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A review of rock slope failures in Malaysia: exploring types, cases, causes, and consequences

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Abstract
Rock slope failures remain a significant concern in regions of Malaysia with varying geological formations. This review examines the challenges posed by these incidents and addresses key knowledge gaps. By providing a comprehensive, multidisciplinary analysis of case studies, technological advancements, climate influences, disaster management, and socio-economic impacts, it offers valuable insights for researchers, engineers, and policymakers. It examines key failure types, including rock falls, slides, avalanches, and general failures, through notable case studies such as Bukit Lanjan (Selangor), Kinta Valley (Perak), and Mount Kinabalu (Sabah). A comprehensive methodology framework was employed, utilizing manual search techniques (handpicking, snowballing, citation, and reference tracking) alongside advanced keyword-based searches with Boolean operators in Scopus, ScienceDirect, and Google Scholar databases. Findings reveal that Malaysian rock slopes are highly susceptible to collapse due to heavy rainfall, human activities, and natural events such as earthquakes. While these factors can act independently, their combined effects significantly amplify failure risks, particularly during intense rainfall. The consequences extend beyond immediate casualties, injuries, and property damage, leading to infrastructure failures, economic disruptions, and environmental degradation. This review underscores the need for sustainable mitigation strategies to address these risks and highlights the urgency of implementing effective solutions to safeguard lives, infrastructure, and ecosystems.

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INTRODUCTION

Complex and uncertain natural disasters cause profound effects on the human population. A significant geological hazard example is landslides, which produce high fatalities annually. Hence, this phenomenon emphasizes the crucial requirement for improved forecasting and prevention methods. Landslide susceptibility is also closely associated with natural slope instability, existing geological vulnerabilities, and human-induced modifications (cut slopes) [1]. Recent studies provide comprehensive insights into this phenomenon across different regions, emphasizing the importance of robust prediction models and prevention strategies. For instance, a study in Ambon City, Indonesia, evaluated factors such as slope inclination, rainfall, and rock type (related to weathering), producing a landslide vulnerability map that aids in slope management [2]. In Turkey, researchers utilized GIS and frequency ratio methods to assess landslide susceptibility, identifying geology, slope, and proximity to rivers as key factors [3]. Similarly, in India, logistic regression models were used to understand the impact of anthropogenic activities on slope stability, highlighting the role of rainfall and soil type [4].

These determinants predominantly facilitate the pervasive incidence of rock slope failures, representing a crucial concern within geology and environmental sciences. The manifestation of rock slope failures in Malaysia presents considerable hazards to infrastructure, the safety of individuals, and the ecological balance. These failures, often triggered by geological, hydrological, and anthropogenic influences, have been documented across diverse regions, particularly in locales characterized by steep inclines and extensively weathered rock formations. The abrupt and potentially disastrous collapses of rock masses substantially influence natural landscapes and human undertakings. This phenomenon predominantly transpires in areas exhibiting a variety of geological configurations [5, 6, 7]. Rock slope stability is essential due to its direct influence on infrastructure safety and durability, and slope failures can lead to severe outcomes. These outcomes include significant financial losses, permanent environmental harm, destruction of essential infrastructure, increased safety risks, and significant disruptions to transportation systems [5][7].

Previous studies have examined rock slope stability from different perspectives. Kinematic analysis is a prevalent technique for evaluating potential failure modes in rock slopes, particularly within limestone terrains [8][9]. Numerical modeling, incorporating probabilistic techniques, assesses slope stability across varying conditions, including seismic events and failures prompted by rainfall [8][10]. In Malaysia, rock slope stability assessments have conventionally depended on kinematic analysis and rock mass rating frameworks. Nevertheless, there is an emerging trend towards adopting numerical methods to enhance precision and dependability [7][9]. An examination of 39 case studies within Malaysia showcases the progression from rudimentary kinematic evaluations to advanced numerical analyses, indicating a growing comprehension of rock mechanics [7]. The technical orientation of current studies frequently overlooks the broader ramifications of rock slope failures, particularly their influence on disaster risk management and policy formulation [7]. A systematic review is needed that weaves technical evaluations and incorporates socio-economic dimensions and policy ramifications, especially in regions like Malaysia, where urban expansion intrudes upon hillside territories [7].

The Malaysian terrain, characterized by deep tropical weathering, poses significant challenges for infrastructure development. This complexity arises due to a combination of steep slopes, high rainfall, and diverse geological formations, which increase the risk of landslides and ground instability. According to a study on Malaysian infrastructure, the government faces numerous challenges in recognizing and measuring infrastructure assets due to the unique features of the terrain, such as long useful life and being part of an asset system or network [11]. Additionally, the Rapid urbanization and extensive transportation network development in Greater Kuala Lumpur, including the Klang Valley, complicate infrastructure development and necessitate advanced planning and management for sustainable growth, as evidenced by concerns over urban sprawl and the need for efficient land use and transit-oriented development [12].

Advanced technologies, such as Unmanned Aerial Vehicles (UAVs) and Light Detection and Ranging (LiDAR), have shown promise in improving infrastructure project outcomes. UAVs offer benefits in surveying and monitoring, but their implementation faces barriers such as regulatory restrictions, industry reluctance, and technical challenges related to data acquisition and quality control. Effective utilization of UAVs could greatly enhance construction efficiency and safety, provided these challenges are addressed [13]. Similarly, LiDAR technology provides highly accurate terrain mapping capabilities; however, its adoption in Malaysia remains limited due to several constraints. These include challenges in data processing and filtering that may result in mismatches, the absence of standardized operational procedures, and a range of technical as well as financial barriers that collectively hinder its large-scale integration into infrastructure projects [14]. In addition to technological challenges, Malaysia's construction industry must adapt to demographic changes, such as an aging population. This demographic shift impacts building design, workforce dynamics, and construction. Preparing for an aging nation involves ensuring that infrastructure is accessible and suitable for senior citizens, which requires additional costs and modifications to current construction practices [15]. The combined effect of these factors underscores the complexity and urgency of addressing infrastructure development challenges in Malaysia’s diverse and rapidly changing landscape.

This paper reviews documented rock slope failures in Malaysia, categorizing them by type and examining their causes and consequences. It integrates geotechnical, environmental, and socio-economic perspectives to develop comprehensive strategies for mitigating these failures. Furthermore, the review aims to bridge these gaps by providing a comprehensive overview, covering case studies, technological advances, climate effects, disaster management, and socio-economic impacts. This multidisciplinary approach offers valuable insights for policymakers, engineers, and researchers in rockfall hazard management.

Government Policies for Slope

Malaysia has initiated the National Slope Master Plan 2009–2023 (NSMP) [16] in response to the significant increase in slope-related disasters. This plan provides a comprehensive framework to reduce landslide damages nationwide by equipping key authorities with the essential tools and information for all phases of the disaster management process. Additionally, key authorities are provided with instructions and concrete resources to enhance their emergency preparedness, response, and recovery capacity. For example, 3D scanners can improve search and rescue, easing rugged terrain-based travel and victim identification. This plan can also establish numerous provisions, such as slope management procedures integrating risk-reduction strategies and improved infrastructure development. Hence, failures are effectively prevented when addressing issues related to slope-related disasters.

The vulnerability of Malaysia to various natural disasters (floods, landslides, and earthquakes) has been acknowledged in the Twelfth Malaysia Plan 2021–2025 (RMKe-12) [17]. Consequently, disaster risk management (DRM) at the national policy level has been elevated to a prominent position. This feature aids in safeguarding the capabilities and infrastructure of Malaysian individuals. A detailed structure concerning proactive strategies is also outlined in the DRM of the RMKe-12. These approaches include early warning technologies and community readiness-related programs in constructing vital infrastructure for disaster prevention measures. For example, these methods are utilized in designing and constructing important structures (buildings and highways). This plan also focuses on capacity building, training, and providing resources to local authorities with emergency responders to handle crisis scenarios successfully.

The 2023 Mid-Term Review [18] of the RMKe-12 has highlighted the dedication of the Malaysian government to landside disaster management prevention using two key initiatives: a landslip early warning system and a National Geological Disaster Centre. Approximately RM 563,000,000 has also been allocated in the 2024 Malaysian budget to enhance landslide readiness. This allocation signifies the significant dedication of the Malaysian government to take preemptive actions to restore and stabilize more than 2,000 high-risk slopes and implement improved monitoring and preventive actions [19].

METHOD

This review initially evaluated relevant studies to identify the correlations between rock slope failure and factors affecting rock stability in Malaysia. A study by [20] proposed using several search algorithms to improve the likelihood of discovering related studies. The study revealed two primary search techniques: manual (handpicking, snowballing, citation tracking, and reference tracking) [20][21] and advanced techniques [constructing queries or search strings using Boolean operators in multiple databases (such as Scopus and Web of Science)] [22][23]. Meanwhile, [24][25] created a Literature Review Protocol (LRP) detailing databases, languages covered, keywords, and search methods.

The relevant studies in this review were initially retrieved from numerous search engines (Science Direct, Scopus, Google Scholar, Mendeley, and the databases of the University for journals, books, and proceedings). Several Boolean operators ("OR", "AND", and "NOT") were then employed to integrate multiple related terms for targeted search results ("Factor", "Rock slope failure", "Rock slope instability", "Cliff collapse", "Slope failure", "Rock Fall", "Rock Slide", "Rock Avalanches", and "Malaysia"). This review also broadly examined studies from the past 20 years, focusing on slope stabilization procedures in Malaysia and Southeast Asia. Subsequently, the data were gathered from their websites or portals for statistical reference. The inter-library lending and document delivery service of the University was also utilized for offline and closed-access articles employing manual methods. Even though the search process in this review yielded numerous articles, only the most pertinent English studies were used.

Case Study for Rock Slides

The predominant rock slope instability type in Malaysia is rock slides. This instability occurs as sliding movements along discontinuities in rock masses and is categorized based on the motion and fracturing of the rock mass. Numerous movement sub-types are observed in the slide, such as rotational, planar, wedge, compound, and regular slides. A study by [26] grouped these slides based on their speed, rock characteristics, and movement patterns. Recent field investigations and kinematic analyses show that discontinuity geometry and basal rupture architecture fundamentally control rock-slope failure modes and their velocities.

i. **Rotational slides:** Slow movement on a curved base, causing the rock mass to rotate forward [26][27].
ii. **Planar slides:** Sliding on a flat plane that daylights; occurs when the slope is steeper than the plane's resistance [26, 28, 29]
iii. **Wedge slides:** A triangular wedge formed by two planes slips downslope along their intersection, often rapidly [26][28].
iv. **Compound slides:** Movement along several connected surfaces, so different parts travel at different speeds [26].
v. **Irregular slides:** Failure follows a rough, discontinuous fracture path, with sudden bursts often triggered by water pressure [26][27].

Another study by [7] conducted a study defining a rock slide as an abrupt and frequently unforeseeable occurrence in which substantial rock masses detach and slide down slopes. Nonetheless, these descriptions were simplified, and real-world rock slides could be more intricate. The intricacy of real-world rock slides is highlighted through various case studies and analyses that reveal the complexities beyond simplified descriptions. For instance, investigations of rock slides in British Columbia that evolved into flow-like landslides highlight the dynamic nature of debris avalanches and flow deposits influenced by ground saturation levels and topographic gradients [30]. Additionally, discussions on advanced monitoring and modeling techniques for rock structures emphasize technological advancements in understanding rock mass stress and deformation [31]. Furthermore, examinations of the hydrology of active rock glaciers in the Austrian Alps demonstrate the impact of weather conditions and meltwater flow on rock glacier discharge patterns [32]. Figure 1 illustrates two sliding failure types on rock slopes: a planar sliding failure observed in an abandoned quarry and a wedge sliding failure on a road-cut slope.

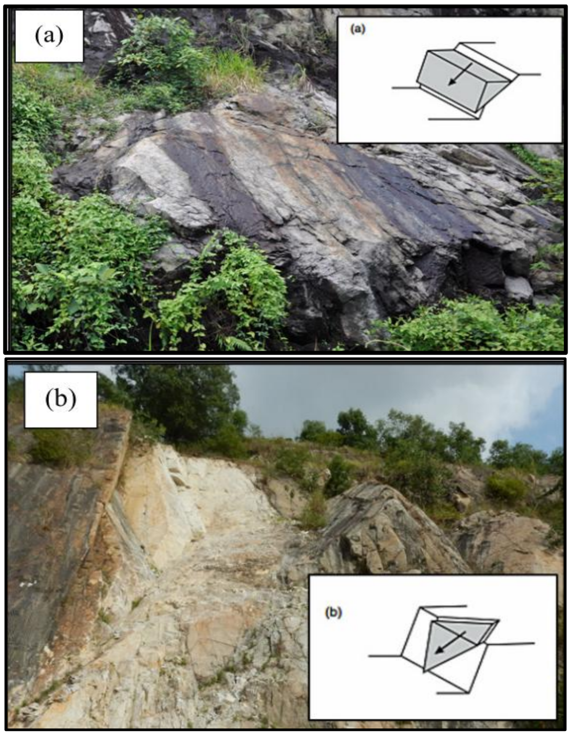

Figure 1. (a) The observed sliding failure on a rock slope (including planar sliding on an abandoned quarry) and (b) the wedge sliding on a road-cut slope [7].

The rock layers were shifted along a noticeable plane, implying their planar nature (see Figure 1(a)). Meanwhile, the rock displacement occurred along two parallel planes, creating a wedge (see Figure 1(b)). Thus, these images aided in classifying the typical rock slope failures.

On November 26, 2003, Malaysia experienced a rock slide at the 21.8-km point of the Bukit Lanjan Interchange on the New Klang Valley Motorway (NKVE. This area falls within the authority of the Petaling Jaya district in Selangor, Malaysia. Approximately 35,000 m^3 of rock debris fell onto the motorway and blocked the road, mainly comprising different angular block sizes. A study by [33] documented that the rock slope failure in Bukit Lanjan was attributed to geological conditions and triggering events. The study revealed that the pre-existing rock mass structure containing steep-dipping faults and unfavorable joint orientations contributed to instability. Conversely, the extended period of heavy rainfall likely triggered the incident.

The failure is confirmed to be caused by a large wedge block formed by the intersection of three key planes as follows [33][34]:

i. A steeply dipping fault plane F1 (dip/dip direction: 80°/225°)
ii. A gently dipping joint plane J1 (dip/dip direction: 60°/070°)

iii. A released plane F2 (dip/dip direction: 78°/327°)

The factor of safety (F.O.S.) also decreased below 1 when simulated water-filled faults and joints from the hydrostatic pressure conditions were integrated into the analysis, suggesting imminent failure. Therefore, the significant impact of high-water pressure on this occurrence was demonstrated. This outcome was reinforced by the unusually high rainfall in November 2003, surpassing records dating back to 1966 [33]. Although the Bukit Lanjan incident did not cause fatalities, the economic repercussions were significant. Figure 2 portrays the massive granite boulders completely obstructing the NKVE highway due to the failed rock mass [33]. This incident cost the Malaysian government approximately RM 836,000,000 (economic cost) due to lost revenues and required corrective actions [16]. The extended traffic disruptions resulting from this incident also substantially impacted businesses and residents in the Klang Valley, exacerbating the economic strain.

Figure 3 depicts a detailed timeline of the Bukit Lanjan rockslide incident and the following rehabilitation actions. The initial image depicted a peaceful green mountainside before the rockslide incident, showcasing stability and lush vegetation. Subsequently, the second image highlighted the immediate aftermath, displaying major collapse and scattered debris, modifying the terrain. The third image then conveyed the beginning of repair work, featuring machinery and terracing efforts to stabilize the hillside.

Figure 2. The rock slope failure incident at the Bukit Lanjan Interchange (KM 21.8 of NKVE) on November 26, 2003. The entire expressway was closed to the public due to the failure of materials obstructing the road [33].

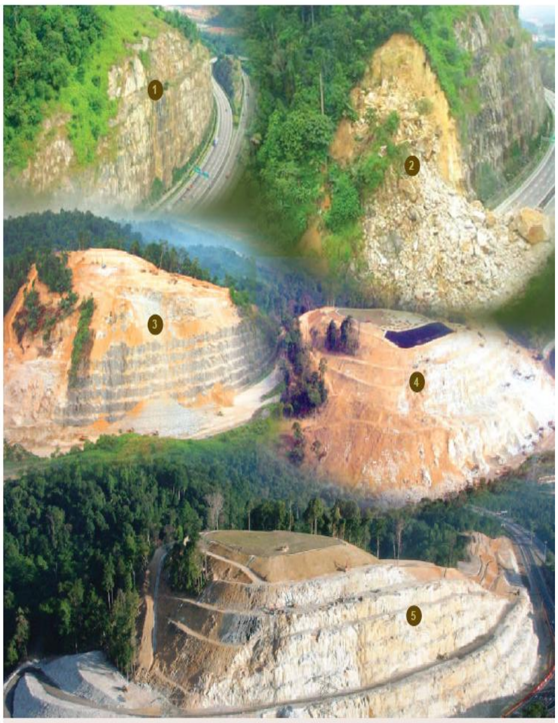

Figure 3. A detailed Bukit Lanjan rockslide incident and the corresponding repair efforts [16]

Likewise, the fourth image demonstrated continued advancements in the restoration process involving enhanced terracing and erosion prevention methods. Finally, the fifth image presented the finished repair work, featuring clearly defined terraces, regrown flora, and preventive measures (stabilizing nets to reduce the risk of future landslides). This process indicated a successful restoration of the site.

Case Study for Rock Falls

Compared to rock slides, which typically entail large-scale mass movements, the detachment and descent distinguish rock falls from the bounce of individual rock or ice fragments [35]. Despite this phenomenon frequently occurring individually or in clusters, the pieces in motion primarily interact with the ground rather than with one another, resulting in minimal fragmentation. Generally, rock falls contain small amounts of debris [35][36]. Nonetheless, this phenomenon can present substantial dangers owing to its rapid speed and erratic paths. Even though slopes are prone to rock falls, natural rock faces in karst landscapes are commonly affected by weathering and erosion, causing discontinuities [37].

The NSMP has stated that the rapid development in Perak (Ipoh area) has led to higher land demands. This finding has resulted in residential and industrial buildings near steep limestone cliffs [16]. A study by [7][38] noted that considerable advancements occurring near certain limestone hills were observed. The study revealed that residential areas with industrial complexes and temples were situated near the hills. Quarrying processes were also ongoing to extract high-quality limestone aggregates in the limestone hill regions. Thus, multiple rockfall-related incidents were documented in the Kinta Valley between 2004 and 2023.

Table 1 shows that between 2004 and 2023, the Kinta Valley, Perak, Malaysia, experienced multiple significant rockfall incidents, highlighting the hazards presented by its limestone-dominated landscape. Casualties and damage effects from events like the 2004 Mount Bercham rockfall and the 2006 Mountain Pass failure, which highlighted deployment scales of catastrophic collapses, present an important risk to life and property. Adding to the public threat, the 2008 Gunung Karang Besar rockfall halted transport, and since then, significant structural damage near services such as the Yee Lee Edible Oils Factory and quarry-related deaths in 2019 stress the occupational danger. Such active and passive monitoring technologies capable of carrying out 3D modeling and lineament density studies can be implemented in areas at risk and highly prone to landslides, which would've been used in recent deaths and damage cases such as the 2022 rockfall incident in Simpang Pulai, and another extreme-damage incident to other vehicles in 2023. This has shown how urgent it is to implement sustainable risk management in Kinta Valley to protect lives and properties.

Even though several aspects could influence the rockfall incidents in Kinta Valley, rainwater was the primary component causing these events. In Malaysia's tropical climate, continuous water flow leads to the prolonged dissolution of limestone, especially along its discontinuities, which in turn causes the deterioration of slope stability over time [7]. This process is a significant factor in the overall weathering of rock masses in the region [7].

Subsequently, the cohesiveness of rocks at joints and cracks was further exacerbated by chemical weathering and quarrying activities. These aspects also occurred alongside other factors, including wind-related plant movement, earthquakes, and vibrations [39]. Another study also discovered numerous elements substantially contributing to rockfall incidents in Kinta Valley, such as seismic activities, water dissolution, and broad joints with faults [40].

Table 1. Significant incidents in Kinta Valley, Perak, from 2004 to 2023

Location of incident	Date of event	Reported Damage/ fatalities	Source
Mount Bercham, Perak	Dec 12, 2004	Structure damage, two deaths, & five injured	[41], [42], [43]
Mountain Pass, silver border-Pahang	April 2006	A mega-sized failure covered 1/4 of the rock body on this mountain.	[41], [42]
Gunung Karang Besar, Keramat Pulai	June 5, 2008	Vehicle damage & one death	[7], [42], [43]
Yee Lee Edible Oils Factory (Gunung Lang, Ipoh)	Feb 13, 2012	Structural damage and no fatalities	[42], [43], [44], [45]
Gua Tempurung, Kampar	April 11, 2012	No reports of structural damage or fatalities	[42], [43], [44], [45]
Quarry at Keramat Pulai, Simpang Pulai	July 1, 2019	Vehicle damage & one death	[7], [46], [47]
	March 8, 2022	Two deaths & two injured	[48]
	Sept 5, 2023	Vehicle damage and one injured	[49]

Case Study for Rock Avalanches

A study by [50][51] found that rock avalanches were remarkable and destructive natural events. The study described that rock avalanches were distinguished by their exceptional speed, enormous size, and the fluid-like movement of fragmented rock. A rock avalanche typically occurs from significant rock slides or collapses, in which large masses (millions of m^3) abruptly break away from a mountainside [50]. The large amount and speed of the sliding rock turn these masses into a fluid-like stream resembling a massive waterfall made of stone [50]. Although the precise mechanisms are still unknown, rock avalanches often result from substantial rock slides or falls caused by different sources. Specific examples that can trigger these catastrophic events include earthquakes, volcanic eruptions, heavy rainfall, and human activities [50]

The precise mechanisms driving rock avalanches remain poorly understood. Numerous studies have investigated potential causes and contributing factors. Research by [50] mentions that the propagation of a rock avalanche is influenced by various factors, with shear forces and internal stress differences playing key roles. These forces are evident in the sedimentary deformation structures observed within the avalanche deposits. Liquefaction is not considered a primary contributor to the propagation of rock avalanches. Rather than the rock mass itself, the nature of the terrain the avalanche travels over significantly influences its movement, highlighting the complex and variable nature of these events [50][51].

Rock avalanches are usually uncommon in Malaysia. Nevertheless, a rare rock avalanche incident occurred in 2015 on the rock face of Mount Kinabalu. This mountainous region is situated in Sabah, the first United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage Site in Malaysia [52]. On June 5, 2015, a 6.0 magnitude earthquake caused rock avalanches on the rocky flanks of Mount Kinabalu, producing noticeable marks on the surface [52, 53, 54]. This earthquake was documented as one of the most powerful natural phenomena following the 6.2 magnitude Lahad Datu earthquake on July 26, 1976 [55]. Consequently, a significant boulder avalanche on the slopes of the mountain caused 18 immediate fatalities [54][55].

Seven pupils and two teachers from the Tanjong Katong Primary School (TKPS), Singapore, and a Singaporean adventure guide who were reported missing following the earthquake have been discovered deceased. Meanwhile, six Malaysians (including four mountain guides) perished. Two tourists (one Chinese and one Japanese national) were also killed [54]. This major incident demonstrated that the implications of the earthquakes, rock falls, and debris flow could heighten the exposure and risk levels due to the mountainous terrain and popular tourist activities (climbing, camping, and tourism) [52].

Figure 4 illustrates the earthquake distribution in Sabah between 1900 and 2019, obtained from the United States Geological Survey (USGS) database. During the period, Sabah experienced 67 light to moderate earthquakes, most of which were below 5.0 on the moment magnitude scale (M_w). However, four significant quakes occurred with magnitudes of 6.0 M_w or higher. These larger earthquakes include the 2015 Ranau earthquake (6.0 M_w), the 1976 Lahad Datu earthquake (6.2 M_w), the 1951 Kudat earthquake (6.1 M_w), and the 1923 Lahad Datu earthquake (6.3 M_w) [55].

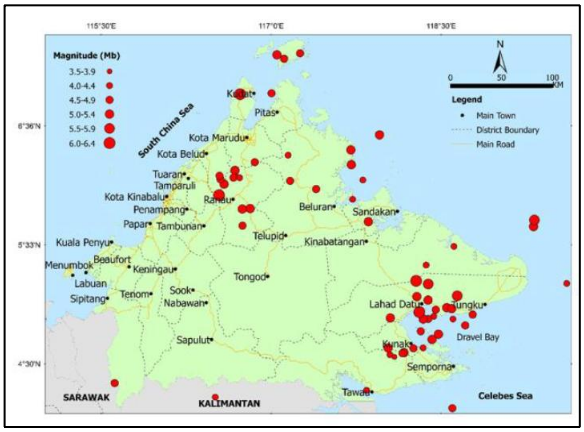

Figure 4. The earthquake distribution in Sabah between 1900 to 2019. This data was extracted from the USGS database [55]

The majority of this seismic activity was concentrated in the Ranau and Lahad Datu regions.

Causes of Rock Slope Failure

Due to the country's rapid infrastructure development and the inherent geological and climatic conditions, rock slope failures in Malaysia are a significant concern. A comprehensive understanding of the key factors, underlying causes, consequent impacts, and mitigation strategies is imperative for effective slope management and safety.

Table 2 summarizes the causal factors contributing to rock slope failures in Malaysia. The table details the effects of weathering, heavy rainfall, seismic activity, and human actions on slope stability. For each factor, relevant processes are outlined, including chemical and differential weathering, pore pressure augmentation due to rainfall, seismic shaking through weathered or fractured rock, and the destabilizing effects of construction and deforestation. This compilation provides a concise framework for comprehending the complex interaction of natural and anthropogenic factors in rock slope instability.

DISCUSSION

Figure 5 illustrates the critical factors, causes, consequences, and mitigation strategies related to rock slope failures, a significant geological risk in Malaysia. This issue was roughly comprehended by categorizing it into two essential aspects: rock movement (failure types: rock slides, rock falls, and rock avalanches) and triggering events (factors generating instability).

Table 2. Causes of rock slope failure.

Cause Factor	Explanation	Ref.
Weathering – Alteration	Weathering changes rock properties, forming weak zones that can lead to slope failure.	[6]
Weathering – Dissolution	In tropical climates, limestone dissolves under moisture, reducing its structural strength.	[7]
Weathering – Cohesive Loss	Chemical weathering reduces the cohesive strength of rock, increasing the risk of instability.	[56]
Weathering – Differential	Varying weathering rates in sedimentary rocks form weak planes, triggering slope instability.	[7]
Rainfall – Heavy Rainfall	Intense, frequent rain saturates slopes and increases pore pressure, reducing friction and stability.	[57], [58]
Rainfall – Intensity & Duration	Prolonged and high-intensity rain further infiltrates slopes, weakening their structure and promoting landslides.	[58], [59]
Rainfall – Monsoon	Seasonal monsoon rains can trigger landslides, especially in areas with already-weathered rock or residual soils.	[56], [60]
Rainfall – Pore Pressure Increase	Rain infiltration raises pore water pressure, lowering effective stress and shear strength.	[58], [59]
Rainfall – Soil Saturation	Extended rainfall saturates fine-grained soils, significantly raising the risk of slope failure.	[57], [58]
Seismic – Activity	Seismic activity can worsen existing rock weaknesses, triggering slope failures.	[56], [61]
Seismic – Regional Risk	Certain areas in Malaysia, such as Bukit Tinggi and Ranau, are more susceptible to seismic disturbances.	[7]
Seismic – Geology & Weathering	Strong shaking from earthquakes or heavy loads can cause a slope to fail, especially in weak rock.	[56]
Seismic – Historical Impact	Events like the 2015 Sabah Earthquake underscore the importance of considering seismic factors in slope stability assessments.	[7]
Human – Activities	Infrastructure development, excavation, and poor land use weaken slopes, triggering failures.	[56], [62]
Human – Environmental Interactions	Deforestation and construction alter drainage patterns, increasing slope instability.	[56], [62]
Human – Infrastructure Development	Building or operating near slopes disturbs natural stability, raising landslide risks.	[56], [62]
Human – Economic & Social Impact	Slope failures result in significant economic losses and social disruption, emphasizing the need for better land-use practices and planning.	[56], [57]

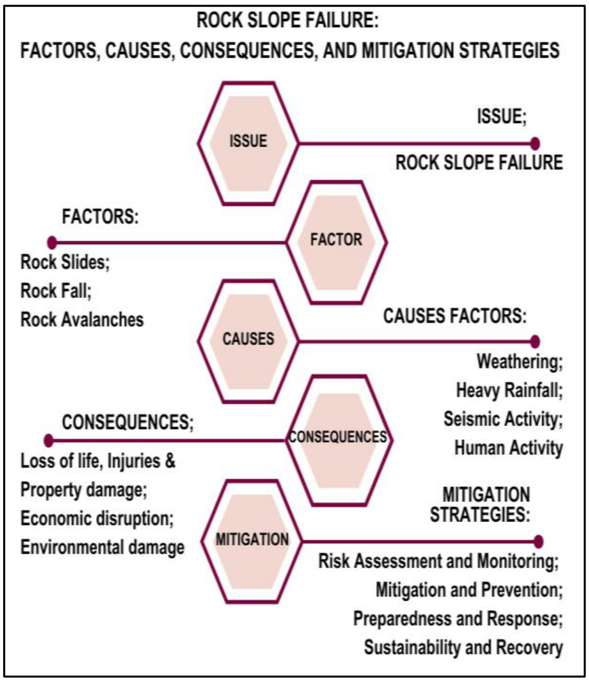

Figure 5. A flowchart indicating the rock slope failure aspects involving factors, causes, consequences, and mitigation strategies.

Each type presents unique challenges based on the movement and volume of rock involved. These failures are often influenced by the geological characteristics of the slope, including the presence of discontinuities such as joints and fractures, the type of rock, and the degree of weathering.

Heavy rainfall has primarily contributed to slope failures in Malaysia [58, 63, 64]. Rainfall infiltrating rock formations increases pore pressure, weakening the rock structure and making slopes more susceptible to failure. Additionally, acidic rain accelerates rock deterioration through chemical weathering, further compromising slope stability [63]. These factors underscore the critical role of rainfall in triggering slope failures in Malaysia, emphasizing the need for comprehensive risk assessment and mitigation strategies to address the challenges posed by changing climatic conditions.

Human actions significantly contributed to rock slope failures. For example, deforestation and construction operations disrupted the equilibrium of slopes, leading to destabilization. Inappropriate construction on unsuitable terrain without adequate planning and measures also increased the likelihood of rock slope failures. Weather conditions, like freeze-thaw cycles, exert additional pressure on rock masses, while seismic events like earthquakes can further destabilize already fragile slopes. This type of seismic activity can cause subsidence movements, leading to slope failure as the land gradually sinks, disrupting the balance and stability of rock slopes. Research has shown that seismic activities in Malaysia, notably the earthquake in Ranau in 2015, have highlighted the vulnerability of slopes to landslides [54][65]. The seismic considerations in structural design, as emphasized after the Sumatra-Andaman earthquake, are crucial to preventing fatalities and injuries caused by structural failures during earthquakes [66]. Studies on bridges in Malaysia have shown varying seismic fragility curves, indicating different probabilities of damage levels based on pier heights and ground motion intensities [67]. Overall, seismic activities can trigger landslides and affect the structural integrity of various types of infrastructure in Malaysia, emphasizing the importance of seismic considerations in design and construction practices.

Due to Malaysia's geographical topography, which features steep hills and densely populated areas, the frequency of rock slope failures could increase. The risk of such failures has also significantly increased, particularly in Malaysia, due to the expansive infrastructure development within and around slopes [62]. There have been various methods in Malaysia to evaluate and reduce slope instability, such as rock mass classification systems, slope mass rating (SMR), including kinematic analysis [7][68]. Besides, geophysical techniques, including electrical resistivity and remote sensing tools such as light detection and ranging (LiDAR), have also been embraced to enhance rock slope stability investigations in the country [68][69]. Similarly, applying soil bioengineering techniques, especially on whole plants, has been identified as an alternative approach for slope stabilization, particularly in low to moderate-risk category slopes [62]. The combination of these efforts is germane to addressing the issues related to infrastructure development and natural factors that lead to failures in slope areas within Malaysia.

Rock slope failures in Malaysia can have severe consequences, as in Table 3, including human injuries or fatalities, property damage, economic disruption, and environmental damage. If these incidents were not mitigated, a chain reaction of impact could be extended in regions surrounding the rock slope failures. These incidents were also costly to resolve.

Table 3. Consequences of Rock Slope Failure

Consequences / Description	Ref.
Loss of Life and Injuries The 1993 Highland Towers collapse killed 48 people. Bukit Lanjan failure (2003) endangered a busy area, while rockfalls at Cheras, damaged property, requiring mitigation.	[7], [64]
Property Damage The Bukit Lanjan incident shut down a major expressway, highlighting the risk of severe property damage and traffic disruption.	[7]
Economic Disruption Slope failures in tourist areas lead to financial losses from disrupted tourism and damaged attractions. Repair, mitigation, and maintenance costs add further economic strain.	[64], [70]
Environmental Damage Slope failures accelerate soil erosion, damage habitats, and disrupt drainage. Sedimentation in waterways can harm flora and fauna, causing long-term ecological effects.	[71], [72]

For example, interruptions of transportation pathways (highways and railways) could produce decreased productivity, freight delays, and higher operational expenses. Another example involved repairing and rehabilitating damaged infrastructure, which created significant financial strain on relevant parties. Therefore, long-term implications could be concerning due to the negative financial impacts, impeding economic expansion, and advancement.

Considerable environmental concerns could be presented from rock slope failure incidents, in which waterway sedimentation, loss of habitat, and soil erosion could occur due to natural landscape modifications. These incidents can also lead to the contamination of water sources by releasing dangerous substances, posing threats to human health and aquatic ecosystems. Therefore, introducing sustainability principles in rock slope management strategies is essential to prioritize preventive actions and minimize the ecological impact of failures. This approach allows for identifying methods to mitigate rock slope failures, as shown in Table 4.

Monitoring and examining failure-prone areas using extensive tests and advanced technologies is essential. In high-risk slope areas, it is necessary to conduct comprehensive tests and utilize advanced monitoring techniques for both control and examination.

Table 4. Rock Slope Failure Mitigation Strategies

Method/ Approach	Key Points	Ref.
Rock Mass Classification & Rating (SMR, Kinematic Analysis)	Systematically evaluate rock-mass quality and discontinuity orientations to diagnose failure modes and prioritize mitigation.	[73], [74]
Geophysical & Remote Sensing (Electrical Resistivity, LiDAR)	Enhances slope investigations by imaging moisture and weak zones; delivers terrain/structural data for assessment, warning, and mitigation.	[75], [76]
Soil Bioengineering (Whole Plants)	Stabilizes low, moderate risk shallow slopes through root reinforcement and erosion control, providing sustainable mitigation alternatives.	[62], [77], [78]
Monitoring & Advanced Technologies (ERT, Passive Seismic, DInSAR, IoT, AI, MEMS)	Enables early warning and risk reduction by monitoring slope movements, moisture changes, and real-time data.	[79], [80], [81], [82]
Mitigation & Prevention (Rock Bolting, Drainage Systems, Retaining Walls)	Implemented after identifying vulnerable slopes to reinforce weak zones, control water flow, and stabilize failing rock masses.	[83], [84], [85], [86]
Regulations, Preparedness & Response	Requires strict geotechnical standards, effective emergency plans (rescue, communication, evacuation), and long-term recovery efforts like replanting.	[16], [87], [88]

Effective methods such as Electrical Resistivity Tomography (ERT) [75][89] can explore subsurface moisture dynamics, a key driver of slope failure events. Advanced monitoring measures like passive seismic monitoring [80] can detect changes in fundamental resonance frequencies and slope deformation, offering a deeper understanding of slope conditions.

Furthermore, contactless methods like DInSAR [79] can be used cost-effectively and efficiently to survey large areas for potential landslide hazards. Integrating technologies such as the Internet of Things (IoT) and Artificial Intelligence (AI) for monitoring soil hydrological conditions and tracking slope movements [81] will enhance early warning systems and reduce risk. The use of Micro Electro Mechanical Systems (MEMS) tilt sensor arrays in monitoring is another option, providing advances in early warning against potentially dangerous slope movements and enabling timely preventive measures, such as evacuation warnings for high-risk areas [82].

Moreover, incorporating the anticipated probability and timing of future failures should also be acquired in improved prediction models by delivering data regarding geological properties, rainfall, and seismic activity for specific mitigation initiatives. Subsequently, different mitigation and preventative techniques (rock bolting, drainage systems, retaining walls) can be implemented after vulnerable slopes are located [83].

Strict regulations and geotechnical expertise should be followed and incorporated into the infrastructure framework as preventive measures. Nonetheless, preparedness and response measures are still crucial if an incident occurs. A prompt and efficient response involving search and rescue operations, communication protocols, and evacuation methods can then be utilized. The long-term management should also include sustainability and recovery initiatives, such as replanting and post-failure recovery plans containing environmental factors.

Benchmarking our Findings Against Literature from Recent Studies

Our finding indicates that the performance of rock slopes is primarily controlled by three factors: unfavorable rock mass structures, such as steep, exposed discontinuities, weathering, and transient forces like rainfall and seismic activity. This aligns with recent studies from Malaysia that highlight the same dominant controls and note an increased risk as urban development expands into hillside areas [7]. The role of seismic loading is strongly supported by the 2015 M_w 6.0 Ranau earthquake. This event generated 5,198 slope movements across ~810 km², demonstrating that slopes with pre-existing structural weaknesses are highly susceptible to rapid failure during seismic shaking. This corroborates our finding that adverse geological structures can lead to co-seismic failure [54]. Additionally, our findings of hydroclimatic impacts reported for the same region further align with our consequence chain, which is multi-temporal satellite analyses show immediate channel adjustments after the earthquake and sustained, five-year geomorphic responses, underscoring how extreme events perturb slope river systems and amplify risk downstream [65]. Finally, our recommendations for risk assessment, continuous monitoring, and preparedness are consistent with current best practices. For example, high-temporal-resolution terrestrial Structure from Motion (SfM) has been used to quantify daily rockfall activity, and automated photo-monitoring systems are now extracting detailed rockfall inventories for hazard evaluation. These approaches support our call for implementing near-real-time surveillance systems for early warning and effective mitigation design [90][91]. In conclusion, our findings on the causes of slope failure, which include structural weaknesses, degradation, and transient forces, are consistently supported by prior research. This convergence with existing event inventories and monitoring studies also extends to the resulting multi-year systemic impacts and the recommended mitigation strategies, such as instrumented monitoring and preparedness. This alignment validates our conclusions and underscores the practical relevance of our recommendations.

CONCLUSION

This review successfully investigated the rock slope failure incidents in Malaysia by presenting the difficulties in areas with varied geological formations. By categorizing failures into types such as rock slides, rockfalls, and rock avalanches, and analyzing the factors affecting these incidents, including natural events such as weathering, heavy rainfall, seismic activity, and human activities, which collectively elevated the likelihood of rock slope failures (particularly during intense rainfall). This review also determined several issues, such as injuries, fatalities, and property damage. These issues demonstrated infrastructure disruptions, leading to economic expenses involving lower productivity, repair expenses, and transportation delays. Overall, Malaysia should use comprehensive mitigation solutions to achieve resilience and sustainability in dealing with rock slope failures. These solutions should include early warning systems, slope stabilizing techniques, and data-informed land-use planning.

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