Case Report

A Geotechnical Investigation of 2017 Chattogram Landslides

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Abstract: In this study, an attempt is made to uncover and discuss the geo-environmental characteristics, triggers, and consequences of a landslide disaster in the Chattogram Hill Tracts (CHT) region of Bangladesh. The hilly areas are composed of Tertiary and Quaternary sediments which have been folded, faulted, uplifted and, then deeply dissected by rivers and other water bodies. This paper presents a case study on the geotechnical investigation and numerical modeling of the landslides of 13 June 2017. A field visit and soil sample collection, followed by laboratory testing were conducted at the landslide-afflicted areas. The study revealed that the soil type was an important factor behind landslides, while high precipitation, hill cutting, deforestation, and unplanned human settlements act as contributing factors behind the landslide disaster. Extensive analysis of the geotechnical facts has been carried out, and an attempt is made to pinpoint the cause. A finite element modeling was conducted using PLAXIS 2D to investigate the failure mechanism. The numerical modeling results have suggested that most of the hill slopes were susceptible to failure after heavy rainfall. A conclusion is drawn that the landslides were triggered by incessant rainfall infiltrating into the subsoil, which led to a notable increase in its degree of saturation and a simultaneous reduction in suction and shear strength of the soil.

Keywords: landslide; case-study; slope-stability; numerical modeling

1. Introduction

The natural phenomenon of landslides is common and a major cause of casualties and damage to public and private property around the world. Over the years, different types of geotechnical investigations and numerical analyses have been conducted for understanding the landslide phenomenon. The triggering factors for landslides include changes in slope geometry, excessive rainfall, infiltration of rainwater, and lack of a proper drainage system [1,2]. Matric suction in shallow soil layers decreases substantially following rainfall events, which is responsible for the triggering phase of landslides [3–6]. Most fatalities during landslides occur due to the unplanned hill cutting and informal settlement at the crest and toe of the hill [7].

There are different methods available to investigate the landslide susceptibility and stability of slopes. Conventional slope stability analysis includes the ordinary method of slices, Bishop method of slices, kinematic analysis, limit equilibrium analysis, etc. The complex nature of the problem has led to limitations in classic geotechnical engineering methods for stability assessments. Therefore, numerical analysis has become more useful to investigate the landslide risk. The finite element method using the plane strain model and phi-c reduction technique is a simple and efficient way to model a stability failure [1]. Moreover, a researcher developed a methodology through numerical analysis which can identify the rainfall-induced landslide-prone areas [8].

Numerous case studies have been conducted all over the world to investigate the causes, triggering factors, damages, casualties, and probable measures to prevent landslide

disasters. In one such study, researchers conducted a case study in Guangdong Province of China [9]. In another similar study, an investigation was carried out on siltstone slope instability using field monitoring and numerical simulations for examining the failure mechanism and formation process of the landslides [10].

Bangladesh is a densely populated country. Approximately 12% of the land area of the country is covered by hilly terrain [11]. Due to a shortage of habitable land, people are compelled to live at the foothills or on the slopes of hills. Frequent occurrences of landslides in the hilly parts of Bangladesh categorize it as one of the most prevalent disasters during the monsoon season. The soil in the Chattogram Hill Tracts (CHT) region (which consists of Rangamati, Bandarban, and Khagrachari) is one such susceptible area for landslides. In general, the soil characteristic of the CHT area is loose silty clay making it prone to landslides [12]. Various human activities including the cutting of trees, and jhum cultivation have made the slopes vulnerable to failures. Moreover, incessant precipitation during the rainy season causes weathering of the landscape, further destabilizing slopes. The CHT region has experienced almost 12 massive landslides in the last five decades [13]. From 2003 to 2017, the year 2017 was the third-worst year in terms of the most number of fatalities [14]. Among them, the 2007 and 2017 landslides were the most catastrophic ones. The landslides of 11 June 2007 had an impact on several places near Chattogram city and was one of the most extreme occurrences in the country's history, which ceased the lives of 127 people. On 13th June 2017, the CHT area faced subsequent episodes of landslides. Many foothill settlements were demolished. Moreover, more than 152 people lost their lives, and the destruction of large areas of resources took place [15]. The field study indicated that the failure patterns of certain landslides were translational, whereas others were rotational.

The landslide disaster that occurred at Chattogram in 2017 is one of the deadliest landslides in Bangladesh that has occurred over the last few decades. There are many suppositions regarding the cause of such massive landslides in 2017. However, there are very few studies that investigated this landslide in the context of an in-depth geotechnical analysis [16]. The objective of this study is to investigate the geotechnical aspects of the catastrophe. Numerical analysis of the failed slopes is conducted to understand the vulnerability of this type of slope. A comprehensive analysis of geotechnical features is conducted, and an attempt is made to identify the reasons. Moreover, precautionary steps have been suggested to prevent such disasters. The consequences of the case study will be helpful for the worldwide geotechnical community with the information on the extent of landslides worldwide and how different communities work to address this hazard.

2. Study Area

2.1. Location

The study area was in the Chattogram Hill Tracts which consist of three districts: Rangamati, Bandarban, and Khagrachari. Among them, the Rangamati district is the most suffered district due to the landslides in 2017. Therefore, the study is focused on the Rangamati district.

2.2. Physiography of the Study Area

The CHT region is a part of the Northern and Eastern Hill region and the High Hill or Mountain Ranges sub-region as per the physiography of Bangladesh. Currently, every mountain range of the Chattogram Hill Tracts is almost a hogback ridge that rises steeply. Maximum ridges have scarps on the west side, with cliffs and waterfalls. The area is characterized by a large network of trellis and dendritic drainages including several major rivers that drain into the Bay of Bengal.

2.3. Geological Formation of the Study Area

The rocks in hilly areas of Bangladesh are mainly quartzite, siltstone, shale, limestone, and conglomerate. Since these rocks are prone to erosion, enhanced land and fertility

degradation takes place and hence causes landslides. On average, the hilly area has a soil loss rate of about 30 Mg ha^{-1} y^{-1} [17]. Erosion is, therefore, a prime concern for landslides.

The hills of Chattogram region developed steeply into narrow ridgelines, ranging in width less than 36 m, with altitudes between 600 and 900 m above sea level [18]. The topography of Chattogram is diverse from the majority of Bangladesh except for Sylhet and the northern part of Dinajpur. Chattogram is part of the hilly regions that expand from the Himalayas. The hills of Chattogram are part of hill groups that extend across Assam and Tripura state through the Feni river.

The CHT originated due to the collision of the tectonic plates between India and Asia. The Indo-Australian plate shifted together towards the south-eastern direction by approximately 1750 km with a drift rate of 6 cm/year after the breakdown of Gondwana-land [13]. Later, India became separated from Australia and began to move north-easterly. Subsequently, the geologic history of the CHT area of Bangladesh continued to develop throughout the Cenozoic age. The hill areas are mainly composed of unconsolidated (loose) sedimentary rocks including sandstone, shale, conglomerate, etc. [19]. Areas that are underlain by shale usually result in heavy silt loam or silty clay loam subsoil which have less stability. A major part of these hilly areas is composed of Girujan clay formations of the Pliocene age, which are mostly loose sediments [20]. The geological composition of the soils is therefore weak; when exposed to steep slopes, they have an increased vulnerability to landslides [21].

2.4. Rainfall Characteristics

High precipitation is a familiar scenario in Bangladesh. Including the CHT area, most parts of Bangladesh, except the relatively dry Rajshahi region, experience at least 200 cm of precipitation each year [2]. The Sylhet division of Bangladesh receives the greatest average rainfall. This region received annual precipitation between 328 and 478 cm per year within the time span of 1977 to 1986 [22].

With a subtropical monsoon climate, Bangladesh is marked by various seasonal diversity in precipitation, temperature, and humidity. Bangladesh experiences about 80% of the precipitation during the monsoon [23]. The fluctuation in air pressure (low and high) which originates from differential heating of land and water results in the monsoon. During the warm months of summer (April and May), hot air blows over the Indian subcontinent, producing low-pressure areas into which cooler, moisture-bearing winds arrive from the Indian Ocean. This is known as the southwest monsoon. This monsoon begins in June and generally lasts through September. There are two branches of the monsoon, one which moves along the western edge of India, and the other which passes over the Bay of Bengal, eastern India, and Bangladesh. This monsoonal wind brings heavy rainfall to this region. Most of the notable landslides observed, took place at an increased amount of rainfall than the monthly mean amount. Usually, a rainfall intensity greater than 40 mm/day taking place over a short period of time is found to be closely related to the major landslide events of the CHT area [19]. Figure 1 shows the values of monthly average and maximum rainfall data in Rangamati, Chattogram station. The rainfall data were collected from the Bangladesh Meteorological Department (BMD). More than 75% of the annual rainfall occurs during the six months of May to October.
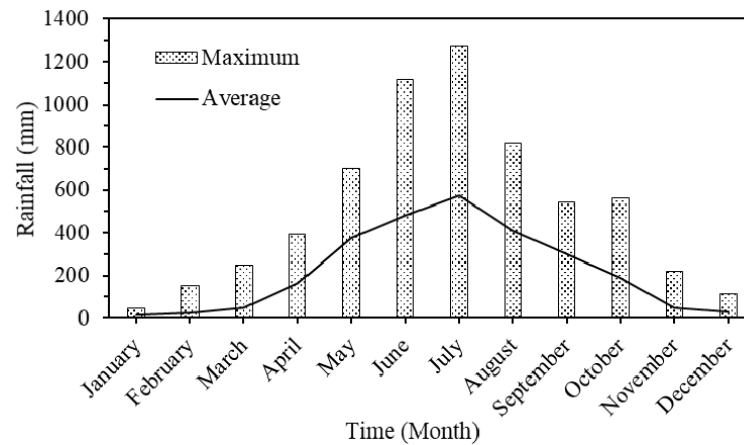
Figure 1. Monthly variation of maximum and average rainfall in Rangamati.

3. Chattogram Landslides of 2017

On 12 June 2017, incessant rainfall (343 mm) triggered multiple landslides and floods in Rangamati, Bandarban, and Chattogram—three hilly regions of Bangladesh, seizing 152 lives. The weather also made it difficult for the rescuers to evacuate the affected communities by causing power outages and telecommunications disruptions across the region. Some incidents of landslides and immediate temporary reactive measures by the local people are shown in Figure 2b,d.

(**a**)

(**b**)

(**c**)

(**d**)

Figure 2. (**a**) Part of the Rangamati-Chattogram road collapsed at Manikchhari; (**b**) people had built a temporary solution after the local road had been damaged near the Rangamati-Khagrachari road; (**c**) heavily damaged Rangamati-Manikchari road; (**d**) temporary measures were taken on the Rangamati District road to reestablish the road network.

3.1. Extent of the Disaster Occurred

The districts of Rangamati, Chattogram, and Bandarban were most intensely affected by the landslide events. Many parts of these districts faced acute fuel, electricity, and water shortages following the devastating event. In certain locations, falling landslide debris have blocked and submerged significant stretches of the Chittagong–Rangamati highway halting traffic on the highway for days. In other locations, the road itself located on the mountain slope appears to have moved from its position towards the valley due to slope failure and resulting in a large movement of significant portions of the mountain slope further towards the valley. The shearing and shifting of the road alignment as a result of the movement of the mountain slope disrupted road communications completely [15]. Significant slope movements were evident from the complete failure of the retaining walls on the valley side by the overturning and loss of support of the retaining wall foundations. A large amount of soft soil debris was observed in certain locations on the valley side. The road edge towards the valley side settled and cracked at various locations. In certain locations, heavy rainfall had completely washed away the underlying road subgrade separating the two parts of the roads at that location [2,16].

The landslide that occurred in Chattogram had few different types. Various classifications of the landslide have been developed by many researchers among which the Varnes classification is well known [24,25]. According to these studies, the present landslide disaster has been classified. From the field observation, it has been found that mostly 'transitional slides' and 'flow'. Figure 2a shows a location where 'flow' landslides occurred, whereas transitional landslides are shown in Figure 2b,d.

It is estimated that the collapsing hill surface and heavy flooding have killed over 152 people across five districts, the other two being Cox's Bazar and Khagrachari [12]. Due to the cessation of road and communication networks in those areas, rescue and recovery teams faced challenging situations. Many homes were buried in mud and debris, including over 5000 houses in the Kawkhali Upazila, Rangamati.

3.2. Main Causes of the Landslides

The main causes of the landslide can be divided into two categories: determinant factors (lithology, soils, slopes, etc.) and triggering factors (rainfall). The study area is dominated by the Dhihing, Dupi tila, Girujan clay, Bokabil, and Tipam sandstone formations. Due to the alteration of sandstone and shale in their geology, Bhuban and Bokabil formations are among the most susceptible to landslides.

Among the different triggering factors, excessive rainfall is the prime factor behind this catastrophe. Because of incessant downpours during monsoon, hilly regions became more susceptible, which generated landslides and mudslides in the hilly area. The mechanism of landslide triggering is thought to be from incessant rainfall, which caused a change in pore water pressure and associated seepage forces [26,27]. During monsoon, loose muddy soil holds moisture, which causes extra weight. Furthermore, the increase in moisture content decreases the shear strength of the soil. Thus, the extra weight added by rainwater and a decrease in shear strength results in landslides. The soil mass experienced eventual sudden acceleration during or after the failure phase, which is a consequence of slope instability, and as a result, continuous shear surfaces are formed through the entire soil mass [28]. The same incident occurred in the case of these devastating landslides.

Heavy rainfall that started in the early morning of 12 June 2017 poured 343 mm (13.5 inches) of rain in the next 24 h and as a result, the landslides occurred [6,15]. Between 12 June and 14 June, 510 mm (20 inches) of rainfall in southeastern Bangladesh was recorded during which a heavy downpour triggered landslides. The slopes became saturated with water, which was the principal cause behind the landslides. Saturation can occur due to multiple reasons including incessant downpour, fluctuations in groundwater levels, and surface-water level variations along coastlines, barrages, dams, and in the banks of reservoirs, canals, and rivers [29]. Moreover, the instantaneous inundation of hill slopes and series of landslides are closely associated with high precipitation and runoff.

4. Field Investigation

The experimental program included the collection of soil samples from landslide-prone areas of Chattogram and different tests that have been carried out on the collected soil samples. The results of the experimental investigation were subsequently used to obtain input soil parameters for numerical modeling.

4.1. Soil Samples Collection

A total of six locations were selected in Rangamati where the 2017 Landslides occurred. Sample collection was performed for both disturbed and undisturbed samples from the failed slopes and an adjacent stable slope beside the landslide. The sample collection was performed in June 2017, just after the landslide catastrophe. The geographical location of Rangamati, Chattogram Hill Tracts, and sample collection points are presented in Figure 3 and Table 1.
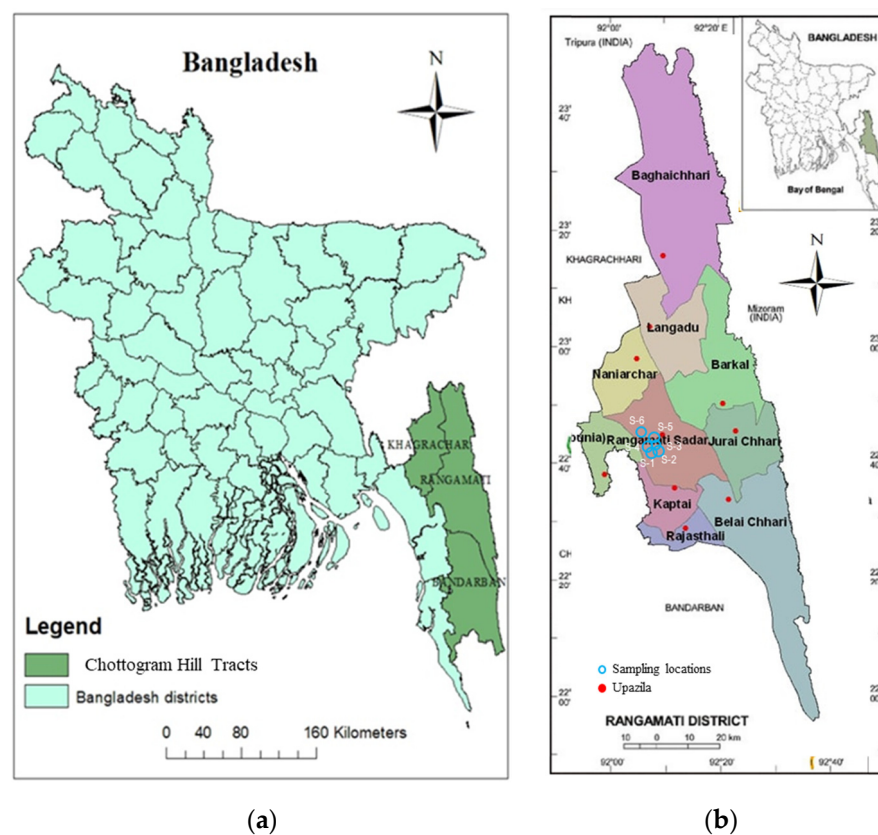

(a)　(b)

Figure 3. (**a**) Map of Bangladesh showing CHT and Rangamati; (**b**) locations of collected soil samples in Rangamati.

In the complex soil composition of the CHT region, the young rocks have higher feldspar contents which are easily erodible. As a result, the soil surface of this hilly area is vulnerable to landslide risks during high precipitation carried by the monsoon wind. The hill soils, which are primarily yellowish-brown to reddish-brown loams, are graded into segregated shale or sandstone along with mottled sand at a variable depth. Some researchers conducted a laboratory investigation on Rangamati soil characteristics and found the most common soil type to be silty clay with low plasticity (liquid limit: 32–40; plasticity index: 15–21) [30].

Table 1. Site locations and slope dimensions.

Sample ID	Location	Latitude	Longitude	Slope Height (m)	Slope Angle
S-1	Manikchari	22°38′55.8492″ N	92°8′15.7956″ E	15	70°
S-2	Manikchari (South)	22°38′41.7948″ N	92°8′18.5316″ E	10	50°
S-3	Shapchari Shalbagan	22°38′49.1352″ N	92°7′50.3904″ E	10	65°
S-4	Deppoyachari	22°38′38.9184″ N	92°8′35.9544″ E	16	70°
S-5	Moddhapara	22°38′46.5684″ N	92°8′45.9984″ E	13	45°
S-6	Kaching	22°41′32.2008″ N	92°6′20.7684″ E	12	50°

Shelby tubes have been used to collect soil samples of both disturbed and undisturbed types to determine the engineering properties and indices of the soils. Laboratory tests were conducted on the collected soil samples according to ASTM specifications. The index and the engineering properties are summarized in Table 2, and the grain size distribution curves are presented in Figure 4a. The liquid limit, along with the plasticity index are presented in Figure 4b. The total shear strength parameters were obtained from the direct shear test conducted on undisturbed soil samples. Based on the index properties, the classification of the soil samples was performed according to the Unified Soil Classification System (USCS). The results of the grain size analysis are harmonious with previous studies [31].
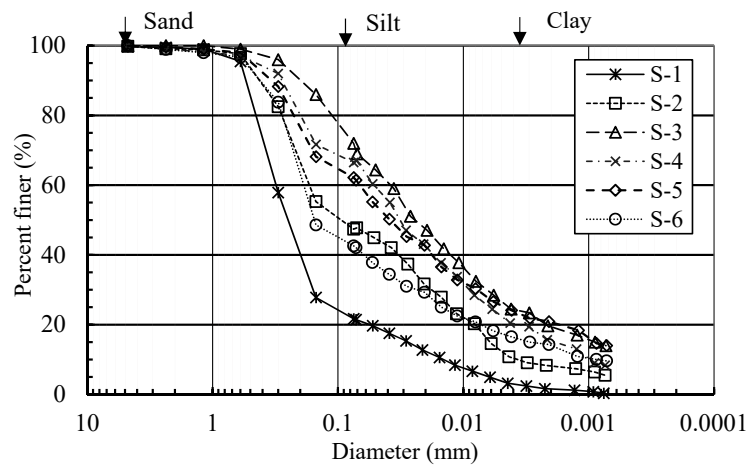
(**a**)
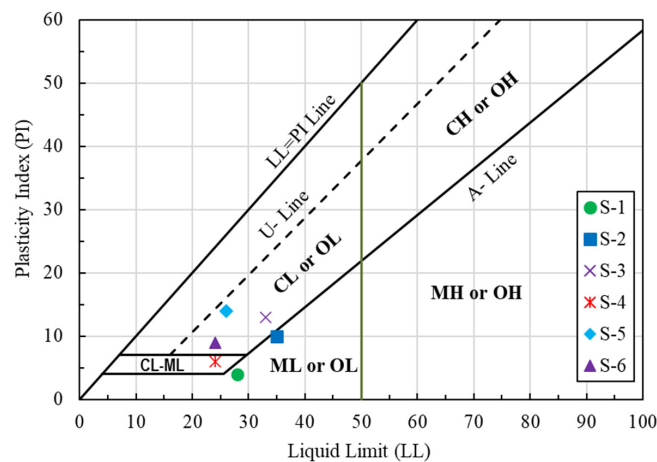
(**b**)

Figure 4. (**a**). Grain size distribution curve of collected soil samples. (**b**) Liquid limit and Plasticity Index of the soil samples on Casagrande's plasticity chart.

Table 2. Index and engineering properties of soil samples collected from each of six landslide slopes (S-1 through S-6; see Figure 2).

	Natural Moisture Content (%)	In-Situ Moist Density (kN/m^3)	Atterberg Limits		% Finer No. 200 Sieve	USCS Soil Classifi-cation	Shear Strength Parameters	
			Liquid Limit	Plasticity Index			Cohesion c (kPa)	Friction Angle φ (°)
S-1	13.34	18.54	28	4	21.7	SM	1.3	39.7
S-2	13.86	19.02	35	10	47.4	SC	8.6	37.3
S-3	25.60	18.98	33	13	72.0	CL	18.1	10.3
S-4	18.41	19.00	24	6	66.5	CL-ML	9.4	27.4
S-5	23.82	19.34	26	14	62.2	CL	12.9	32.7
S-6	15.46	16.80	24	9	42.6	SM-SC	1.8	30.2

4.2. Observations during the Site Visit

Different types of soil such as silty clay, lean clay, clayey sand, etc., were observed during the site investigation. Figure 5 shows two soil layers: sand and clay/shale at Shapchari Shal Bagan near Rangamati-Manikchari road which is located in the landslide areas. The bedding of the soil formation is almost horizontal. It is also observed that an alternate layer of sand and very thin films of clay/shale are present. These mountains and valleys were primarily reddish to reddish-brown sandy silt or clayey sand with little cohesion or friction at the remolded state. It is the view of the authors that the soils of many parts of the mountain region have metamorphosed over geological time and cemented to silty sandstone or shale-like material. According to a study, discontinuities or changes in constituents produce structural fragility below the uniform material, which can turn into preferential failure surfaces, especially when planar [19]. This type of discontinuity was observed in most of the locations where the landslide occurred in CHT in 2017. Discontinuities allow pathways for rainwater seepage through the layers. As a result, the bond between the sand and clay/shale layers becomes reduced over time. Additionally, the drainage facilities of the hill slopes were not designed in most cases. As a result, rainwater cannot seep out of the soil; instead, water percolates through the soil and increases pore pressure with additional hydrostatic force.

Sand

Clay/Shale

Figure 5. Different layers of soils at Shapchari Shal Bagan located in the landslide areas.

In some of the locations, it was observed that the hill soil was formed with loose and wearable particles, i.e., feldspar. One such loose soil strata of the sloping surfaces can be

observed in Figure 6 (top). This type of formation can be easily undercut by an agent such as water or wind. Due to the low shear strength of the collected samples as found from the laboratory tests, the slopes were susceptible to failure. Moreover, in some locations, there are steep slopes near roads. These slopes consist of loosely bound soil particles and layered soil strata, as shown in Figure 6 (bottom).
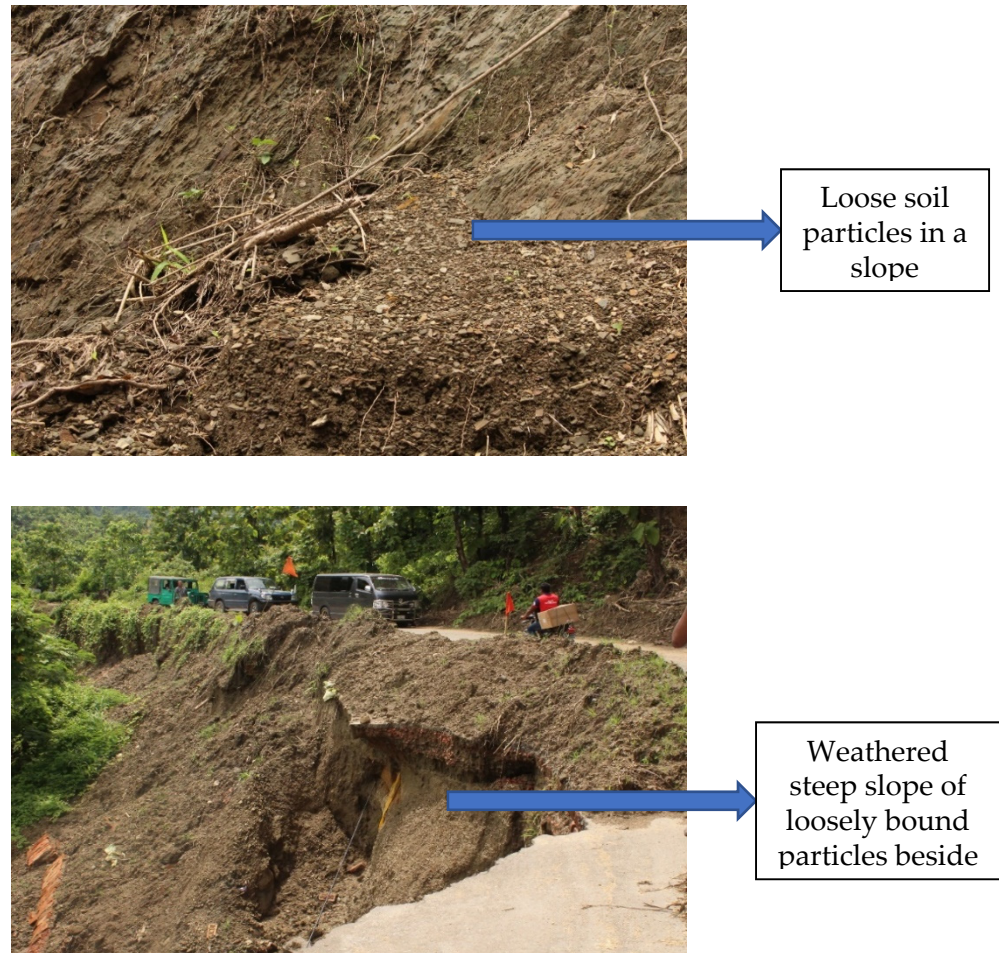

Figure 6. Loose soil particles in a sloped surface (**top**) and a weathered steep slope composed of loose, layered soil strata beside a narrow road (**bottom**).

The hillslope angle plays an important role in landslides. Since Bangladesh is a low-income developing country, it is very difficult to stabilize the vertiginous slopes in the hilly regions due to budget constraints. Therefore, steep slopes have often been kept untreated year after year.

Heavy rainfall played an important role in the landslide disaster. The shear strength was reduced to a great extent due to the infiltration of rainwater into the soil. The positive pore water pressures developed within the soils, which decreased the effective stress and consequently lowered the shear strength of the soil. Therefore, a total stress analysis was conducted in the subsequent numerical modeling section.

From the field investigation, several factors have been observed for which the landslide risk was higher. First of all, in Chattogram, the usage of land was unplanned. Private houses, grocery shops, and restaurants had been constructed on the downhill of the road (Figure 7a). For this purpose, the natural stability of the hills might have been disrupted. In addition, a proper drainage system was not maintained, which triggered the flash flood and the eventual landslides at Bilaichari; as shown in Figure 7a.
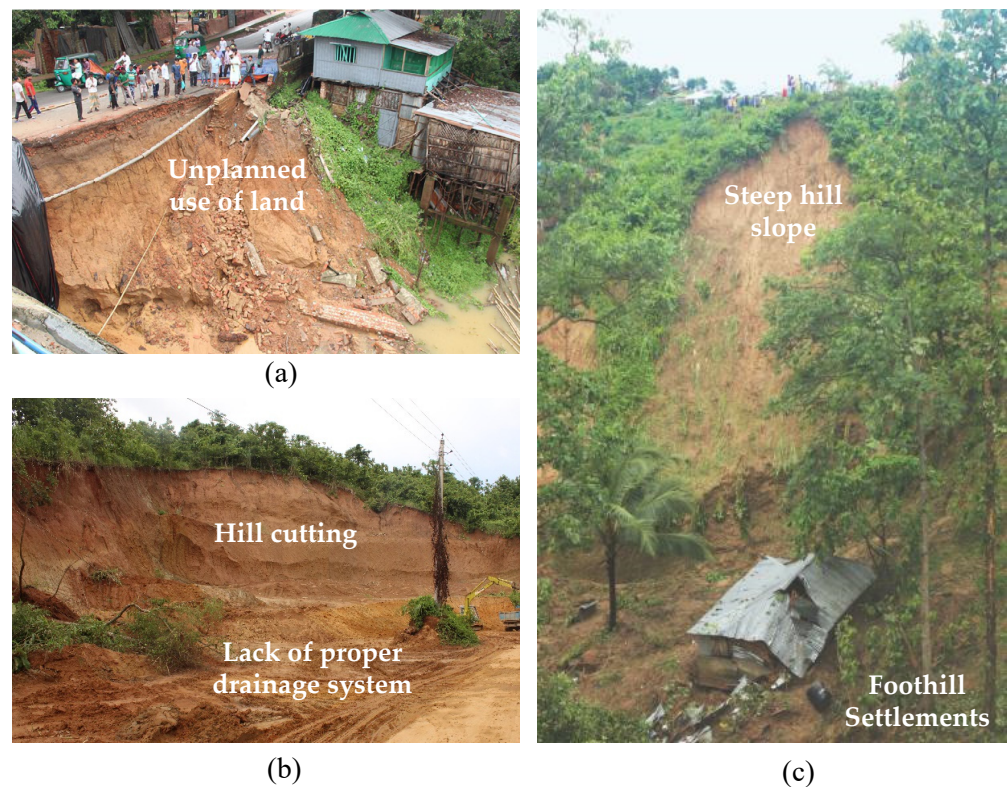
Figure 7. (**a**) Partially damaged road in Bilaichari, Rangamati; (**b**) unplanned road construction without proper drainage system; (**c**) slope failure due to a steep slope and unauthorized foothill settlement at south Manikchari.

The cutting of trees in the hilly region, especially that of deep-rooted plants, lowers the strength of the soil grains to make a bond among them. Unplanned hill cutting is ongoing due to many reasons such as sand collection, road construction, administrative infrastructure development, etc. Figure 7b shows the usual practice of road construction where the hill cutting was carried out without proper slope stabilization. The results of hill cutting left a very steep slope. Hence, during incessant rainfall, these slopes become vulnerable to failure. Furthermore, during road construction, proper drainage must be provided to reduce the risk of slope failure.

Unplanned foothill settlements are one of the major reasons for the toe slope failure. Due to rapid urbanization in Bangladesh, land for domestic household use has become less available. In addition, it is more economical for those people with low incomes to live on the foothills of slopes, as these sites are less desirable. Due to the lack of a proper monitoring system, the foothill settlements are increasing day by day. Thus, the toe of the slope becomes dangerous for inhabitants. Figure 7c shows a failed slope with a house at the toe in Rangamati, following the 2017 landslides.

5. Numerical Modeling

A finite element analysis has been performed to investigate the failure mechanism of slopes that failed during the 2017 landslides investigated herein. The finite element method (FEM) is one of the most popular tools to analyze slope stability problems. Previously, many researchers have used FEM for analyzing landslides [32–34]. Therefore, in this study, the stability of slopes prone to landslides has been evaluated with FEM.

5.1. Methodology

To develop numerical models, the PLAXIS 2D software was used—a two-dimensional finite element program that is used to perform various analyses related to geotechnical engineering including deformation and stability analyses [35]. A plane strain model was

used in the analysis. The Mohr–Coulomb soil model was used for the deformation analyses utilizing 15 node triangular elements. The Mohr–Coulomb model assumes that the failure is determined by the maximum shear stress and normal stress acting on the failure plane. The Mohr–Coulomb model can be expressed as follows:

$$\tau = c + \sigma \tan(\phi) \tag{1}$$

where τ is the shear strength, σ is the normal stress, c is cohesion and ϕ is the friction angle.

Standard fixities were applied as boundary conditions. These boundary conditions were selected according to the physical slopes. The bottom layer of the model was assumed to restrain all movements (vertical and horizontal) of the soil mass. The sides of the model were restrained against horizontal movement. The sides can only allow vertical movements along the z-direction. Initially, the global coarseness of the mesh was selected as standard coarse mesh (around 100 triangular elements). The mesh was further improved by convergence analysis of different mesh dimensions and mesh densities. A typical finite element mesh for evaluating the slope stability is shown in Figure 8.
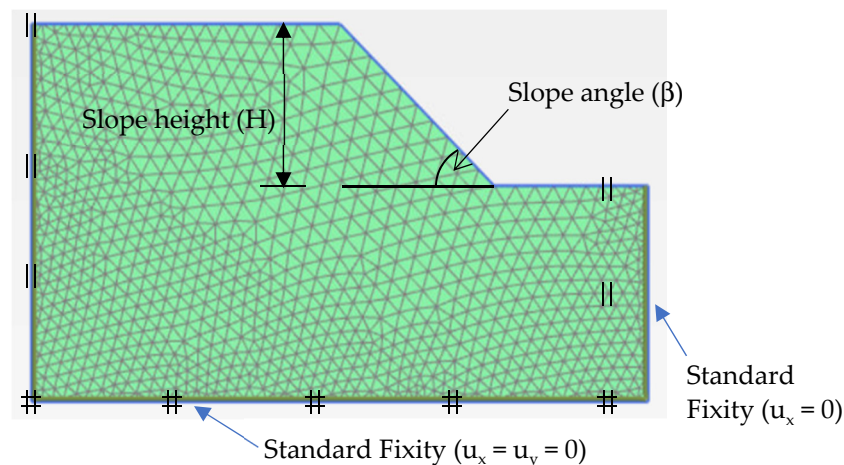

Figure 8. Typical finite element mesh for the slope model in PLAXIS 2D.

The soil of the present study was modeled according to the Mohr–Coulomb (MC) model. For an elastic perfectly plastic Mohr–Coulomb model, five input parameters are required, i.e., E (Modulus of Elasticity) and ν (Poisson's ratio) for soil elasticity; ϕ and c for soil strength, and ψ as an angle of dilatancy. This model demonstrates a 'first-order' approximation of soil behavior and is typically used for a first analysis of the problem considered. Generally, effective stress states at failure can be reasonably explained based on the Mohr–Coulomb failure criteria with effective strength parameters ϕ' and c'. An undrained effective stress analysis was performed in combination with ϕ' and c' to simulate the material's undrained shear strength. Although the hill slopes consist of different layers of soil (Figure 5), the numerical modeling was conducted assuming only one layer of soil throughout the soil.

5.2. Result and Discussion

The analysis results show that the factor of safety (FS) for all six landslide slopes (Table 2; Figure 2) is less than 1.4. According to a previous study, an FS less than 1.4 is questionable for dams and slopes and an FS less than 1.0 is unsafe [36]. The obtained FS indicates that some of the slopes were supposed to fail (S-1, S-3, S-4, and S-6) and some of the slopes (S-2 and S-5) were prone to failure. The FS of slopes more than one might get unstable due to heavy rainfall. The FS is minimum for the slope with soil S-3 because the slope consists of soft clay with low cohesive strength. Since the soil is clay, the friction angle is negligible. Thus, a significant portion of shear strength is provided only from the cohesion parameter, rather than from the friction angle. Furthermore, with the increase in

depth, shear strength does not increase for pure cohesive soil. Natural moisture content is very high, 25.6%, almost close to the saturation limit (27.7%). Besides, excessive rainfall infiltrates into the soil and can make clay very soft. Thus, the shear strength can be reduced with precipitation, and eventually, the slope fails.

On the other hand, the FS is maximum for the slope with soil S-2 since the friction angle is quite high (ϕ = 37.34°) and shear strength comes from both cohesion parameter and friction as well. Moreover, the FS is high because of a relatively lower slope angle, and 13.9% moisture content which is less than the saturation water content (21.6%).

A model test was conducted on the collected soil sample (S-2) to evaluate the infiltration property. Collected soil was placed in a glass model keeping the unit weight of the remolded soil similar to the field. The slope was kept similar to S-2 site conditions. An artificial rainfall simulator was used to simulate the rainfall scenario during the landslides [37]. The results indicated that for 94 mm of rainfall, the infiltration and the runoff water were found to be 39 mm and 55 mm, respectively. The amount of infiltrated water was relatively high compared to other studies with vegetated slopes [38]. Due to increased infiltration, there is an increase in moisture content of the soil which has two possible effects: a decrease in shear strength of soil and an increase in the overall weight of the soil. The former decreases the mobilized shear strength while the latter increases the driving force. Both are responsible for decreasing the overall stability of a slope.

From the numerical analyses, the failure patterns are observed for each case. These failure patterns are presented in Figure 9 and Table 3. It is observed that for slopes with soil S-2, S-3, S-4, and S-6, the failure surface intersects at the toe of the slope. This type of failure is called a toe failure. Such a failure is usually seen in sandy-type soils having moderate to a high angle of friction with little cohesion and steep slopes [39,40]. On the other hand, a shallow wedge type failure is observed for the slope with soil S-1 (little cohesion with a high angle of internal friction), which indicates the failure surface intersecting with the hill slope above its toe, forming a wedge. In the case of S-5, a face failure occurs which indicates the failure of slope at a shallower depth and at the middle of the slope. According to the literature [31], it is found that hills with a slope angle greater than the internal angle of friction are prone to failure. In this study, the ϕ values of the existing slopes are smaller than the slope angles which means that the obtained results are harmonious with previous literature. For soil S-3 (CL), failure is a deep-seated base failure, which is usually encountered in cohesive soil. The resulting failure surface can also be explained from the field observation of the site. In Figure 7c, the toe failure pattern at the south of Manikchari (S-2) is shown, which is quite similar to the FEM analysis shown in Figure 9b.

Table 3. The factor of safety and failure types from different slopes (S-1 through S-6).

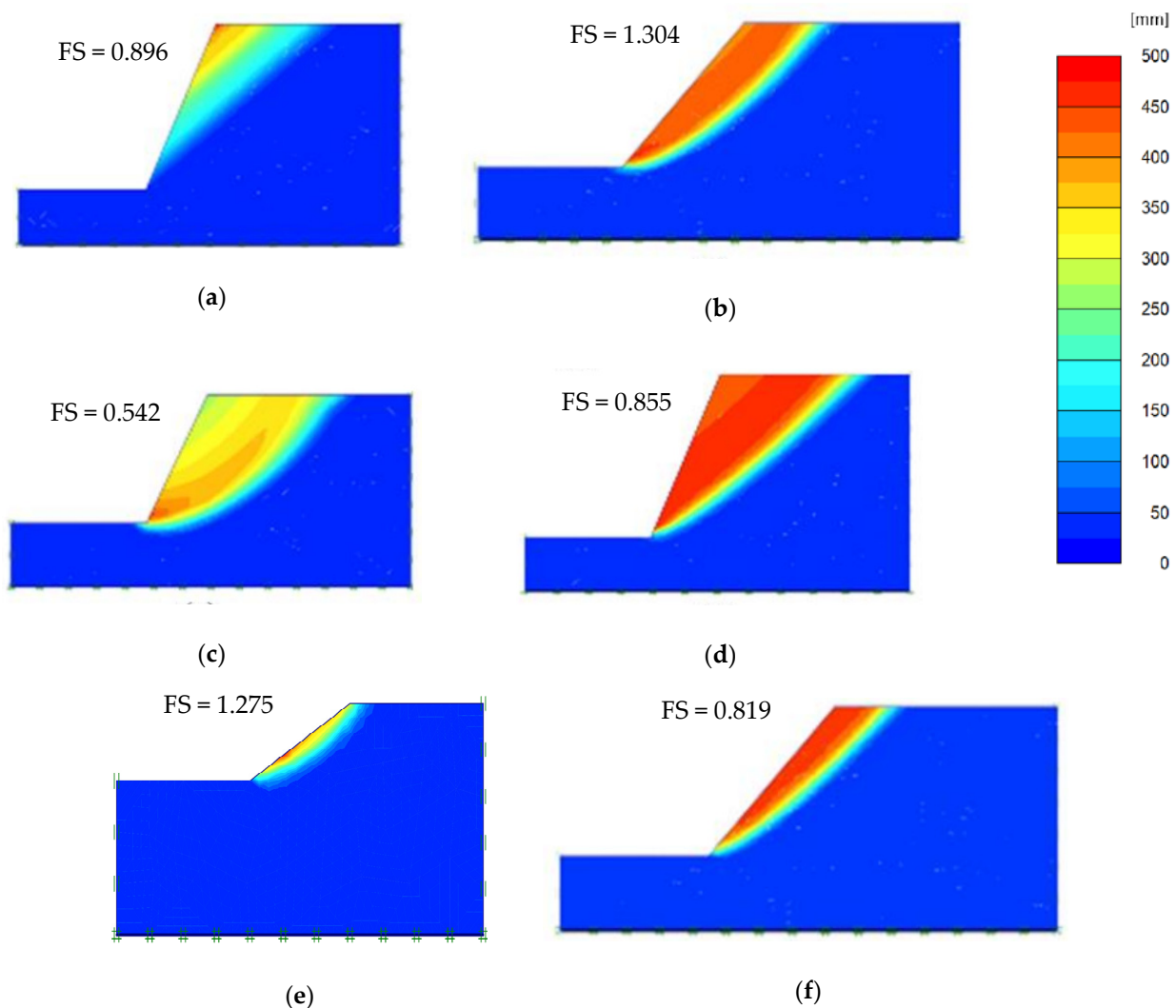| Sample ID	USCS Soil Classification	Factor of Safety (before Rainfall)	Failure Type
S-1	SM	0.896	Shallow wedge failure
S-2	SC	1.304	Toe failure
S-3	CL	0.542	Toe failure
S-4	CL-ML	0.855	Toe failure
S-5	CL	1.275	Face failure
S-6	SM-SC	0.819	Toe failure

Figure 9. Failure surface from the numerical analysis: (**a**) shallow slope wedge failure and local failure for S-1; (**b**) toe general slope failure for S-2; (**c**) base failure for S-3; (**d**) toe general slope failure for S-4; (**e**) shallow surface slope failure for S-5; (**f**) slope toe, surficial failure for S-6. The contours indicate the displacement of the sliding soil mass.

6. Remedial Measures for Landslide Prevention

The selection of proper actions should be established on the evaluation of risk, precariousness, probable outcomes, constructability, environmental effects, and costs. Usually, two types of approaches can be taken for the prevention of the disaster: one is structural solutions, and the other is non-structural solutions.

Structural measures including safety, building codes, and improved drainage facilities are indispensable for the alleviation of landslide risk. In Bangladesh, retaining walls are widely used to stabilize a slope, which is a costly technology. Therefore, new affordable and sustainable technology should be explored to stabilize the slopes. One of the sustainable solutions for landslide disasters is the bioengineering technique using vegetation [41–43]. The inclusion of vegetation in slopes increases the shear strength of soil, which eventually increases the factor of safety and reduces the erosion potential [44,45]. For shallow slope failures, this method has been proven to be effective, economical, and environment friendly [46]. However, for deep-seated failure and retaining walls, internal slope reinforcement (e.g., soil nailing, recycled plastic pins) can be adopted for the likely vulnerable slopes [47–49]. Slope drainage is one of the most successful measures to improve the FS. Horizontal drains can be installed to reduce water entry and accelerate rainwater discharge.

Non-structural measures are as important as structural solutions. Land use vulnerability assessment and zoning, relocation of the foothill settlements, administering hill cutting by enforcing proper legal provisions, real-time monitoring, and early warning, etc. measures can be taken for the mitigation of landslides [50]. Moreover, in relation to early warning systems, the calculation of rainfall thresholds can be a good solution for landslide prevention [10]. Landslide susceptibility mapping needs to be conducted for identifying landslide-prone areas [51]. Finally, landslide risk reduction strategies need to be developed by policymakers, engineers, and geologists which can ensure the safety of the people and their properties [52,53].

7. Conclusions

Landslides have become a common disaster in Bangladesh. Based on a review of the referenced documentation, site visits, soil characterization, and numerical modeling, the primary causation for the Chattogram landslides 2017 is excessive rainfall, an improper drainage system, and soft soil deposits of the slopes. The important outcomes can be summarized as follows:

- All the existing hill slopes had slope angles greater than $50°$, and from the numerical analysis, it is found that most of the slopes were susceptible to failure. Therefore, the angle of slopes must be lowered or soil retaining measures need to be adopted for increasing the stability and safety of the slopes.
- The hill slopes are vulnerable to rainfall-induced failure due to the soil type, which is silty clay in most cases. This type of soil leads to soil saturation, which, in turn, triggers landslides.
- The results of the FEM analysis were found similar to the field observations. Depending on the type of soil and angle of the slope, different types of failure occur.
- Addressing the failure mechanism and field investigation of the soil, adequate measures should be taken to prevent landslides. Appropriate water drainage systems, retaining systems for protection of hill slopes and valleys, geofabric slope protection and erosion control systems, natural and plant-based efficient biological protection systems, etc., should be considered.

This study can be helpful for identifying the hill slopes that are prone to landslides. Further investigation can be conducted with subsoil investigation (e.g., Standard Penetration Test, Cone Penetration Test, etc.) which can provide detailed information about different soil layers. A landslide susceptibility map needs to be developed using an integrated sensing system based on remote sensing using satellite, unmanned aerial vehicle (UAV), and the Internet of Things (IoT) technology. An acoustic emission landslide early warning system can also be developed. These technologies will be able to predict the landslide-prone zones based on the rainfall intensities. Thus, appropriate measures can be taken to minimize damages.

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