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# Investigating the slope stability of three hillocks along with their geotechnical properties

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**Abstract**

Slope stability analysis is crucial in assessing the stability of slopes of hillocks, hills, dams, and earth and rock structures. Some hillocks within the Shahjalal University of Science and Technology, Sylhet, Bangladesh, may fail in critical situations. Three hillocks were selected for study in this research, named Gazi Kalu (GK), Saheed Minar (SM), and the hillock beside Bangabandhu Hall (BH). Disturbed and undisturbed samples were collected from each hillock for testing field moisture content, field density, grain size analysis, specific gravity, compaction characteristics, permeability, and shear strength parameters. Then Factor of Safety (FOS) of each hillock was analyzed by the Limit Equilibrium Method considering their existing condition, increasing surcharge load, and increasing slope angle. The FOS of GK, SM, and BH hillocks are 2.05, 2.11, and 1.84, respectively, in their existing condition. GK is vulnerable beyond the 64.2° slope angle for its surcharge of 0.355 kPa. SM hillock is vulnerable beyond a 45.3° slope angle with a current surcharge of 12.84 kPa. On the other hand, the safest slope angle of the BH hillock is 46°, close to the existing condition of 43°, making the slope the most vulnerable among the three hillocks in this study.

***Keywords:*** *Slope stability; geotechnical characterization; hillocks; Geo5; factor of safety.*

## 1 Introduction

Landslides are vital geotechnical threats, particularly vulnerable in nations with hilly terrain. The shallow slide, also known as slope failure, is one of several landslide types and is harmful not only in steeper mountainous areas but also equally damaging in minor hillocks, roadways, and earth dams (McColl, 2012). There are many hills and hillocks in Bangladesh's south-eastern and north-eastern parts. The slopes of these hills and hillocks have lasted naturally for many years and may collapse due to various reasons such as changes in the landscape, earthquakes, groundwater flows, heavy rainfall, reduction of shear strength, change in stress, and weathering (Sultana, 2020). Also, due to rapid urbanization, people settle in the hills and hillocks without following proper construction methods. Artificial activities like cutting hills, cultivation, and deforestation weaken the slope of the hills and hillocks, which leads to catastrophic failure. The soil type and strength, stratification, discontinuities, seepage of water through the slopes, groundwater level, and slope geometry are the primary elements that influence the stability of the hill slopes (Islam et al., 2015). Failure of hill slopes, especially during the rainy season, and other natural events like earthquakes caused heartrending events in Bangladesh (Ahmed, 2021). The hilly areas of Sylhet and Chittagong region of Bangladesh are vulnerable to slope failure problems. Hence, the slope of the hills and hillocks must be adequately analyzed to determine their stability before any hazardous events occur. Numerous researchers actively investigated different types of slopes using several methods. Islam and Hoque (2014) analyzed the slope of the Surma riverbank using the limit equilibrium method (LEM) and finite element method (FEM), producing a successful assessment of safety factors. Wang and Lin (2007) and McColl (2012) also used the LEM and FEM to research different sloping conditions regarding the geological location and formation. Cai and Ugai (2003) compared the FEM and LEM for slope stability analysis and demonstrated that LEM analysis gives a similar safety factor in simple cases. In the case of simple geometries, where complex material responses are not expected or data is limited, it is necessary to make an initial stability estimate before undertaking a more complex analysis, and the analysis may better be undertaken in LEM software such as GEO5. Shahjalal University of Science and Technology (SUST) is not only renowned for its educational expertise but also renowned for its unparalleled natural beauty. There are many hillocks at the SUST Campus, such as the hillock on which Shaheed Minar (SM) was built, the hillock beside Bangabandhu Hall (BH), and the most attractive and larger one is Gazi Kalu (GK) hillock. This study analyzed these three hillocks' existing soil conditions, slope angle, and surcharge load by the LEM. GEO5 software was used to investigate the factor of safety in different slope angles and surcharge conditions. This analysis demonstrates the present condition of these hillocks and provides information for future construction possibilities and feasibility.

## 2 Methods and Materials

### 2.1 Sample collection

The disturbed and undisturbed soil samples from the hillock of Shaheed Minar (SM), Gazi Kalu (GK), and Bangabandhu Hall (BH) have been collected for testing geotechnical properties. In situ moisture content and field density at selected locations of the hillocks were carried out. Samples were transported to the laboratory and stored following standard procedure for detailed geotechnical analysis.

### 2.2 Test methods for geotechnical characterization

According to ASTM 1556 (2000), the test procedure was employed to examine the field density of soil using the sand cone method. Sieve analyses were conducted to determine the distribution of the larger-sized coarser particles following ASTM D6913 (2009). After analyzing the percentage of gravel, sand, silt, and clay particles, the soil sample of all hillocks was classified according to USDA-Soil Survey Staff (1999). Laboratory compaction tests were carried out to establish a relationship between the moisture content and the dry density of soil for a stated compaction effort according to ASTM D698 (2007). Then, soil samples were taken for permeability test using the constant head method ASTM D2434 (2000). A direct shear apparatus was employed to examine the cohesion values and angle of internal friction following ASTM D3080 (2011). A linear Mohr-Coulomb failure envelope can be obtained from the shear stress vs. normal stress plot, and the angle of internal friction of the samples, $\phi$, and cohesion, c, were determined.

### 2.2 Software analysis for slope stability determination

Since the 1930s, the LEM has successfully been used to analyze slopes. The LEM methods for investigating the equilibrium of soil mass tend to slide down under the effect of gravitational force (Cheng et al., 2007). Transitional or rotational movement is used on anticipated or established potential slip surfaces under the geomaterial. Currently, most analyses involve LEM analysis, the more straightforward approach to analyzing slope stability and give satisfactory accuracy (Kalatehjari & Ali, 2013). The application of the limit equilibrium method was done in this study using Geo5 software. The limit equilibrium method includes the analysis of Bishop, Spencer, Morgenstern-Price, and Fellenius/Petterson.

## 3 Results and Discussion

### 3.1 Geotechnical properties

The field densities of the soil sample from GK, SM, and BH hillocks were 1.48 gm/cm$^3$, 1.39 gm/cm$^3$, and 1.43 gm/cm$^3$, respectively. The test results show that the average moisture content of the soil samples from GK, SM, and BH hillocks were 19.3%, 10.54%, and 6.14%, respectively. The average specific gravities of the soil samples from GK, SM, and BH hillocks were 2.74, 2.65, and 2.68, respectively. Among the soil samples from three hillocks, the GK showed the highest specific gravity, and the soil sample from SM had the lowest specific gravity, as described in Table 1. Figure 1 describes the grain size distribution graph of the soil samples from GK, SM, and BH hillocks. The soil sample of the GK hillock contained 8.57% of clay, 81.93% of silt, and 9.5% of sand, the SM hillock sample comprised 0.55% of clay, 9.85% of silt, and 89.6% of sand, and the sample of the BH hillock is 55.3% of clay, 19.8% of silt, and 24.9% of sand, and classified according to USDA-Soil Survey Staff (1999) based on the grain size distribution. The dry density of different soil samples in different water content obtained in the compaction test is shown in Figure 3. The maximum dry density of the GK is 1.65 gm/cm$^3$ with an optimum moisture content of 19.8%, whereas the sample from the hillock of SM gives a greater MDD value of 1.89 gm/cm$^3$ and a lower OMC value of 10.62%. The sample from the hillock of BH has a MDD of 1.67 gm/cm$^3$ with an OMC of 18.14%, as described in Table 1.

Table 1. Geotechnical properties of soil.

| **Index Properties** | **GK** | **SM** | **BH** |
|---|---|---|---|
| Field density (gm/cm³) | 1.48 | 1.39 | 1.43 |
| Moisture content (%) | 19.3 | 10.54 | 6.12 |
| Specific gravity | 2.74 | 2.65 | 2.68 |
| Optimum moisture content (%) | 19.8 | 10.62 | 18.14 |
| Maximum dry density (gm/cm³) | 1.65 | 1.89 | 1.67 |
| Unit weight (kN/m³) | 16.48 | 13.64 | 14.03 |
| Angle of friction, $\varphi'$ | 20° | 57.3° | 19.6° |
| Cohesion (kN/m²) | 47 | 0 | 52 |
| Slope angle, $\beta$ | 40.1° | 36.4° | 43° |
| Height (m) | 16 | 11.58 | 14.7 |
| Coefficient of permeability, $k$ (m/sec) | $1.58 \times 10^{-7}$ | $5.60 \times 10^{-7}$ | $9.90 \times 10^{-8}$ |
| Soil type | silt | sand | clay |

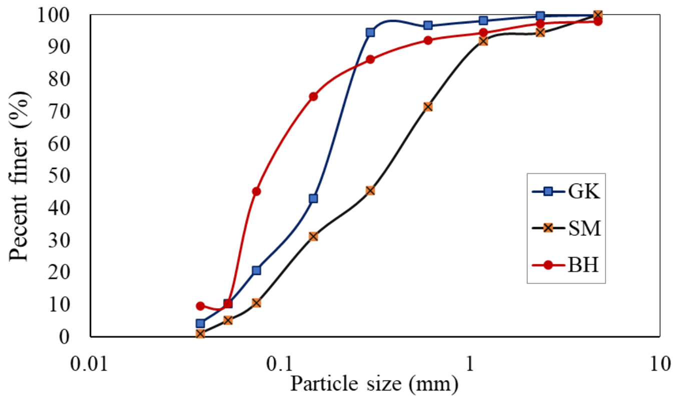
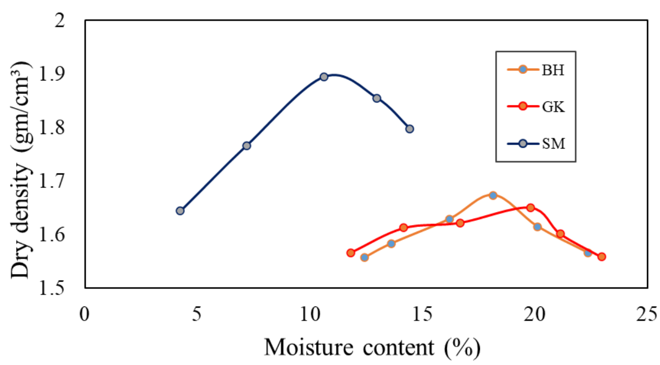



Figure 1. Grain size analysis of soil samples from the hillocks.

Figure 2. Compaction test results for soil samples from different hillocks.

Again, the sample from the hillock of SM gave the lowest OMC of 10.62%, while the sample of the GK hillock contained the maximum OMC of 19.8%. The average values of coefficient of permeability, $k$, for the samples from GK, SM, and BH hillocks are $1.58 \times 10^{-7}$ m/sec, $5.60 \times 10^{-7}$ m/sec, and $9.90 \times 10^{-8}$ m/sec, respectively. As described in Figure 4, the soil sample of SM is mostly previous, having the highest $k$ value, and the soil sample of BH is mostly impervious, while the clayey silt soil sample from hillock GK stays in the middle among the three soil samples. The lower seepage rate of water during heavy rainfall can be dangerous for the slope containing clay soil because of the development of high excess pore water pressure on the soil (Okamoto et al., 2018). In comparison, sandy soil with a higher permeability value infiltrates most of the water and results in less pore water pressure, which ensures a greater slope safety factor during rainfall or oversaturated conditions. From the plot of Figure 4, the cohesion for the soil sample of the hillocks GK, SM, and BH was 47 kN/m², 0 kN/m², and 52 kN/m², respectively. The angle of friction for the soil samples of GK, SM, and BH hillocks was



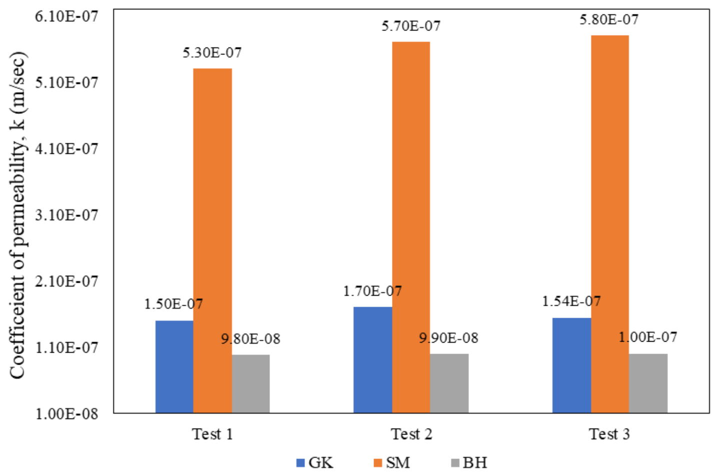



Figure 3. Permeability of soil samples from different hillocks.

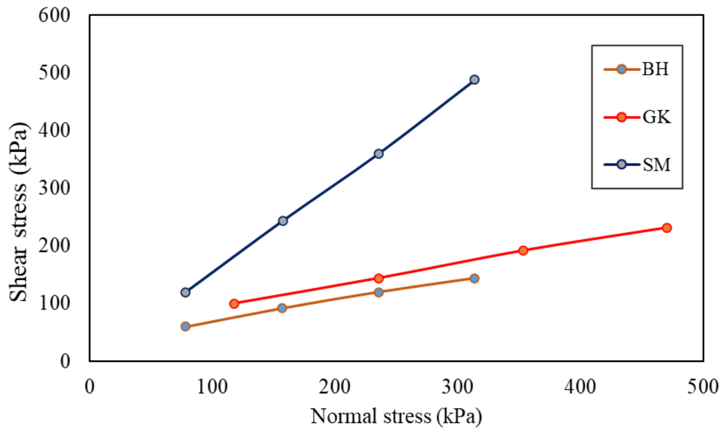



Figure 4. Direct shear test results on soil samples from different hillocks.

found as 20°, 57.3°, and 19.6°, respectively. The friction angle contributes to the slope's stability in a large way; the more friction a soil sample has, the slope becomes more stable. On the other hand, the clay soil's cohesion lessens the slope's stability (Chen et al., 2021). Based on the shear strength parameter of the soil sample from three hillocks, the BH hick is more vulnerable due to the cohesion being the most and the friction angle being the least, and with a 20° angle of friction, GK is almost the closest to BH. While the hillock SM has a maximum friction angle of 57.3° and a minimum cohesion of 0 $kN/m^{2,}$ making the slope more stable against loading (Chen et al., 2021).

### 3.3 Existing slope geometry

The existing slope geometry of three hillocks is described in Table 1. The average slope angle, $\beta$ of GK hillock, was 40.1°, while the height was 16 m. The SM hillock has a slope angle of 36.4° with a height of 11.58 m, while the hillock of BH has a slope angle of 43° with a height of 14.7 m.

### 3.4 Effects of the existing slope with surcharge

Based on the existing geometry of every hillock, the obtained critical slip surface and factor of safety from **various** reasons responsible for slope failure are shown in Figure 5. While software analysis shows the critical slip surface for the hillocks GK and BH in a curved or larger region, the SM hillock shows a slip surface almost adjacent to the existing slope (Figure 5). The existing surcharge and slope angle allow the SM hillock to be in a stable condition; hence, the SM hillock's failure surface is not wider compared to the hillocks GK and BH in Geo5 slope stability analysis. For the hillock GK, the existing surcharge of 0.355 $kN/m^2$ and slope angle of 40.1°, the factor of safety is 2.05. From the model, it is predicted that it is safe up to a slope angle of 64.2° for

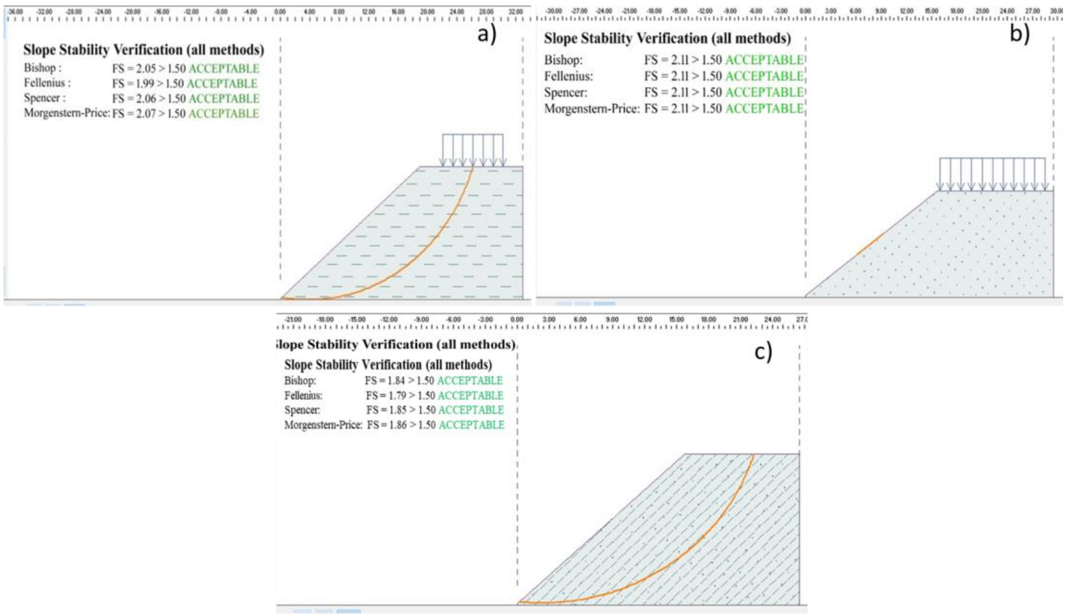



Figure 5. Slope stability analysis by Geo5 for different hillocks, a) GK, b) SM, c) BH.

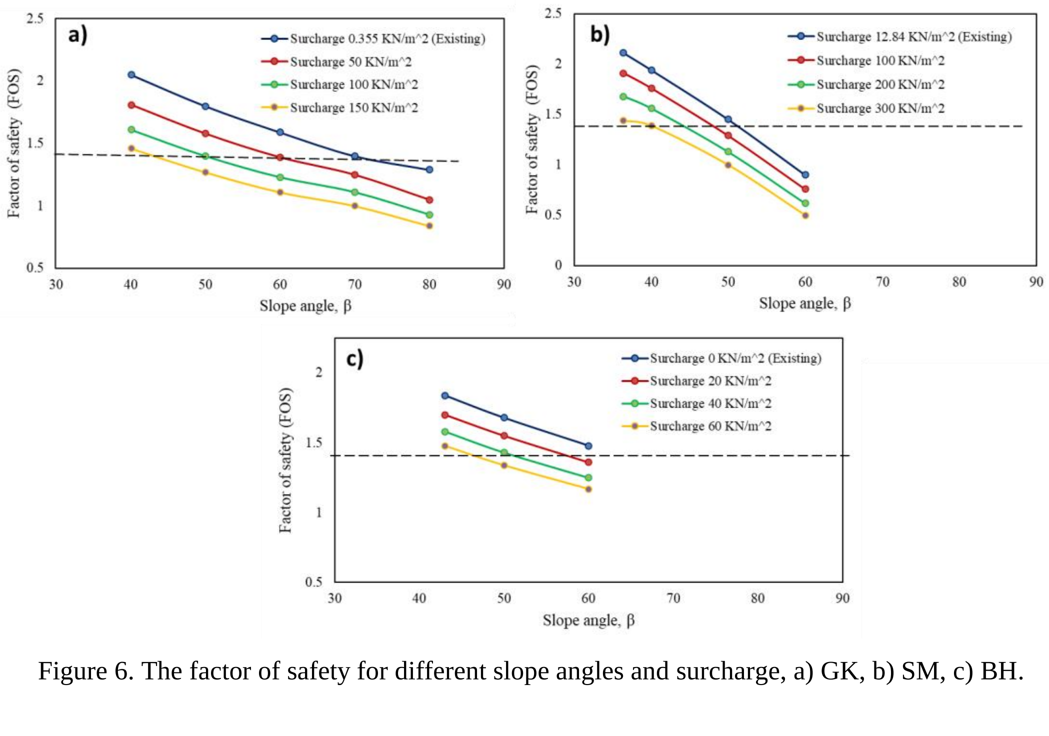



Figure 6. The factor of safety for different slope angles and surcharge, a) GK, b) SM, c) BH.

the existing surcharge (0.355 kN/m²) (Figure 6). Again, the factor of safety of the slope GK reduces with the increase in surcharge and goes below 1.5 for a surcharge of 150 kN/m² with the existing slope angle; GK is safe to carry up to 140 $kN/m^2$ with the existing slope angle. Figure 6(b) indicates the existing surcharge of the hillock SM is about 12.84 kN/m² and a slope angle of 36.4°, a factor of safety is found as 2.11. The factor of safety reduces with an increase in slope angle with the existing surcharge of 12.84 kN/m² and stays at 1.5 for a 49° slope angle. It can safely carry a surcharge of 100 kN/m² at a 45.6° slope angle and a 200 kN/m² surcharge at a 41° slope angle. The factor of safety never reaches 1.5 for a surcharge of up to 275 kN/m² but may fail for the surcharge beyond 275 $kN/m^2$ with the existing slope angle of 36.4°. Figure 6(c) describes the hillock BH for the existing slope angle of 43°; the factor of safety is 1.84 with no surcharge. The slope is safe up to 59° slope angle without applying any surcharge. On the other hand, the slope is safe up to a slope angle of 52.5° with a surcharge of 20 kN/m² and up to a slope angle of 46.5° with 40 kN/m². The BH hillock is unstable on its existing slope at an applied surcharge of 75 kN/m² or more. Cutting the slope will increase the slope angle; hence, the slope of the hillock will be failure prone. According to the stability analysis of the slopes for different hillocks in Geo5, the hillock BH is most vulnerable at its existing and under an additional surcharge. Again, being classified as clayey soil, the soil of BH hillock has a lower permeability, infiltration rate, lower angle of friction, and greater cohesion value. In comparison, the hillock of SM stays in a less vulnerable condition and is predicted to be stable even with a greater slope angle and additional surcharge. The slope of SM is also the safest because of significant permeability, angle of friction, and less cohesion which will generate low excess pore water pressure and ensures more stability under different conditions (Okamoto et al., 2018).

## 4 Conclusion

The factor of safety and critical slope surface for each hillock were determined by Geo5 software for their existing geometric condition and for a change in slope angle and increasing surcharge. According to the findings from this study, the following conclusions can be drawn:

- GK is vulnerable beyond a slope angle of 64.2° at its existing surcharge of 0.355 kN/m². With the existing slope angle, GK can safely uphold up to approximately 140 kN/m² surcharge load.
- SM is the most stable slope. However, it is vulnerable beyond a slope angle of 49° at the existing surcharge of approximately 12.84 kN/m².
- BH is the most vulnerable slope and has less FOS among the hillocks, even without any additional surcharge. It can carry up to 40 kN/m² surcharges at its slope angle of 43°.
- The laboratory test results of permeability, angle of friction, and cohesion support the analysis of Geo5 software.

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