33RD ANNUAL PROFESSOR CHIN FUNG KEE MEMORIAL LECTURE

Presented at Malakoff Auditorium,
Wisma IEM, Petaling Jaya,
Selangor Darul Ehsan, Malaysia
on 21st October 2023

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He was also a member of the Commissioner of Enquiry (2013 – 2014) to investigate the causes of failure of the UMNO Building and collapse of Ramp 2 the Second Penang Bridge. Dato' Gue is the current Chairman of the Penang Technical Advisory Panel (since 2013) appointed by the Chief Minister of Penang.

In 2017, he was again appointed by the Governor of Penang as member of the Commissioner of Enquiry to investigate the causes of landslide at Taman Sri Bungah in Penang.

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LANDSLIDES: HOW, WHY AND THE WAY FORWARD

(Date received: 05.12.23/Date accepted: 28.12.23)

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ABSTRACT

Slopes sometimes slide and cause damage and disruptions for the public. Landslides can be triggered by a combination of natural factors such as intense and prolong rainfall, soil properties and steep gradient slope. Human activities such as deforestation, improper construction practices and inadequate drainage systems can also contribute to landslide occurrences. Landslide mitigation is crucial to reduce the loss of lives, protect infrastructures, and ensure public safety. Given that landslides occur more frequently during intense and prolong rainfall, it's important to have effective strategies in place to minimise their impacts. This paper aims to provide insights into the causes of landslides, their impacts, and effective strategies for mitigation. Examples of successful landslide mitigation and management initiatives are included. The comprehensive approach, which involves education, research, planning, and collaboration, has the potential to significantly mitigate landslides. The way forward is to establish a centralised slope agency to lead and assist local authorities is an important strategic move. This agency as an One Stop Centre (OSC) could provide expertise, guidance, and control for slope-related projects, ensuring that proper standards are met. The Centre also provides risk assessment of existing slopes, mitigation measures and carries out research and development on improving slope engineering. Collaboration between government agencies, academic institutions, industry professionals, and local communities is key to the success of landslide mitigation efforts.

Keywords: Landslide, Misconceptions on Slopes, Landslide Risk Assessment, Remediation Measures, Way Forward

1.0 INTRODUCTION

Malaysia experiences frequent landslides with a number of major slope failures with high casualties and economic losses. These are associated with the increased concentration of developments on steep terrain and close proximity to slopes in recent years.

The most recent and notorious example was the Batang Kali Landslide on 16 December 2022, where 31 lives were lost. Another notorious example was the collapse of the Block 1 apartment of Highland Tower and killed 48 people on 11 December 1993. These notorious landslides had aroused concern among government agencies and stakeholders on the safety of buildings on hillsites.

Climate conditions in Malaysia are characterised by relatively consistent temperature and pressure, high humidity and particularly abundant rainfall with annual rainfall intensity of over 2500mm. Most of the landslides in Malaysia are triggered by the high rainfall and more than 80% of landslides were caused by man-made factors mainly related to design and construction errors (Gue & Tan 2006).

Media coverage after a landslide often includes hypotheses and suggestions to prevent recurrence. Some of these are quite factual while other suggestions and comments are hasty and misleading. This paper aims to explain in simple terms with examples about how and why landslides occur. It also outlines some suggestions for landslide mitigation and improvements on slope engineering.

1.1 Anatomy of Landslides

Figure 1 shows a typical slope consisting of (i) ground profile with some vegetation, (ii) groundwater table, (iii) partially saturated soil above the groundwater table, (iv) saturated soil below the groundwater table and (v) weathered and/or competent rock.

In the analysis of slope stability to determine whether a slope is safe, potential slip surfaces (Figure 2) are postulated on a slope cross-section. These slip surfaces are analysed in terms of the total driving forces and total resisting forces. The factor of safety (FOS) is determined from the ratio of resisting forces to driving forces. The lowest FOS is the critical stability of the slope.

With the above features of a typical slope, this paper describes several fundamental concepts found in slope stability. The first concept is friction. Friction is generated between two bodies when the bodies are moving against each other as shown in Figure 3. From the illustration, there is a normal force (N) causing the two bodies to come in contact, a driving force (T) and frictional resistance (F). Two important events arise: (1) If T increases, F also increases until a limit in which the two bodies will slide against each other; (2) As N increases, F increases as well. F is a function of soil properties and the weight of the two bodies in contact.

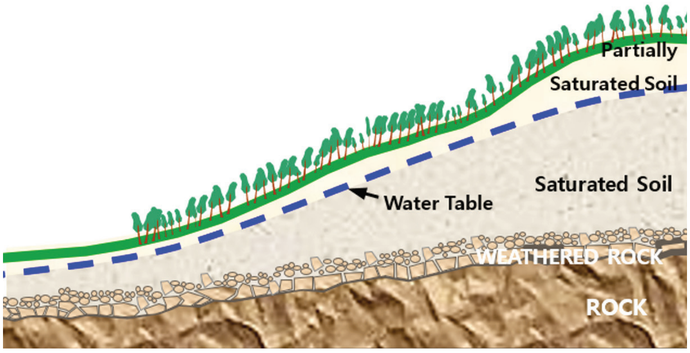

Figure 1: Anatomy of a Typical Slope (Gue & Tan 2003)

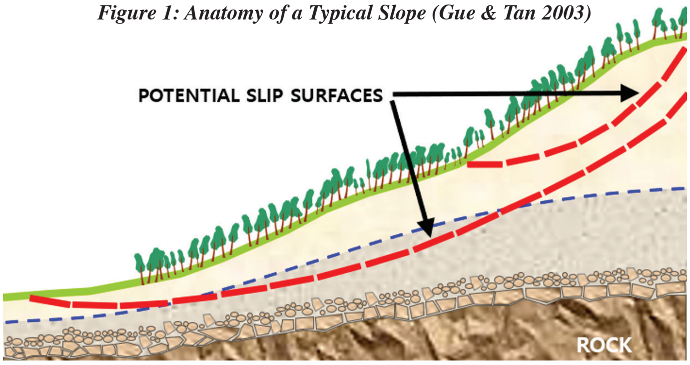

Figure 2: Potential Slip Surfaces (Gue & Tan 2003)

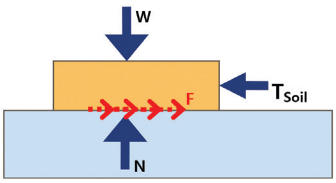

Figure 3: Concept of Friction (Gue & Fong 2003)

In slope stability, the main properties of soil for slope analysis are soil unit weight (γ), apparent cohesion (c'), and friction angle (ø'). Relating the earlier concept of friction to slope stability, the forces N and T can be replaced by the force components in the slope; N is analogous to the self-weight of the soil, F is the shear resistance at the potential slip surface and T is the driving forces caused by soil self-weight and/or surcharge (Figure 4). The governing equation for the resistance of the potential slip surface to shearing is based on the Mohr-Coulomb equation:

$$\tau = (\sigma_n - u)\tan(\phi') + c'$$

Where τ is shear stress, σ_n is the normal vertical stress, u is the pore water pressure, ø' and c' are the friction angle and apparent cohesion of soil respectively.

Therefore, in a slope stability analysis, a slope is unstable when the summation of shear force or resistance along the potential slip surface is less than the driving forces.

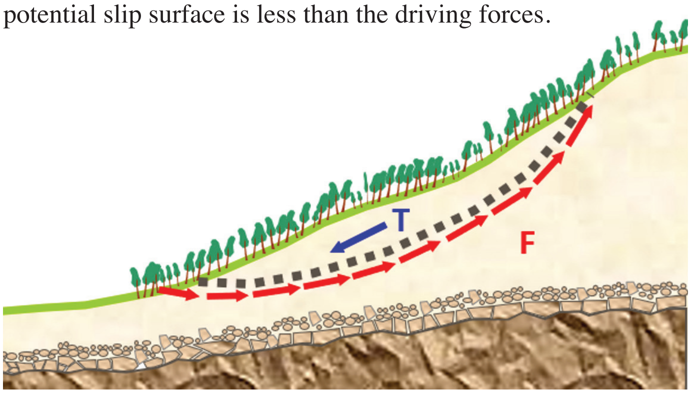

Figure 4: Friction Concepts in Slope (Gue & Fong 2003)

The second concept is the role of water pressure in slope stability analysis. In soil, water pressure exists if the soil is below the groundwater table (saturated soil). The main effect of water pressure on a sliding plane is the reduction of normal pressure or forces on soil particles to soil particles at contact. Thus, the shear stress is reduced and correspondingly the shear resistance is also reduced.

The third concept is suction. Suction occurs in partially saturated soils where water is drawn out of the voids between soil particles mainly through evaporation. This creates a vacuum effect pulling the soil particles together, which increases normal pressure, or forces on the soil particles thereby increasing the shear resistance. However, the suction effect in slopes is temporary and is easily diminished when water re-enters into the voids (for example, infiltration during prolonged rainfall).

1.2 Factors Attributed to Landslides

A study of causes of landslides such as design and construction errors, geological features, and maintenance was carried out by Gue & Tan (2006) based on 49 case investigations of primarily large landslides in residual soils. The results of the study are shown in Table 1.

Table 1: Causes of Landslides (Gue & Tan 2006)

Causes of Landslides	Number of Cases	Percentage (%)
Design errors	29	60
Construction errors	4	8
Design and construction errors	10	20
Geological features	3	6
Maintenance	3	6
Total	49	100

The results of the investigations indicate that 60% of the failures are directly due to inadequacy in design alone. The inadequacy in design was generally due to a lack of understanding and appreciation of the subsoil conditions and geotechnical issues. Failures due to construction errors alone, either of workmanship, materials or lack of supervision contributed to 8% of the total cases of landslides. About 20% of the landslides investigated were caused by a combination of design and construction errors. For landslides in residual soil slopes, the landslide caused by geological features only accounted for 6%, the same as the percentage contributed by lack of maintenance.

1.2.1 Design and Construction Errors

The majority of these failures investigated by Gue & Tan (2006) were avoidable if extra care had been taken and input from engineers with relevant experience in geotechnical engineering had been sought from the planning to the construction stages. Many of the landslides which were caused by design errors reported above happened due to the following reasons:

- The abuse of the prescriptive method on the slope gradient (slope angle) adopted for cut or fill slopes without proper geotechnical analyses and assessments. It is common in Malaysia to find many cut slopes formed for residual soils that are 1V:1H (which means one vertical: one horizontal i.e. 45 degrees angle). Based on literature published on residual soils and the author's own experience in residual soils, it is very unlikely, for residual soils to have the effective parameters (c', ø') to maintain the stability of high slopes even without water table and geological features unless it is a rock slope. The author's own experiences indicate that the ø' values of residual soils are generally in the range of 29° to 36° and mainly depend on the particle size distribution of the materials. Therefore, if proper analyses of the slope stability were carried out with correct soil parameters, most of these 45° gradient slopes would not have a sufficient factor of safety (FOS) recommended against slip failure in the long term, even with some effective cohesion. In summary, engineers should not prescribe slope gradients (e.g. 1V:1H) without proper geotechnical investigation, analysis, and design.

- Subsurface investigation (S.I.) and laboratory tests were not carried out to obtain representative soil parameters, subsoil, and groundwater profiles for the design and analysis of slopes. Therefore, analyses and designs carried out were not representative of the actual site conditions and thus were unsafe.
- A lack of good understanding of fundamental soil mechanics, such as the most critical long-term condition of cut slopes i.e. the "Drained Condition". Therefore, it is necessary to adopt effective shear strength parameters for the "Drained Analysis" for cut slopes in residual soils instead of undrained shear strength (s_u or c_u).

For landslides that were caused by construction errors alone or combined with design errors, the reasons are as follows:

- Tipping or dumping of loose fill materials down slopes to form a filled platform or filled slope which is contrary to the normal specification for earthworks. This is a construction deviation for earthworks construction in Malaysia. Contractors carrying out the filling works on slopes find it convenient and easy to dump or tip soils down slopes to form fill slopes. The condition is worsened by not removing the vegetation on slopes, causing the bio-degradable materials to be trapped beneath the fill, forming a potential slip plane with the bio-degradable materials (vegetation). The improperly compacted fill slopes, having a very low Factor of Safety, are likely to fail in the long term.
- Over-excavation of cut slopes. Contractors unintentionally over-excavate cut slopes and then try to fill back the excavated materials to reform the slope to the required gradient. The improperly compacted loose materials eventually slip.

Failure of slopes and retaining walls can also take place if the temporary works (e.g. temporary excavation) are not properly designed and constructed. The way to prevent these bad construction practices is to strictly enforce full-time supervision legally required by Inspectors of Works (IOW) of the design consultant together with reliable and responsible earthwork contractors having clear approved method statements with quality control for construction.

1.2.2 Maintenance

Poorly maintained slopes can lead to slope failures. These include damaged/cracked drains, inadequate surface erosion control, and clogged drains. The common problem of landslides caused by lack of maintenance is clogged drains. Clogged drains often cause large volumes of water to gush down slopes, eroding it and later the formation of gullies. These gullies then further deteriorate and this finally leads to landslides.

Figure 5 shows the formation of rills and gullies and Figure 6 shows localised landslips caused by erosion which propagated with time into landslides when maintenance was ignored. If proper maintenance was carried out, then these small defects would have been rectified and landslides caused by erosion would have been prevented.

Figure 5: Gullies on Slope (Gue & Tan 2003)

Figure 6: Localised Erosion on Slope (Gue & Tan 2003)

1.2.3 Geological Features

Landslides due to geological features contributed to about 6% of total failures investigated. However, it should be recognised that these geological features, such as discontinuities in residual soils, especially sedimentary formations, are usually difficult to detect during the design stage even with extensive subsurface investigation (e.g. boreholes, geophysical methods) by an experienced engineering geologist or engineer who carries out geological mapping at the site prior to cutting. Most of these geological features can only be detected after exposing the slopes during excavation. Therefore, it is better to carry out confirmatory geological slope mapping of the exposed slopes after excavation by an experienced engineering geologist or geotechnical engineer to detect any geological discontinuities that may contribute to potential failure mechanisms, namely planar sliding, anticline sliding, active-passive wedges, etc.

Since geological discontinuities could not be fully addressed during the design stage, design engineers should make conservative assumptions for the soil/rock parameters and the groundwater profile to ensure adequacy in design. Besides that, they should only carry out adjustments on site after geological slope re-mapping and re-analysis of the cut slopes. When optimistic assumptions were made during the design stage and the results obtained during construction on sites that were less favorable, expensive options such as retaining walls or slope strengthening using soil nails are required due to space and boundary constraints. Thus, the safety of slopes may be compromised due to unbudgeted strengthening and additional protection works being needed.

1.3 Abuse of the Prescriptive Method

The abuse of the prescriptive method by engineers on the selection of slope gradient (slope angle) to be adopted for cut or fill slopes has been adopted in Malaysia. In these cases, the slope gradient was specified without proper geotechnical analyses. It is common in Malaysia to find many residual soil cut slopes that are 1V:1H (which means one vertical: one horizontal i.e. 45° angle).

The proposed gradient of 1V:1H was borrowed from obsolete methods for slopes along roads adopted in the early sixties and seventies in Malaysia. This obsolete method does not warrant an adequate FOS against failure required for slopes with high risks to life (to take care of public safety) and high risks of economic losses. The FOS against slope failure recommended for high risk-to-life and high economic risk is 1.4. In addition, previous slopes along roads are common with low heights, either one to two berms height (less than 10m) and therefore the impact of landslide is less severe. There are incidents indicating that the abuses of the prescriptive method are also extended to retaining walls and soil nailed slopes. This is of major concern for the safety of the public as the consequences of failure of high walls or high soil nailed slopes are much more severe.

In order to show the danger of specifying unsafe slope gradients, a simple stability analysis for a typical cut slope and soil nailed slopes using soil strength parameters that are common for residual soils was conducted. Figure 7 shows a typical cut slope in residual soil with a slope gradient of 1V:1H (45 degrees), based on a soil strength of c'=1kPa and ø'=33° which is a typical value for residual soils in Malaysia. The FOS obtained is 1.0 (imminent failure) even without groundwater and geological features. However, if the soil has higher shear strength (c'- ø'), then the FOS will increase and vice versa if the shear strength is lower. Design engineers must be aware that every slope should be designed based on the representative soil strength parameters, groundwater levels, unit weights, and correct geometry instead of relying on bad past experiences using the prescriptive method. Although there are many cut slopes in Malaysia that are 45° and did not fail, these slopes are either assisted by suction (which is not reliable in the long term) or they are weathered rocks (class II to III) with high effective shear strength. Understanding fundamental soil mechanics is necessary when designing slopes to prevent failures.

Figure 8 shows the typical soil nailed slopes in residual soil with a slope gradient of 4V:1H, based on a soil strength of c'=1kPa and ø'=33°. For all four analyses, the length of soil nails adopted is 9m. The FOS of a single berm soil nailed slope (5m high) with and without groundwater is higher than required at 1.4. However, when the height of the slopes increases to three (3) berms, the FOS reduces to 1.2 and 1.1 respectively for slopes with groundwater. It is obvious that as the height of the slope increases, the length of the nails should be increased and should be at closer spacing to improve the FOS. Liew & Liong (2006) highlighted two cases of soil nailed slopes failures and Chow & Tan (2006) presented design methodologies for proper design of soil nails. In summary, it is dangerous to abuse the prescriptive method and not carry out proper design for slopes, either reinforced or unreinforced.

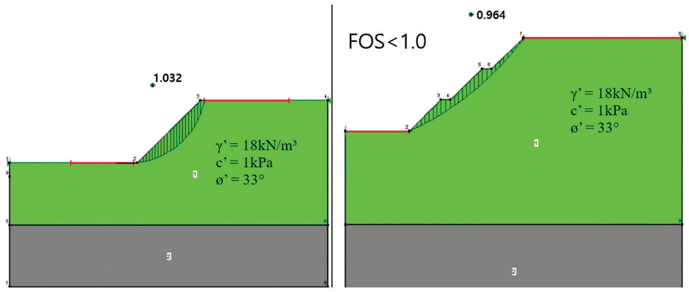

Figure 7: Insufficient Factor of Safety (FOS) for 1V:1H (45 degrees) slope based on moderately conservative soil parameters and groundwater profile (Gue & Tan 2006)

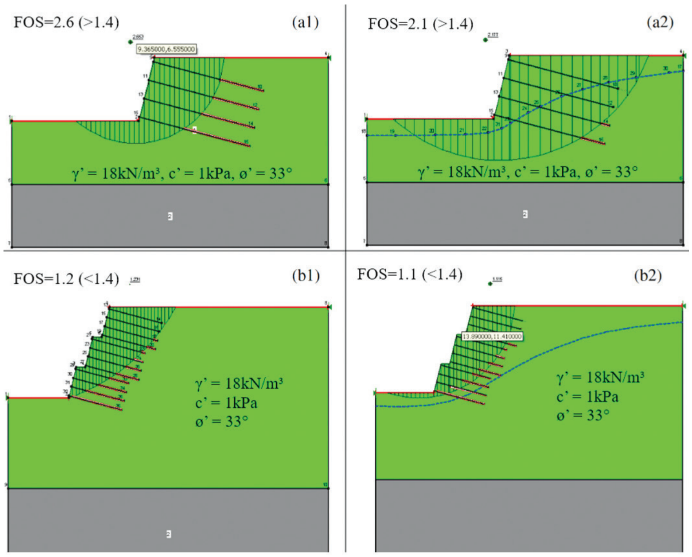

Figure 8: FOS obtained for soil nailed slopes with 9m length nails (Gue & Tan 2006)

Another example of errors in design or construction is adopting a design for other configurations without further analysis. Figure 9 shows common errors that have occurred in Malaysia. Figure 9a shows a rubble wall which is properly designed with adequate FOS against bearing capacity, sliding, overturning, and slip failure. However, due to site conditions, the retained height was increased on site. The wall was constructed wrongly (Figure 9b) following the original drawings without changing the base width (W) despite the height (h2) had been increased. Another example of design error where the sloping backfill was not taken into account (Figure 9c), where the base width (W) is same as the one without sloping backfill (Figure 9a). Therefore, the adopted wall without detailed analyses is not safe and could fail. Figure 10 shows a picture of the Taman Hillview failure site and Figure 11 shows an unsafe and unengineered rubble wall after failure.

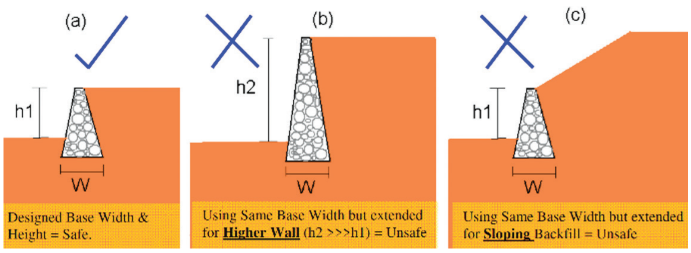

Figure 9: Example of design errors for rubble walls (Gue & Tan 2006)

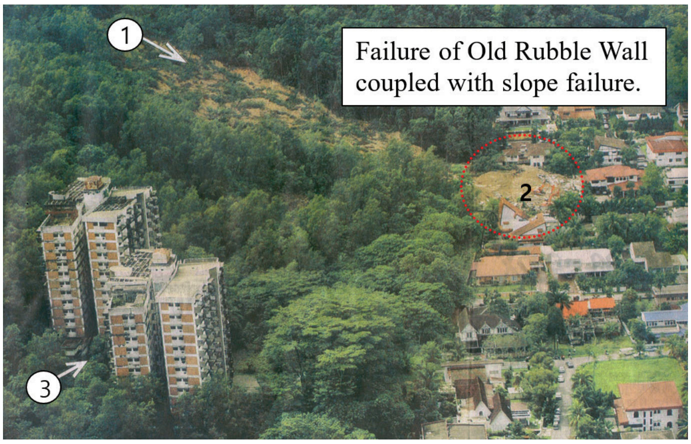

Figure 10: Wall and Slope failures at Taman Hillview (2002). (1) Location of unsafe rubble wall that failed (2) Location of collapsed bungalow (3) Remaining two blocks of Highland Tower that collapsed in 1993 (Gue & Tan 2006)

Figure 11: Collapsed rubble wall at Taman Hillview failure site (Gue & Tan 2006)

2.0 COMMON MISCONCEPTIONS

Gue & Fong (2003) highlighted some of the common misconceptions often appear in media about slope safety and explained the misconceptions which include the following:

- Soil tests show that the slope is safe
- Heavy rain causes slope failures
- Erosion will not cause slope failures
- Retaining walls always prevent slope failures
- Slopes are maintenance free
- Slopes have been standing for more than 10 years, so natural slopes are safe
- EIA reports ensure safety
- Geological reports show that the slope is safe

Another common misconception is that slopes at higher altitudes are inherently unsafe. This belief is not accurate, as one of the primary factors determining slope safety is the gradient of the slope itself, rather than its altitude. Safety on slopes depends on various factors, including geological conditions, soil properties, vegetation, and erosion control measures. Therefore, the specific characteristics of a slope shall be assessed rather than making generalized assumptions based solely on its altitude.

3.0 IMPORTANT ACTIONS FOR SUSTAINABLE HILLSITE DEVELOPMENT

Sustainable hillsite development requires a holistic approach that considers the natural environment and terrain-specific characteristics. It's crucial to work with geological and environmental experts where required and follow local regulations and best practices to ensure the long-term stability and safety of hillsite developments while minimising their environmental impact.

3.1 Optimised Earthworks

When planning construction on a hillsite, the designer shall exercise caution when determining where and how to excavate or add fill to the terrain. This careful consideration helps optimise earthworks by minimising unnecessary disturbance to the natural landscape. Additionally, the implementation of techniques such as selective terracing can significantly reduce the requirement for extensive earthworks and concurrently mitigate erosion risks.

Although retaining walls and soil nailing is generally more costly than normal earthwork solutions, however with proper planning, the use of these retaining systems at critical areas will be effective in reducing significant earthworks that are more expensive as shown in Figure 12.

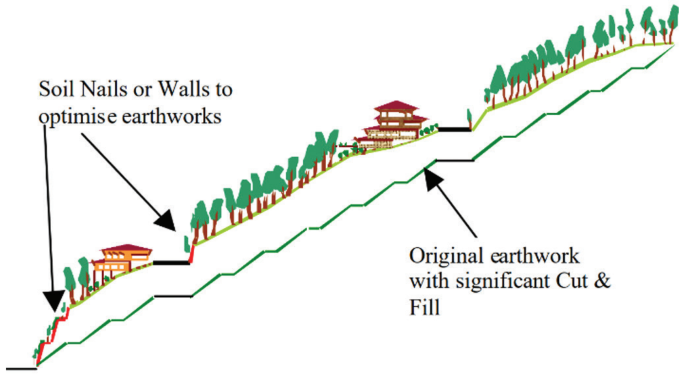

Figure 12: Method to Optimise Earthworks (Gue & Tan 2003)

3.2 Treatment for Existing Water Flow

Understanding and managing natural water flow on the hillsite is vital. Redirecting water without due consideration can result in adverse consequences like erosion, landslides, and flooding. Therefore, strategies such as contour forming or swales enable the natural management and control of water flow, thereby promoting sustainable hillsite development.

When construction necessitates the placement of fill over an existing valley or intermittent stream, it is recommended to incorporate subsoil drainage systems as shown in Figure 13. These drainage systems serve the purpose of diverting water from the upstream area to the designated final discharge point.

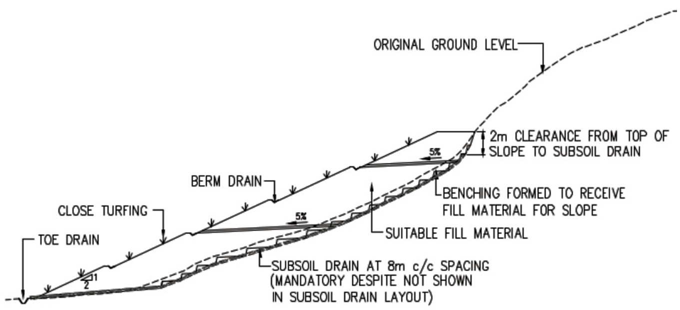

Figure 13: Typical details of subsoil drains

Moreover, in cases where dominant depressions are identified within the untouched terrain upstream of the planned slopes, it is advisable to create dry creeks as shown in Figure 14. These dry creek beds are designed to capture minimal surface runoff on the original, undisturbed terrain, particularly in areas susceptible to continuous surface erosion along the depression zone. This approach helps in effectively managing water flow while minimising erosion risks in critical areas.

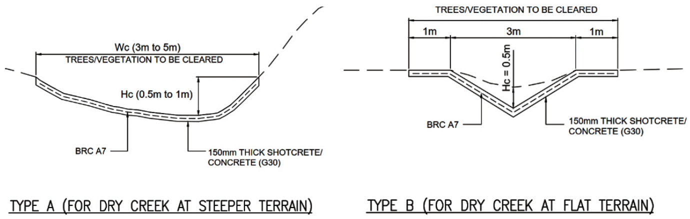

Figure 14: Typical details for dry creek along depression area on original untouched terrain

3.3 Proper Drainage System

To ensure effective management of water runoff, it is crucial to establish a comprehensive drainage system. This system should be designed to capture and divert water away from vulnerable areas. A network of channels, culverts, and retention basins shall be implemented strategically to manage water runoff effectively and mitigate the risk of erosion.

At the interface between cut and fill embankments, the installation of reinforced concrete (RC) drains is required to provide a durable and stable means of channeling water away from this transition zone. Besides that, drainage systems at the interface between cut and filled embankments shall be properly connected to downstream drainage infrastructure. This interconnected approach facilitates the continuous flow of water away from the hillsite and towards designated discharge areas.

By incorporating these measures into the design and construction of the drainage system, the risk of erosion and water-related issues in hillsite developments can be significantly reduced, contributing to the long-term sustainability of the slopes.

3.4 Proper Slope Toe Protection Structures

To safeguard against erosion and enhance slope stability in hillsite development, it is strongly recommended to install erosion control structures such as riprap, particularly when there is water flow along the slope toe as shown in Figure 15. These structures play a critical role in reinforcing the hillsite's integrity by effectively managing water flow and preserving slope stability.

Figure 15: Sample photo of slope toe with erosion control structures (Source: https://www.youtube.com/watch?v=GS0aL9FX0vo)

3.5 Regular Slope Maintenance

Sustaining the stability of a hillsite requires ongoing maintenance. It is imperative to consistently inspect and promptly address any erosions, soil displacements, or loss of vegetation.

3.6 Landslide Risk Reduction Strategy

To effectively manage landslide risks, initiate a thorough landslide risk assessment encompassing various crucial elements. This assessment entails the evaluation of geological conditions, slope gradients, soil properties, and the examination of historical landslide data. Following this assessment, formulate a comprehensive risk reduction strategy, which may encompass slope stabilisation such as application of soil nails, rock bolts, or the installation of rock catch fences. This strategy should be tailored to the specific conditions and vulnerabilities identified during the assessment.

4.0 THE WAY FORWARD

The majority of the landslides as discussed in Section 1 were avoidable if extra care taken and input from engineers with relevant experience in geotechnical engineering was utilised from planning to construction.

Hence, it is crucial to improve the current practice of slope management and engineering to avoid the recurrence of failures. Figure 16 summarises the identified key areas where improvement and initiatives are needed in slope management and engineering.

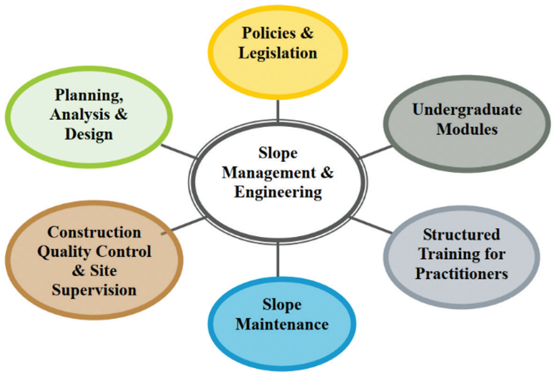

Figure 16: Key areas for improvement in slope management and engineering (Gue & Wong 2008)

4.1 Policies and Legislation

The first authority to document hillsite development guidelines was the Urban and Rural Planning Development in 1997. The guidelines addressed the issues of planning and development in Highlands on slopes, natural waterways, and water catchment areas (Abdullah *et al*. 2007). In June 2002, the Minerals and GeoScience Department Malaysia produced guidelines on hillsite development. The guidelines considered the angle of natural slopes, type of terrain, type of activity, severity of erosion and extent of vegetation. Terrain could be classified into four categories termed Classes I, II, III and IV. Class I is the least severe in terms of terrain grading whereby slope angles are less than 15°. Class IV is for slopes with an angle of more than 35° and is classified as the highest risk, where no development is allowed.

Apart from this, there are also numerous other guidelines and regulations related to slope management from the following government and private agencies:

a) Department of Environment (DOE)
b) Minerals and GeoScience Department (JMG)
c) Majlis Perbandaran Ampang Jaya (MPAJ)
d) Ministry of Housing and Local Governments (MHLG)
e) Urban and Rural Planning Department (JBPD)

f) The Institution of Engineers, Malaysia (IEM)
g) Penang Safety Guideline for Hillsite Development

However, some of these guidelines and regulations are unclear and do not add value in terms of safety enhancement, slope stability and protection, environmental friendliness and sustainability of engineering projects. These guidelines and regulations should be harmonised and improved by developing unified guidelines for good practices in planning, designing, construction, site supervision, maintenance and monitoring of engineered slopes. The Institution of Engineers, Malaysia (IEM), under its own initiative, formed a task force in 1999 to formulate policies and procedures for mitigating the risk of landslides in hillsite development. IEM (2002) produced a Position Paper for Mitigating the Risk of Landslide on Hill-Site Development and updated the updated policies and procedures in 2009, with the aim of providing uniform, consistent, and effective policies and procedures for consideration and implementation by the Government of Malaysia. However, the recommendations proposed by IEM were not readily accepted and acted on by the Government – the main stakeholder. The two recommendations implemented by the Government of Malaysia after the collapse of the bungalow at Taman Hillview are as follows:

a) The establishment of a centralised agency for slope management and engineering under the Minister of Housing and Local Government. However, Malaysian Government appointed Public Work Department (PWD) to set up the centralized agency called Slope Engineering Branch of PWD; and
b) The introduction of accredited checkers for geotechnical and structural works for hillsite development by The Board of Engineers, Malaysia.

Consequently, the current legal and regulatory framework should be reviewed and enhanced, including policies and legislation on landslide risk reduction management, mechanisms and processes in enforcement etc. In the aspect of development planning, the relevant policy should cut across development in both urban and rural areas for housing, infrastructure, agriculture, forestry, mining, etc. Procedures and guidelines on planning and implementation should incorporate an effective risk assessment and mitigation system with attention to possible environmental impact, mitigation, enhancement and sustainability. The Malaysian legal framework can be enhanced by emulating certain provisions in the legal and regulatory framework for development planning used by Hong Kong (Chan, 2007), Italy (Casale and Margottini, 1999), etc. For areas where field mapping has been done and hazard maps are available, these should be used to evaluate the level of inherent hazard on site and an appropriate approval procedure may be implemented. As the Slope Engineering Branch of PWD has already started with ground mapping to produce hazard maps for sensitive areas like Ulu Klang, usage of such hazard maps should be incorporated into the current system of development approval and enforcement.

The main stakeholders involved in the harmonisation and standardisation of policies and legislation are illustrated in Figure 17. Participation from these stakeholders is very important for the success of developing comprehensive policies and regulations for subsequent implementation.

In order to achieve improvements in landslide mitigation and risk reduction, success at the implementation stage is vital. Two different stages of implementation are identified and they are the preparedness stage and the mitigation stage. In the preparedness stage, the appropriate laws and regulations, implementation and enforcement policies and guidelines for development planning, training schemes for stakeholders and promotion schemes for community awareness should be geared towards effective landslide mitigation and risk reduction management.

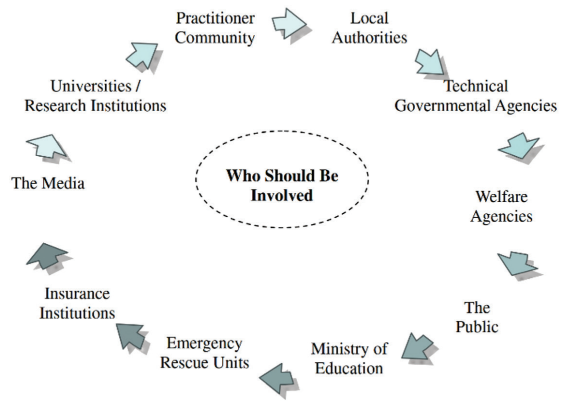

Figure 17: Formation and Implementation of a National Slope Master Plan (Gue & Wong 2008)

In the mitigation stage, significant resource allocation from the main stakeholders is essential as this consists of planning and enforcement of good practices in new development, retrofitting of existing high-risk areas, research and development and exploring advancement in technology and methodology. A similar approach has been adopted in Hong Kong where landslide mitigation and risk reduction have been incorporated into two components, first in planning control of new developments, and subsequently in retrofitting existing slopes at risk (Chan, 2007). Figure 18 illustrates the success of Hong Kong's Geotechnical Engineering Office (GEO) in reducing the risk of landslides. Such policies have contributed significantly to landslide mitigation and risk reduction in Hong Kong with tremendous success. Furthermore, the entire implementation procedure should be entrenched with a "check and review" or audit benchmarking system for continuous policy refinement. With that, the formulated template of a National Slope Master Plan may become a flagship programme, serving as a blueprint for a structured and systematic implementation plan.

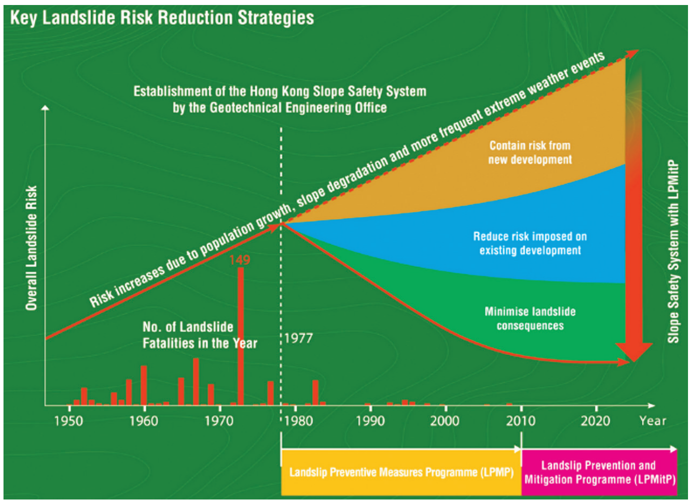

Figure 18: Key Landslide Risk Reduction Strategies
(Source: GEO, Civil Engineering and Development Department, CEDD's website)

For the way forward, it is recommended to establish an Independent Centralised Federal Agency to manage hillsite developments and mitigate landslides where the scope shall include:

- Approval & control of new slopes
- A One Stop Center (OSC) with expertise in slopes
- Risk assessment of existing slopes
- R&D and improvement on slope engineering

4.2 Planning, Analysis and Design of Slopes

4.2.1 Desk Study

Desk study includes reviewing of geological maps, memoirs, topographic maps and aerial photographs of the site and adjacent areas so that the engineers are aware of the geology of the site, geomorphology features, previous and present land use, current developments, construction activities, problem areas such as previous slope failures, etc.

4.2.2 Site Reconnaissance

Site reconnaissance is required to confirm the information acquired from the desk study and also to obtain additional information from the site. For a hillsite development, it is also very important to locate and study the existing landslip features that can act as indicators of the stability of a site.

4.2.3 Subsurface Investigation

Subsurface Investigation (SI) should be properly planned to obtain representative subsurface conditions of the whole slope such as the profiles of soils, bedrock, geological weak zones, clay seams or layers, and groundwater profile. The planning of exploratory boreholes should take into consideration of slope profile instead of following a general grid pattern. A minimum of three boreholes per cross-section (one on slope crest, one at mid-slope and one at slope toe) is recommended to obtain representative subsurface conditions of a whole slope. In addition, the design engineer must attempt to identify clay seams with the potential of inducing a perch water profile. This could be done by superimposing the classification of subsoil in proportion on the cross-section of a slope, as shown in Figure 19 to examine its influence on the stability of a slope.

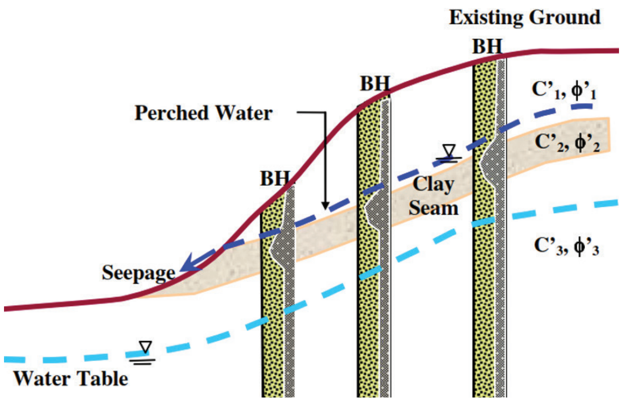

Figure 19: Potential Clay Seam on Slope (Gue & Wong 2008)

4.2.4 Analysis and Design of Slopes

The design of slopes should use correct information on soil properties, groundwater profile, site geology, selection and methodology for analysis, which are important factors that require the special attention of design engineers. A detailed analysis of soil slopes can be found in Tan & Chow (2004) and Gue & Tan (2000).

Selection of FOS against a slope failure should follow the recommendations of the Geotechnical Manual for Slopes (GEO, 2000) of Hong Kong, with minor modifications to suit local conditions, which are normally selected with consideration to two main factors, namely, Risk-to-life or Consequence to life (e.g. casualties) and Economic Risk or Consequence (e.g. damage to property or services). Further details on the selection of FOS can be found in Gue & Tan (2000).

4.2.5 Design of Cut and Fill Slopes

The vertical interval of slopes between intermediate berms is usually 5m - 6m in Malaysia. GEO (2000) recommends that the vertical interval of slopes should not be more than 7.5m. The berms must be at least 1.5m wide for easy maintenance. The purpose of berms with drains is to reduce the volume and velocity of runoff on the slope surface and the consequent reduction of erosion potential. The adopted slope gradient and berm height should depend on the results of analyses and designs based on moderately conservative strength parameters and representative groundwater profiles.

For fill slopes, vegetation, topsoil and any other unsuitable materials should be properly removed before placing of fill. The foundation should also be benched for keying fill into an existing slope. A free-draining layer conforming to the filter criteria is normally required between the fill and natural ground to eliminate the possibility of pore pressure developing and causing slope instability, especially when there are existing intermittent streams and depressions. Sufficient numbers of discharge drains should also be placed to collect the water in the filter layer and discharge it outside the limits of the fill and away from the slope.

4.2.6 Surface Protection and Drainage

Surface drainage and protection are necessary to maintain the stability of the designed slopes through reduction of infiltration and erosion caused by heavy rain, especially during monsoon seasons. Runoffs from both slopes and catchment areas above a slope should be effectively cut off, collected and led to convenient safe points of discharge away from the slopes. Details on surface protection and drainage can be found in Gue & Tan (2000).

4.2.7 Catchment Study

Catchment study should be carried out for the provision of surface drainage capacity. Under-provision of surface and subsurface drainages can lead to infiltration and spillage of the surface runoffs to slopes, causing surface erosions and resulting in slope deterioration over time which may trigger landslides.

4.2.8 Fill Slopes Over Depressions and Valleys

Depressions and valleys are the preferred water path of natural surface runoffs. Streams or intermittent streams are usually formed at depressions and valleys, especially during heavy rain. Intermittent streams at depressions or valleys also transport sediments from upstream and deposit these sediments at the depression or valley and form a layer of soft or loose material with debris. For slopes which are formed by filling over a depression or valley, the possibility of saturation of slopes and slip planes through the pre-existence of weak, soft or loose layers with debris is high.

Therefore, extra care should be taken on the fill slopes over depressions or valleys by adopting the following measures to mitigate the risk of landslides: -

1) Provide adequate surface drainage by calculating the capacity required based on catchment study to reduce infiltration of surface runoffs to slopes.
2) Subsurface drainages should be adequately provided to drain water from slopes to avoid erosion and rising of the groundwater level. An increase in groundwater level will reduce the FOS of slopes; and
3) Replace shallow and soft materials or debris with good compacted fill materials during the filling works to enhance slope stability.

4.2.9 Slopes Next to Water Courses

Slopes adjacent to water courses such as river banks, beaches, pond sides, etc., should be robustly designed for the probable critical conditions such as saturated slopes with rapid drawn-down conditions, scouring of slope toes due to flow and wave actions, etc. Thus, properly designed riprap or other protection measures are needed over the fluctuating water levels.

4.3 Construction Control and Site Supervision

Independent site supervision personnel are important as consultant's representatives to provide impartial decisions and ensure satisfactory construction quality. In addition, all earthworks and infrastructure contracts should have also included appropriate contractual requirements and penalty clauses such that the Contractor's responsibility is clearly stated and accounted for during the tender stage. Such an approach is able to facilitate fair and transparent tender procedures for the benefit of all parties involved.

4.3.1 Site Supervision and Coordination

Supervising personnel should have sufficient knowledge and experience in geotechnical engineering to identify any irregularities in the subsurface conditions (e.g. soil types, surface drainage, groundwater, weak planes such as clay seams etc.) that may be different from those envisaged and adopted in the design. Close coordination and communication between design engineer(s) in the office and supervising Inspectors of Works (IOW) are necessary so that modification of the design to suit the change in site conditions can be carried out when needed. This should be carried out effectively during construction to prevent failure and unnecessary remedial works during the service life of the slopes. Supervising IOW should keep detailed records of the progress and the conditions encountered when carrying out the work, in particular if irregularities like clay seams or significant seepage of groundwater are observed. Sufficient photographs of the site before, during and after construction should be taken. These photographs should be supplemented by information such as dates, weather conditions or irregularities of the subsoil conditions observed during excavation.

4.3.2 Construction Control via Contractual Measures

There should be contractual provisions to protect the environment against inappropriate ground disturbance by contractors for both temporary and permanent earthworks. Such legal provisions should be included in the relevant Specifications for Earthworks.

Furthermore, contractors are required to quote for temporary slope protection works so that the Engineer's specifications for temporary protection are not compromised. Contractors should be penalised for not providing the required precautionary measures during the course of work, especially on the protection of borrow pits. The control on temporary works should also be included in the construction drawings. In addition, the construction drawings should also include the appropriate construction sequence for cut and fill slopes.

In the event that a borrow pit is used, engineers should ensure it is cut to a gentle and stable gradient to allow for appropriate discharge of surface run-off. Meanwhile, the slopes should be closed turfed to minimise soil erosion and washing away of fine particles that may cause slope instability. The above requirements should be highlighted to the contractor through the specifications.

An extract from a sample Specifications for Earthworks and appropriate construction sequence for cut and fill slopes can be found in Gue & Wong (2008).

4.3.3 Filling of Slopes

Whenever possible, construction works should be arranged such that fill is placed during the dry season, when the moisture content of the fill can be better controlled. When filling, tipping should not be allowed and all fill should be placed in layers not exceeding 300mm to 450mm thick depending on the type of compacting plant used (unless compaction trials proved that thicker loose thickness is achievable) in loose form per layer and uniformly compacted in near-horizontal layers to achieve the required degree of compaction for fill to be placed on slopes is usually at least 90% to 95% of British Standard maximum dry density (Standard Proctor) depending on the height of the slope and the strength required.

4.3.4 Cutting of Slopes

Cutting of slopes is carried out from the top to the bottom, followed by works such as drainage and closed turfing. When carrying out excavation of cut slopes, care must be taken to avoid overcutting and loosening of the finished surface which may lead to severe surface erosion. It is also a good practice to construct first the interceptor drains with proper permanent or temporary outlets and suitable dissipators before bulk excavation is carried out.

4.3.5 Surface Protection of Slopes

For all exposed slopes, protection such as closed turfing or hydroseeding should be carried out within a short period. The period should be limited to 14 days and 7 days during the dry

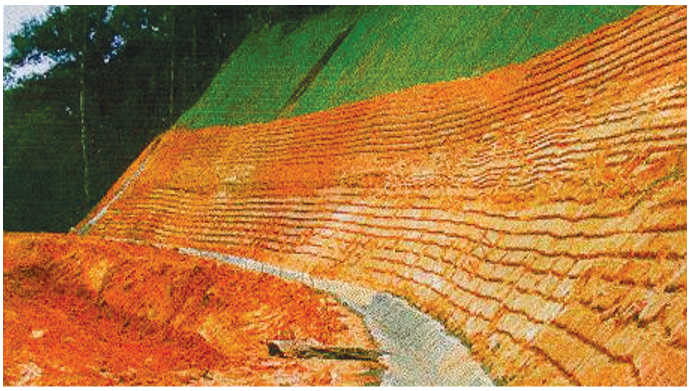

Figure 20: Example of Horizontal Groves (Gue & Wong 2008)

and wet seasons respectively after the bulk excavation or filling for each berm. All cut slopes should be graded to form horizontal groves (not vertical groves as shown in Figure 5) using suitable motor graders before hydroseeding. Figure 20 illustrates an example of the horizontal groves formed using suitable motor graders. This is to prevent gullies from forming on the cut slopes by running water before the full growth of the vegetation, and also to enhance the growth of vegetation.

4.4 Slope Maintenance

4.4.1 Guidelines for Slope Maintenance

A good reference for engineers is Geoguide 5 – Guide to Slope Maintenance (2021) and for laymen, the Layman's Guide to Slope Maintenance from GEO, CEDD of Hong Kong.

Geoguide 5 (2021) recommends that maintenance inspections be sub-divided into four categories:

a) Routine Maintenance Inspections, which can be carried out by any responsible person with no professional geotechnical knowledge (layman),
b) Engineer Inspections for Maintenance, which should be carried out by a professionally qualified geotechnical engineer,
c) Regular Checks of Buried Water-carrying Services, which should be carried out by a specialist leakage detection contractor, and
d) Regular Monitoring of Special Measures, which should be carried out by a firm with special expertise in the particular type of monitoring service required. Such monitoring is only necessary where the long term stability of the slope or retaining wall relies on specific measures which are liable to become less effective with the passage of time.

4.4.2 Frequency of Maintenance Inspections

Since Malaysia has at least two monsoon seasons, Routine Maintenance Inspection (RMI) by a layman should be carried out at least twice a year for slopes with negligible or low risk-to-life. For slopes with high risk to life, more frequent RMI is required (once a month). In addition, it is good practice to inspect all the drainage channels to clear any blockage by siltation or vegetation growth and repair all cracked drains before the monsoon. Inspection should also be carried out after every heavy rainstorm.

Category B, Engineer Inspection for Maintenance, should be taken to prevent slope failure when the Routine Maintenance Inspection by laymen observes something unusual or abnormal, such as the occurrence of cracks, settling ground, bulging or distorting of walls or settlement of the crest platform. Geoguide 5 (2021) recommends an Engineer Inspection for Maintenance to be conducted at a minimum of once every five years and more frequently if requested by those who carry out the Routine Maintenance Inspections. More frequent inspections may be desirable for slopes and retaining walls in the high risk-to-life category. Such regimes of regular maintenance inspection should be made known to all property owners and be enforced by the relevant authorities. The regulator may then implement the appropriate orders (in accordance with the available legal/regulatory framework) if the property owners refuse to carry out their duty diligently.

4.5 Undergraduate Training

Apart from improving the policies and legislation for implementation by the government on slope engineering and management, emphasis should also be given to improve undergraduates' understanding of slope engineering fundamentals. This is currently lacking and is one of the most important components in improving slope engineering.

As such, the proposed strategy is to develop training modules for the undergraduate curricula and course notes for engineering undergraduates. The training modules should cover adequate fundamentals of slope engineering, which include planning of subsurface investigation works, compiling and interpreting soil parameters and water profiles from the subsurface investigation works, followed by analysis, design, specifications, site supervision, construction control, monitoring and maintenance.

Government and private universities should review and update the undergraduate modules on slope engineering from time to time with the assistance of active and experienced practitioners to ensure graduates possess enough fundamentals to meet industry needs. The regular updates may be further improved by pooling resources from a group of universities and passionate practitioners so that the contents and quality of the lecture modules are not compromised. Knowledge sharing between lecturers and practitioners can also be achieved through workshops and forums to share experiences on landslide mitigations and risk reduction.

4.6 Structured Training Modules for Practitioners

As Engineers are the professionals involved in specifying the required landslide mitigation measures, providing structured training to practitioners would be the best way to improve slope engineering practices. Such training should also serve as a reminder to practitioners and professionals who are involved in slope engineering work to practice ethically and professionally. They should be reminded to only practice in the area of their expertise to ensure public safety. Therefore, the continuing professional development (CPD) scheme implemented by the Board of Engineers, Malaysia (BEM) should be enforced to ensure practicing engineers continue updating themselves. Furthermore, collaboration and working partnerships should be established between professional bodies like The Institution of Engineers, Malaysia (IEM), technical agencies, academia, federal, state and local governments and private industry. Structured training programmes for professionals and sub-professionals with certifications and accreditation systems should also be implemented to update and improve the capacity and competency of stakeholders involved in slope management and engineering.

Training of different stakeholders, and gathering of comments on conflicts and weaknesses of existing guidelines or procedures can facilitate standardisation or harmonisation of practices/procedures and formulation of relevant guidelines related to slope management and engineering. With appropriate and sufficient training together with the adoption of best practices and technology, landslides can be mitigated.

4.7 Research & Development

Apart from structured training modules, all practitioners can take another step ahead with Research and Development (R&D) to enhance safety, environmental protection and sustainability, speed of construction, and economic aspects related to slope management and engineering.

Among others, R&D on a simplified laboratory test to derive soil properties would be a top priority. It is particularly useful in establishing a framework for the relationship between friction angle and soil classification. In addition, efforts could also be channeled to correlate soil friction angle against the percentage of fines. By understanding the inversely proportional relationships, practitioners may be able to appreciate the change in material behavior and its sensitivity towards material particle size distribution. However, the above-proposed R&D topics would not be achievable without high-quality sampling and testing techniques. Therefore, these are the challenges to the current slope engineering industry waiting to be tackled by practitioners and academics.

As slope stability analyses are heavily dependent on the accuracy of groundwater profile estimation, the behavior of groundwater fluctuation during dry and wet seasons should be evaluated through research and development. Such understanding of groundwater fluctuation for countries with tropical weather like Malaysia would be highly beneficial as terrestrial rainfall is known to be highly unpredictable. The knowledge of groundwater fluctuation can help formulate design procedures for subsoil drainage systems, such as horizontal drains and their spacing.

5.0 LANDSLIDE RISK ASSESSMENT

Landslide risk assessment is a critical process aimed at identifying areas that are susceptible to landslides. It serves as a foundation for implementing effective remediation measures to minimise the impact of landslides. Additionally, raising public awareness about landslide risks and safety measures is essential to empower communities to take proactive steps to mitigate and respond to landslide events.

Landslide exposure risk can be defined as a comprehensive assessment that takes into account three key components: landslide hazard, exposure, and vulnerability. This assessment quantifies the likelihood of loss of life, injuries, and damage to physical structures. This approach is vital for developing a clear understanding of the potential consequences of landslide events.

In the context of Malaysia, the "Guidelines for Landslide Vulnerability Assessment and Development of Risk Index for Critical Infrastructure (CI)" published by CREAM (2020) provides valuable insights into landslide risk assessment. However, it's important to note that this qualitative method for risk assessment, which uses a risk assessment matrix, primarily focuses on hazard and vulnerability;

Landslide risk, R, is defined as

$$R = H \times V,$$

where H is the hazard measurement, and V is the vulnerability measurement. While this approach is valuable for assessing the convenience and safety of public and mass users, a more comprehensive assessment may be necessary for a broader range of stakeholders.

The international risk classification matrix, as modified from Ko Ko *et al*. (1999) and recommended by CREAM as shown in Table 2, is a useful tool. This matrix categorises the likelihood of landslide hazards based on the vulnerability of critical infrastructures (CIs) or elements-at-risk. It offers a systematic way to evaluate and prioritise landslide risks.

In practical terms, landslide risk assessment serves as a supporting tool for:

- Land Use Planning: It informs decisions about where and how to develop urban, urban highlands, suburban, and rural areas. By identifying high-risk zones, planners can make informed choices to reduce exposure to landslides in vulnerable areas.
- Prioritising Mitigation Plans: It helps prioritise areas for landslide risk mitigation efforts. This ensures that resources and efforts are allocated effectively to protect lives, properties, and critical infrastructures.
- Risk Management: It forms the basis for developing and implementing risk management strategies. This includes preparedness, response, and recovery plans to enhance the resilience of communities and cities in the face of landslide hazards.

Table 2: International risk classification matrix modified from Ko Ko et al. (1999)

Likelihood (hazard)	Consequences to property (Vulnerability)				
	Very High	High	Medium	Low	Very Low
Very High	VH	VH	H	H	M
High	VH	H	H	M	M
Medium	H	H	M	M	L
Low	H	M	M	L	VL
Very Low	M	M	L	VL	VL

where

VH – Very high risk, **H** – High risk, **M** – Moderate risk, **L** – Low risk, and **VL** – Very low risk.

Ultimately, the goal of landslide risk assessment is to contribute to the formation of sustainable development by minimising the impact of landslides on both human safety and infrastructure.

6.0 LANDSLIDE REMEDIATION MEASURES

The choice of landslide remediation measures depends on various factors, including the slope's characteristics (e.g., gradient, soil or rock type, water catchment), the severity of the landslide risk, and budget considerations. Professional geotechnical engineers typically conduct site-specific assessments to determine the most suitable approach and design a customised solution based on the unique conditions of each slope. Regular monitoring and maintenance of the remediation measures are essential to ensure their continued effectiveness in mitigating landslide risks over time.

6.1 Modification of Slope Geometry

This approach involves altering the physical characteristics of a slope to make it more stable and less prone to landslides. One common method is to create terraces or benches on steep slopes. This involves cutting a slope into a series of flat, horizontal platforms or steps. Terracing helps to reduce the overall slope angle, which can reduce the gravitational forces acting on a slope.

6.2 Drainage Improvement

Effective drainage improvement measures can significantly reduce the risk of landslides by managing water flow and minimising the saturation of the slope. However, it's essential to consider site-specific factors, such as soil type, rainfall patterns, and geological conditions, to design and implement an appropriate drainage strategy.

6.3 Internal Soil or Rock Slope Reinforcement

Internal slope reinforcement is a landslide remediation measure aimed at strengthening the stability of slopes to prevent or mitigate landslides. This approach involves reinforcing the slope from within, typically by adding structural elements or materials that enhance its safety. Here are some key methods and considerations for internal slope reinforcements:

- Soil Nails / Rock Bolts:

These are long, threaded steel rods that are embedded into the rock or soil mass within the slope. They are used to provide additional support and structural integrity to the rock or soil. Rock bolts or soil nails resist tension forces within the slope and help prevent the separation or sliding of rock or soil.

6.4 Soil or Rock Slope Surface Protection

Soil or rock slope surface protection is aimed at safeguarding the outer layer of a slope to prevent erosion, instability, and potential landslides. This approach involves adding protective materials or structures to the surface of the slope to enhance its stability and resilience. Here are several key methods and considerations for implementing soil or rock slope surface protection:

- Mesh and Netting Systems:

Installing mesh or netting on the slope's surface can help contain loose rocks and debris, reducing the risk of rockfalls and landslides. These systems are typically made of high-strength materials and provide a protective barrier.

- Shotcrete:

This is a type of sprayed concrete applied to a slope's surface, providing additional structural support, stabilising loose materials, and preventing erosion.

- Rockfall Barriers:

In areas with a high risk of rockfall, rockfall barriers can be installed. These barriers consist of steel cables and support posts designed to intercept and deflect falling rocks away from vulnerable areas, such as roads or structures.

7.0 CONCLUSIONS

Landslides are complex disasters with significant impacts on communities, infrastructures, and environment. Understanding the causes, mechanisms, and consequences of landslides is crucial for effective risk management and mitigation.

External factors like heavy rainfall, earthquakes, and human activities can trigger landslides by increasing pore pressure, reducing friction, or altering slope's stability. Geological and geomorphological factors such as slope angle, rock or soil type, geological structures, and landform characteristics play significant roles in landslide susceptibility. Furthermore, some human activities such as deforestation, construction, mining, and improper land use practices can destabilise slopes, increasing the vulnerability of landslides.

Landslides pose a range of threats and challenges which include:

- Landslides can result in casualties, damage to homes, infrastructures, and disruption of communities;
- Landslides lead to soil erosion, sedimentation of rivers and lakes, loss of biodiversity, and altered landscapes;
- Landslides impose substantial economic losses, including rescue and recovery expenses, repairs and reconstruction of infrastructures, and loss of agricultural productivity.

To address the risks associated with landslides and enhance resilience, several strategies and approaches are essential and discussed in Section 4. Local authorities lack expertise in the management of the hillsite developments. They depend on JKR to provide them with ad-hoc advice, which is less effective as the state JKR also lacks expertise in this specialised field. These weaknesses were identified by the cabinet in 2009 and resulted in the National Slope Master Plan (2009 – 2023) under the purview of the Minister of Works.

For the way forward, it is recommended to establish an Independent Centralized Federal Agency to manage hillsite developments and mitigate landslides where the scope shall include:

- Approval & control of new slopes
- A One Stop Center (OSC) with expertise in slopes
- Risk assessment of existing slopes
- R&D and improvement on slope engineering

In conclusion, landslides are hazards that require a multidisciplinary and proactive approach to minimise their impact on society and environment. By systematically combining scientific knowledge, community engagement, and effective risk reduction measures, we can work towards a safer and more resilient future in the face of landslide hazards.

8.0 ACKNOWLEDGEMENT

The author would like to express his sincere gratitude to Ir. Kang Yee Ping and to all those who have assisted in preparing this manuscript. ■

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