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Kinematic and limit equilibrium analyses of rock slope along Lebuhraya Pantai Timur 1 (LPT1) from km 90 to km 149

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Abstract: Slope failure is a significant geotechnical issue observed in various regions worldwide, posing a threat to critical infrastructure, such as the Lebuh Raya Pantai Timur 1 (LPT1) highway in Malaysia, which is founded on the Semantan Formation, while the westernmost outcrop near Lanchang (km 90) consists of acidic igneous rocks. The objective of this study is to assess the stability of the rock slopes of the LPT1 highway corridor, identify the factors contributing to slope instability and recommend appropriate mitigation measures. The study involves both qualitative data, obtained through field observations and quantitative data through experimental methods, and numerical modeling techniques, including kinematic analysis and the limit equilibrium method. In the kinematic analysis, possible failure modes such as plane, wedge, and toppling failures were identified. The Limit Equilibrium Method (LEM) was employed to calculate the factor of safety (FoS) under standard conditions. The results suggest that overall the slope is generally stable; however, localized instabilities may occur due to wedge failure mechanisms. The calculated FoS values range from 0.4 to 2.2, indicating a stability range from low to high. By focusing on failure mechanisms, the impact of discontinuities, and the role of shear strength and water content, this study offers valuable insights. The findings contribute to the development of reliable remedial measures to mitigate slope failure risks and enhance the stability of other crucial infrastructures. In response to potential risks, the concessionaire of the highway has already taken proactive steps to implement stabilization measures, reinforcing the slopes to ensure their safety and mitigate failure risks moving forward.

Keywords: Slope stability, rock slope failure, Semantan Formation, LPT1 highway, kinematical analysis, Limit Equilibrium Analysis, factor of safety

INTRODUCTION

Slope failure, a prevalent geotechnical hazard, frequently occurs in areas with complex geological formations, such as the Semantan Formation along the Lebuh Raya Pantai Timur 1 (LPT1) highway. These failures often lead to landslides that obstruct traffic, damage infrastructure, and pose risks to human life. Slope geometry, discontinuities, and the shear strength of the rock mass primarily influence rock slope failures. The orientation of discontinuities, the slope's steepness, and the rock's mechanical properties all contribute to the overall stability. Discontinuities, including joints, bedding planes, and faults, act as potential failure surfaces, while the rock mass's shear strength determines the material's ability to resist sliding along these surfaces (Barton, 2006; Wyllie & Mah, 2017). In tropical environments like Malaysia, heavy rainfall and water infiltration have a pronounced effect on rock slopes, not only by increasing density and pore pressure but also by reducing the strength and stiffness of the rock, leading to significant instability (Rahardjo *et al*., 2010; Pan *et al*., 2020). Therefore, slope stability analysis is crucial for identifying high-risk areas and developing effective mitigation strategies to reduce potential hazards.

Addressing the issue of slope failure requires a combination of detailed field investigations and robust modelling techniques. Traditional methods, such as kinematic analysis and the Limit Equilibrium Method (LEM), are valuable tools for assessing potential failure modes and calculating the Factor of Safety (FoS) under different conditions (Azarafza *et al*., 2021). Kinematic analysis helps determine failure modes, such as planar, wedge, and toppling failures, by analysing the orientation of discontinuities. LEM provides a quantitative approach to assess the stability of slopes by calculating the FoS for various strengths. Identifying critical slope sections, understanding failure mechanisms, and implementing effective stabilisation measures can significantly reduce the

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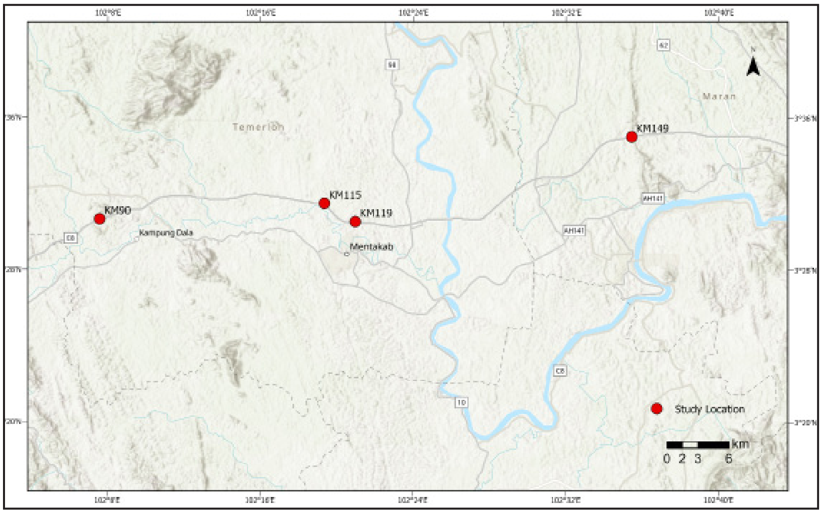


Figure 1: Location of selected study areas (km 90, km 115, km 119 and km 149) (map source: Esri, 2024).

risk of slope failure (Pal *et al*., 2011). These stabilisation measures, which may include techniques such as rock bolting, shotcrete, and proper drainage systems, are vital for mitigating slope instability and ensuring the safety and resilience of infrastructure (Rajendra Kumar *et al*., 2024).

The Semantan Formation, exposed along the Lebuh Raya Pantai Timur (LPT1), provides significant insights into sedimentary processes within the Triassic flysch basin, which once separated western and eastern Malaya. The area between Karak and Temerloh exhibits thinly bedded sandstone-mudstone flysch-like facies, while thicker sandy turbidites dominate near Temerloh and Maran, indicating proximity to the ancient shelf. At Chenor junction, deep-marine facies reveal evidence of large-scale submarine mass-transport processes, including gravity-slide blocks, slumps, debris flow deposits, and thrust faults. The Chenor mass-transport complex features slump deposits interbedded with turbidites and debrites, with gravity-induced deformation, such as rotational slumps and soft-sediment folds. The westward-verging folds and thrusts suggest multiple turbidity flow events and mass-transport activity on the Triassic slope (Madon, 2010). Deposition mainly occurs through high-to-low-density turbulent gravity flows, sandy and muddy debris flows, and suspension flows, with small slumps forming of mass transport deposits (Mohamed *et al*., 2022).

This study aims to evaluate the stability of selected rock slopes along the LPT1 highway, identifying key factors contributing to instability and proposing mitigation strategies, in conjunction with the ongoing efforts by the highway concessionaire to enhance slope.

STUDY AREA

The study area is located along the LPT 1 highway, between km 90 (Lanchang, Pahang) and km 149 (Chenor, Pahang). The westernmost outcrop near km 90 exposes acidic igneous rocks (rhyolite), while the subsequent sections (km 115–km 149) predominantly expose Semantan Formation sediments comprising shale and sandstone. The distance of the study area covers approximately 55 km, as shown in Figure 1. The exact location of the study area is between the latitudes and longitudes of 3.510748°N, 102.124645°E to 3.58814°N, 102.6157°E. Rock slopes were excavated for highway construction.

METHODOLOGY

A geological field study was conducted to assess the joints and their configurations in the rock formations revealed on the slope surfaces, along with changes in the slope conditions. This study involved gathering representative rock samples from various locations and types to ascertain the non-kinematic properties of intact rocks through lab tests. Laboratory measurements of non-kinematic strength characteristics of the intact rock samples were used to establish an accurate estimation of rock mass properties for the non-kinematic portion of the study. A flowchart depicting the simulation of slope stability, moving from field data assessments to laboratory experiments and non-kinematic analysis, is illustrated in Figure 2.

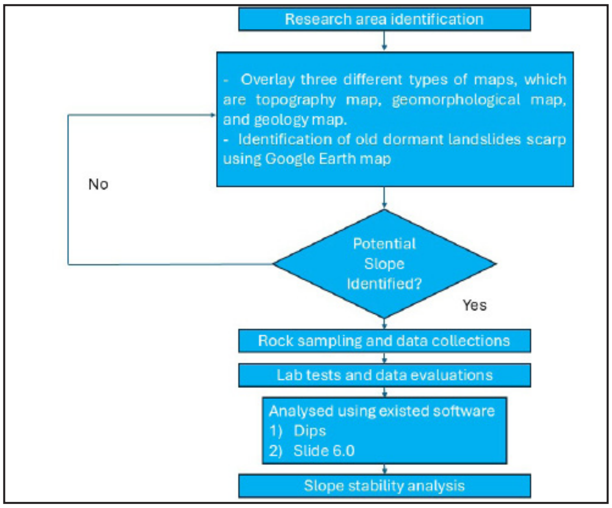


Figure 2: Flowchart of methodology.

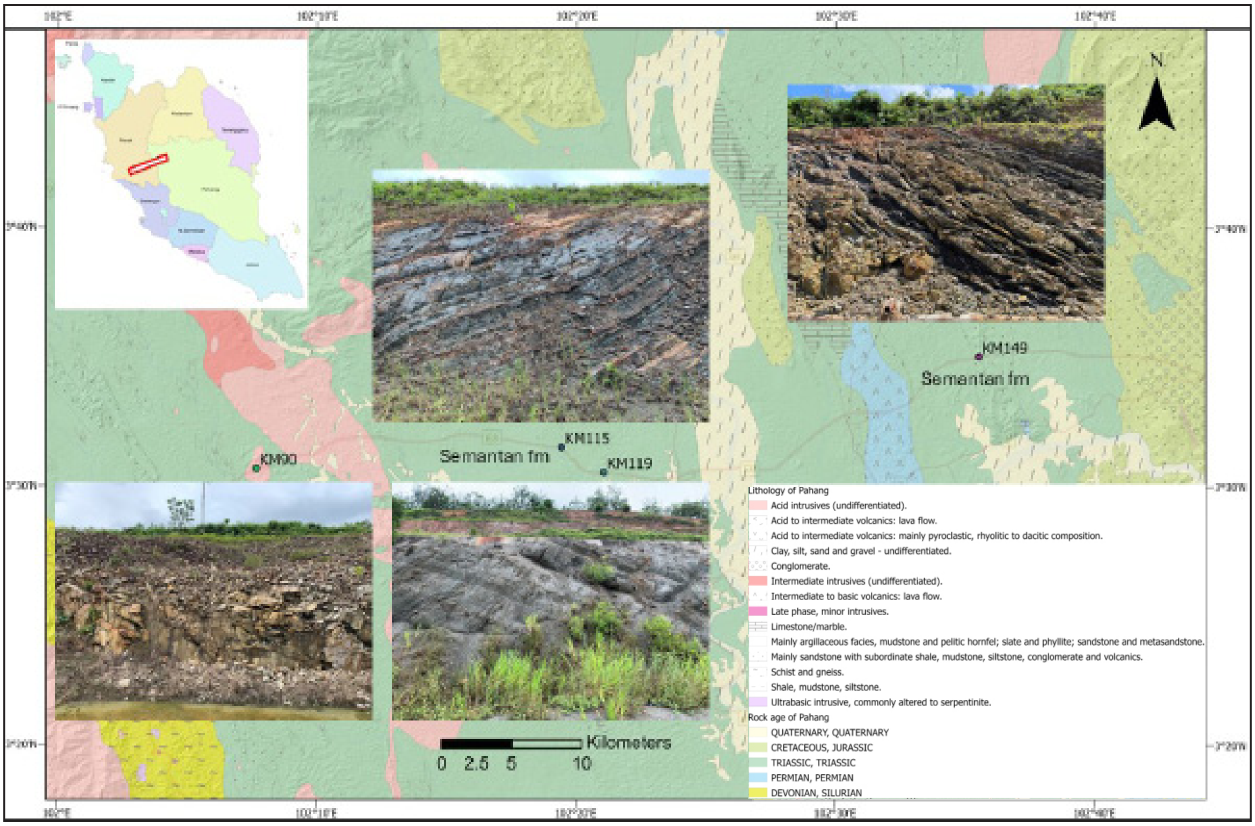


Figure 3: Geological map shows the lithology of selected study areas (Source: Jabatan Mineral dan Geosains, 2014).

Rock sample collection

The geology of the study area is characterised by acidic igneous rocks at km 90 (rhyolite) and metasedimentary rocks of the Semantan Formation (interbedded shale and sandstone) between km 115 and km 149. Rock samples were collected from four sites along the LPT1 highway, representing both the rhyolite at Lanchang (km 90) and the metasedimentary units of the Semantan Formation at the remaining locations (Sulaiman *et al.*, 2021) (Figure 3). The observed variability in the rock samples can be attributed to the complex geological history of the region, which is influenced by the subduction of the Indian Ocean Plate and the associated volcanic activities (Zaenudin *et al.*, 2020).

Laboratory test

The direct shear test (ASTM International, 2021) is used to determine the shear strength of rock specimens, particularly along discontinuities or fractures (Figure 4). This test provides valuable data for assessing slope stability, foundation behaviour, and the shear resistance of rock masses. It measures the cohesion (c) and the angle of internal friction (φ) of the rock specimen or discontinuity surface.

A normal load is first applied vertically to simulate in situ stress conditions. Then, a horizontal shear force is gradually applied to the upper half of the shear box while the lower half remains stationary. This force is increased until the rock specimen fails along the discontinuity or until a specific displacement is reached. The normal load, shear force, and horizontal displacement are recorded throughout the test. The test is often repeated at different normal stress levels, and the results are analysed by plotting shear stress against normal stress. The cohesion and angle of internal friction are then determined using the Mohr-Coulomb failure criterion (Deere & Miller, 1966).

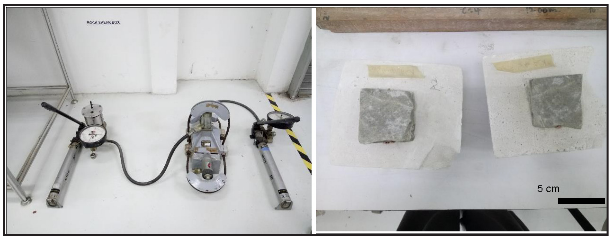


Figure 4: (a) Rock shear box apparatus (b) Sample in a mould for shear box testing.

The Mohr-Coulomb failure criterion is expressed as in Equation 1:

$$\tau = c + \sigma_n .\tan(\varphi) \quad \text{Equation 1}$$

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

From this plot, *c* is the y-intercept, and the angle of internal friction (φ) is the slope of the line.

The uniaxial compressive strength (σ_c) can be estimated from the Schmidt R value measured on an unweathered rock surface with a specific unit weight (γ). The empirical correlation developed by Barton & Choubey (1977) was used to determine the rock's uniaxial compressive strength (UCS) based on the relationship described in Equation 2, which links UCS to rock parameters through observed trends in experimental data.

$$\log10(\sigma c) = 0.00088.\gamma.R + 1.01 \qquad \text{Equation 2}$$

where σ*c* is the uniaxial compressive strength (UCS) in MPa; γ and R are the dry rock densities in kN/m^3 and average Schmidt hammer rebound value, respectively.

Kinematic analysis is essential in evaluating rock slope stability, especially where rock mass discontinuities are unfavourably oriented. This method is used to predict various types of failures, including planar, wedge, and toppling failures, based on the orientation of joints, fractures, or bedding planes within the slope (Zhou *et al*., 2016). Discontinuities significantly affect slope stability by serving as potential failure surfaces, and kinematic analysis assesses whether these surfaces are likely to lead to slope failure under certain conditions (Yan *et al*., 2021). The study gathered necessary parameters such as the orientation, spacing, and persistence of discontinuities through field surveys and geotechnical investigations. The data were processed using the DIPS software, a tool specialising in stereographic projection to visualise and analyse the orientation of discontinuities. The scan-line survey, a technique used to collect structural data from exposed rock faces, provided essential inputs for the kinematic evaluation.

LEA is a common approach for determining the stability of slopes by analysing various slip surfaces to find the critical failure surface (Rahman *et al*., 2023). Slide 6.0 was selected for this study because of its ability to perform detailed 2D slope stability analysis, which is critical for understanding the failure mechanisms of rock slopes. The software supports the input of field-measured discontinuity orientations and slope geometry, allowing precise modelling of the wedge, planar, and toppling failures. It has the ability to calculate the factor of safety (FoS) (Rocscience, n.d). Slide 6.0 allows engineers to evaluate how the material behaves under stress, strain, and shearing during construction, simulating conditions like those encountered in road building.

The analysis becomes robust and detailed by using LEA, particularly through models such as Slide 6.0. The model assists in predicting failure mechanisms like planar or rotational slips based on the stress distribution and material properties. The factor of safety, a key metric, is calculated by comparing resisting forces to driving forces. If this ratio is below 1, it signals potential failure. Furthermore, advanced tools within SLIDE allow optimisation of search algorithms to identify critical slip surfaces, often refining conventional methods that might overlook more subtle or critical failure surfaces.

RESULTS AND DISCUSSION

The results of the kinematic analysis are shown in Figure 5 and Table 1. The modes of failure are planar, wedge, and toppling failures. The wedge failures are potential in slopes km 90, km 115, km 119, and km 149. The wedge failure in slope km 90 has been kinematically formed by the intersection of plane J3 with J4 and J5. For slope km 115, wedge failure formed when plane B1 intersected with J2 and J4. As for slope km 119, the wedge failure formed when plane J1 intersected with planes B1, J3, and J4. Lastly, the wedge failure for km 149 formed when plane B2 intersected with planes J2, J3, and J4. Planar failure formed in slopes km 119 and km 149, while toppling failure only formed in slope km 115. The toppling failure for km 115 only involved a small scale of failure.

The Mohr-Coulomb criterion identifies the shear strength of discontinuities as a fundamental factor in the stability of rock slopes. This shear strength can be quantified through the parameters of cohesion and the angle of internal friction. Discontinuities, such as joints and faults, play a significant role in the mechanical behaviour of rock masses. The shear strength of these discontinuities directly influences the stability of slopes. Studies indicate that variations in the cohesion and friction angle of these discontinuities can lead to different stability outcomes for the same slope configuration (Mukhlisin & Zainal, 2020; Keawsawasvong *et al*., 2024). The stability of selected slopes or factors of safety are shown in Table 2. The limit equilibrium analysis (non-kinematic analysis). The method indicates that only slope km 90 is generally stable according to the Jabatan Kerja Raya (JKR) (2010) standard guideline. As per the JKR Guidelines for Slope Design (JKR, 2010), untreated slopes, including cut slopes, fill slopes, and embankments, must be designed with a berm width of 2 meters and a berm height of 6 meters, ensuring a minimum Factor of Safety (FoS) of 1.30. Treated slopes, on the other hand, are required to have a minimum global FoS of 1.50.

The Limit Equilibrium Method (LEM) was employed to assess the factor of safety (FoS) and analyse surface failure on both sides of the highway slopes. This analytical approach, primarily utilising the Slide 6.020 application, serves as the primary technique for evaluating failure surfaces and determining the factor of safety under normal conditions.

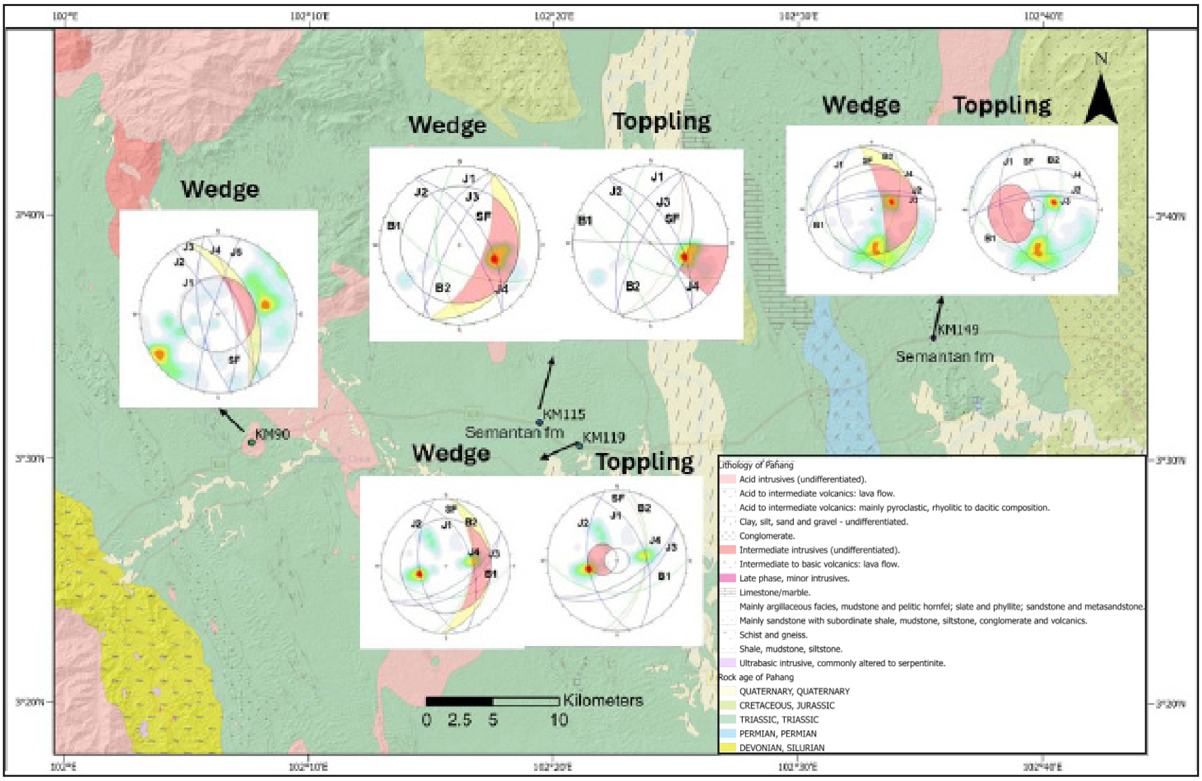


Figure 5: Geological and kinematic analysis of slope failures along the LPT1 highway on the Semantan Formation and acidic igneous rocks. The map highlights the lithological units, slope locations (km 90, km 115, km 119, and km 149), and stereonet plots for slope stability analysis, showing various failure mechanisms, including wedge, planar, and toppling failures (source: Jabatan Mineral dan Geosains, 2014).

An FoS of 2.2 indicates that km 90 operates with a significant safety margin (Figure 6). This level of safety is typically acceptable for structures where high reliability is essential, such as in critical infrastructure or where failure could result in severe consequences. The JKR established guidelines in 2010 indicating that for unreinforced slopes, the minimum factor of safety (FoS) should be 1.3, while for reinforced or treated slopes, the minimum FoS is set at 1.5. Consequently, an FoS exceeding 2 is generally considered adequate for most structural applications, ensuring stability under typical conditions.

An FoS of 1.0, as referenced in km 115, signifies that the structure is functioning at its maximum capacity limit (Figure 7). This situation presents no safety margin, rendering it susceptible to additional loads or unexpected stresses. Such conditions signify potential instability; therefore, the highway concessionaire has implemented systematic reinforcement and continuous monitoring of the affected slopes. Preventive engineering interventions, including the establishment of a sufficiently wide buffer zone designed to intercept potential rockfall material before it reaches the roadway, have been undertaken to ensure long-term slope stability and mitigate associated geotechnical risks. The JKR guidelines indicate that an FoS of 1.0 is deemed unacceptable, serving primarily as a threshold rather than a desirable safety standard.

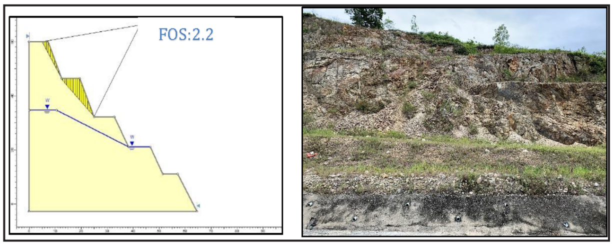


Figure 6: Stability model with a calculated factor of safety (FoS) of 2.2, indicating a stable slope. The right image shows the corresponding rock slope in the field.

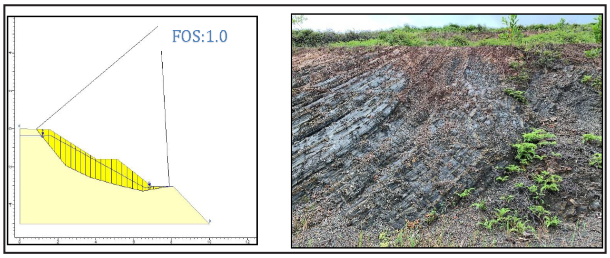
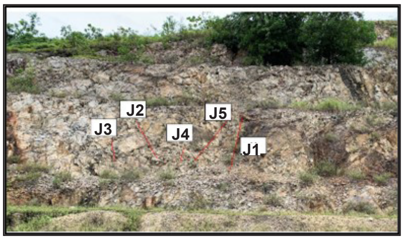
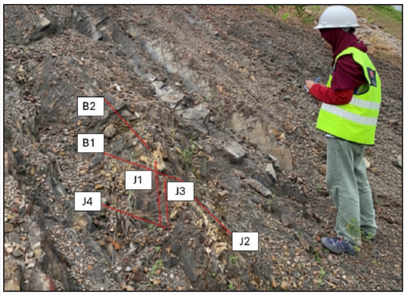
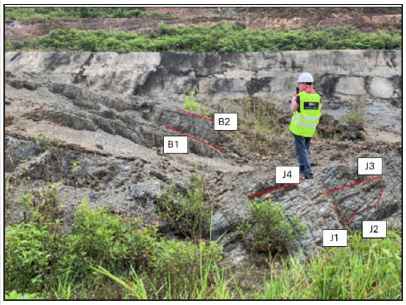
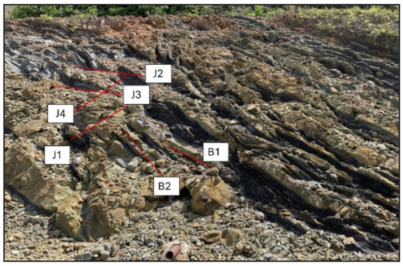


Figure 7: Stability analysis and field observation of a slope along the LPT1 highway. The left image displays a slope stability model with a factor of safety (FoS) of 1.0, indicating a marginally unstable slope. The right image shows the corresponding slope in the field.

Table 1: Summary of key parameters for kinematic analysis, including slope face orientation, major planes of weakness, lithological composition, and modes of failure.

Slope	Lithology	Slope face (dip/dip direction)	Major planes	Mode of failure
km 90	Rhyolite	60/67	63/260 (J1) 84/56 (J2) 56/65 (J3) 65/82(J4) 81/286(J5)	Wedge 
km 115	Shale	55/112	55/206(B1) 57/266(B2) 51/293(J1) 77/57(J2) 76/297(J3) 53/58(J4)	Wedge and toppling 
km 119	Shale	45/94	40/180(B1) 45/179(B2) 45/70(J1) 45/260(J2) 42/148(J3) 55/149(J4)	Planar and wedge 
km 149	Shale	70/80	22/194(B1) 50/251(B2) 38/110(J1) 59/352(J2) 68/353(J3) 28/341(J4)	Planar and wedge 

Note: J = Joint, B = Bedding plane

Table 2: Shear strength parameters for non-kinematic analysis.

Locality	Internal angle friction, φ (degrees)	Cohesion, kPa	FoS
km 90	39	600	2.2
km 115	17	120	1.0
km 119	20	100	0.4
km 149	19	110	0.6

FoS values below 1 indicate that the applied load exceeds the system's capacity, leading to potential failure. km 119 and km 149, with FoS values of 0.4 and 0.6, respectively (Figures 8 and 9), are significantly under the safe threshold. To address potential instability, the highway concessionaire implements targeted remedial and safety measures to ensure slope stability.

Despite the relatively high FoS of 2.2, the presence of a wedge failure mechanism at km 90 introduces the potential for localised instability, particularly if the conditions promote sliding change. Wedge failures occur when two or more discontinuity planes intersect, forming a wedge that can slide along the line of intersection. Although the current FoS suggests that the slope is stable under normal conditions, specific external forces can significantly alter the balance between resisting and driving forces, increasing the risk of failure. Even small changes in frictional resistance along discontinuities can disproportionately affect the likelihood of wedge failure, particularly in steep rock slopes (Goodman, 1989). The highway concessionaire has implemented targeted reinforcement and remediation measures to enhance slope stability and reduce failure risk.

The kinematic analysis identified a potential for wedge failure at km 90 through the intersection of discontinuity planes J3, J4, and J6. This technique rests on the geometrical relations between discontinuities and the orientations of the slope face, outlining the theoretical modes of failure. On the other hand, the LEM analysis showed an elevated factor of safety (FoS = 2.2) for km 90, indicating overall stability under the prevailing conditions.

This potential gap stems from the assumption made on the different methodologies, which is that the kinematic analysis tends to ignore other material strength parameters, such as the cohesion and the friction angle, which are necessary to prevent the slope from failing. The LEM takes these parameters together with the shear strength of the rock mass and provides a numerical evaluation of the slope stability.

For the case of km 90, the high values for the cohesion (600 kPa) and the friction angle (39°) are more likely to provide slope stability, and they geometrically tend to wedge failure. It is important to note that other approaches are used in tandem to aid in understanding slope stability more deeply because using only one method can result in underestimating or overestimating risks.

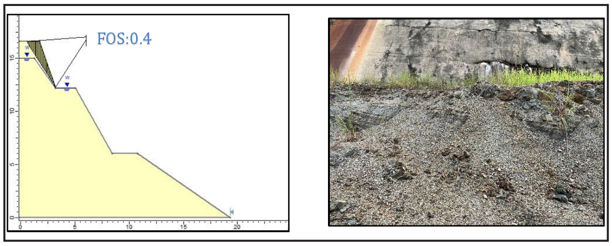


Figure 8: Stability analysis of a slope with a factor of safety (FoS) of 0.4, indicating a potential slope failure. The right image shows the corresponding slope in the field.

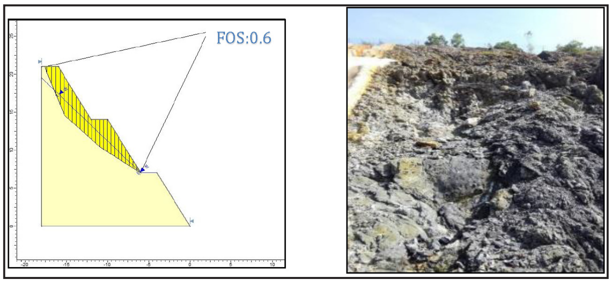


Figure 9: Stability analysis of a slope with a factor of safety (FoS) of 0.6, indicating a potential slope failure. The right image shows the corresponding slope in the field.

The combination of wedge and toppling failures makes km 115 particularly unstable. An FoS of 1.0 already indicates that the slope is operating beyond the limit of stability, and the presence of both failure types suggests that any slight change—such as joint widening, increased water pressure, or erosion—could trigger a significant collapse. Toppling failures are particularly challenging to predict since they often result from a progressive loss of support at the base of the rock mass. The mutual interaction between the two mechanisms means that as toppling progresses, it can trigger or exacerbate the wedge failure, and vice versa. According to Piteau & Peckover (1978), joint widening and erosion significantly contribute to slope failure mechanisms by progressively weakening the rock mass and decreasing resistance along discontinuities.

At km 119 and km 149, the presence of both wedge and planar failures, combined with the very low FoS values (0.4 and 0.6), indicates severe instability. Planar failure typically occurs when friction along the sliding plane is reduced, such as through the presence of water or loose material on the sliding surface. Combined with wedge failure, it suggests that entire slope sections are in immediate danger of sliding or collapsing. The combination of planar and wedge failures significantly increases the risk of slope collapse, as both failure types can interact to reduce the overall resistance to sliding, especially when exacerbated by factors like water infiltration and joint widening (Rahman *et al*., 2023).

This research deals with the stability of slope rock along the Semantan Formation, which is known to be geologically complex and prone to slope failures. The study focuses on slope stability in relation to applied geology and engineering to develop and enhance the safety of the LPT1 highway, a critical transport corridor. Additionally, this study highlights the importance of applying many analysis methods for better comprehension of slope stability, which is essential when designing infrastructure and planning risk for this and similar formations.

CONCLUSION

To sum everything up, rock slope stability assessment along the LPT1 highway, which traverses both Semantan Formation sediments and acidic igneous rocks near Lanchang, has provided important information about the causes of slope failure and what can be done. The prevalence of slope failures in areas with complex geological formations, particularly in tropical environments like Malaysia, highlights the significance of understanding discontinuity characteristics and shear strength parameters in slope stability analysis. These factors are critical to identify high-risk areas and develop effective mitigation measures. Traditional methods such as kinematic analysis and the Limit Equilibrium Method (LEM) have proven valuable in assessing potential failure modes and calculating the factor of safety (FoS) under different conditions, providing essential data for understanding failure mechanisms and implementing effective stabilisation measures such as rock bolting, shotcrete, and drainage systems. The LEM and kinematic analyses reveal both stable and unstable slope sections. The critical findings reveal that some parts of the slope need immediate remedial action to prevent slope failure. Additionally, the presence of wedge and toppling failures in certain slope sections underscores the possibility of localised instability and how tenuous the slope's stability really is as conditions change. Overall, this research emphasises the need for thorough fieldwork, sound modelling skills, and monitoring for the stability and resistance of infrastructure subject to slope failure.

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AUTHORS CONTRIBUTION

NAA contributed to the data analysis and interpretation, as well as the writing of the manuscript.

ZMY contributed to the conceptualisation of the study and reviewing of the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest.

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