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Mitigating Slope and Embankment Erosion in Malaysia: Case Studies and Integrated Approaches

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Abstract

Malaysia faces severe slope and embankment erosion, a critical geohazard driven by heavy rainfall, intense tropical weathering, and poorly planned development. This results in significant economic and human losses, with failures largely attributed to human factors in design, construction, and maintenance. Current mitigation employs conventional methods such as gabions for immediate stability and soft or bioengineering for ecological control. While integrated approaches are crucial, they face challenges in long-term performance, maintenance, and addressing systematic human errors, which contribute to 57% of landslides, 29% of structure or design factors and 14% of geological factors. This paper critically analyses integrated solutions in Malaysia, focusing on their long-term efficacy and capacity to mitigate human-induced vulnerabilities, aiming to provide actionable insights for resilient and sustainable erosion control.

1. Introduction

Slope and embankment failures, encompassing phenomena such as landslides and various forms of erosion, constitute a significant global geohazard, responsible for immense annual losses [1]. The worldwide economic impact of landslides is substantial, accounting for 0.53% of deaths and 14% of financial losses, collectively exceeding USD 1 billion [2]. Over the past two decades, the global economic damage attributable to landslides has increased by more than 147%, with Southeast Asia bearing a disproportionately large share of this damage [3]. This escalating trend highlights a critical regional vulnerability that extends beyond national boundaries. Understanding Malaysia's specific issues can thus offer valuable perspectives applicable to the broader regional context, as the problem is accelerating and concentrated in this part of the world.

Zulkafli & Majid [4] reported approximately 171 landslide cases in Malaysia between 2007 and 2016. There were approximately 440 landslide cases from 1973 to 2007, with 31 incidents resulting in around 600 fatalities, all of which occurred in Peninsular Malaysia [5]. Regions such as Penang Island are particularly vulnerable to landslides, which have led to devastating environmental impacts, the collapse of critical infrastructure, loss of arable land, and tragic loss of life. The consistent occurrence of these events across Cameron Highlands, Hulu Langat, Penang Island, and Kuala Lumpur indicates that slope erosion is not an isolated or localised issue but rather a pervasive national challenge with significant human and economic costs. The Sabah and Sarawak regions are also not exceptionally affected. Several landslide-related incidents had been reported. Due to the intense tropical weathering driven by these climate factors, Malaysia is highly vulnerable to slope erosion and instability, particularly along its extensive river systems and coastline. Supported by inventory data from NATSIS JMG (see Fig. 1), 9616 slopes across the nation have been inventoried by JMG, revealing notable variation in the distribution of critical slopes despite a consistent total number of slopes in Malaysia. Fig. 1 indicates 84 slopes considered as low-critical, 84 slopes as medium-critical, and 86 slopes considered as high-critical, summing to 254 critical slopes so far in Malaysia [6]. However, the Sabah and Sarawak regions are still not yet fully inventoried due to the geographical challenges.

Fig. 1 *Inventory of current slope in Malaysia in the year 2025 [6]*

Environmental deterioration, infrastructure damage, and potential risks to human safety have challenged engineers to develop effective designs that integrate conventional and innovative methods for both natural and man-made slopes and retaining structures. Furthermore, an unvegetated or bare slope, often faced with rapid urbanisation and extensive land clearing, is highly susceptible to erosion due to insufficient surface cover. The synergistic combination of exposed slopes, inadequate slope management practices, poor planning, and intense rainfall directly contributes to slope failures and landslides. Soil erosion, specifically, presents a significant and ongoing challenge in housing areas, leading to considerable property damage and losses.

Studies indicate that human error accounts for 57% of landslides, 29% are due to physical factors, and 14% are due to geological factors [7]. This paper aims to provide an overview of the challenges of slope and retaining wall erosion in Malaysia. Furthermore, it details typical stabilisation practices and categorises them into hard engineering, soft engineering (bioengineering), and integrated approaches. The objective is to distil effective strategies and highlight best practices that have emerged from Malaysia's experience in managing this critical geohazard.

2. Environmental and Geological Drivers of Erosion in Malaysia

Malaysia's geographical position within the tropical monsoon region makes it particularly susceptible to slope and embankment erosion, and it consistently ranks among the top 10 countries globally for landslide frequency [3]. The equatorial climate, characterised by intense and prolonged rainfall, is the primary natural trigger of slope failures and erosion [8]. A series of hydrological consequences, including higher groundwater tables, greater pore-water pressure, activation of seepage flow, and increased moisture content, result from this heavy precipitation. This significantly reduces overall slope stability and soil shear strength.

The tropical climate also drives intense chemical weathering and leaching, leading to the formation of deep, thick soil profiles known as saprolites [8]. Studies on basaltic regoliths in Malaysia reveal intense, rapid weathering, marked by extreme depletion of major elements and significant enrichment of iron and titanium, which can influence clay aggregation and overall soil structure [9]. Common soil types found in Malaysia's upland regions, such as Ultisols and Oxisols, are inherently acidic and particularly susceptible to erosion [10]. Furthermore, weathered granitic bedrocks, prevalent in many cut slopes, are considerably weaker than their consolidated counterparts, thereby further compromising slope stability [8].

(a) (b)

Fig. 2 *Slope erosion disaster in Malaysia (a) Batu- Inas, Kuala Pilah; and (b) Batang Kali, Selangor [11]*

Topographical and geological features also play a crucial role in slope stability. Steep, high slopes inherently require greater intrinsic strength to maintain stability [1], with hilly terrains featuring slope angles between 20 and 34 degrees being particularly susceptible to mass wasting [8]. This vulnerability is frequently compounded by human-induced modifications, such as extensive hillside cutting for highway development or the placement of heavy materials on already compromised slopes. Such interventions drastically alter natural gradients, frequently destabilizing man-made cut-slopes exceed 5-10m in height [8], as exemplified by the roadside cut-slope failure at Batu-Inas, Kuala Pilah (see Fig. 2(a)). While human activities often serve as primary catalyst for these failures, inherent geological discontinuities in residual soils further undermine long-term slope integrity [1].

This intense tropical weather generates deep, clay-rich, and chemically altered soil profiles (saprolite) that possess low shear strength. The catastrophic landslide at Batang kali, Selangor (see Fig. 2(b)), tragically illustrates this phenomenon, where prolonged heavy rainfall interacted with weathered saprolithic soils to trigger a massive, high velocity debris flow [10], [12]. This, slope instability in tropical climates is not merely a consequence of precipitation volume, but rather a dynamic interaction between rainfall and highly weathered geological profiles.

Consequently, rapid urbanization and extensive development on sensitive, high-relief terrain remain the primary drivers behind the escalating frequency and severity of landslides in Malaysia [3]. This upward trend highlights a fundamental friction between the demands of rapid economic expansion and the imperatives of environmental sustainability. It suggests that current engineering designs, zoning regulations, and maintenance protocols are either structurally insufficient or inadequately enforced to withstand the challenges of Malaysia's wet tropical environment. Ultimately, the persisting threat is not due to a lack of scientific understanding regarding landslide mechanics, but rather a systemic governance challenge in consistently implementing and enforcing robust mitigation strategies.

Table 1 shows the compilation of case studies of erosion incidents in Malaysia. A significant observation from various studies is the direct causal link between erosion and larger slope failures or landslides. Erosion is frequently identified as a primary trigger or an integral part of the failure mechanism, often described as "erosion-induced slope failure" or a process that "steers towards slope failures, which then result in landslides". This direct relationship highlights that addressing erosion in its incipient stages is crucial for preventing more catastrophic slope failures. The case studies reveal a persistent and evolving challenge of erosion and landslide incidents in Malaysia.

The years 1993 to 2012, encompassing incidents at Highland Towers, Bukit Antarabangsa, and Puncak Setiawangsa, consistently point to inadequate urban planning and engineering practices, particularly in drainage systems and slope design [1]. A critical pattern emerges where high pore water pressure, often exacerbated by prolonged rainfall as at Tanah Ringlet, Cameron Highlands [13], overwhelms compromised infrastructure. In contrast, more recent incidents from 2022 to 2024, such as those at Sungai Choh Riverbank [14] and Taman Mas, Puchong [15], underscore the increasing vulnerability of riverine and coastal environments to surface runoff and bank collapse. This shift in focus from engineered slopes to natural waterways suggests a broader systemic issue in which rapid development and climate-related hydrological changes intersect. The inclusion of a case involving insufficient reinforcement at Tabuan Heights [16] and Kuala Krai [17] further highlights a systemic failure in implementing robust mitigation strategies.

Managing erosion is therefore not merely about maintaining surface stability but constitutes a fundamental component of broader landslide prevention efforts, suggesting that early detection and preventative measures can be highly effective in reducing severe, destructive events. This is clearly demonstrated by the 2011 slope failure tragedies at Sungai Ruil, Cameron Highlands, and the Hidayah Madrasah Al-Taqwa Orphanage, Hulu Langat [18]. In these catastrophic events, active geomorphological processes—specifically severe erosion—were identified as primary drivers, contributing to critical hazard parameters of 54% and 39% respectively [18].

Referring to Fig. 1, NaTSIS JMG [6] categorised the high critical slope as showing the immediate and comprehensive remediation, often involving robust engineering solutions. In contrast, medium and low critical slopes might benefit from less intensive but equally important measures, such as enhanced monitoring, the deployment of early warning systems, and targeted stabilisation efforts. Effective mitigation, as underscored by the data, requires an integrated, multidisciplinary approach. This approach extends beyond conventional engineering solutions such as slope stabilisation, improved drainage systems, and the construction of reinforced structures, to encompass broader strategies.

Table 1 *Case studies of erosion and landslide incidents in Malaysia*

Incidents	Year	Primary Cause(s)
Highland Towers, Ulu Klang, Selangor [1]	1993	Urban slope failure, inadequate drainage, an uncompleted drainage system, poorly designed walls, and extensive terracing
Taman Hillview [1]	1993	Improper design practices, a poor drainage system, prolonged rain, and high pore water pressure
Bukit Antarabangsa, Kuala Lumpur [1]	2008	Improper design practices, a poor drainage system, prolonged rain, and high pore water pressure
Taman Zooview [1]	2006	Poorly maintained/damaged drainage on a failed slope, soil creeping
Sg Ruil, Cameron Highland & Hidayah Madrasah Al-Taqwa Orhanage, Hulu Langat [18]	2011	Geomorphological processes (including erosion), a high percentage of critical hazard parameters (54% and 39% respectively)
Puncak Setiawangsa [1]	2012	Loose soil from earth dumping, poorly maintained/damaged drainage, leaking water pipe, prolonged rainfall
Kuala Krai, Kelantan [17]	2014	Existing protection structures (gabion, concrete walls, vegetation) failed due to hydraulic action and structural issues, aggravated by subpar construction and insufficient maintenance
Sungai Choh Riverbank, Selangor [14]	2022	High surface runoff is causing severe erosion along approximately 200 m of the riverbank, posing a risk of collapse to nearby housing developments
Langkawi Federal Route [12]	2022	Continuous rainfall and a major landslide
Batang Kali, Hulu Selangor-Genting Highland [10]	2022	Continuous rain caused the soil structure to weaken, slope to become unstable
Malaysian Anti-Corruption Academy (MACA) and Malaysian Institute of Integrity (IIM), Kuala Lumpur [19]	2023	Leakage from the underground pipe and water accumulation after heavy rainfall.
Wisma YPR, Seputeh, Kuala Lumpur [19]	2023	Unstable retaining wall due to surface runoff caused by heavy rainfall
Tanah Rata-Ringlet, Cameron Highland [13]	2024	Heavy rainfall
Taman Mas, Puchong, Selangor [15]	2024	The unstable riverbank collapsed and submerged the water treatment plant project to a depth of 19 m
Tabuan Heights, Kuching, Sarawak [16]	2024	Continuous rainfall and no reinforcement mitigation cause the structure of the fence to collapse

3. Mitigation of Slope Stabilisation Practices in Malaysia

The occurrence of slope failure and retaining wall collapses in Malaysia is a multifaceted phenomenon governed by the interaction of geological, environmental, and anthropogenic factors as happened at Wisma MACA and YPR [19]. While general factors (rainfall, soil, human activity) are universally applicable, various case studies highlight regional variations in the *dominant* triggers and their specific combinations. This suggests that effective mitigation requires localised assessments and tailored solutions that prioritise the most potent regional factors, rather than a generic, one-size-fits-all approach. Erosion control techniques are critical interventions that mitigate soil loss and prevent slope failures, particularly in regions prone to heavy rainfall and unstable terrain, such as Malaysia. These techniques are generally categorised into vegetative, structural, and hybrid approaches. Recent advancements in erosion control emphasise their effectiveness, sustainability, and adaptability to local conditions.

Fig. 3 shows typical structural techniques for mitigating slope erosion and serving as retaining walls. There are various typical retaining wall systems used in Malaysia, such as gabion walls (gravity retaining walls), soil nailing, and guniting (shotcrete). This type of mitigation can be considered because of economic reasons. But it still has disadvantages, such as lateral pressure from backfill and soil movement. A gabion wall can topple if improper design and construction, i.e., inadequate wire connections or improper backfilling, contribute to instability and the risk of toppling. To mitigate the risk, a gabion wall or an omega wall can be integrated with geosynthetics (geogrids) to improve stability when encountering taller walls or challenging soil conditions.

(a)

(b)

Fig. 3 *(a) Gabion wall; and (b) Interlocking blocks known as Omega bricks*

Slopes that are denuded of vegetation or have insufficient surface cover become highly susceptible to erosion. The absence of plant cover means the soil surface is directly exposed to the erosive impact of rainfall, leading to rapid soil detachment and runoff. The repeated emphasis on "unvegetated or bare slopes are prone to erosion due to the lack of or insufficient surface cover" and the mention of shallow-rooted greenery used for aesthetics underscore that vegetation is not merely an aesthetic feature but a crucial engineering component for slope stability. Its removal or inadequate replacement significantly compromises soil integrity by reducing surface protection, root reinforcement, and infiltration control.

This indicates that reforestation, appropriate selection of deep-rooted plant species, and bioengineering solutions are not just "green" initiatives but essential, cost-effective engineering practices for long-term slope stabilisation and erosion control. Fig. 4 shows the hydroseeding and erosion-control blanket techniques (using paddy, palm, or coconut fibre) on the slope. The environmental impact of erosion control techniques is critical, particularly in ecologically sensitive areas. Sustainable techniques, such as vegetation cover and biodegradable erosion control blankets, are preferred for their ability to support biodiversity and integrate seamlessly into the natural environment.

(a)

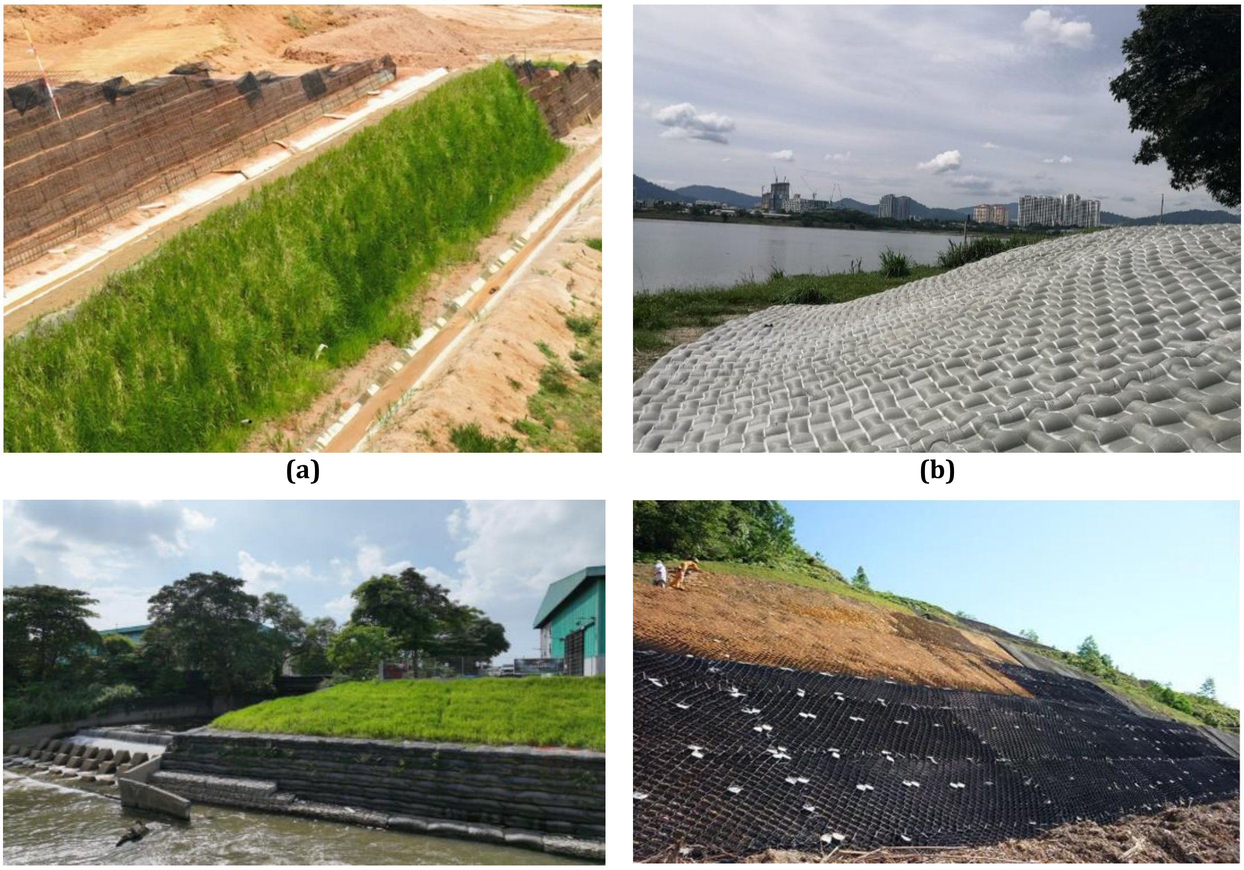
(b)

Fig. 4 *Vegetation slope (a) Erosion control blanket; and (b) Vegetation of signal grass on slope [20]*

Fig. 5 shows that the local company Fibromat (M) Berhad [20] has adopted an integrated approach. Integrated approaches that combine elements of structural and flexible engineering (geosynthetics) are increasingly adopted to address complex challenges in Malaysia. Several case studies illustrate the application and outcomes of their combined strategies. As presented in Table 1, all slope failures were mitigated using various techniques. For example, a slope repair project in Langkawi involved constructing a 30 m-high geosynthetics-reinforced slope integrated with a gabion [12]. This case exemplifies a sophisticated integration of structural reinforcement and bioengineering to rehabilitate a high, steep, failed slope. These include combinations such as gabion-soil nails on the front face of slopes, coupled with geogrid-geosynthetic systems and water-pressure dissipation channels on the back face [21].

In Fig. 5(a), the implementation of a geogrid wall, in conjunction with an erosion control blanket (ECB), serves a dual purpose: providing structural stability while promoting the establishment of a dense vegetative cover. This approach is mirrored in Fig. 5(b), Fig. 5(c) and Fig. 5(d), which demonstrate the strategic integration of both hard and soft engineering solutions. Fig. 5(c) shows the use of gabion mattresses as a hard, traditional method for riverbank stabilisation, while Fig. 5(b) and Fig. 5(d) highlights the soft-engineering technique of slope repair using geocells and hydroseeding to enhance both stability and landscape aesthetics.

Case studies, such as the Kuala Krai riverbank failure, where a mix of gabions, concrete walls, and vegetation failed due to severe erosion and floodwaters, highlight critical issues stemming from poor construction methods and inadequate maintenance [17]. Budget constraints also frequently lead to projects being implemented in stages or phases, which can compromise the overall effectiveness of the intended design protection [22]. While successful integrated and advanced mitigation strategies have been proposed and some case studies exist, there is a recurring theme of significant challenges to their widespread and effective implementation. Issues like poor construction, inadequate maintenance, budget constraints, and the inability of existing methods to consistently withstand extreme events suggest a substantial gap between theoretical knowledge and practical, long-term performance in Malaysia's dynamic environment. This situation points to the need for robust, adaptable, and economically viable integrated solutions that address not just the technical aspects but also the socio-economic and management realities that influence their success.



(a) (b)

(c) (d)

Fig. 5 *Integrated approaches (a) Geogrid wall incorporates ECB and hydroseeding at Johor Bahru; (b) Incomat Crib at Batu Muda, Selangor; (c) Gabion mattress integrated with PPW geobag, TRM securemat and hydroseeding at Subang; and (d) Slope repair using geocell and hydroseeding [20]*

4. Conclusion

The pervasive issue of slope and embankment erosion in Malaysia poses a significant and escalating threat, driven by a complex interplay of environmental factors, particularly intense rainfall and tropical weathering, and human-induced vulnerabilities. While Malaysia's rapid development has necessitated extensive infrastructure in challenging terrains, the historical record of frequent and costly landslides underscores a critical disconnect between developmental ambitions and effective, sustainable mitigation practices. A substantial portion of these failures is attributable to human factors, including design flaws, improper construction, and inadequate maintenance, highlighting a systemic challenge that extends beyond purely technical engineering solutions.

The analysis of the NATSIS JMG data for 2025 provides a crucial overview of Malaysia's slope stability landscape. Geographically, states such as Sabah, Johor, Kelantan, Pahang, Perak, and Terengganu exhibit the highest concentrations of critical slopes, highlighting regional vulnerabilities. While mitigation works have been completed for a small percentage of critical slopes (approximately 14.6%), the majority remain under monitoring or are awaiting active intervention, underscoring the considerable scale of the ongoing challenge.

Current mitigation strategies, encompassing both robust hard engineering and eco-friendly soft/bioengineering approaches, each possess distinct advantages and limitations. Hard structures offer immediate and strong protection but can incur high costs and environmental trade-offs, sometimes displacing erosion problems. Conversely, soft and bioengineering methods are sustainable and integrate with natural systems, yet their applicability is often limited to lower-risk scenarios, and their long-term performance, particularly for synthetic components, may degrade.

Despite successful integrated case studies, a notable gap persists between theoretical understanding of integrated solutions and their consistent, long-term, and resilient implementation in practice. Challenges such as poor construction quality, inadequate maintenance, and budget constraints frequently compromise the effectiveness of designed measures, especially when confronted with extreme weather events. This indicates a need for a more holistic approach that not only focuses on innovative technical solutions but also systematically addresses the socio-technical, policy, and long-term management dimensions critical to successful and sustainable erosion control.

This paper addresses these critical gaps by providing a comprehensive and critical analysis of integrated approaches to slope and embankment erosion control in Malaysia. It delves into the practicalities of integration, scrutinizes long-term performance and adaptability under specific Malaysian conditions, and explicitly examines how these approaches can mitigate human-induced vulnerabilities. By synthesizing existing knowledge and exploring the potential of innovative, eco-friendly integrated solutions, this study aims to offer actionable insights for practitioners, policymakers, and researchers. The goal is to foster the development and implementation of more resilient, cost-effective, and environmentally sustainable erosion control strategies, thereby safeguarding Malaysia's landscapes, infrastructure, and communities against future hazards.

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Conflict of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

Author Contribution

The authors confirm their contribution to the paper as follows: ***Draft manuscript preparation:*** *Siti Farhanah S. M Johan, Abang Nur'Iman Aiman Abang Mohamad Najib;* ***Data collection:*** *Noorhayatie Yusof. All authors reviewed the results and approved the final version of the manuscript.*

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