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Integrated Assessment of Soil Shear Strength and Rainfall-Induced Slope Stability in the Balukhali Rohingya Refugee Camp, Ukhiya, Cox's Bazar, Bangladesh: Implications for Sustainable and Climate-Resilient Infrastructure

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Abstract

In the Balukhali Rohingya refugee camps of Cox's Bazar, Bangladesh, temporary shelters are packed with dense construction. Landslides are caused by heavy rainfall, a common geo-hazard, because the hill-cut slopes with low vegetation cover have low geotechnical competence. While some studies have explored rainfall thresholds, few have analyzed the hydro-mechanical failure mechanisms specific to the Balukhali camp. This study investigates shear strength and rainfall-induced hydraulic changes, combining direct shear tests and numerical modeling. Soil samples indicated variable cohesion and friction angles. In the Rohingya refugee camps of Cox's Bazar, Bangladesh, excessive rainfall often leads to landslides, exacerbated by poorly constructed shelters on steep to moderately steep slopes. While some prior research has focused on rainfall thresholds and land use, few studies address the combined hydro-mechanical failure mechanisms specific to Balukhali camp. This study investigates the interplay between shear strength and hydraulic changes due to rainfall through direct shear testing and numerical modelling. Soil samples from two boreholes revealed cohesion values between 4.48 and 17.40 kPa and internal friction angles ranging from 16.75˚ to 34.29˚. An analysis of rainfall from 2008 to 2020 characterized conditions leading to slope instability, with safety factors dropping from 1.362 in dry conditions to around 0.76 after heavy rainfall due to increased pore water pressure (PWP). The findings highlight that rainfall-induced reduction in

effective stress is a critical cause of slope failure, suggesting a need for a hybrid infrastructure approach for improved bioengineering and drainage over uniform hard-engineering solutions.

Keywords

Shear Strength, Rainfall-Induced Slope Instability, Pore Water Pressure, Factor of Safety, Sustainable Infrastructure

1. Introduction

Rainfall-induced landslides are one of the most chronic and destructive geohazards in humid, hilly, and tectonically active areas, and their effects are magnified in areas where the slopes have been modified for informal or emergency housing (Ahmed et al., 2020). Anthropogenic processes such as vegetation clearance, the creation of cut slopes, and the disruption of drainage can increase a slope's geomorphological susceptibility, and these processes can occur over a time span of months rather than decades, unlike natural land-use change.

Balukhali Camp is located in the low Tertiary hills of Ukhiya Upazila, Cox's Bazar, Bangladesh, where the topography is largely composed of small hillocks and valleys and has been significantly altered since the introduction of the Rohingya people into the area (Hassan et al., 2020). The natural slope morphology has been changed since 2017 with extensive vegetation clearance and hill cutting, resulting in higher exposure to rainfall-induced slope instability (Ahmed et al., 2020). Balukhali is a region that is also important for studying landslide susceptibility and slope stability due to the interaction of steep terrain, monsoon rainfall, geological conditions, and intensive anthropogenic modification in the Rohingya settlement region (Sami et al., 2024). Hossain et al. (2024) and Kamal et al. (2022b) discussed the hidden geohazards of the Cox's Bazar area. Jafrin et al. (2025) discussed some Site Characterization and rainfall-induced landslide risk assessment results of the Balukhali Rohingya Refugee Camps of Ukhiya, Bangladesh. A spatial risk assessment at a broader spatial scale supports the findings that precipitation, slope, geology, land use, and population density are controlling risk factors in the Ukhiya-Teknaf settlement area (Sami et al., 2024).

The mechanism of slope failure is known in accordance with the Mohr-Coulomb criterion; the shear strength of a soil available for failure is proportional to the cohesion and internal friction angle of the soil. This criterion is, however, not enough to explain the failure dates of rainfall events because the mobilized shear resistance along a potential failure surface is not constant, but rather depends on the hydraulic state of the slope. Each of these processes, caused by infiltration of rainwater, decreases effective stress and, as a result of the effective-stress form of the Mohr-Coulomb criterion, decreases available shear resistance. However, recent rainfall-induced landslide prediction literature highlights the advantages of

physically based models over rainfall threshold-based ones, with a focus on calculating the effect of rainfall on slope stability (Ebrahim et al., 2024).

In spite of this work, there exists a specific gap in the Balukhali camp: there is no published work that utilizes both a detailed geotechnical characterization and coupled seepage-slope stability modelling for Balukhali, compared to the comprehensive hazard and risk mapping of the wider Ukhiya region (Kamal et al., 2022a) and the extensive geotechnical characterization of Kutupalong (Kamal et al., 2022b). This is a significant gap since it is known that shear strength in hill-cut residual soils can vary significantly over short distances, both laterally and vertically, with lithology, so a risk inference made from regional or neighboring camp data cannot necessarily be directly applied to a specific slope.

This study aims to address the limited understanding of site-specific hydro-mechanical failure mechanisms at Balukhali by integrating soil shear-strength characterization, rainfall and antecedent-rainfall analysis, and coupled SEEP/W, SLOPE/W modelling. The resulting changes in pore water pressure and Factor of Safety are interpreted to support sustainable, climate-resilient slope infrastructure strategies for the resource-constrained humanitarian setting.

2. Study Area: Geological and Environmental Setting

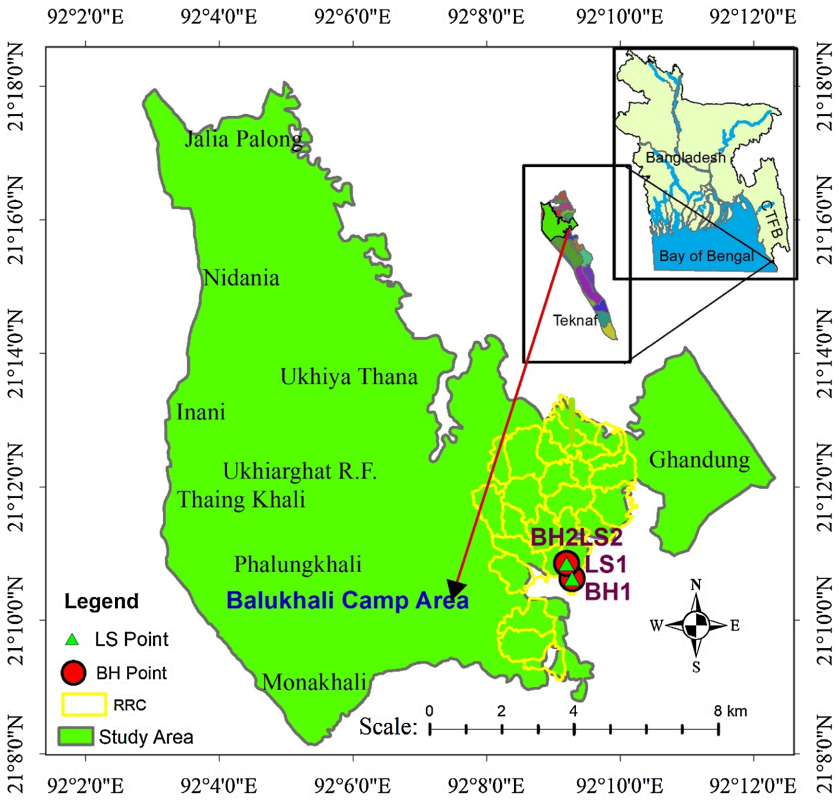


Figure 1. Location map of Balukhali Rohingya refugee camp.

Balukhali Rohingya Refugee Camp is one of the largest refugee camps in the world and is located in the Ukhiya Upazila of Cox's Bazar District in Bangladesh. It is

situated approximately 60 km south of the city of Chittagong and about 9 km east of the town of Ukhiya. It lies in the southernmost region of Bangladesh, which is bordered on the north by Ramu Upazila, the south by Teknaf Upazila, the east by Naikhongchhari Upazila and the Arakan state of Myanmar, and the west by the Bay of Bengal. After a reconnaissance survey, two borehole (BH-1, BH-2) locations have been selected for drilling and sample collection where landslide already took place. The study area (**Figure 1**) extends from 21˚09'28.67"N latitude to 92˚09'09.15"E longitude. A borehole location map of the study area is shown in **Figure 1**. The regional geology consists of Neogene clastic sedimentary sequences with alternations of sandstone, siltstone, and shale, which are highly susceptible to differential weathering and formation of low-cohesion residual soils on the cut faces (Kamal et al., 2022b). The climate is tropical monsoonal with a heavy rainfall season from June to September. The rainfall data analyzed in this study are from the period of 2008-2020.

3. Materials and Methods

3.1. Overall Research Framework

The study integrates three sources of evidence, sourced from the field and lab direct shear testing, rainfall analysis, and numerical seepage stability modelling, and a framework of interpretation that directly connects the mechanical properties of the soils to the hydrologic changes due to rain and to the Factor of Safety.

3.2. Field Investigation and Soil Sampling

In the Balukhali camp area, two boreholes (BH-01 and BH-02) were selected, and representative undisturbed soil samples were collected from each borehole (**Figure 2**). Four non-cohesive sand samples were selected from BH-01 (UD-02, UD-04) and BH-02 (UD-03, UD-05) at shallow, intermediate, and deeper sampling intervals (**Table 1**) to represent the natural variability of the soil profile and to preserve the *in situ* fabric and structure relevant to slope-stability analysis, which carries *in situ* soil moisture conditions. Four samples were taken for direct shear tests from various depths and lithologies.



Figure 2. Drilling and soil sampling.

Table 1. Two boreholes with depth and lithology.

BH No.	Sample No.	Depth (m)	Lithology
BH-01	UD-02	2.59 - 3.04	Yellowish brown color, medium to fine-grained loose sand (SP) with some silt, micaceous nature, pebble, cobble also present.
	UD-04	7.16 - 7.62	Bluish grey color, fine to very fine-grained sandy shale (ML), moderately compact, and shows some silty nature, iron incrustation at the top.
BH-02	UD-03	4.11 - 4.57	Yellowish brown color, oxidized, very fine to fine-grained sand (SC) with some silt and clay.
	UD-05	7.16 - 7.62	Yellowish brown color, fine to medium sand (SP), moderately compact, porous, oxidized; at the bottom part, an organic layer is found.

3.3. Direct Shear Testing

Direct shear tests can be performed under several conditions. The sample is normally saturated before the test is run. The test is run at the *in situ* moisture content. The specimen dimensions are diameter 6.35 cm, height 1.9 cm, and cross-sectional area 31.67 cm^2. Samples were sheared at least three times under the same normal pressure, with standard loads of 10, 20, and 30 kg.

A sample is placed within a shear box (Figure 3) that has two stacked rings to hold it; the contact between the two rings is roughly at the sample's midpoint. The upper ring is pulled laterally while the specimen is subjected to a vertically imposed confining force until the sample fails or reaches a predetermined strain. Following each other in a series of tests, a set of standard loads of 10, 20, and 30 kg was applied. Frequent records of the applied load and the resultant strain were used to create a stress-strain curve for each confining stress.



Figure 3. Direct shear testing.

Shear strength parameters were determined from direct shear tests and the shear stress-normal stress relationship was explained using the Mohr-Coulomb failure

criterion in accordance with ASTM D3080, 2011.

$$\tau = c + \sigma \tan\varphi$$

where τ is shear strength (kPa), c is cohesion (kPa), σ is normal stress (kPa), and φ is the angle of internal friction (degrees).

The analyzed samples reveal that the cohesion value varies from 4.48 to 17.40 kPa and the angle of internal friction 16.75˚ to 34.29˚. The results vary with depth at different sampling locations.

3.4. Rainfall Analysis

Records of rainfall in the Cox's Bazar region collected from the Bangladesh Meteorological Department (BMD) between 2008 and 2020 were analyzed using monthly in-situ observations to establish the monthly, seasonal, and annual variability at the study site, particularly during the monsoon. Seasons considered as winter (December-February), pre-monsoon (March-May), monsoon (June-September) and post-monsoon (October-November) and numerical modelling used 147 mm Rainfall over 24 hours, 343 mm Antecedent Rainfall over 3 days rainfall considered for study (Hossain et al., 2023; Hossain et al., 2024). The materials uploaded suggest that the threshold of rainfall for the wider Ukhiya area for the onset of slope failure conditions at 140 - 280 mm which is similar to the cumulative-rainfall approach to landslide early warning applied in Cox's Bazar by Hossain et al. (2024) and Ahmed et al. (2020).

3.5. Seepage and Slope Stability Analysis

The seepage and slope stability analyses were conducted numerically with SEEP/W and SLOPE/W software tools, involving field-based slope geometry, geotechnical parameters, and the rainfall boundary conditions. To model three scenarios, dry-season conditions, an intense rainfall event, and an antecedent-rainfall condition (a few days of cumulative rainfall) for a longer period were used. The pore-water pressure and matric-suction distribution from the seepage analysis were used as the input to the limit-equilibrium stability analysis.

For calculating slope stability, the "Bishop Simplified Method of Slices" was used with Seep/W and Slope/W software by Geoscience Limited, Calgary, Canada, to delineate the slope model.

This involves specifying the water levels and flow rates at the boundary of the model. Seep/W allows for the analysis of both steady-state and transient seepage conditions. The material properties of the soil or rock, geology, and rainfall, including the permeability, porosity, and compressibility, are considered. These properties are used to simulate the flow of water through the soil and rock, and to calculate the seepage pressures and velocities. Seep/W uses the finite element method to model seepage. This involves dividing the soil and rock into small elements and solving a set of equations to determine the flow of water through the elements. Seep/W provides a variety of analysis tools for interpreting the results of the analysis, including contour plots of the seepage pressures and velocities, flow nets, and

animations of the seepage flow. Seep/W also includes advanced features for modeling complex seepage conditions, such as flow through fractures or layered soil profiles. It allows for the analysis of seepage under different boundary conditions, such as rainfall, groundwater recharge, or changes in the water table.

Slope/W is a popular geotechnical software used for slope stability analysis and modeling. It is developed by GeoStudio, a leading provider of geotechnical software. This involves defining the slope angles, soil layers, soil properties, rainfall, permeability, and other relevant factors that may affect the slope stability. Slope/W uses the limit equilibrium method for slope stability analysis. This method assumes that the slope fails along a certain failure plane, and the stability is determined by comparing the resisting forces with the driving forces acting on the slope. Slope/W allows for the analysis of different types of failure modes, such as circular, non-circular, and translational slides. After defining the slope geometry and material properties, the user can perform the slope stability analysis using Slope/W. The software calculates the factor of safety for the slope and provides a graphical representation of the failure surface, which can be used to evaluate the stability of the slope.

Slope/W also allows for the analysis of various factors that can affect slope stability, such as pore water pressures, seepage forces, seismic forces, and external loads. The software provides tools for analyzing these factors and allows the user to evaluate the effect of different scenarios on the slope stability.

4. Results

4.1. Soil Shear Strength

When direct shear tests were carried out on the four samples, significant differences in mechanical behavior were found. The range of cohesion is 4.48 - 17.40 kPa and the angle of internal friction is 16.75˚ - 34.29˚, with average values of 11.07 kPa and 27.16˚, respectively. The lowest cohesion value was for loose sandy material, whereas the highest was for relatively fine-grained material, which is influenced by fines (silt or shale), as would be expected, with greater apparent cohesion with increasing fines content. While this is broadly similar to the shear-strength characterization previously reported by Kamal et al. (2022b) for the cut slopes at the adjacent camp of Kutupalong, the average cohesion of their pooled direct shear sample (6.75 kPa) is within the range but not as high as the mean of the Balukhali samples reported here. The physical properties of the soil samples, the direct shear test results under the applied normal loads, and the resulting shear strength parameters are presented in **Tables 2-4**, respectively. The relationships between shear displacement and shear stress, and between normal stress and shear stress, for the samples of BH-01 and BH-02 are shown in **Figure 4** and **Figure 5**, respectively, and the superimposed data are presented in **Figure 6**.

Shear strength parameters (cohesion, friction angle) for all four samples examined (**Table 4**), as a function of borehole depth. Here, shows that cohesion increases with depth (**Figure 7**), whereas internal friction angle decreases with depth for representative samples.

Table 2. Summary of physical properties of soil samples from selected boreholes.

Parameters	BH-01 (UD-02)	BH-01 (UD-04)	BH-02 (UD-03)	BH-02 (UD-05)
Av. Wet Weight	36.57 gm	35.92 gm	42.15	42.74
Av. Dry Weight	31.47 gm	28.51 gm	33.47	36.32
Moisture Content (%)	32.92%	33.56%	50.70%	32.18%
Wet Density (gm/cc)	1.8	1.8	2.06	2.09
Dry Density (gm/cc)	1.39	1.73	1.1	1.4

Table 3. Summary of direct shear test results under different normal loads (10, 20, 30 kg load).

Test No.	Normal Load (kg)	Normal Stress (kg/cm²)	Normal Stress (kPa)	Horizontal Load Dial Reading	Max Horizontal Shear Force (kg)	Maximum Shear Stress (kg/cm²)	Shear Stress (kPa)
BH-01 (UD-02)	0	0		0	0	0	
	10	0.3158	30.9659	27	8.37	0.2643	25.9178
	20	0.6315	61.9317	48	14.88	0.4698	46.0761
	30	0.9473	92.8976	71	22.01	0.6950	68.1542
BH-01 (UD-04)	0	0.0000		0	0	0.0000	
	10	0.3158	30.9659	28	8.68	0.2741	26.8777
	20	0.6315	61.9317	44	13.64	0.3648	35.7750
	30	0.9473	92.8976	56	17.36	0.4643	45.5318
BH-02 (UD-03)	0	0.0000		0	0	0.0000	
	10	0.3158	30.9659	28	8.68	0.2741	26.8777
	20	0.6315	61.9317	42	13.02	0.4111	40.3166
	30	0.9473	92.8976	56	17.36	0.5482	53.7554
BH-02 (UD-05)	0	0.0000		0	0	0.0000	
	10	0.3158	30.9659	30	9.3	0.2937	28.7976
	20	0.6315	61.9317	50	15.5	0.4894	47.9959
	30	0.9473	92.8976	71	22.01	0.6950	68.1542

Table 4. Shear strength parameters of the soil samples.

BH No.	Sample No.	Depth (m)	Cohesion (c) kPa	Friction Angle (φ)
BH-01	UD-02	2.59 - 3.04	4.48	34.29˚
	UD-04	7.16 - 7.62	17.4	16.75˚
BH-02	UD-03	4.11 - 4.57	13.43	23.46˚
	UD-05	7.16 - 7.62	8.96	32.42˚
Overall shear strength parameters of Balukhali Camp			**11.07**	**27.16˚**

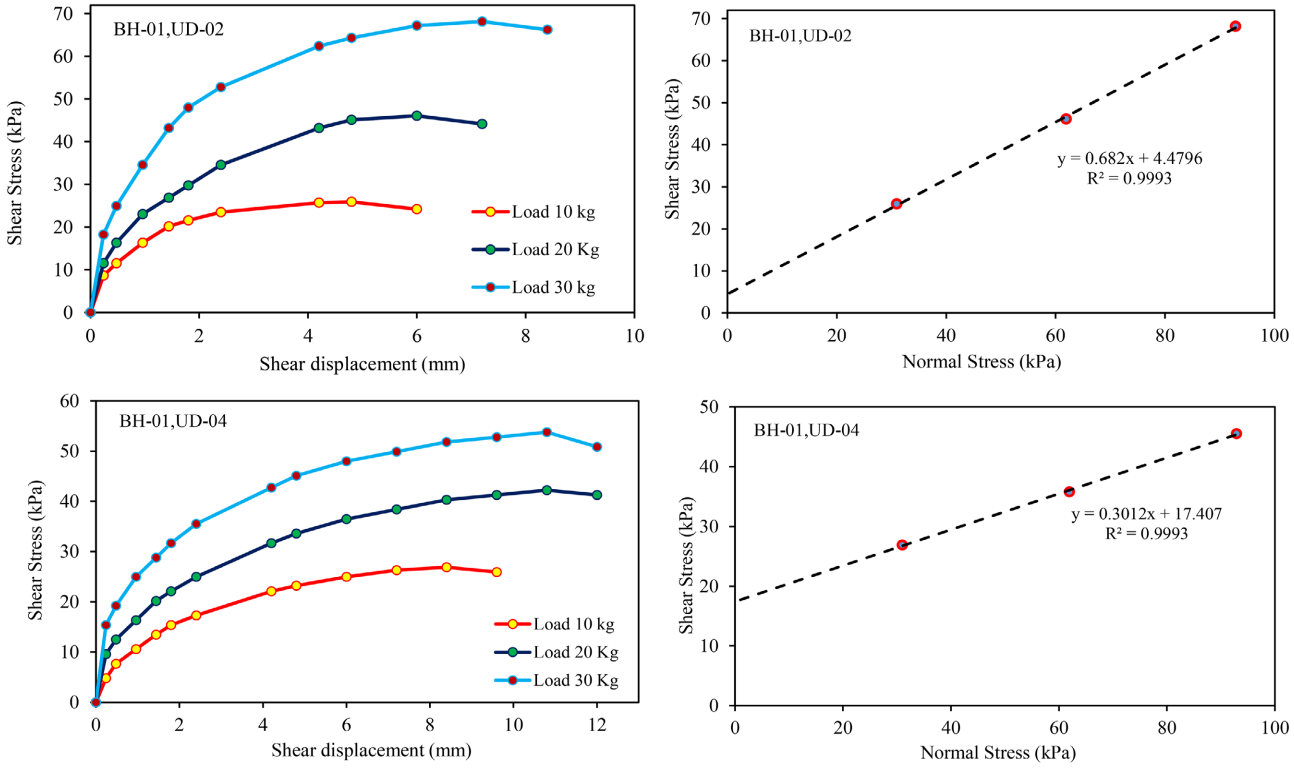


Figure 4. Relationship between shear displacement vs. shear stress and relationship between normal stress vs. shear stress of samples of BH-01.

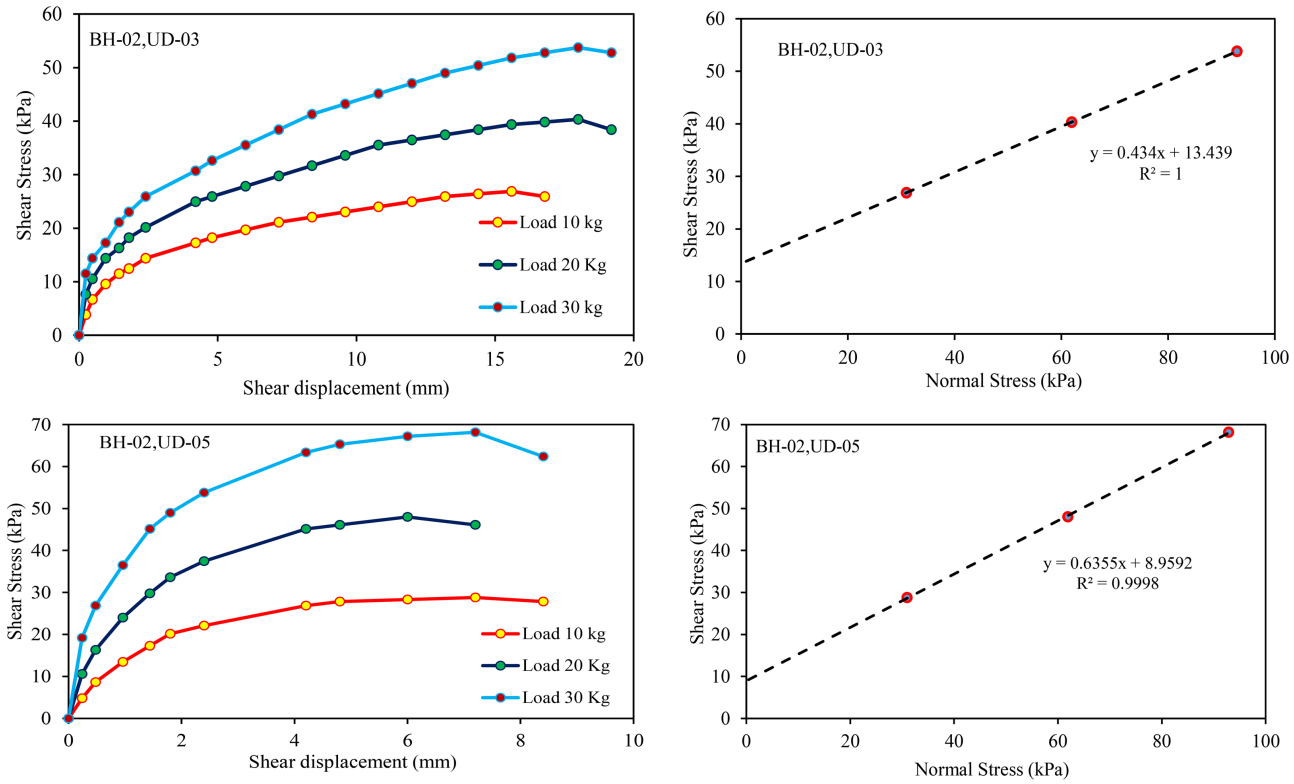


Figure 5. Relationship between shear displacement vs. shear stress and relationship between normal stress vs. shear stress of samples of BH-02.

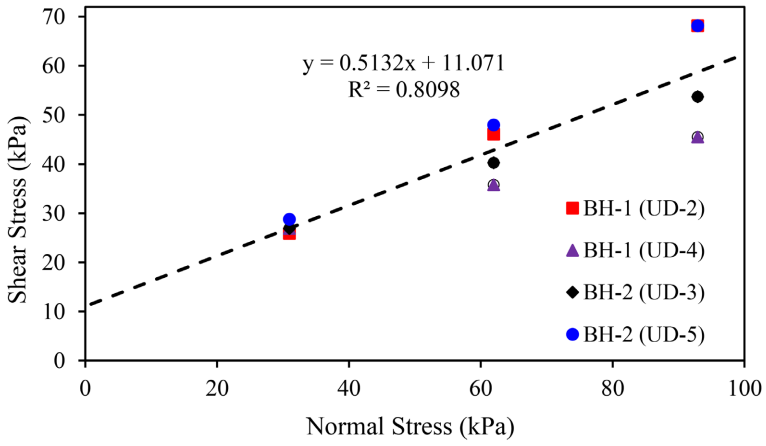


Figure 6. Superimposed data of shear displacement vs. shear stress and relationship.

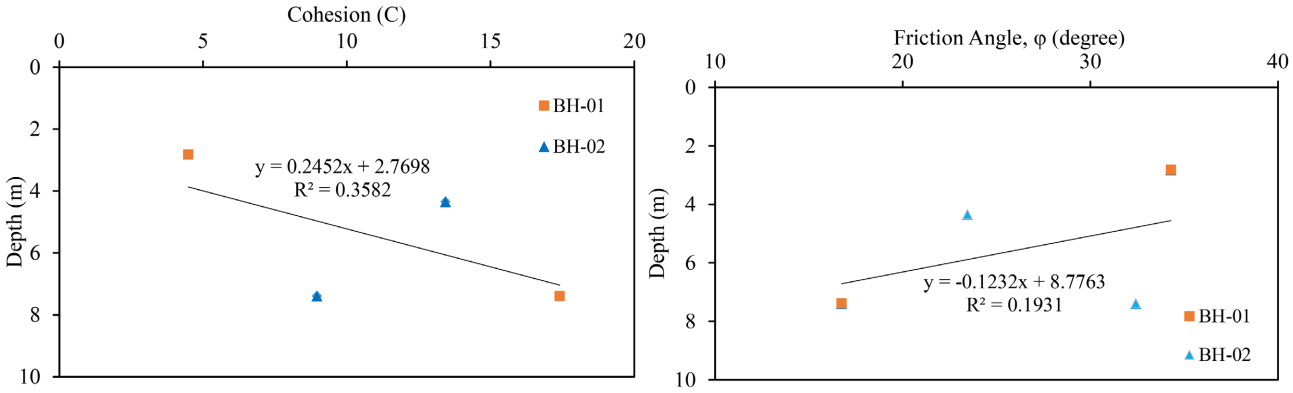


Figure 7. Variations of cohesion (C) and angle of internal friction (φ) with respect to depth (m).

4.2. Rainfall Characteristics

The 13-year period of rainfall data reviewed (2008-2020) shows that the majority of the annual rainfall is provided by the monsoon period (Figure 8) and that this

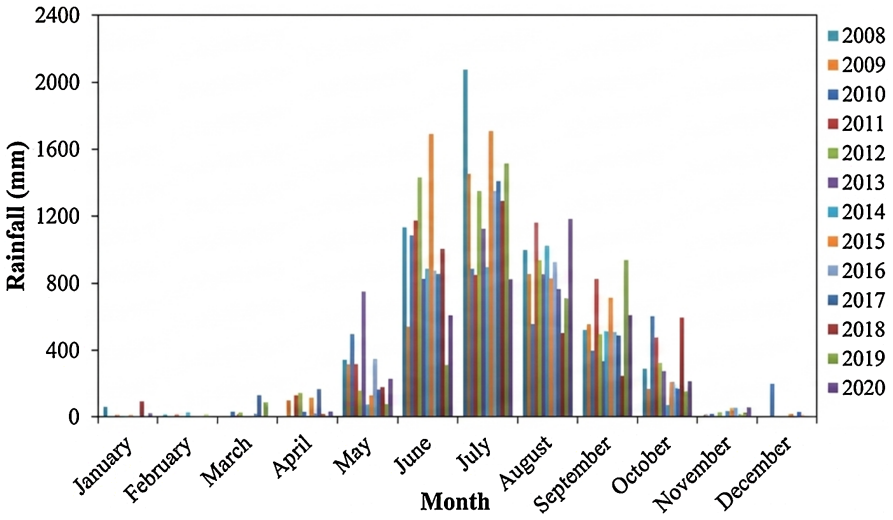


Figure 8. Monthly rainfall analysis.

is the climatic condition most important in the context of slope instability at the site. Approximately 140 - 280 mm is considered a threshold for favorable failure conditions in general for the Ukhiya area (Hossain et al., 2024), and the cumulative precipitation for the days to weeks before an event is considered as another relevant condition.

4.3. Rainfall-Induced Hydraulic Response

The modelled slope had negative pore-water pressure (matric suction) that helped to increase the shear resistance in dry conditions. The rainfall and antecedent-rainfall scenarios have shown that infiltration progressively decreased matric suction and increased pore water pressure within the slope profile, consistent with the rise of the phreatic surface in the slope profile.

4.4. Slope Stability Results

The study uses field landslide observations (Slope Geometry), borehole data, groundwater conditions, and measured soil properties to develop the numerical models (Figure 9).

The dry-condition Factor of Safety (FoS) for the representative slope was around 1.362. After this scenario of high-intensity rainfall, Fs reduced to about 0.810; after this scenario of antecedent rainfall, Fs reduced further to about 0.76. The slope analyses after rainfall are shown in Figure 10, and the Factor of Safety values for all scenarios are summarized in Table 5.

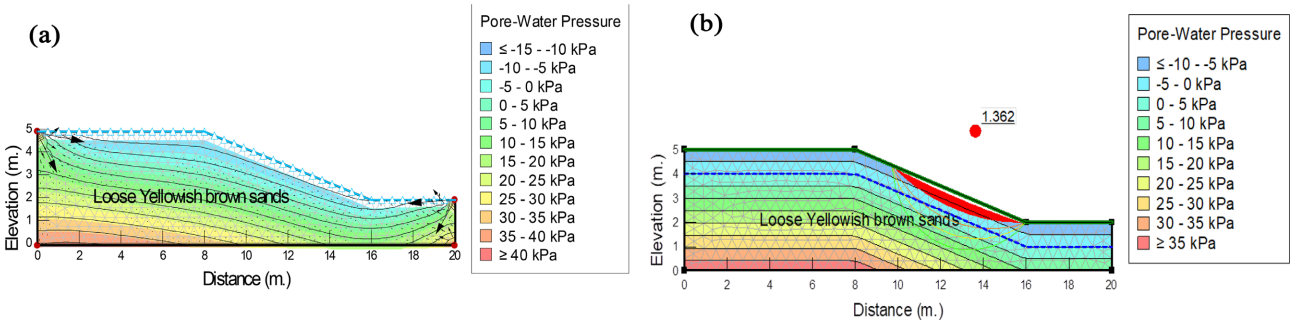


Figure 9. Initial (a) seepage and (b) slope before rainfall at Balukhali camp.

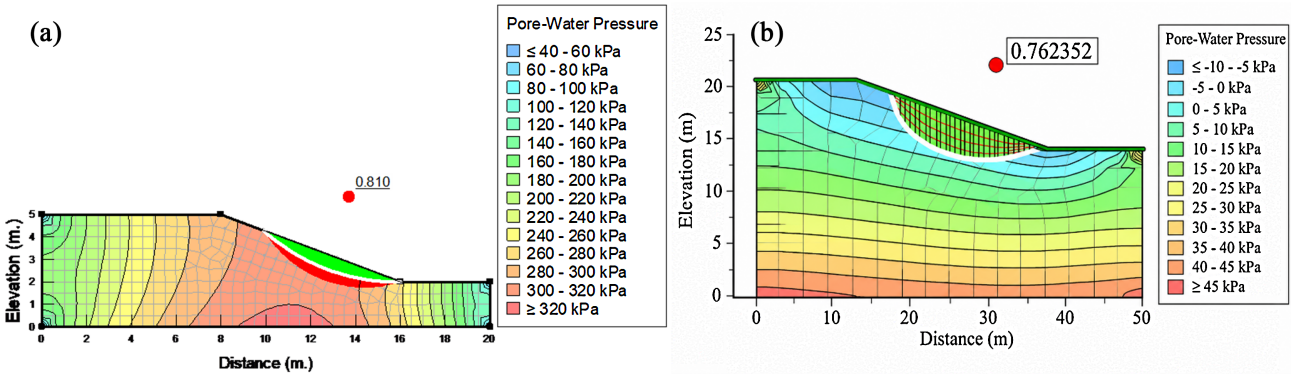


Figure 10. Slope analysis at Balukhali after rainfall at (a) 147 mm rainfall, (b) 343 mm antecedent rainfall.

Table 5. Factor of Safety for various rainfall and groundwater conditions (for a representative slope).

Scenario	Factor of Safety (Fs)	Hydraulic Condition
Dry Season	1.362	Negative pore-water pressure/matric suction present
Intense Rainfall (During Monsoon) (147 mm)	0.810	Reduced suction, increased pore water pressure
Antecedent Rainfall (343 mm)	0.76	Further reduced suction reduced factor of safety values

5. Discussion

5.1. Interpretation of Soil Shear Strength

This observed variation in cohesion and friction angle is in line with the lithologically and weathering-heterogeneous residual soil profile common in the Neogene sequence of clastic deposits in this part of Cox's Bazar. The relationship between cohesion and degree of fineness is as expected for soil-mechanical behavior, and for only four samples, this is only a suggested depth or lithological trend and should not be considered validated. Comparing with the average cohesion of the pooled Kutupalong data (Kamal et al., 2022b) reveals a slightly larger range of cohesions, but not enough to suggest there is any significant difference between the two data sets, as it is hard to statistically compare because of differing sample sizes between the two studies. A comparison with previous studies of landslide risk in the Cox's Bazar Rohingya settlement area is presented in Table 6.

5.2. Rainfall Soil Slope Interaction—Coupled Model

The numerical modelling directly supports rainfall infiltration, reduction in matric suction and increase in pore-water pressure, reduction in effective stress, reduction in mobilized shear resistance, and finally, reduction in Factor of Safety (from 1.362 to 0.810 to 0.76 across the three modelled scenarios). This is not a rainfall-only effect, as the same rainfall input will result in different reductions in Fs for different antecedent hydraulic states of the slope and different shear strength parameters for the slope. This is a general mechanism that is in line with the focus of recent physically based landslide prediction literature that emphasizes coupling of hydrological and mechanical processes, instead of empirical rainfall thresholds alone (Ebrahim et al., 2024). The conceptual hydro-mechanical framework that relates the relationships between rainfall, infiltration, pore-water pressure, shear strength, and slope stability.

5.3. Innovative Sustainable and Climate-Resilient Infrastructure Perspective

If only dry-season stability was used to estimate risk, then the magnitude of Fs reduction observed here (from a nominally stable value during the dry season of >1.3 to <1.0 when rainfall occurs) would be a significant underestimate. This is

Table 6. Comparison with previous studies of landslide risk in the Cox's Bazar Rohingya settlement area.

Study	Location	Methodology	Main Finding	Limitation	Contribution of Present Study
Hossain et al. (2023)	Ukhiya (Rohingya refugee camp and hilly areas) of Cox's Bazar, Bangladesh	Geotechnical condition-based integrated engineering-geological and geotechnical assessment of geo-hazards in the geo-hill areas of Rohingya camp	Highlighted various geo-hazard interactions in the camp context and stressed the importance of hill cutting, vegetation clearing, rainfall, unstable ground conditions, and other geotechnical issues for sustainable development	Regional camp-scale assessment, limited site-specific quantitative slope stability and coupled rainfall-seepage modelling	Conducts site-specific Balukhali slope characterization, lab-based shear-strength parameters, and numerical seepage slope-stability assessment to quantify changes in Factor of Safety due to rainfall
Ahmed et al. (2020)	Cox's Bazar District (camp-wide)	Geospatial susceptibility mapping rainfall threshold early-warning system	Identified cumulative rainfall thresholds and land-cover change as key landslide drivers	Regional scale; not site-specific shear strength data	Provides site-specific shear-strength and seepage/stability data for Balukhali
Kamal et al. (2022b)	Kutupalong Rohingya Camp	Direct shear testing, geological/geomorphological characterization	Average cohesion 6.75 kPa; low residual soil strength drives shallow failures	Limited to Kutupalong; no coupled seepage-stability modelling reported	Extends comparable shear-testing approach to Balukhali and couples it with SEEP/W, SLOPE/W modelling
Kamal et al. (2022a)	Kutupalong Rohingya Camp	Hazard exposure vulnerability risk mapping	Camp 10 identified as highest-risk zone; risk map validated against historical events	Risk framework, not a mechanical/hydraulic process model	Adds a process-based (mechanical hydraulic) account of why rainfall triggers failure
Sami et al. (2024)	Ukhiya and Teknaf upazilas (host refugee area)	AHP-based multi-criteria spatial risk mapping	Precipitation, slope, geology, land use, and population density are key risk factors	Susceptibility-mapping scale; no laboratory or numerical stability data	Provides slope-scale numerical Fs values that complement area-scale susceptibility maps

in line with the ongoing increase in the use of a hybrid approach over isolated hard-engineering solutions in recent literature, where water-triggered landslides are combined with a mixture of hard and soft measures (Thakur et al., 2024), and the explicit inclusion of the mechanical and hydrological effects of vegetation in the modeling of slope stability (DiBiagio et al., 2024).

Conceptual categorization of the slope stabilization approaches in the context of rainfall-induced landslides at Balukhali can be divided into green, grey, and smart approaches. In terms of slope protection, green measures can provide mechanical root reinforcement, hydrological regulation, and control of surface erosion, such as deep-rooted native vegetation, contour planting, and bioengineering (Bordoloi & Ng, 2020). The stabilizing effect of vegetation is strongly influenced by plant properties, root structure, and local soil hydrology conditions and cannot be assumed to increase the Factor of Safety beyond a desired level without investigation. Rainfall-induced increases in pore-water pressure can be more directly

addressed through the use of grey infrastructure such as surface and subsurface drainage systems that can control and facilitate the removal of pore water. Therefore, these measures are useful where pore-pressure development is determined to be the main failure mechanism, in addition to vegetation-based stabilization. Infrastructure information for the anticipation of rainfall-induced slope instability can be provided through smart infrastructure (Ahmed et al., 2020; Bordoloi & Ng, 2020), which consists of rain gauges, rainfall-threshold warning systems, pore-water-pressure and groundwater monitoring, hazard mapping using GIS, and community-based early-warning systems. Ahmed et al. (2020) showed here how geospatial early-warning technologies could be used in the context of the Rohingya camp, giving direct regional relevance to this approach. To extend these previous works, this study suggests a conceptual Green Grey Smart framework for site-specific engineering design of landslide resilience at Balukhali in the future. The framework is provided as a recommendation for the future, not as an engineered stabilization technique, which was not tested in this study. Its effectiveness is dependent on the site-specific design, and numerical modelling and field testing of each proposed intervention. Empirical calibration of the individual components of the framework should therefore be given high priority in further research to address the specific geotechnical and hydrological conditions found in Balukhali.

6. Engineering Implications and Risk-Based Infrastructure Prioritization

With the limited resources available in many humanitarian settlements, investment in infrastructure is best targeted to locations that are most sensitive to rainfall given geotechnical and hydraulic conditions. Here, based on the overall findings, infrastructure prioritization for the Ukhiya hills and Teknaf area is listed in Table 7.

Table 7. Risk-based infrastructure intervention framework (conceptual, based on the present findings).

Risk Level	Geotechnical Condition	Rainfall Sensitivity	Monitoring Requirement	Recommended Intervention
High	Low cohesion, steep cut slope, Fs approaching or below 1 under rainfall	High rapid loss of suction under monsoon rainfall	Continuous pore-water-pressure and rainfall monitoring	Engineered drainage, toe support/retaining measures, bioengineering, priority for numerical re-assessment
Moderate	Intermediate shear strength, moderate slope angle	Seasonal instability during sustained monsoon periods	Periodic monitoring, rain-gauge coverage	Improved drainage, vegetation reinforcement, erosion control
Low	Comparatively stable dry- and wet-season Fs	Lower hydraulic sensitivity	Periodic inspection	Vegetation restoration, runoff management, land-use control

7. Conclusion

Samples tested directly from the Balukhali camp area yielded cohesion values between 4.48 and 17.40 kPa and friction angles between 16.75˚ and 34.29˚, with the average friction angle values roughly similar to those reported for the nearby

Kutupalong camp, but the average cohesion values somewhat higher. The Factor of Safety for a typical slope, calculated through Coupled SEEP/W, SLOPE/W modelling, decreased from about 1.362 for dry conditions to about 0.810 after heavy rainfall and 0.76 for a few consecutive days of antecedent rainfall conditions.

The results show that the soil shear strength is an intrinsic property of the soil that dominates the instability of the soil in the study area, while the reduction of matric suction and increase in pore-water pressure due to rainfall are also influential factors that determine the instability of the soil by reducing the shear strength along the potential failure surface. During rainfall, P.W.P. gradually diminishes with time and increases risk and instability, as discussed by Hossain et al. (2024). The study is presented here as an integrated, process-based hydro-mechanical interpretation rather than a statistical correlation.

Infrastructure-wise, the volume of Fs reduction due to rainfall indicates that a combination of drainage, bioengineering, and monitoring of rainfall and pore pressure should be prioritized over hard engineering in general, and applied only where necessary based on slope-specific risk.

8. Limitation

Four samples from two boreholes used in the analysis were collected from low, medium, and high depths at significant landslide locations; however, the interpretation of subsurface soil structure was based on a limited number of boreholes and soil samples, which may not adequately represent the lateral and vertical heterogeneity of the study area. The available samples provide localized information and may not capture variations in lithology, soil texture, weathering, and structural conditions between investigated locations. Consequently, the interpreted subsurface soil profile and associated engineering properties should be considered representative rather than fully continuous across the study area. This limitation may introduce uncertainty in the spatial extrapolation of soil properties and in the interpretation of slope failure mechanisms. Future studies should incorporate a larger number of samples from different slope positions, depths, geological units, and moisture conditions, together with additional laboratory testing and field verification, to better quantify the spatial variability and uncertainty of the shear strength parameters. Additional boreholes, geophysical investigations, and spatially distributed sampling are recommended to improve the confidence of subsurface structural interpretation.

Author Contributions

Sheikh Jafia Jafrin contributed to the development of the research framework, write-up, and design of this study. A. T. M. Shakhawat Hossain supervised the whole research work and publication process. Mahmuda Khatun provided technical support to this research. H. M. Sayem contributed to the concept of the work. Md. Hasan Imam contributed to its revision and feedback. Jarin Tasnim Zeba supported laboratory testing at the initial stage. The research involved field investiga-

tion, soil sampling, laboratory testing, rainfall data collection and analysis, and numerical modelling of rainfall-induced slope stability. The authors contributed to the interpretation of the geotechnical and numerical modelling results. Sheikh Jafia Jafrin prepared the initial draft of the manuscript. The co-authors critically reviewed the manuscript, provided feedback, and contributed to its revision. All authors read and approved the final version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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