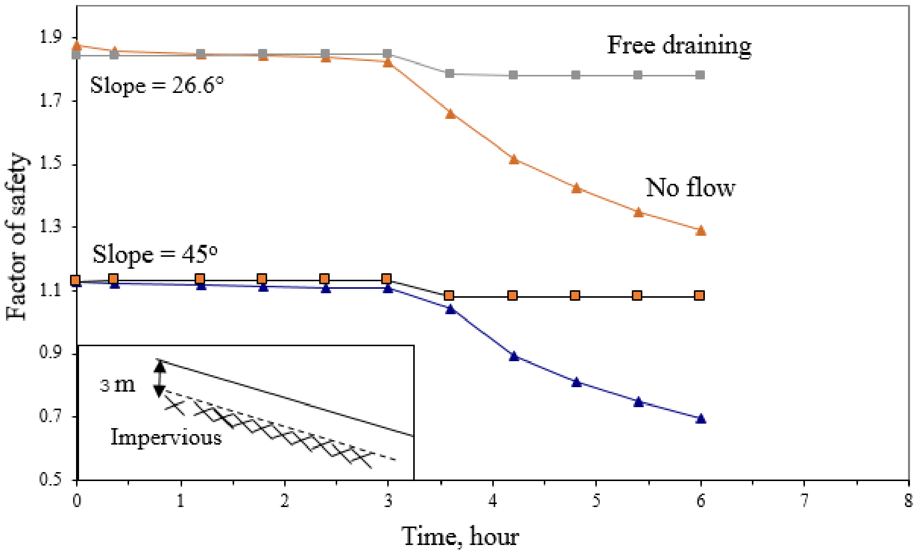


Figure 14 Factor of safety during rainfall intensity of 40 mm/hr. a) no flow bottom boundary b) unit gradient bottom boundary

8. Prediction criteria for landslide

An approximation of the failure depth of an infinite slope leading to debris flow or/ landslide can be made using the soil-water characteristic curve by making some simplifying assumptions.

(1) The first assumption is that the soil moisture status before significant rainfall is equivalent to the volumetric water content at field capacity, θ_f, which may be determined directly from the SWCC at a suction of 33 kPa. At atmospheric pressure, the SWCC can also measure the water content in the moistened state, denoted by θs. Soil porosity (n) and saturating capacity (S_r) are two different concepts; θ_s should be greater than or equal to 90- 95% of saturation (S_r).

(2) The second assumption is that infinite slopes are unstable due to saturation (this supposition is more correct for slopes with gradient $\beta > \phi'$).

(3) Finally, we assume that all rainfall infiltrates the ground before the soil becomes saturated, with very little water leaving the area as runoff or by deep percolation. The critical rainfall rate, Rc, is the amount of rainfall needed to completely soak a uniform soil slope to the critical depth, Dc, at which point slope failure will occur. The formula is $R_c = \left(\theta_s - \theta_f\right).D_c$.

9. Conclusion

Landslides have become a recurrent natural disaster in Bangladesh, particularly in the Chattogram region. An analysis of various data sources, site inspections, soil characteristics, and numerical modeling has shed light on the primary causes and important findings:

(1) Hill Slopes and Soil Properties: The hill slopes in the area have steep angles exceeding 45 degrees. Moreover, the prevalent soil type is silty clay, making these slopes highly vulnerable to failure, especially during heavy rainfall. Soil-water characteristic curves indicate the soil's propensity to become silty with low air entry suction values. Notably, the saturated volumetric water content (θ_s) closely matches the field water holding capacity (θ_f), with a minor difference of 4-8%.

(2) Mechanism of Slope Failure: Through numerical modeling, it has been demonstrated that slope failure is primarily triggered by a sudden change in pore water pressure. When the wetting front reaches the undrained bottom of the soil slope, the pore water pressure transitions from zero to a hydrostatic condition immediately. This abrupt increase in pressure significantly destabilizes the slope, potentially serving as a critical threshold for failure.

(3) Early Warning System Application: The results of this study have practical implications for the

development of early warning systems aimed at mitigating flash floods and landslides. Utilizing the field water-holding capacity (θ_f) from soil-water characteristic curves, particularly at a suction level of 33 kPa, can estimate the amount of rainfall required to saturate the slope. This information can be integrated with rainfall measurements to provide advance warnings. Furthermore, the continuous monitoring of pore water pressure in the field allows for the direct calculation of the slope's factor of safety using effective stress stability equations.

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