

Slope Stability Assessment of the Aburi Mountain Road-Cut, Eastern Ghana

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ABSTRACT

Slope instability along mountainous transportation corridors presents a recurring geotechnical hazard in tropical, highly weathered terrains. This study assesses the stability of rock slopes along the Aburi Mountain road cut in the Eastern Region of Ghana using integrated engineering-geological mapping, rock mass classification, and kinematic analysis. Detailed field investigations were conducted across four slope windows, and rock mass conditions were evaluated using the Rock Mass Rating (RMR) and Mining Rock Mass Rating (MRMR) systems. Stereographic kinematic analyses were applied to evaluate the likelihood of planar, wedge, and toppling failures. RMR values range from 27 to 44, while MRMR values vary between 30 and 37, classifying the rock masses as poor. Kinematic results indicate that all mapped slopes are susceptible to structurally controlled failures, with wedge and planar modes being most critical. Groundwater seepage, intense jointing, and anthropogenic disturbance further reduce slope stability. The study highlights the urgent need for engineered stabilization and drainage measures along this critical road corridor to reduce hazards and enhance public safety.

Keywords: slope stability, rock mass rating, kinematic analysis, slopes, Aburi, Ghana

Date of Submission: 05-02-2026

Date of acceptance: 16-02-2026

I. INTRODUCTION

Slope failures along transportation corridors pose significant geotechnical and societal concerns, particularly in regions characterized by steep topography, complex structural geology, and high rainfall (Hoek & Bray, 1981; Hudson & Harrison, 1997). Excavation of natural slopes for road construction alters in situ stress conditions and exposes pre-existing discontinuities, often resulting in progressive and long-term instability (Hoek & Bray, 1981). In tropical environments, intense chemical weathering, high rainfall, and groundwater infiltration further accelerate rock mass degradation and reduce shear strength along discontinuities (Dearman et al., 1978).

In Ghana, several major highways traverse structurally complex terrain within the Akuapem-Togo Range, a belt characterized by strongly deformed and metamorphosed rocks (Kesse, 1985). The Aburi Mountain road is one such corridor, serving as a vital link between Accra and the Akuapem highlands. The road-cut slopes along this corridor have experienced repeated failures manifested as rock falls, surface cracking, and localized collapses, posing risks to commuters and adjacent infrastructure. These failures are commonly associated with unfavorable geological structures, inadequate drainage conditions, and disturbances induced by historical blasting during road construction (Hudson & Harrison, 1997).

Despite the strategic importance of the Aburi Mountain road, systematic geotechnical assessments of slope stability remain limited. This study therefore, aims to (i) characterize the engineering geological conditions of the road-cut slopes, (ii) evaluate rock mass quality using empirical classification systems, and (iii) identify dominant kinematic failure mechanisms. The outcomes are intended to support hazard mitigation and slope management strategies consistent with sustainable infrastructure development.

II. LITERATURE REVIEW

2.1 Rock Slope Failures along Transportation Corridors

Rock slope instability along highways and road-cut corridors is a well-documented geotechnical problem, particularly in mountainous regions where excavation exposes structurally controlled rock masses. Previous studies have shown that road construction alters stress regimes and creates new free faces, increasing the likelihood of planar, wedge, and toppling failures governed by discontinuity orientations (Hoek & Bray, 1981). Transportation corridors are especially vulnerable because slopes are often cut at steep angles with limited allowance for long-term weathering and groundwater effects (Hudson & Harrison, 1997).

In many developing countries, road-cut slopes are designed with minimal geotechnical input, relying largely on empirical judgment rather than systematic rock mass characterization. This practice has been linked to

recurrent slope failures, rock falls, and maintenance challenges along major highways (Wyllie & Mah, 2004). Empirical and kinematic approaches, therefore, remain essential tools for preliminary and regional-scale slope stability assessments.

2.2 Influence of Geological Structure and Discontinuities

Geological structures such as bedding, foliation, joints, and faults exert primary control on rock slope behavior. In metamorphic terrains, anisotropy introduced by foliation and schistosity strongly influences failure mechanisms, often promoting planar sliding or flexural toppling (Goodman, 1989). The orientation, spacing, persistence, and infilling of discontinuities determine whether slopes remain stable or fail under gravitational loading (Hoek & Bray, 1981). Fault zones further weaken rock masses by increasing fracture density and reducing intact rock strength. Studies in structurally complex terrains demonstrate that slopes located near major faults exhibit lower rock mass ratings and higher susceptibility to instability (Palmström & Broch, 2006). These effects are particularly pronounced where excavation intersects pre-existing shear zones.

2.3 Effects of Tropical Weathering and Water

Tropical climatic conditions significantly accelerate rock mass degradation through intense chemical weathering and cyclic wetting and drying. Weathering reduces intact rock strength and increases joint aperture and clay infilling, thereby lowering shear resistance along discontinuities (Dearman et al., 1978). In humid tropical regions, groundwater infiltration into discontinuities elevates pore water pressures and reduces effective normal stress, often triggering slope failures during or after heavy rainfall events (Wyllie & Mah, 2004). Several studies have emphasized the role of inadequate drainage in destabilizing road-cut slopes, particularly where surface runoff and seepage are not properly managed (Hudson & Harrison, 1997). The combined influence of weathering and groundwater is therefore a critical consideration in slope stability assessments in tropical environments.

The effect of water on the slope can be considered into two-fold. One is groundwater or an aquifer below the surface that generates pore water pressure, and the other is rainwater infiltration that seeps through the surface and flows along the slope, generating water pressure. It is related to the surrounding precipitation levels, topography, nearby water masses, and the geo-hydrological characteristics of the rock mass (Sjöberg, 1999).

Water can change the angle of repose. Dry unconsolidated grains will form a pile with a slope angle determined by the angle of repose. The angle of repose is the steepest angle at which a pile of unconsolidated grains remains stable and is controlled by the frictional contact between the grains. In general, for dry materials, the angle of repose increases with grain size, but usually lies between about 45 ° and 300 °. Slightly wet unconsolidated materials exhibit a very high angle of repose because surface tension between the water and the solid grains tends to hold the grains in place. When the material becomes saturated with water, the angle of repose is reduced to very small values, and the material tends to flow like a fluid. This is because the water gets between the grains and eliminates grain-to-grain frictional contact.

Slopes observed at the study area were moist to wet. At some places, water was seen dripping from the surfaces of the slopes (Figure 1). The water helps to reduce friction between the rocks, making it easier for the rocks to fail. Water in rocks also increases the weathering of rocks, and as a result, the specific gravity of the rocks is reduced, and this goes a long way to reduce the strength of the rocks.



Figure 1: Water dripping from the surface of a rock in the study area

2.4 Rock Mass Classification Systems

Rock mass classification systems provide a practical framework for quantifying rock quality and supporting engineering design decisions. The Rock Mass Rating (RMR) system developed by Bieniawski (1989) remains one of the most widely applied methods in civil and mining engineering. RMR integrates key parameters, including intact rock strength, RQD, discontinuity characteristics, groundwater conditions, and joint orientation. For excavated slopes affected by blasting and stress redistribution, the Mining Rock Mass Rating (MRMR) system offers additional refinement by incorporating adjustment factors related to weathering, induced stresses, and excavation damage (Laubscher, 1990). Numerous studies have demonstrated the usefulness of combining RMR/MRMR classification with kinematic analysis for slope stability evaluation, particularly where data availability limits advanced numerical modeling (Palmström & Broch, 2006).

2.5 Previous Studies in Ghana and Similar Terrains

Engineering geological studies in Ghana have highlighted the influence of structural complexity and weathering on slope stability within the Akuapem–Togo Range. The region is characterized by highly deformed metamorphic rocks that exhibit poor rock mass quality when exposed by excavation (Kesse, 1985). Although previous works have documented landslides and rock falls along major highways, detailed slope-scale stability assessments remain limited. This study builds on established empirical and kinematic approaches by applying them systematically to the Aburi Mountain road-cut, thereby contributing site-specific data and analysis to the growing body of slope stability research in tropical metamorphic terrains.

III. GEOLOGICAL AND ENVIRONMENTAL SETTING

3.1 Study Area

Aburi is located in the Akuapim South District of the Eastern Region of Ghana, approximately 20 km northeast of Accra (Figure 2). The area lies within the Akuapem-Togo Range and is characterized by steep relief overlooking the Accra Plains. The studied road-cut forms part of a major transportation corridor frequently used by commuters, residents, and government officials.

The Aburi area experiences a semi-equatorial tropical climate with two distinct rainy seasons, typically from April to July and September to November. Mean annual rainfall ranges between approximately 1,250 and 2,000 mm, with high rainfall intensities during peak wet periods (Dickson & Benneh, 2004). These climatic conditions promote intense chemical weathering and sustained groundwater recharge within the rock mass. Dense forest vegetation characterizes much of the Akuapem–Togo Range; however, vegetation cover along the road-cut has been significantly disturbed by construction activities and urban development. Groundwater seepage and damp zones observed along slope faces indicate active subsurface flow, which is known to reduce effective normal stress and shear strength along discontinuities in tropical rock slopes (Dearman et al., 1978; Wyllie & Mah, 2004).

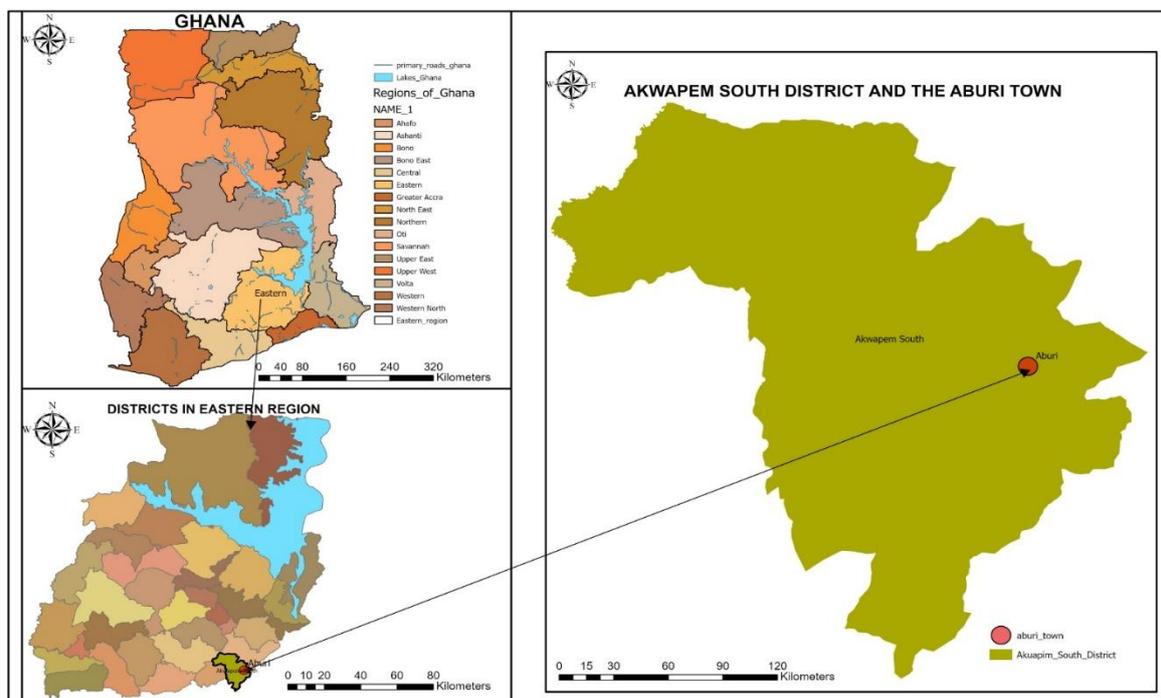


Figure 2: Map of the study area

3.2 Geology of the study area

The study area is underlain by rocks of the Togo Structural Unit, composed predominantly of metamorphosed sedimentary sequences including quartzites, phyllites, and schists (Figure 3). The Togo rocks are highly deformed sedimentary succession of alternating arenaceous and argillaceous protoliths metamorphosed into quartzites, phyllites and schists (Kesse, 1985). Regionally, these are sandwiched between gneiss-granitoid basement terrain of the Dahomeyan Supergroup to the East, and the least deformed and metamorphosed Buem structural unit to the West. Stratigraphically, the Togo Structural unit is underlain by the Dahomeyan, and overlain by the Buem. They are in contact through thrust-faulting, both to the East and the West, known as the Western and Eastern boundary faults (WBF and EBF) respectively. The west boundary fault also contacts the Birimian Cape Coast granitoid and the Voltaian sediments.

Tectonically, the area falls under the part of SE-Ghana and its off-shore area characterized by the Akwapim fault zone. This fault zone comprises a northeast–southwest running system of faults which is outlined by the Western Boundary Fault (WBF) and the Eastern Boundary Fault (EBF) as described by Ahmed et al. (1977). These lithologies have been subjected to multiple deformation phases associated with the Pan-African orogeny, resulting in intense folding, faulting, and foliation development (Kesse, 1985; Griffis et al., 2002). The area is structurally influenced by the Akuapim Fault Zone, which has contributed to high fracture density and reduced rock mass competence along the road-cut slopes (Junner, 1940; Kesse, 1985). Such structural complexity creates persistent discontinuities that predispose excavated slopes to structurally controlled failures.

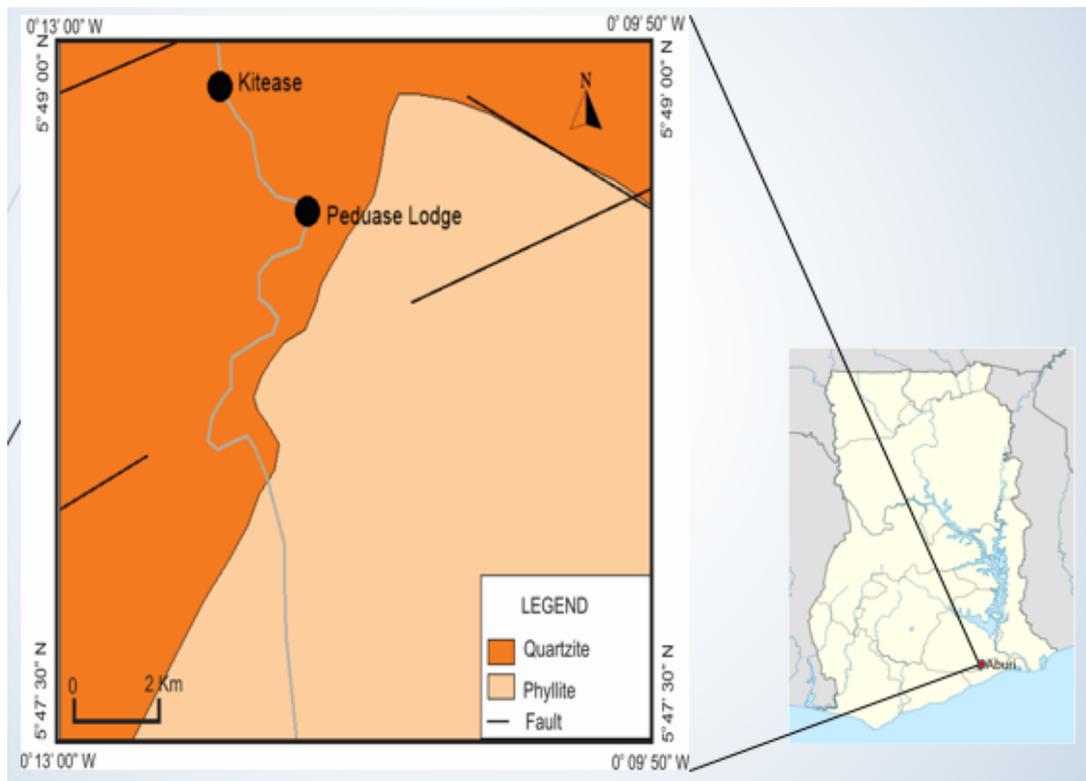


Figure 3: Geological map of the study area

IV. MATERIALS AND METHODS

4.1 Field Investigation

Detailed engineering geological mapping was conducted along the road-cut using the window mapping technique. The slope was divided into four windows, each approximately 30 m wide. Structural data—including dip and dip direction of bedding planes, joints, and faults—were collected using a prismatic compass. Additional observations included discontinuity spacing, infilling material, weathering grade, groundwater conditions, and estimates of intact rock strength.

4.2 Rock Mass Classification and Kinematic Analysis

Rock mass quality was quantified using the Rock Mass Rating (RMR) (Bieniawski, 1989) and Mining Rock Mass Rating (MRMR) systems (Laubscher, 1990). Parameters considered included intact rock strength, Rock Quality Designation (RQD), joint spacing, joint condition, groundwater conditions, and adjustment factors for blasting, weathering, joint orientation, and induced stress. Indicative Overall Slope Angles (IOSA) and bench

face angles were derived from RMR values. Kinematic stability analyses were performed using stereographic projection techniques implemented in DIPS software. Planar, wedge, and toppling failure conditions were evaluated for each window based on the orientation of discontinuities relative to slope faces, friction angles, and daylighting conditions.

The RMR and MRMR were calculated for the rocks based on the parameters that were derived from the mapping. They were calculated using the formulas:

I.

$$\text{RMR} = \text{RQD} + \text{IRS} + \text{Js} + \text{Jc}$$

II.

$$\text{MRMR} = \text{RMR} \times \text{I} \times \text{B} \times \text{O} \times \text{W}$$

Where **RMR** is **Rock Mass Rating**

I is **Induced Stress**

B is **Blasting Effect**

O is **Joint Orientation**

W is **Weathering Effect**

The indicative overall slope angle (IOSA) was determined from the calculated MRMR which is given by:

III.

$$\text{IOSA} = 0.5 (\text{MRMR}) + 30$$

IV Calculation of Bench Face Angle (BFA)

$$\tan A = 1 / [(W/H) + (1/\tan B)]$$

Where **A** is **Overall Average Slope Angle**

B is **Bench Face Angle**

H is **Vertical height of bench**

W is **Horizontal Width of bench**

V. RESULTS

5.1 Rock Mass Rating

The calculated RMR values for the mapped windows range from 27 to 44, classifying the phyllite–quartzite rock mass as poor quality. After applying adjustment factors, MRMR values range from 30 to 37. Corresponding IOSA values vary between 40° and 49°, indicating steep but marginally stable slopes under current conditions. The average RMR, MRMR, IOSA and the bench face angles for the phyllite/quartzite which is the majority rock type in the area is summarized in Table 1.

Table 1: Summary of average RMR, MRMR and IOSA values using (Laubscher, 1990)

WINDOW NUMBER	ROCK TYPE	RMR (%)	MRMR (%)	IOSA	CLASSIFICATION	BENCH FACE ANGLE
1	Phyllite/Quartzite	44	37	49	Poor Rock	62
2	Phyllite/Quartzite	35	30	40	Poor Rock	50
3	Phyllite/Quartzite	27	32	44	Poor Rock	55
4	Phyllite/Quartzite	30	35	43	Poor Rock	54

5.2 Kinematic Stability

Kinematic analyses indicate that all four windows are susceptible to multiple modes of failure. Planar failure is possible where discontinuities daylight the slope face and fall outside the friction cone (as shown in Figure 4, Figure 5, Figure 6, and Figure 7). Wedge failure is prominent in areas with intersecting joint sets, particularly in Window 4 (Figure 8, Figure 9, Figure 10, and Figure 11). Toppling failure is also likely due to steeply dipping discontinuities oriented unfavorably with respect to the slope (Figure 12, Figure 13, Figure 14, and Figure 15).

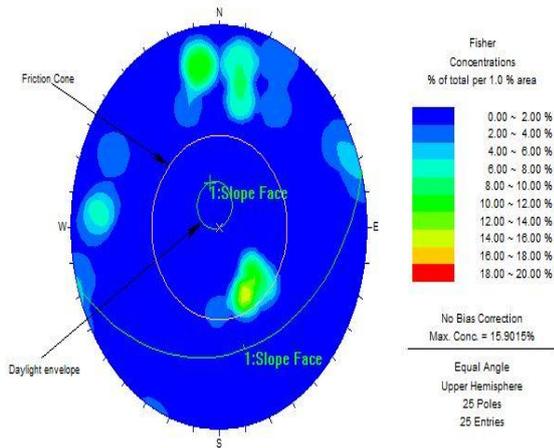


Figure 4: Planar analysis for window 1

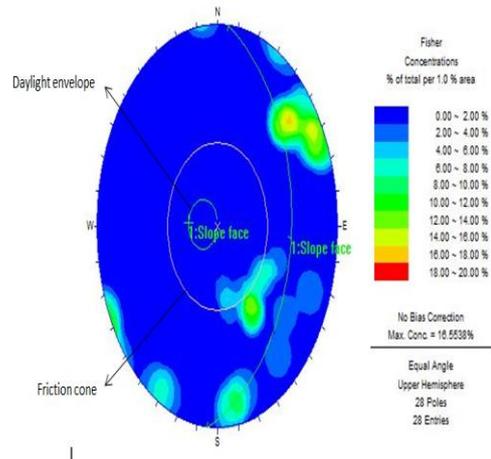


Figure 5: Planar analysis for window 2

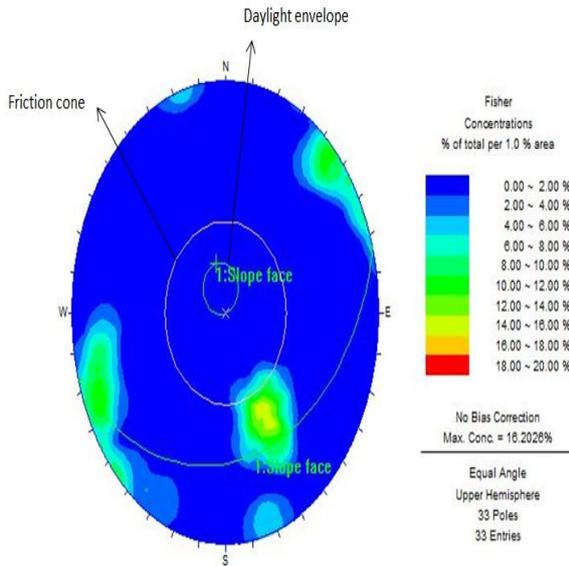


Figure 6: Planar analysis for window 3

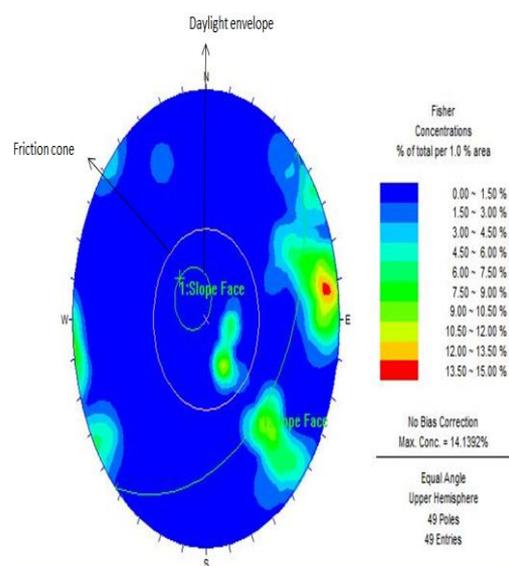


Figure 7: Planar analysis for window 4

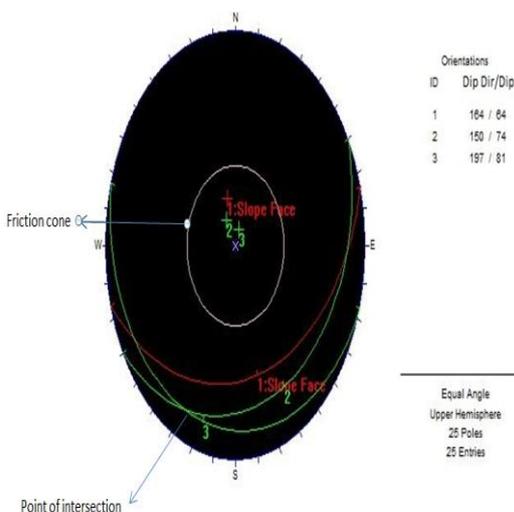


Figure 8: Wedge analysis for window 1

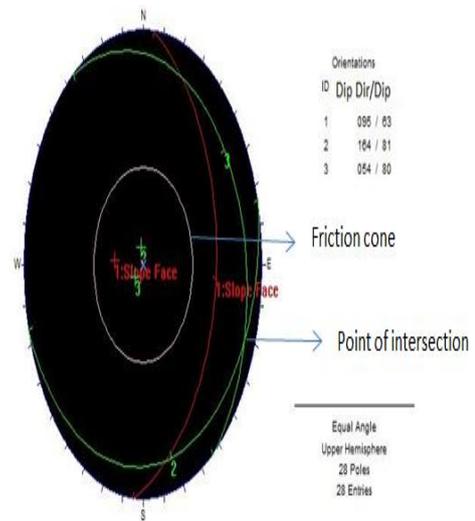


Figure 9: Wedge analysis for window 2

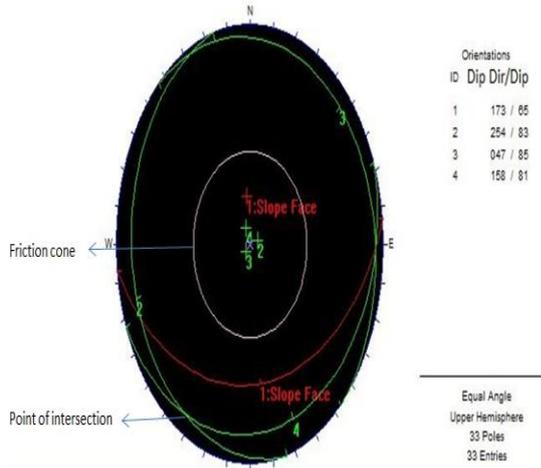


Figure 10: Wedge analysis for window 3

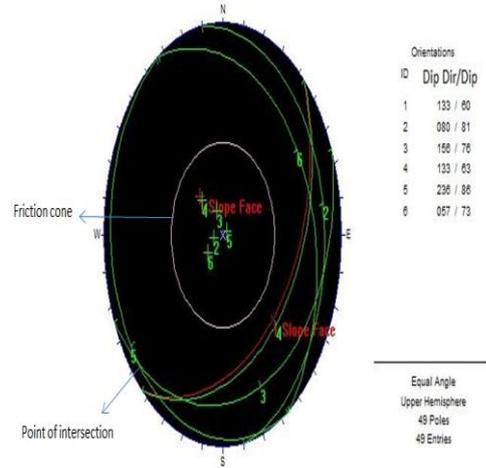


Figure 11: Wedge analysis for window 4

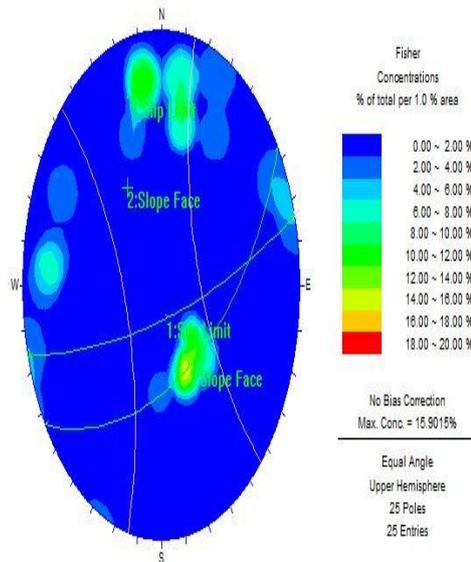


Figure 12: Toppling analysis for window 1

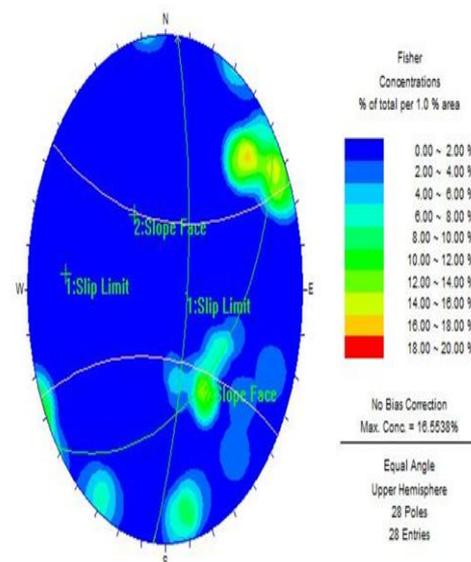


Figure 13: Toppling analysis for window 2

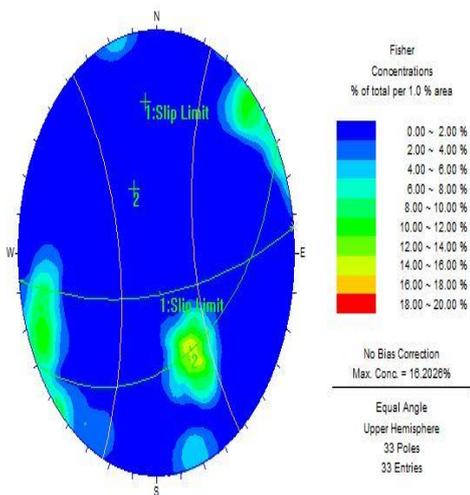


Figure 14: Toppling analysis for window 3

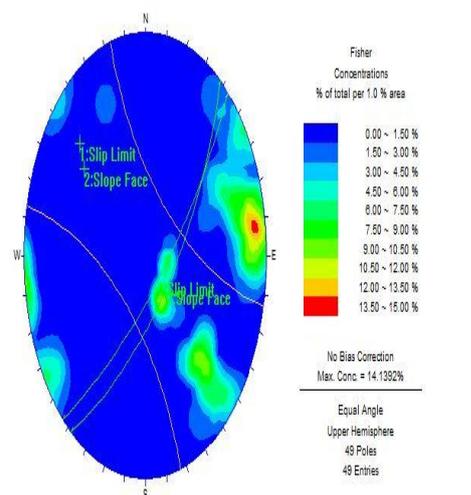


Figure 15: Toppling analysis for window 4

VI. Discussion

The stability conditions observed along the Aburi Mountain road-cut slopes are primarily controlled by poor rock mass quality and adverse structural orientations. RMR and MRMR values obtained from the study indicate generally weak to fair rock mass conditions, reflecting the combined effects of intense deformation, weathering, and excavation-induced disturbance. Similar relationships between low rock mass ratings and increased slope instability have been widely reported for excavated slopes in metamorphic terrains (Bieniawski, 1989; Palmström & Broch, 2006). The reduced MRMR values further highlight the influence of blasting damage and stress redistribution during road construction, which are known to increase discontinuity persistence and aperture, thereby decreasing slope stability (Laubscher, 1990).

Kinematic analyses reveal that planar sliding, wedge failure, and toppling constitute the dominant potential failure mechanisms along the studied road cuts. These failure modes are structurally controlled by foliation planes, joint sets, and fault-related discontinuities that daylight on the slope faces. Such structurally governed failures are characteristic of foliated metamorphic rocks and have been extensively documented in rock slope studies worldwide (Hoek & Bray, 1981; Goodman, 1989). The intersection of multiple joint sets within the influence zone of the Akuapim Fault Zone further enhances wedge formation, increasing the likelihood of instability under gravitational loading.

Tropical weathering plays a critical role in degrading the mechanical properties of the rock mass along the Aburi Mountain road. Chemical alteration of primary minerals, together with the development of clay infillings along discontinuities, reduces shear strength and promotes progressive failure mechanisms (Dearman et al., 1978). Observed groundwater seepage along slope faces suggests that pore water pressures contribute to reductions in effective normal stress, particularly during the rainy seasons. The destabilizing influence of groundwater on rock slopes in humid tropical environments is well established and is frequently implicated in rainfall-induced slope failures (Wyllie and Mah, 2004).

The combined results of rock mass classification and kinematic analysis demonstrate the importance of incorporating geological structure, weathering state, and groundwater conditions into slope design along transportation corridors. Empirical classification-based approaches, such as RMR and MRMR, when integrated with kinematic analysis, provide an effective framework for identifying unstable slope segments where advanced numerical modeling may not be feasible (Palmström & Broch, 2006). For the Aburi Mountain road, mitigation measures such as improved surface and subsurface drainage, localized scaling, rock bolting, and slope re-profiling should be prioritized in zones identified as kinematically unstable, consistent with established rock slope engineering practice (Hoek & Bray, 1981).

The findings of this study are consistent with earlier investigations of road-cut slopes in tropical and structurally complex terrains, where instability has been linked to unfavorable discontinuity orientations, intense weathering, and inadequate drainage (Hudson & Harrison, 1997; Wyllie & Mah, 2004). Within Ghana, the results corroborate regional observations that slopes developed within the Akuapem–Togo Range are particularly susceptible to structurally controlled failures once exposed by excavation (Kesse, 1985). By providing a site-specific assessment of the Aburi Mountain road, this study contributes additional empirical evidence to support improved geotechnical design and maintenance strategies for road infrastructure in similar geological settings.

VII. Conclusion

This study assessed the stability of the Aburi Mountain road-cut slopes using rock mass classification and kinematic analysis. The results indicate that the phyllite–quartzite rock masses are of poor quality (RMR 27–44; MRMR 30–37) and are structurally predisposed to planar, wedge, and toppling failures across all mapped windows. The instability is primarily controlled by unfavorable discontinuity orientations, intense weathering, and groundwater influence.

Overall, the Aburi Mountain road-cut represents a geotechnically vulnerable corridor requiring systematic slope management. The integrated application of RMR, MRMR, and kinematic analysis provides a reliable basis for identifying unstable sections and informing targeted mitigation to enhance public safety and infrastructure resilience.

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