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Landslide Susceptibility Analysis of Geological Formations: A Case Study of the Dupi Tila Formation in the Rangamati Area

Shakhawat Hossain[1], Mahmud Al Noor Tushar[1*], Shariful Islam[1], Md. Zayed Abdur Razzak[1], Sushmita Hossain[2] and Mohammad Rajib[3]

[1]Department of Geology, University of Dhaka, Dhaka 1000, Bangladesh
[2] Chemistry Division, Atomic Energy Centre, Bangladesh Atomic Energy Commission, Dhaka 1000, Bangladesh
[3] Institute of Nuclear Minerals, Atomic Energy Research Establishment, Bangladesh Atomic Energy Commission, Ganakbari, Savar, Dhaka 1349

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ABSTRACT: This study investigates the landslide susceptibility of the Dupi Tila Formation by analyzing geological parameters such as lithology, clay mineralogy, rock weathering, and structural features. The Dupi Tila Formation comprises poorly consolidated sandstone and shale layers. The percentage of mudrocks in this formation is about 32-38%. X-ray diffraction (XRD) analysis identified illite, chlorite, smectite, and kaolinite as the major clay minerals present in the formation. The qualitative analysis of the degree of weathering in outcrops shows a high degree of weathering indicated by the disintegration of grains and the presence of chemically altered minerals. Chemical Index of Alteration (CIA), Modified Potential Weathering Index (MPWI), and Kornberg Weathering Index (A) computed from the major oxide concentration of Dupi Tila Formation suggest that the weathering potential of this formation is high. The formation contains closely spaced bedding planes and two crisscrossing joints that can act as planes of weakness. Landslides can be triggered by the repeated widening of these planes of weakness caused by the saturation of clay minerals during periods of heavy rainfall. The comparable sizes of the fallen rock blocks and the joint spacings imply that structural features have played a role in landslide occurrences. Rockfall, topple, and translational slides are the major landslide types in the formation. While the position of the formation in the flank of the anticline makes the slope unfavorable for landslide occurrences, intense rainfall, and slope modification can make it susceptible to landslides. The results of this study demonstrate the significant impact of geological factors on landslide occurrences. Thus, a detailed geological analysis should be integrated into the landslide susceptibility analysis workflow to accurately identify and delineate at-risk areas.

Keywords: Landslide susceptibility; Dupi Tila Formation; Clay minerals; Weathering

INTRODUCTION

Bangladesh is located at the junction of the Eurasian Plate, the Indian Plate, and the Burmese Plate (Hossain et al., 2020). The tectonic setting and location of Bangladesh often result in natural disasters like earthquakes, landslides, severe flooding, and riverbank erosion. These, along with low economic growth and a population density above the world average, are significant obstacles to the development of Bangladesh. Among the disasters, the landslide is getting much attention nowadays due to its frequent occurrences and significant adverse impacts on lives and the economy; in the last 20 years, landslides caused at least 300 deaths and a consequential financial loss of 1.17 billion USD (Sultana, 2020).

The Chattogram Hill Tracts have experienced the highest number of landslides over the years. This region includes Bandarban, Rangamati, and Khagrachari districts. The average elevation of hills in this area is between 600 and 900 meters above mean sea level, and their amplitude decreases toward the west. Most rock types in these areas are unconsolidated to moderately consolidated sedimentary rocks, such as shale, siltstone, sandstone, and conglomerate (Khan et al., 2012). There have been several studies on landslide occurrences in the Bengal basin (Ahmed, 2021; Sarker and Rashid, 2013; Mahmood and Khan, 2010). Most of the studies aimed at understanding the landslide mechanisms and processes at specific sites using a remote sensing approach and then characterizing the landslide susceptibility of areas based on chosen parameters (Ahmed, 2021; Sarker and Rashid, 2013; Mahmood and Khan, 2010; Mutizwa-Mangiza et al., 2011; Mia et al., 2016). They identified heavy rainfall, hill cutting, unconsolidated

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Corresponding author: Mahmud Al Noor Tushar
Email: mant@du.ac.bd

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rock formation, and steeper slopes as the main causative factors of landslide occurrences. These are the most common causes of landslides all over the world. Other factors like clay mineralogy, degree of rock weathering, and planes of weakness also play critical roles in landslide occurrences. However, almost all the studies overlooked these key geological parameters (e.g., clay mineralogy, rock weathering), and the landslide susceptibility map did not include the extent of Tertiary Formations. Hence, the resultant susceptibility map needs to be more accurate.

All the rock units exposed in the hilly areas are divided into different geological formations. They have definite distribution patterns, distinct lithologies, clay mineral types, weathering potential, and structural features. Identifying and mapping these formations in the field is essential to delineate the rock units of similar characteristics. Certain conditions such as weak lithology, higher clay percentage, high degree of weathering, and planes of weakness make a formation more vulnerable than others. Thus, preparing a detailed geological map with formation boundaries and their key characteristics should be the first step for landslide susceptibility studies. Then a holistic approach should be taken considering all the external factors such as rainfall, hill cutting, and deforestation for a comprehensive mapping of landslide susceptibility.

This research aims at identifying and estimating the key geological parameters such as lithology, clay mineralogy, rock weathering, and planes of weakness of Dupi Tila Formation in the Rangamati area and then evaluate their impact on landslide susceptibility of this formation combined with other external factors responsible for landslide occurrences. The rationale for choosing Dupi Tila Formation is mainly because significant infrastructures in the Rangamati area are built on this formation.

METHODOLOGY

Study Area

Rangamati is located in the southeastern part of Bangladesh (Fig. 1). It is one of the three hill tract districts (BBS, 2013). Rangamati is bordered in the north by the Indian state Tripura, in the south by Bandarban, in the east by the Indian state Mizoram and the Chin state of Myanmar, and in the west by Khagrachhari and Chittagong districts (BBS, 2013). Hills and valleys characterize the geography of the region. They were formed when the Indian plate was subducted beneath the Burmese plate in the east (Curray et al., 1982). Due to its proximity to the collision zone, the hills are higher in magnitude, and the amplitude of folds decreases to the west (Khan et al., 2017). On the eastern flank of the Rangamati Anticline, the Dupi Tila Formation is of particular interest because of the widespread infrastructure and settlements found there.

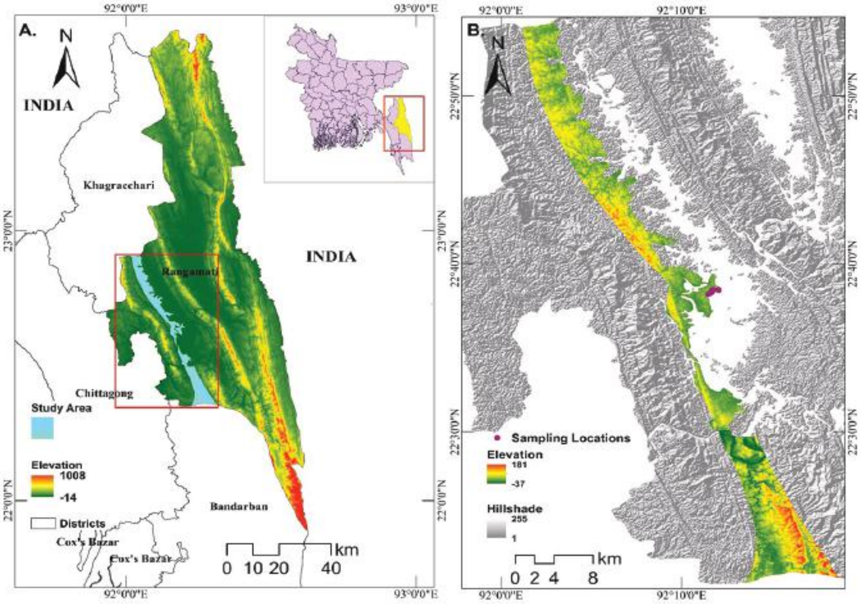

Figure 1: (A) Elevation Map of the Rangamati area Showing the Extent of the Study Area and (B) Slope Map of the Study Area with the Sampling Locations

Fieldwork and Laboratory Analysis

The study involved both fieldwork and laboratory analysis. Activities included sample collection, field measurements, sample preparation, and laboratory analysis (Fig. 2). A detailed Dupi Tila Formation geological study was carried out in the Rangamati Area. The main objective of the field investigation was to collect representative samples and take *in situ* field measurements of some key geological parameters, such as lithological characterization of the studied rock units, their attitude, the orientation of structural features like joints, attitude of the joint plane, type and degree of slope, relation between slope and bedding dip, etc. A total of 22 samples were collected by hand auger from outcrops and weathered zones of the Dupi Tila Formation of Rangamati Sadar Upazila. After that, the samples were prepared for laboratory analysis by removing unwanted fractions, drying, heating, etc. After the primary processing, the clay potions were separated from samples through sieving for XRD and XRF analysis to depict the clay mineralogy and major oxide concentrations of the studied rock units, respectively. For XRD analysis, the samples were prepared by following the guidelines of USGS, and the final analysis was performed under the existing instrumental setup of the Center for Advanced Research in Sciences (CARS), University of Dhaka, Bangladesh. The clay minerals were recognized by the presence or absence of peaks at specific 2 thetas (θ) values as per Hillier (2003). The semi-quantitative estimation of the clay minerals was made after Schultz (1964). XRF analysis of the powdered samples has been performed under the existing instrumental setup of the Atomic Energy Center, Shahbag, Dhaka, Bangladesh. Major oxide concentration data from XRF have been used to compute different geochemical indices by applying scientifically proven equations to evaluate the degree of weathering in the tertiary formations. The equations are as follows:

a) Chemical Index of Alteration (CIA) using the following equation. It would be better if the citation was placed before the equations.

$$CIA = [Al_2O_3 / (Al_2O_3 + CaO + K_2O)] \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

(Nesbitt and Young, 1982)

b) Modified Potential Weathering Index (MPWI)

$$MPWI = [(Na_2O + K_2O + CaO + MgO)/(Na_2O + K_2O + CaO + MgO + SiO2 + Al_2O_3 + Na_2O + CaO)] \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

(Vogel, 1975)

c) Kornberg weathering index (A)

$$A = [(SiO2 + Na_2O + K_2O + CaO)/)/(Na_2O + K_2O + CaO + SiO2 + Al_2O_3] \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

(Nesbitt and Young, 1982)

The data from the abovementioned field and laboratory analyses have been compiled to assess the landslide susceptibility of the Dupi Tila Formation in the Rangamati area.

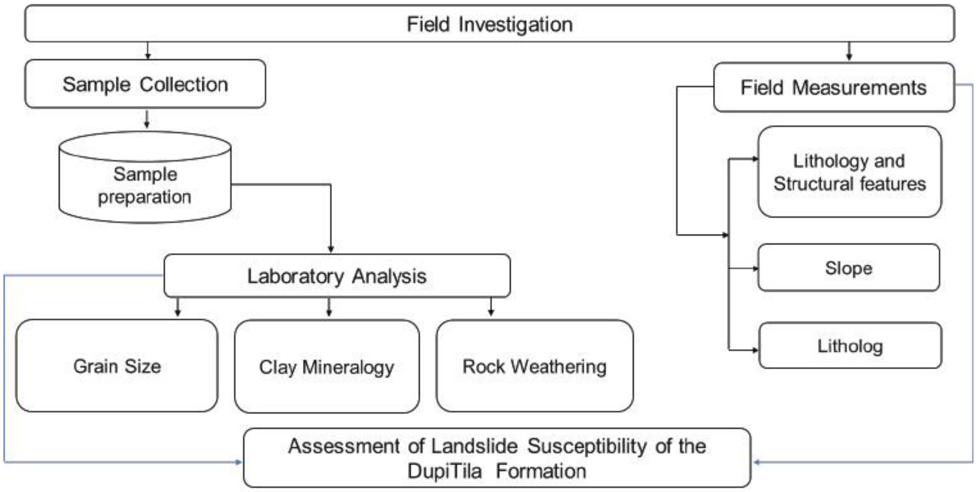

Figure 2: Flowchart of the Different Steps Performed to Evaluate the Geological Causes of Landslides in the Dupi Tila Formation

RESULT

Several geological parameters have proved their vitality in landslide occurrences in various scientific research. This research looked at some main parameters, such as lithology, clay mineralogy, rock weathering, planes of weakness, and slope.

Lithology

The study area consists of fluvial-channel and floodplain deposits (Figs. 3A & 3D). The channel deposits are generally 2–4 m thick, have erosional bases (with erosional relief of tens of centimeters), contain trough cross-bedded and flat to low-angle bedded sandstone, and are fining upward (Fig. 3B). The thickness of the trough cross bed sets is typically 50 to 100 cm. Sand grains are relatively fresh in some channel units, whereas they are deeply weathered in others. Floodplain deposits consist of mottled, yellowish-brown to grey, silty clay paleosols (Fig. 3C). Small quartz pebbles and clay galls are abundant.

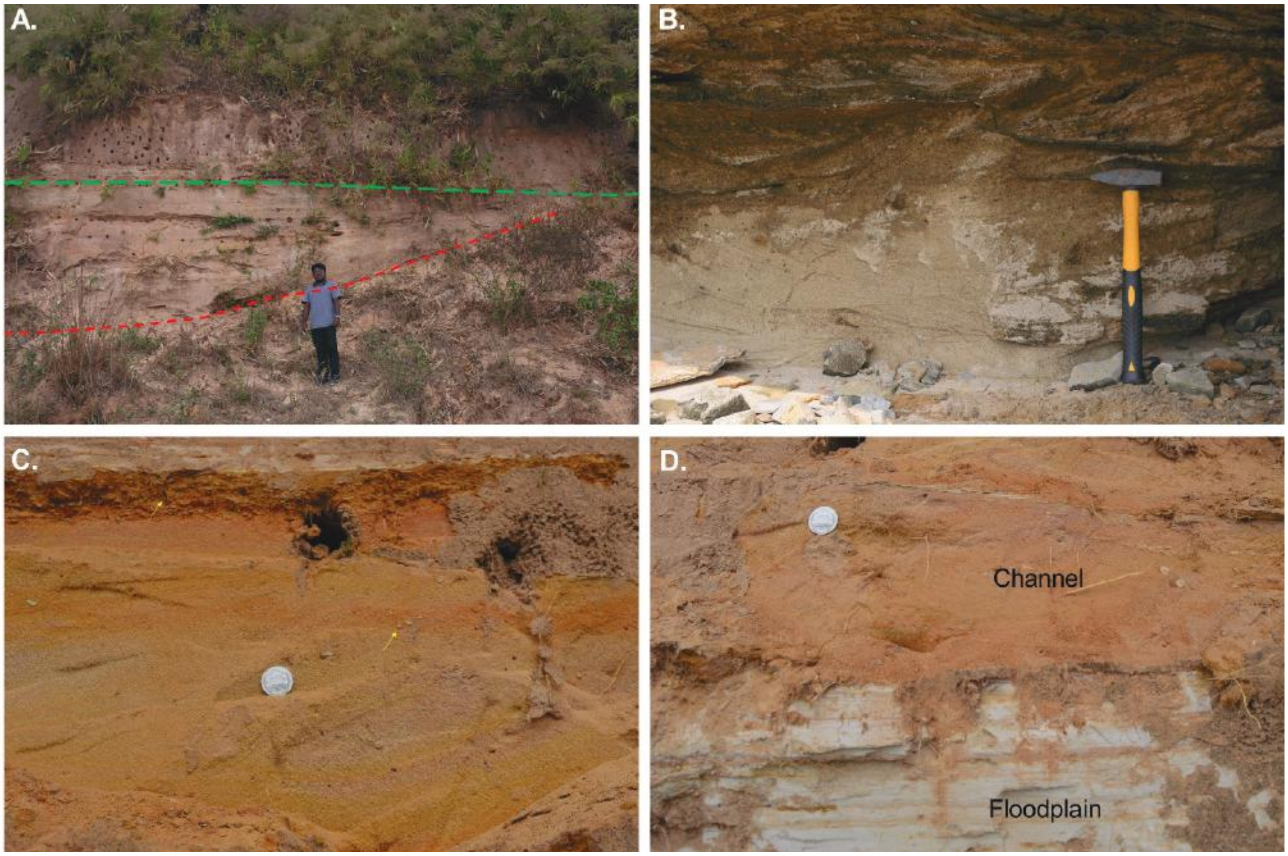

Figure 3: A) Lateral Accretion Deposits with an Erosional Channel Base (Red Dashed Line), B) Trough Cross Bedding Representing the Channel Deposits, C) Quartz Pebbles and Clay Galls (Yellow Arrow) Indicating Fluvial Channel Deposits, and D) Channel and Floodplain Facies Showing Distinct Contrast in Lithologies

Clay Mineralogy

The identification of clay minerals accurately is often difficult due to the extreme fineness of the grains, and estimating clay minerals for a geological formation is even more difficult due to the lack of suitable technology. However, the clay mineral percentage can be estimated from the percentage of mudrocks. Since clay minerals constitute about ~60% of the mudrocks (Blatt and Robert, 1996; Ferriday and Montenari, 2016), it can be concluded that formation with a higher mudrocks percentage has higher clay minerals. Based on the observations in the studied sections and published literature (Gani and Alam, 2004; Roy et al., 2012; Munim, 2017), it is found that the ratio of sandstone and mudrock facies in the Dupi Tila Formation is about 68:32 to 62:38. Therefore, it can be said that the formation has a significant amount of clay minerals (Fig. 4).

Figure 4: Litholog Constructed at Kerani Pahar Section Showing the Representative Facies Present in Dupi Tila Formation. Channel and Floodplain Deposits are the Sandstone and Mudrock Facies, Respectively

Clay-rich rocks are more susceptible to weathering and landslides, but estimates of the clay mineral percentage in rocks are not always enough; identifying the type of clay mineral is more important since some clay minerals have swelling properties.

The X-ray Diffraction (XRD) analysis of a representative sample from the Dupi Tila Formation was performed to identify the clay mineral types. The analysis shows that sediment samples from the Dupi Tila Formation are mainly composed of Quartz, Feldspar, Mica, and Clay (Fig. 5). In all the samples, quartz is dominant among the non-clay minerals. The clay minerals identified from the XRD analysis are Illite, Chlorite, Smectite, and Kaolinite.

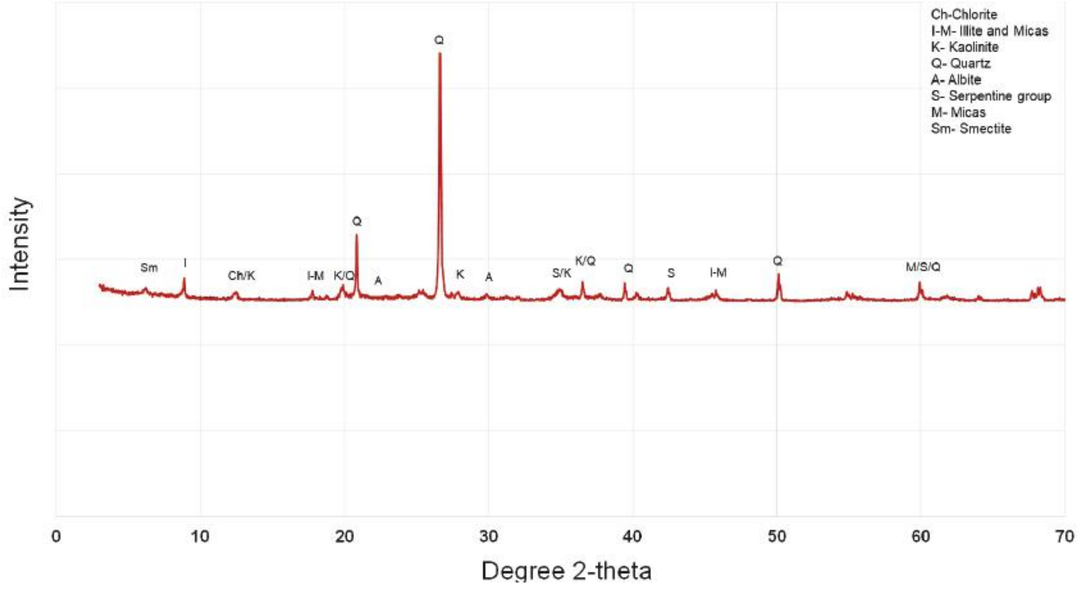

Figure 5: XRD Plot Showing the Identified Clay Minerals in Dupi Tila Formations

The percentage of the clay minerals was calculated using the empirical method developed by Schultz (1964). The calculation shows that illite is the most abundant clay mineral in the Dupi Tila Formation, followed by chlorite, smectite, and kaolinite (Table 1).

Table 1: Clay Mineral in the Dupi Tila Formation

Lithologic Unit	Clay Minerals			
	Illite	Chlorite	Smectite	Kaolinite
Dupi Tila Formation	54.76	18.90	11.68	11.00

Degree of Weathering

Qualitative Analysis

Weathering plays a significant role in landslide occurrences by reducing rock strength. Following the scale of weathering of rocks from the Geological Society of London, the studied section of Dupi Tila Formation showed moderate to high weathering as indicated by the reddish-brown to orange color of sandstone and disintegration of grains (Fig. 6). The powdery white grains are interpreted to be the weathering product of clay minerals and feldspars. A slight hammering with the geological hammers causes the exposed rocks to break and disintegrate easily, and even in some places, rocks are broken by hand. Therefore, the overall intact rock strength of Dupi Tila, according to the "simple means test of rock strength," ranges from <1.25 MPa to 50 MPa. The thick pile of weathered sediments and broken fragments cover the foot of the slope.

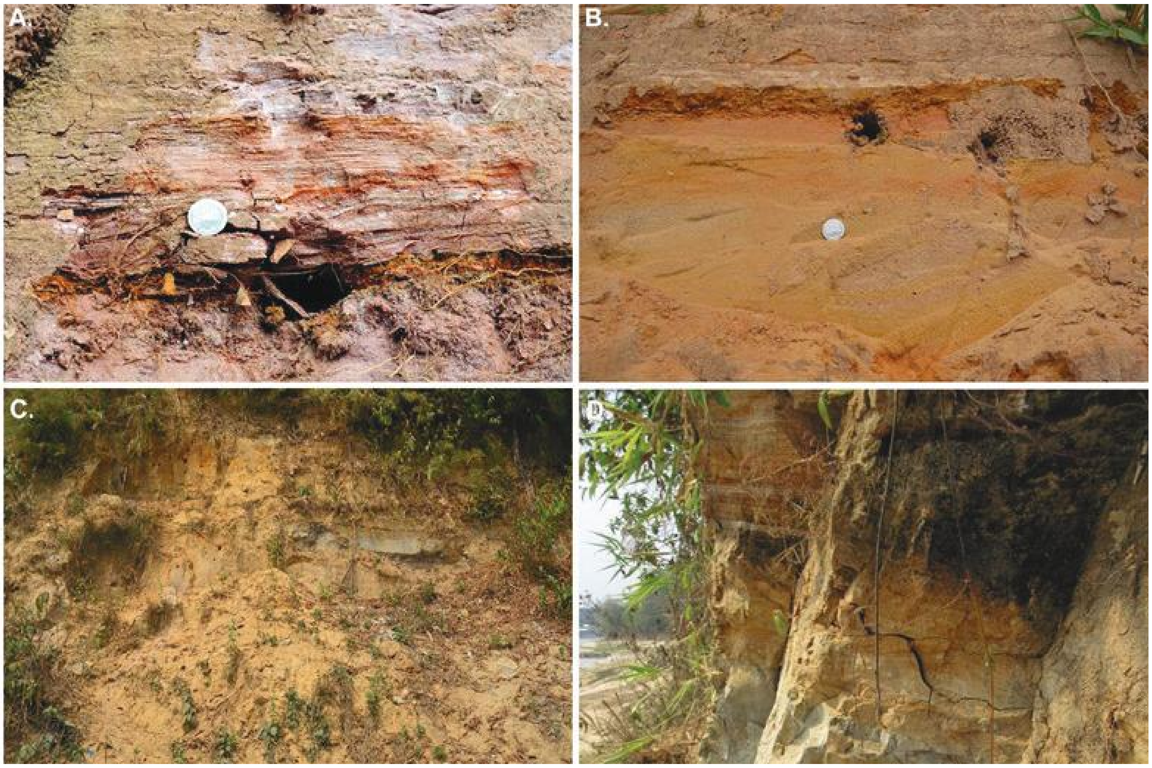

Figure 6: Roots in (A) are Suggestive of Paleosol Formation Due to Intense Weathering. Yellow and Orange Color Sandstone (B-C) Indicating Significant Weathering at Kerani Pahar near Polwel Park, Rangamati. (D) Powdery Whitish to Reddish-Brown Clay at Kerani Pahar

Quantitative Analysis

Many statistical relations in the form of geochemical indices like the Chemical Index of Alteration (CIA) (Nesbitt and Young, 1982), Modified Potential Weathering Index (MPWI) (Vogel, 1975), and Kornberg weathering index (A) (Nesbitt and Young, 1982) have been computed to investigate the degree of weathering. In the current study, all indices above have been computed using major oxide composition derived from XRF analysis of the representative samples from the studied formation.

The Dupi Tila Formation is characterized by alternating medium to fine-grained sandstone and mudstone layers. The percentage of mudrocks in this formation is around 32-36%. Table 2 shows the major oxide concentration of representative sandstone (sst) and mudstone (mst) samples from the Dupi Tila Formation.

Table 2: Major Oxide Concentration of Selected Samples from Dupi Tila Formation

	DS1	DS2	DS3	DS4	DS5	Average
Lithology	mst	mst	mst	sst	sst	
Major Oxides (wt %)						(wt %)
SiO_2	69.06	72.89	70.67	81.47	80.29	74.88
Al_2O_3	20.38	18.15	17.87	10.69	12.37	15.89
Fe_2O_3	3.76	3.105	3.615	0.45	0.9	2.37
MnO	0.02	0.02	0.02	0.01	0.01	0.02
MgO	0.14	0.245	0.19	0.235	0.27	0.22
CaO	0.86	0.15	0.58	1.57	1.37	0.91
Na_2O	0.05	0.155	0.105	2.01	2.47	0.96
K_2O	0.83	0.63	0.89	0.115	0.12	0.52
TiO_2	1.32	1.37	1.34	0.2	0.12	0.87
P_2O_5	0.035	0.035	0.035	0	0.035	0.03

On average, SiO_2 and Al_2O_3 constitute 90.78 wt% of the studied samples. SiO_2 content of the Dupi Tila formation ranges from 69.06 to 81.47 wt%, with an average value of 74.88 wt%. The average SiO_2 content is 80.88 wt% for the sand unit and 70.87 wt% for the mud unit. Al_2O_3 content of the formation ranges from 10.69 to 20.38 wt% with an average value of 15.89 wt%. The average Al_2O_3 concentration is higher in mud units (18.8 wt %) than in sand (11.53 wt %). Different weathering indices have been computed for Dupi Tila formation using the major oxide concentrations from Table 2.

Table 3: Weathering Indices for the Dupi Tila Formation

Weathering indices	DS1	DS2	DS3	DS4	DS5	Average
CIA	92.13	95.10	91.90	74.31	75.75	85.84
MPWI	1.98	1.24	1.88	4.07	4.33	2.70
A	0.78	0.80	0.80	0.89	0.87	0.83

The CIA value ranges from 74.31 to 95.10, averaging 85.84 (Table 3). The average CIA value is higher in mud units (93.04) than in sand units (75.03) of the Dupi Tila formation. The value of MPWI ranges from 1.24 to 4.33, with an average value of 2.69 (Table 3). The value of A ranges from 0.78 to 0.89, with an average value of 0.83 (Table 3).

Planes of Weakness

The plane of weakness or discontinuity surface in rock masses affects their bulk strength and causes instability against gravitational pull on a slope (Lisle and Leyshon, 2004). In geology, joints, faults, fractures, bedding planes, cleavages, etc., are considered planes of weakness. The orientation of the plane of weakness in an area has a great impact on the stability of the rock masses (Lisle and Leyshon, 2004).

In the study area, two sets of crisscross joints are present that are oriented at 230° (NE-SW) and 170° (SE-NW) (Fig. 7). The northeast-southwest trending set of joints is remarked as joint set 1, where joint planes are very steep with a dipping angle of 80° in the southeastern direction. In contrast, the southeast-northwest trending set of joints is remarked as joint set 2, where joint planes dip with the angle of 30° in the eastern direction.

Figure 7: (A) Two Sets of Crisscross Joints and (B) The Blocks of Rocks Breaking Away (Inside Blue Ellipse) Along the Joint Planes

Topographic Slope

The rock mass can be stable at any slope angle in a massive, competent state. Still, when the rock mass is subjected to jointing, fracturing, and weathering, its stability begins to reduce, and the angle of repose starts to decrease. In a disintegrated state, the maximum angle of repose for any sediment is about 45°. The higher slope value increases the risk of the downward movement of sediment and rock in that section by intense rainfall under the gravitational pull.

Within the study area, the regional slope is about 5–8° measured from satellite images (Fig. 8A). However, hill cutting and previous landslides make the slope very steep, in some cases vertical, locally. Local slopes measured in the area range from 85 to 88°, which is risky for the loosely compacted and jointed sediments of the Dupi Tila Formation (Fig. 8B).

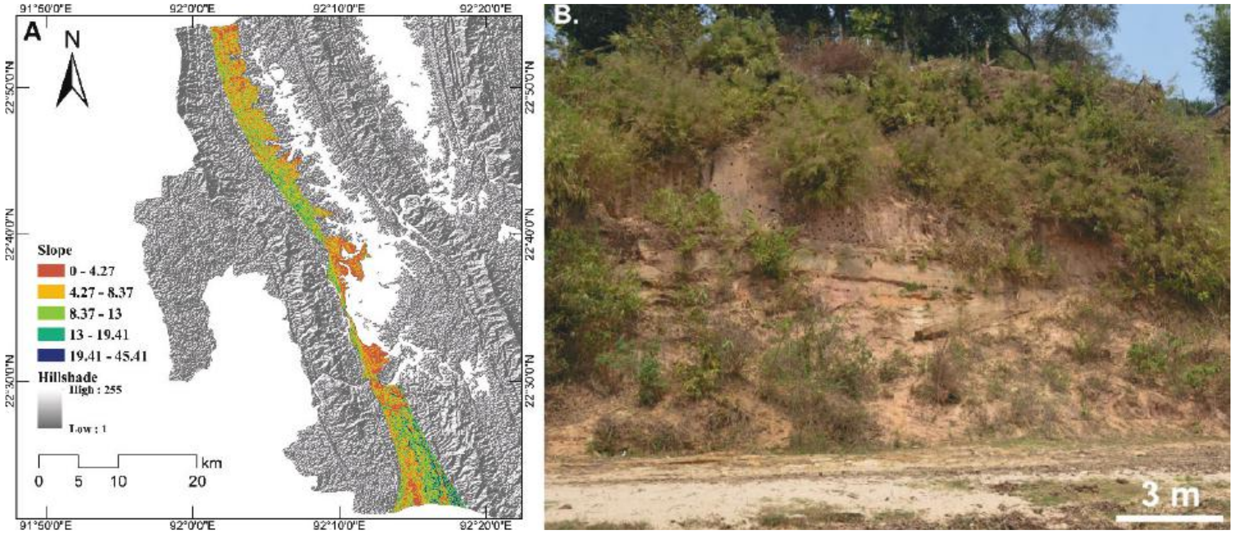

Figure 8: (A) Slope Map of the Study Area Shows the Average Regional Slope is from 5-8 Degrees. (B) Front View of a Cliff at Keranipahar Showing a Slope of Nearly 90 Degrees Formed Due to Human Intervention

DISCUSSION

The main objective of this study was to determine the landslide susceptibility of the Dupi Tila Formation based on geological parameters. For this, detailed fieldwork and laboratory analysis were performed to determine the lithology, clay mineral percentage, weathering potential, and planes of weakness in this formation.

The Dupi Tila Formation represents meandering fluvial deposits (Alam et al., 2003; Johnson and Alam, 1991). Sandstone and shale are the predominant rock types, and they occur as alternating layers in this formation (Fig. 4). Sand units are dominantly unconsolidated and argillaceous. When they get saturated with rainwater, these rocks become very weak. This formation also contains clay minerals in significant quantity. The sources of clay minerals are floodplain mud containing a large amount of clay and feldspars within formation sand that transform into clay with a wide range of compositions and structures through chemical weathering of exposed rock by the combined action of rainwater and continuous exposure to the daylight (Abbott, 2017). The identified clay minerals are illite, chlorite, smectite, and kaolinite. Among them, smectite is the most dangerous because of its swelling properties. During a rainfall event, clay minerals and sand within the formation adsorb the water through pore spaces, fractures, and joints. Clay minerals continuously change their structural conditions by absorbing, adsorbing, and removing water and other elements that cause changes in strength and weakening of the clay over a certain period of months or years (Abbott, 2017). Adsorbed water causes the spreading of clay particles apart, absorbed water causes the expansion of clay, and they lessen the strength of clay together (Abbott, 2017). After that, during heavy rainfall, a huge amount of water enters the formation through the joints, fractures, and pore spaces, creating an extra heavy weight on the already weakened rock. At the same time, the water entering through the joints exerts an outward expansion pressure on the rock blocks. As a result, the downward gravitational force exceeds the shear force, and the rock blocks start to move or fall along the slope (Brand et al., 1984; Hencher, 1987; Sharp et al., 1972).

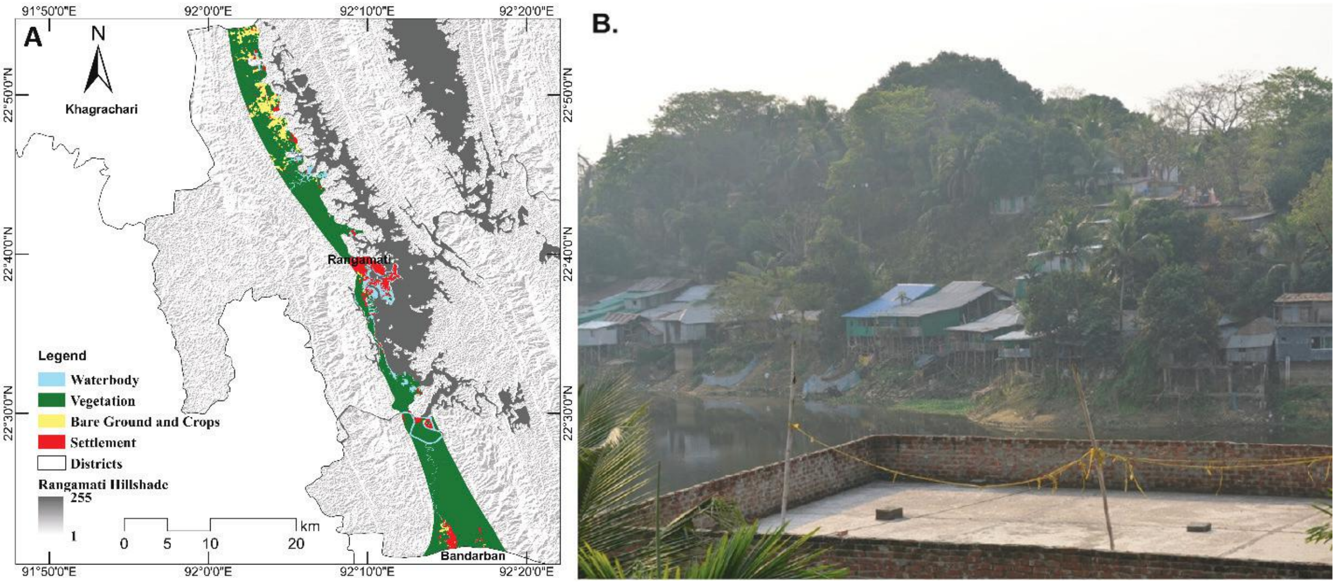

Figure 9: (A) The Landuse-Landcover (LULC) Map of the Study Area Showing the Density of Settlements in the Dupi Tila Formation and (B) The Vulnerable Structures Built on the Slope

The strength of the rock unit largely determines landslides, which in turn is related to the degree of weathering. Field observations and the high value of Al_2O_3, Chemical Index of Alteration (CIA), Modified Potential Weathering Index (MPWI), and Kornberg weathering index (A) suggest this formation is highly susceptible to weathering. The weathering of feldspar with time facilitates the Al_2O_3 enrichment, which is why Al_2O_3 is the driving factor of the above-mentioned equations. The higher the clay content, the higher the Al_2O_3, the higher the CIA, the higher the weathering potential (Rahman and Suzuki, 2007; Wei et al., 2004). The sharp contrast in average CIA values between the mudstone (93.04) and the sandstone (75.03) units of the studied formation justifies the statement. From the major oxide concentration data, it can be concluded that the unweathered sandstone unit of the Dupi Tila Formation will offer more resistance to slope failure.

The planes of weakness also play an essential role in landslide occurrences. Two sets of joints have been identified, and they are closely spaced. Joint planes can act as water seepages through which rainwater easily enters the formation and, simultaneously, as a sliding surface along which overlying rock masses can easily slide downward in response to increased gravitational force. Rainwater causes the internal weathering and erosion of rock masses and reduction of the shear strength. This weakening process takes an extended period. After that period, during an episode of heavy rainfall, a huge amount of water percolates through these joint planes. It adds extra weight to the rock mass by saturating sediments that increase the gravitational force and reduce the shear strength along these planes. At the same time, rainwater exerts an expansion force on the overlying rock masses (Brand et al., 1984; Hencher, 1987; Sharp et al., 1972). Finally, sediments start to move downward as a landslide.

Slope and geological surface orientation (e.g., the orientation of the bedding plane) relative to slope are critical factors for landslide occurrences. Although the elevation and slope angle is lower in the area, there are many landslides with short runout of the limited volume of debris in this formation. Short-runout landslides dominate the landscape with medium slopes. In sandy bodies and clayey/shale interlayers, movements ranging from slow to rapid begin on irregular, non-discrete, matrix-poor surfaces. There is no established channel for the movements, and they are not confined. The size of shallow landslides is determined using the thickness and degree of saturation of the soil in the formation. The landslides occurred through soil saturation by rainwater for a sufficient depth.

There are two types of relationships between slope and lithologic units. One is a dip-slope state, where the slope and lithologic units dip in the same direction with different dipping angles. Another is a back-slope state, where the slope and lithologic units dip in opposite directions. An angular relation between slope and lithologic units promotes landslide in the dip-slope state when lithologic units are moderate to steeply dipping but not steeper than the slope angle of the area. In this situation, bedding planes can act as sliding surfaces along which the overlying sediments can quickly move downward as a landslide. However, there is no chance of downward movement along the bedding planes in the back-slope state because of their opposite dipping direction. Therefore, in general, landslides cannot occur in a back-slope state. However, landslides can occur in the back-slope state when structural features such as joints are present. There is a relation between the slope and joints. If joint planes dip with a steep angle but not steeper than the slope angle, there is a chance of planer or wedge failure depending on the number of joint sets. When one set joint is parallel to the slope, plane failure can occur, and when two sets of joints crosscut each other and intersect the slope obliquely, wedge failure can occur (Lisle and Leyshon, 2004). In the study area, when the relationship between the regional slope and the attitude and orientation of joint sets is considered, the 5–8° regional slope (Fig. 8A) indicates joints have little role in the planer or wedge failure as the joint planes and intersection point of joint sets are steeper than the regional slope and the condition for failure is slope must be steeper than the joint planes (for planer failure) and the intersection point of joint sets (for wedge failure) (Lisle and Leyshon, 2004).

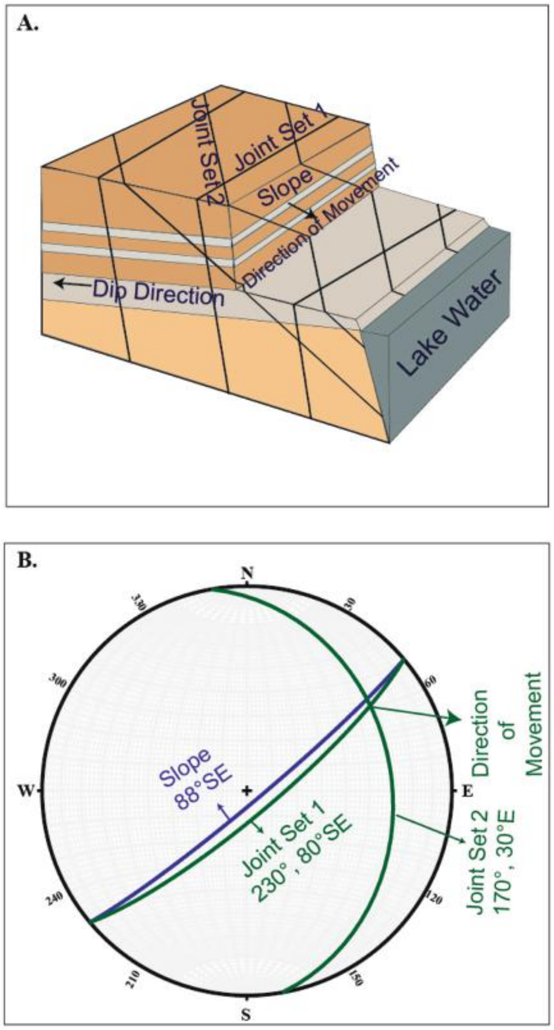

Figure 10: (A) Schematic Diagram and (B) The Stereonet Showing the Relationship Between the Bedding Plane, Joints, and Topographic Slope

When the local condition of the slope is considered, the scenario changes. Human intervention and landuse patterns modify the slopes into steeper ones (Fig. 9); as a result, the slope becomes steeper than the joint planes, and the intersection point of crosscutting joint sets (Fig. 10) and the failure initiates. Therefore, local modification of slopes intensifies the role of joints in slope failure as structural features. Both types of failure can occur, where joint set 1 (less steep than the slope) running almost parallel to the slope causes the planer failure, and the intersection point (less steep than the slope) of joint sets 1 and 2 causes the wedge failure in the sections (Fig. 10) (Lisle and Leyshon, 2004). Therefore, from a regional perspective, the slope-joint relation has little role in landslide occurrence, but from a local perspective, this relationship may play a significant role in landslide occurrence.

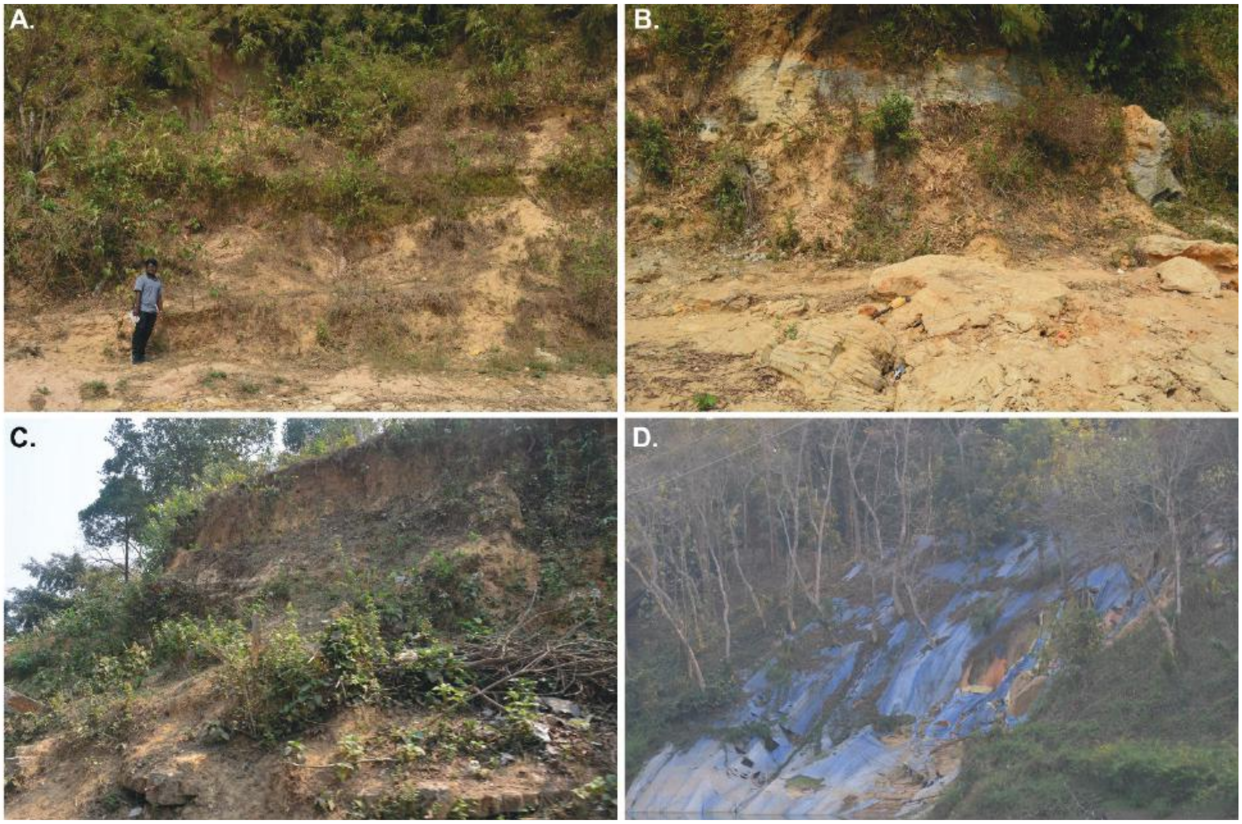

Figure 11: Different Types of Landslides Observed in the Dupi Tila Formation During Field Investigation. (A & D) Translational Slide, (B) Rockfall, and (C) Slumping are Dominant Landslide Types. Due to Relatively Dimmed Topography, the Runout Distances are also Smaller

Landslides in the Dupi Tila Formation are mostly rockfall and topple (Fig. 11). Some translational landslides are also observed (Fig. 11). In mud-dominated sections, rockfall and topple are dominant because of the blocky nature of the mud. The slide is prominent in sand-dominated sections because the water is easily absorbed through less consolidated Dupi Tila Sand. Still, when it reaches the interbedded mud units, their downward movement is interrupted, and the water is absorbed by the clay, and with time, they become weakened. Then During a heavy rainfall event, as a huge amount of water enters the formation, all water cannot be absorbed by the formation clay. As a result, the weight of the overlying sand units starts to increase, and due to the saturation of the sand, they start to lose their grain-to-grain contact and turn into slurry. Finally, when the gravitational pull exceeds the frictional force of the formation, the sand starts to move downward along the slope, even in the backslope direction, by breaking the weakened clay into small fragments. The depth of the failure depends on the equilibrium state of the slope and the extent of the weathering action.

CONCLUSIONS

The study involved detailed fieldwork and laboratory analyses to investigate the landslide susceptibility of the

Dupi Tila Formation based on geological parameters. The main geological parameters selected for landslide susceptibility analysis are lithology, clay mineralogy, rock weathering, and planes of weakness. Unconsolidated sandstone and shale layers are the main lithologies of the formation. For identifying the role of clay mineralogy, first, the exposed Dupi Tila Formation was mapped and then logged in the outcrop to estimate the mudrocks percentage of this formation. The Dupi Tila Formation contains about 32-38% of mudrock. Considering the positive correlation between mudrock percentage and clay mineral percentage, it is concluded that the formation has a significant quantity of clay minerals. The dominant clay minerals are illite, chlorite, smectite, and kaolinite. They constitute about 54.76%, 18.90%, 11.68%, and 11.00% of the clay fractions of the studied formation, respectively. The presence of smectite could lead to landslide occurrences due to its swelling properties. Field investigation and analyzing the oxides by calculating different weathering indices in the form of the Chemical Index of Alteration (CIA), Modified Potential Weathering Index (MPWI), and Kornberg Weathering Index (A) suggest this formation has high weathering potential. As weathering leads to the weakening of rocks, the rocks of this formation have a high potential to slide/fall during intense rainfall. Two crisscrossing joints have been identified in the outcrop. Along with the closely spaced bedding planes, these joints act as planes of weakness, as evidenced by blocks displaced with the orientations parallel to these joints. The clay minerals along these joints become saturated during heavy rain, causing the joint plane to widen. Repetition of this process several times might result in rockfalls and slides.

The main landslides type in the formation are rockfall, topple, and translational slides. In places, the falling mass has the same dimensions as the joint spacing, indicating that the joints are the primary cause of rockfalls. Translational slides occurred mostly in homogeneous thick sandy intervals. In the relatively fresh outcrops, the formation seems strong. Its position in the flank of the anticline makes the slope unfavorable for landslide occurrences as the hills in the anticline flank are relatively small in height. Based on this study, it is stated that the lithology, clay mineralogy, degree of weathering, and joints of the Dupi Tila Formation make this formation very susceptible to landslides. These geological parameters may initiate, accelerate, and exacerbate landslide processes during heavy rainfall and hill cutting.

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