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Influences of the hill geometry and geotechnical properties on the landslide susceptibility- A case study

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Abstract

Controlling factors for landslide occurrences is critical for understanding the underlying triggers and vulnerabilities, allowing preventative steps to be taken to avert disasters and protect vulnerable people. In addition, effective mitigation techniques can be adopted by recognizing these characteristics, resulting in safer and more resilient solutions in landslide-prone locations. The research aims to assess the geometrical and geotechnical properties associated with landslides and identify the controlling factors influencing the occurrences of landslides, especially in Chattogram region. A local hill in Chattogram city was studied in this research using LimitState GEO software to investigate landslides susceptibility, numerically. The study focused on evaluating the slope stability of the hill in terms of Factor of Safety (FS), and Spearman's rank correlation method was used for correlation analysis. The findings indicated that the current geometry of the hill is highly unstable. Additionally, the study revealed significant associations between FS and slope height (following an exponential relationship) as well as slope width (following a linear relationship). The depth of toe, toe width, and crest width reached their highest FS values at approximately 1.75m, 7.5m, and 7.0m, respectively, with the maximum FS value being around 3.0 for the studied hill. Concerning the geotechnical properties of the hill slope soil, only the angle of friction (Φ) exhibited a significant positive correlation (ρ = -0.80) with FS at a 95% confidence interval. The findings can be used as instrumental tools in identifying the causes of historical landslides. Furthermore, the findings of this study will aid threatened residents/communities, urban planners, and engineers in planning and decision-making for emergency decisions, landslide risk reduction, and the development of effective risk prevention and mitigation strategies, thereby reducing future landslide.

Keywords: *Landslide; angle of friction; slope of the hill; factor of safety; correlation analysis.*

1 Introduction

The landslide hazard in Chattogram Hill Tracts Districts (CHTD) is a burning issue for Bangladesh over the last few decades. The issue is triggering day by day due to the knowledge deficiencies, limitations of information/guidelines and scope of facilities for landslide hazard in the CHTD. Bangladesh is the world's largest delta, with 82% flat territory and 18% steep terrain (Akter et al., 2016). Geographically, the Chattogram Hill Tracts Districts (CHTD) are more prone to different calamities, where landslides are one of the most devastating hazards causing fatalities, soil/ mass/debris movement, loss of ecological systems, damage of different physical assets, financial loss, and environmental degradation (Khan & Sarkar, 2019; Mourin et al., 2019a; Rabby et al., 2022; Rabby & Li, 2020). The landslides happened during monsoon in the hilly areas of Bangladesh killed 3-152 inhabitants and affected 0.25-1.5 million people by each incident. The extent of the landslide disasters in 2007, 2010, and 2017 were seen the worst (Abedin et al., 2020; Ahmed, 2015). On 18 June 2022, four people were killed by a landslide in Chattogram city (The-Daily-Star, 2022). The CHTD are overlain by Surma and Tipam strata rocks for which this mountainous terrain is complicated with younger rocks having larger concentrations of easily weatherable feldspars. As a result, the soil in this terrain is extremely vulnerable to landslides. Landslides have become more common in recent years resulting from global climate change that exacerbates heavy and persistent rainfall. The primary reasons of landslide hazard in the hilly areas are the insufficient knowledges about the preventive/protective measures for the landslides. Some studies were conducted on landslide for different districts of Bangladesh including Chattogram (Ahmed, 2015; Chakraborty et al., 2019; Islam et al.,

2017; Khan & Sarkar, 2019), Rangamati (Abedin et al., 2020; Hafsa & Rahman, 2020; Khatun et al., 2018; Rabby et al., 2022) and Bandarban (Rabby & Li, 2020; Ullah, 2021). Ahmed (2015) conducted a study to prepare the landslide susceptibility maps for Chattogram metropolitan area (CMA) of Bangladesh using GIS based multi-criterial decision evaluation methods including Artificial Hierarchy Process (AHP), Weighted Linear Combination (WLC), and Ordered Weighted Average (OWA). The accuracies of the methods ranges from 84% to 95% (Ahmed, 2015). The intensities of landslide susceptibilities in Chattogram were found to be very low, low, moderate, high and very high in the area of 13%, 53%, 15%, 13% and 6%, respectively (Islam et al., 2017). Moreover, about 16-25% areas of Rangamati district are found highly susceptible to landslide by WOM and AHP methods (Khatun et al., 2018). Particularly, six (06) locations are deemed to be highly vulnerable among the 348 landslide vulnerable areas in the Rangamati district. Ullah (2021) reported that 91% of landslide events were occurred within a 10º slope, and 65% were occurred within a free height of 50m. Wubalem and Meten (2020) prepared landslide susceptibility maps in the Goncha Siso Eneses area, one of the most landslide-prone regions in northwest Ethiopia, using nine associated factors, including land use-land cover (LULC), rainfall intensity, slope, aspect, curvature, lithology or geology, distance to stream, distance to lineament, and distance to springs/water bodies where the accuracies were found about 80-89%. Similar study was conducted by Wubalem (2021) in northwestern Ethiopia using statistical methods where six factors including lithology, land use-land cover, distance to stream, slope, aspect, and curvature where accuracies were about 89% (Wubalem, 2021).
In existing literature, researchers have identified multiple factors influencing landslide susceptibility, such as geological, social, and environmental considerations. However, there is a noticeable gap in the existing literature, especially concerning Bangladesh, where the specific influences of geometrical and geotechnical properties on landslide occurrences have not been thoroughly explored. Therefore, the primary goal of this research is set to evaluate the status of various geometrical and geotechnical properties linked to landslides and hence to identify the influence factors for landslide occurrences.

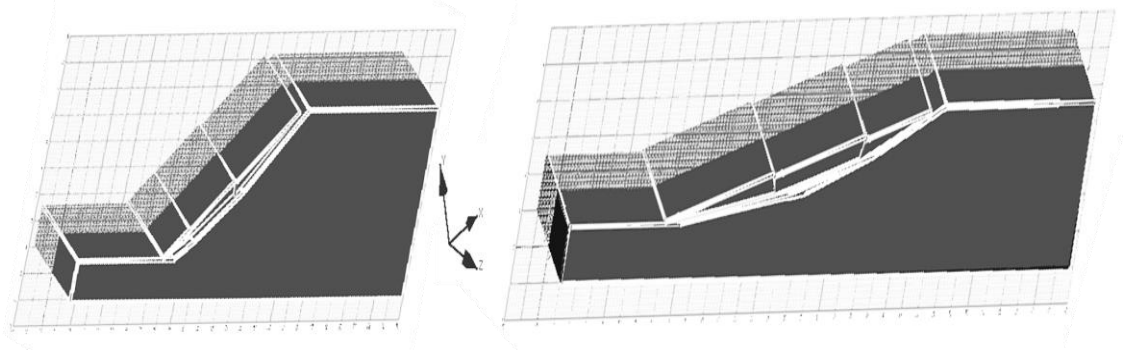
2 Methods and Materials

2.1 Study Area, Data Collection and Model Setup

The Study was conducted in a hill, locally known as "Kata Pahar" (22˚21’57.7’’N and 91˚47’28.3"E) is situated (as seen in figure 1) near Agrani Bank society in Beltoli, Akbar shah, Chattogram. A landslide took place in the Beltali area of Akbarshah, Chittagong, during hill-cutting activities on 07 April, 2023, at approximately 6:15 pm (Barua, 2023). The landslide occurred as a group of laborers attempted to cut steep ground in the area in preparation for the ongoing illegal construction of roads at that specific location.

(a) (b)

Figure 1: (a) Hill considered in this study, (b) current situation of the hill after landslide.



(a) (b)

Figure 2. Model setup for (a) actual hill geometries (H_S: 5.6m, W_S: 7.5m, d_t : 1.52, w_t: 6.7m, w_c : 9m) and (b) proposed hill geometry (H_S: 3m, W_S: 15m, d_t : 1.52, w_t: 6.7m, w_c : 9m) in LimitState GEO.

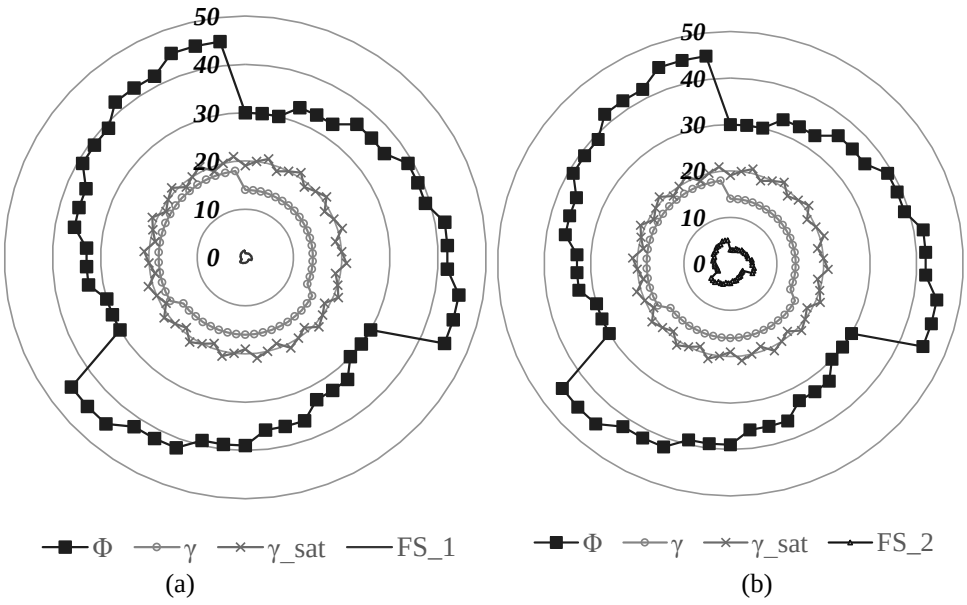
Four (04) individuals were rescued from the site and immediately transported to Chittagong Medical College Hospital by the Fire Service and Civil Defense and one (01) person was declared deceased (Daily-bangladesh, 2023; Kalerkantho, 2023). Three (03) representative soil samples were collected from top, middle and bottom of the slope of the hill. The samples were sealed and taken to the Geotechnical Engineering laboratory of Chittagong University of Engineering and Technology (CUET) within 24 hours. Different geotechnical properties (angle of friction, Φ; dry unit weight, γ; saturated unit weight, γsat; classification of soil etc.) were determined following the standard protocols. The geometry of the hill (slope height, HS; slope width, WS; depth of toe, dt; toe width, wt; Crest width, wc) were also taken manually through field survey. The geometry data and properties of soil were assigned and model set up was prepared (see figure 2) on LimitState GEO v. 3.6 for further numerical simulation. Actual model set up (see figure 2a was prepared and stability was checked for existing geometry and found unstable. Therefore, a new geometry (figure 2b) was proposed after successive trial and error.

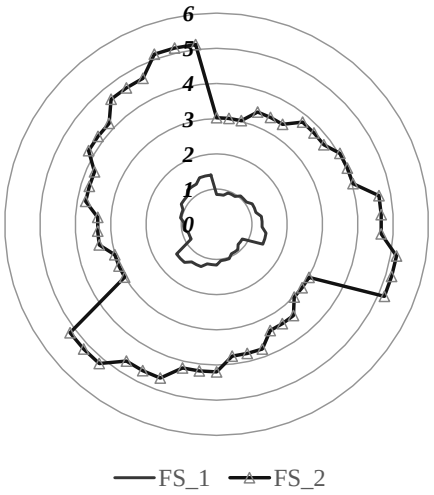
2.2 Data Analysis

The factor of safety (FS) is a critical parameter used to assess the stability of a hill slope. It represents the ratio of resisting forces to the driving forces and is essential for ensuring the slope's safety. A slope with FS greater than or equal to 1.0 indicates that the slope is stable, while an FS less than 1 suggests that the slope is at risk of collapse. The Bangladesh National Building Code (BNBC 2020) recommends a minimum value of FS of 1.5 to define a stable slope in natural condition, while different geotechnical structures are recommended to have FS values ranging from 1.4 to 4.0. Radar plots were used to compare the actual geometrical properties and proposed geometrical properties, along with their corresponding factors of safety considering different geotechnical properties (Φ: 30º-45º, γ: 14-18 KN/m^3, γ_{sat}: 19-21 KN/m^3). Additionally, FS values were plotted for various combinations of geometrical properties (H_S: 1.5-7.5m, W_S: 1.5-20m, d_t: 0.5-3m, w_t: 4-9.5m, w_c : 3-13.5m) to investigate the changes of FS with geometrical properties. Spearman's non-parametric rank correlation method was used to determine the association among geometrical properties, geotechnical properties and FS at 95% confidence interval (Spearman, 2008) in order to find the critical influencing factors with their values that influences the FS of the slope.

3 Results and Discussion

The figure 3 represents the variation of FS with different geotechnical properties for both the actual and proposed geometries of a hill through radar plot and the legends FS_1 and FS_2 represent the factor of safety for the actual and proposed geometry, respectively. The factor of safety values, FS_1 and FS_2, show significant variability, ranging from 0.83 to 1.42 and 3.01 to 5.17, respectively. The values of FS_1 and FS_2 provide insights into the stability of the hill under existing and proposed conditions. Higher values of FS indicate a more stable slope, while lower values imply a higher risk of potential failure. It is observed that both FS_1 (see figure 1) is consistently lower for all the combinations of geotechnical properties and slope geometries presented which implies that the existing geometry of the hill may be at risk of instability and potential landslide occurrences.

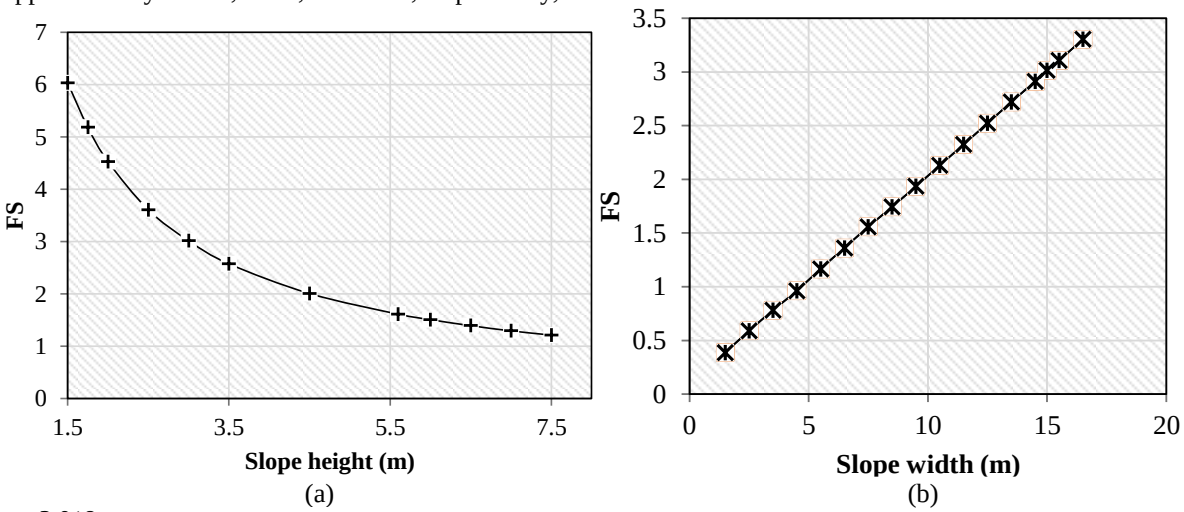




(c)

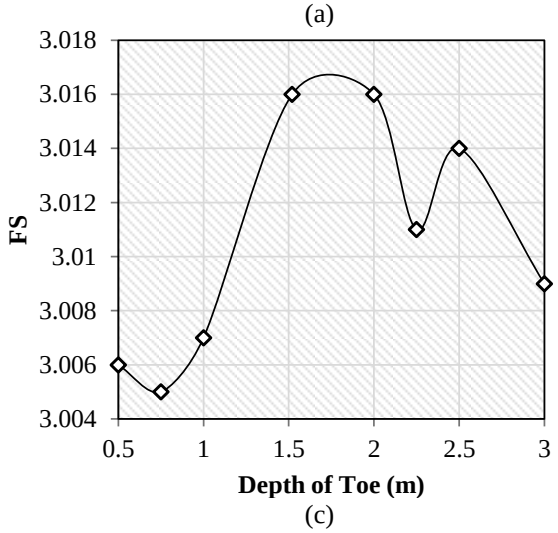
Figure 3. Variation of factor of safety (FS) with different geotechnical properties (a) actual geometries, (b) proposed geometries (c) FS for both actual and proposed geometries of the hill.

Figure 4 depicts the variations of the FS with different geometrical properties of the modified hill slope. The figure 4 highlights how FS changes with adjustments in these properties. Specifically, the size of slope width exhibits a linear relationship with FS, while slope height shows an exponential relationship. Notably, slope height and slope width have a significant impacts on FS (as shown in Figure 4a and 4b). However, the depth of toe, toe width, and crest width do not exhibit such clear mathematical relationships with FS (as depicted in Figure 4c and 4d). FS steadily increases with increasing slope width, while it decreases exponentially with increasing slope height. The depth of toe, toe width, and crest width reach their highest FS values at approximately 1.75m, 7.5m, and 7.0m, respectively, with the maximum FS value recorded as about 3.0.

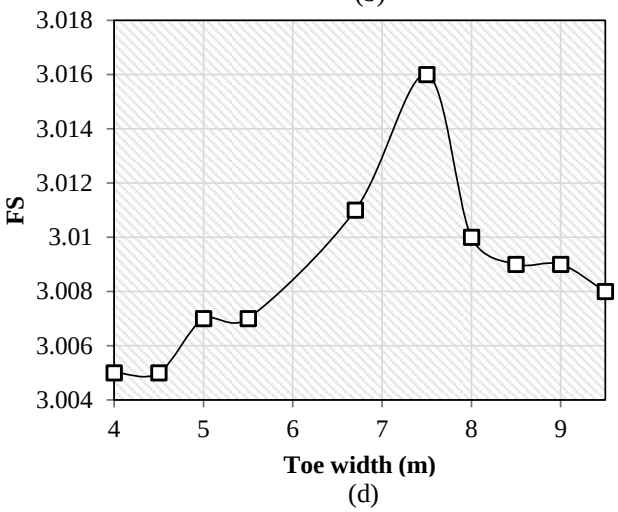


(a)

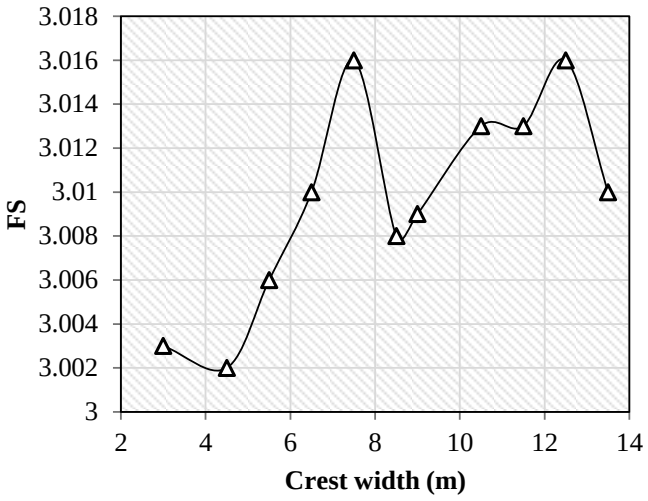
(b)



(c)



(d)



(e)

Figure 4. Variation of factor of safety (FS) with different hill geometry: (a) slope width, (b) slope height, (c) depth of toe, (d) toe width, (e) crest width

Figure 5 shows the correlation between geometrical and geotechnical properties and the FS. Both slope height and slope width demonstrate statistically significant associations with FS among the geometrical properties. Slope height is negatively and significantly correlated (correlation coefficient, ρ = -0.42), indicating that FS tends to decrease as the slope height decreases.

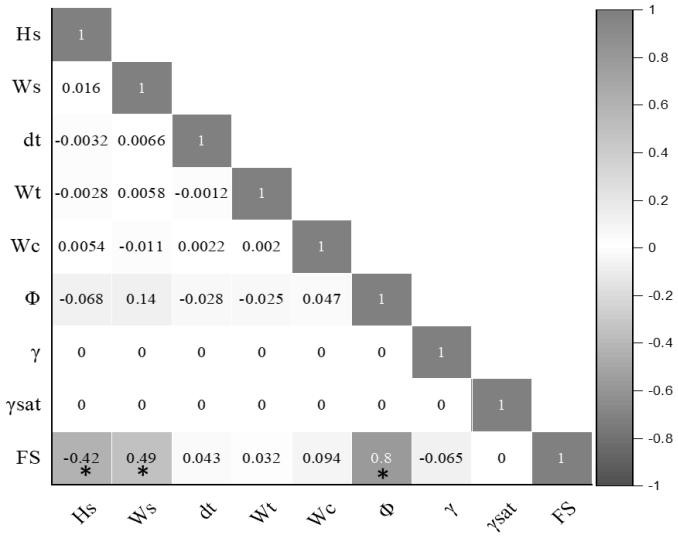


Figure 5. Correlation plot among geometry of the hill, geotechnical properties and factor of safety (*α<0.05).

Conversely, slope width is positively and significantly correlated (ρ = 0.49), indicating that FS increases with an increase in slope width. This aligns with the trends observed in Figure 4. Regarding the geotechnical properties of the hill slope soil, only the angle of friction (Φ) exhibits a significant positive significant correlation (ρ = 0.80) with FS at a 95% confidence interval. This implies that the angle of friction (Φ) has a notable and meaningful impacts with FS.

4 Conclusion

This research conducted a comprehensive assessment of geometrical and geotechnical properties of a hill located in Chattogram, Bangladesh on the landslide susceptibility. The study unveiled critical insights using LimitState GEO software and Spearman's rank correlation method. The existing hill geometries were found to be highly unstable with Factor of Safety values ranging from 0.83 to 1.42. However, FS values significantly improved, ranging from 3.01 to 5.17 with the proposed modifications. Furthermore, slope height exhibited an exponential relationship with FS (ρ = -0.42), while slope width demonstrated a linear relationship (ρ = 0.49), showing their impact on slope stability. Additionally, the angle of friction (Φ) displayed a significant positive correlation (ρ = 0.80) with FS, emphasizing its influence. These findings provide crucial data to enhance landslide risk assessment and develop effective prevention strategies for safeguarding local communities.

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