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A Review of Rock Slope Stability Assessment Practice in Malaysia
(Ulasan Amalan Penilaian Kestabilan Cerun Batuan Di Malaysia)

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ABSTRACT

Rock slope stability assessment in Malaysia has become increasingly important as new developments encroach hillsides around major cities. This article reviews historical case studies to present a general picture of rock slope assessment practice in Malaysia, especially on methods and output of the case studies. Common methods include use of locally developed rating systems, Rock Mass Rating (RMR) and its derivatives, kinematic analysis, and numerical analysis. Application of these methods must be suitable with site conditions, while its advantages and disadvantages must be recognized by the assessor. Emergence of new technologies greatly improves the speed and quality of data acquisition provided. A total of 39 case studies on different lithologies were examined, in which progress were notable from kinematic analysis-based assessments to incorporation of rating systems and numerical analysis. This article recommends several improvements for rock slope assessment practice. These include an establishment of a local good practice guide in the assessment, incorporation of numerical analysis into standard practice, improving utilization of new technologies, more attention to the influence of weathering, and consideration of seismic influence in seismically active regions. Utilization of numerical methods and other contemporary methods reflects increasing understanding of rock mechanics which is vital to rock slope stability assessment among local practitioners. Improved rock slope assessment allows for a more accurate stability determination and decisive mitigation measure recommendations, which is to be done by competent engineering geologists, in line with Geologist Act 2008.

Keywords: Engineering geology; rock slope; slope failure; stability analysis

ABSTRAK

Penilaian kestabilan cerun batuan di Malaysia menjadi semakin penting berikutan pembangunan baharu yang melibatkan sisi bukit di sekitar bandar utama. Kertas ini mengulas kajian kes untuk mempersembahkan gambaran am amalan penilaian kestabilan cerun batuan di Malaysia, khususnya kepada metodologi dan hasil kajian kes tersebut. Metodologi yang sering digunakan meliputi sistem perkadaran yang dibangunkan untuk kegunaan tempatan, Perkadaran Jasad Batuan (RMR) dan terbitan, analisis kinematik, serta analisis numerik. Aplikasi teknik tersebut haruslah bersesuaian dengan keadaan tapak, manakala kelebihan dan kekurangannya perlu diketahui oleh penilai. Kemunculan teknologi baharu memperbaik kelajuan dan kualiti data yang diperoleh. Sebanyak 39 kajian kes yang mempunyai litologi yang berlainan telah diteliti, dengan perkembangan dikenal pasti daripada penilaian berasaskan analisis kinematik sehingga penggunaan sistem perkadaran dan analisis numerik. Kertas ini mencadangkan beberapa penambahbaikan untuk amalan penilaian cerun batuan. Antaranya adalah penubuhan satu panduan cara kerja baik dalam penilaian, penggabungan analisis numerik ke dalam amalan piawai, menambahbaik penggunaan teknologi baharu, perhatian kepada pengaruh luluhawa, pertimbangan pengaruh seismik di kawasan yang aktif seismik. Penggunaan kaedah numerik dan kaedah kontemporari lain mencerminkan pertambahan kefahaman berkenaan mekanik batuan yang penting dalam penilaian kestabilan cerun batuan dalam kalangan pengamal setempat. Penilaian cerun batuan yang ditambahbaik membolehkan penentuan kestabilan yang lebih tepat dan cadangan langkah mitigasi yang tertentu; yang sepatutnya dilakukan oleh ahli geologi kejuruteraan yang kompeten, selaras dengan Akta Ahli Geologi 2008.

Kata kunci: Analisis kestabilan; cerun batuan; geologi kejuruteraan; kegagalan cerun

Introduction

Rock slope stability assessment has long been a subject of interest among engineering geologist and geotechnical engineer in Malaysia. Despite most of slopes in Malaysia being composed of soil material due to deep tropical weathering, rock slopes have become increasingly important with developments spreading into hilly and mountainous areas, where steep cuts are made to accommodate infrastructure. Multiple rock slope related issues and assessments have been recorded and published. Published account of rock slope stability assessment in Malaysia practice can be traced back to early 80s including works by Ibrahim and Ibrahim (1983).

However, due to differences in academic background of practitioners, their methodology often varies and potentially result in different assessment results even on a same slope. Most of published assessments were primarily based on kinematic analysis, with stability ratings becoming increasing popular in recent years. Several Malaysian institutions and practitioners also published their own assessment systems based on Malaysian case studies. Therefore, a thorough review is needed to identify the current pattern of rock slope assessment practice in Malaysia, and how the differences in methodology would influence the rock slope stability assessment. In this paper, the previous publications were reviewed based on their primary method, where advantages and limitations for each method are examined. Several practical improvements are suggested at the end of this review.

Reported rock slope instabilities in Malaysia

Common rock slope stability issues in Malaysia may influence the trend of rock slope assessment practice. While rock slopes are rather uncommon compared to the soil slopes due to intense tropical weathering, rock slope instabilities are well recorded through academic publications and news reports. Some of the major recorded events are summarized in Table 1.

Based on classifications by Cruden and Varnes (1996), Hungr, Leroueil and Picarelli (2013), and Varnes (1978), there are several identified rock slope failures observed in Malaysia.

TABLE 1. List of significant recorded rock slope failure incidence in Malaysia. These are reported in published documents, more cases are often gone unreported when not involving fatalities/ damages. This list refers to rock slopes only, while most failure involves a mixture of rock and soil

Date	Location	Nature of event	Casualties	References
26/11/2004	Bukit Lanjan, Selangor	Massive rock slope failure	-	Hamzah et al. (2015)
2/12/2004	Bercham, Ipoh	Rock fall	2	Hamzah et al. (2015)
April 2006 – Ongoing	Gunung Pass, Perak	Massive rock slope Deformation	-	Hamzah et al. (2015)
5/6/2008	Keramat Pulai, Perak	rock fall	1	Norbert et al. (2015)
4/6/2015	Mount Kinabalu, Sabah	Multiple Earthquake-induced rock avalanches	-	-
1/7/2019	Simpang Pulai, Perak	Rock fall	1	The Star Online (2019)
6/11/2020	Merapoh, Pahang	Massive rock falls	-	New Strait Times (2020)

Rock Falls

As natural rock slopes are relatively uncommon, occurrences of rock fall are restricted to excavated rock slopes and karstic terrain with rocky hills. Fahmi et al. (2015) has mapped rock fall potential area in Kinta Valley, where karstic limestone hills are identified as potential rock fall sources. Quarries (Figure 1(a)) and construction sites (Figure 1(b)) are among rock falls hotspot due to absence of mitigation measures, and cases have often gone unreported. Natural limestone hills do pose rock fall hazard, threatening structures nearby.

Rock Slides

Rock slides are the most common forms of rock slope instabilities in Malaysia. They occur as sliding along discontinuities present in rock masses. The slide covers multiple movement sub-types including rotational, planar (Figure 2(a)), wedge (Figure 2(b)), compound, and irregular slides. This is also the most studied type of failure, often attributed to abundance of case studies. 2003 Bukit Lanjan rock slope failure is the most popular case study, despite no casualty, due to sheer volume of sliding rock mass (Komoo, Singh & Othman 2004; Sapari et al. 2011).

Rock Avalanches

Rock avalanches occur when large rock slides disintegrate rapidly in downslope movement along steep slopes, forming extremely rapid flows of fragmented rock (Hungr, Leroueil & Picarelli 2013). Although almost unheard of in Malaysia, rock avalanches occurrences have been locally recorded. The reported case was the rock face around Mt. Kinabalu, post-2015 earthquake. Rock avalanches left distinct scars around Mt Kinabalu's rocky flanks.

Rock Slope Deformation

This is another type of rock slope instability that has rarely been discussed in Malaysia. Rock slope deformation refers to deep-seated slow deformation of hill slopes (Hungr, Leroueil & Picarelli 2013). It may only be detected with sagging of slope crests and development of cracks or faults, without a well-defined rupture surface. Such instability usually related to large-scale movement, as observed in Gunung Pass, Perak. This case has often been studied by local and international researchers to understand its movement (Habibah et al. 2010; Kuraoka et al. 2016; Malone et al. 2008; Mustafa, Pradhan & Tehrany 2013).

FIGURE 1. (a) shows a fatal rock fall incidence within a quarry in Kinta Valley (The Star Online, 2019), (b) shows a fallen granite rock within a construction site in Klang Valley in 2018 and (c) shows a large-scale limestone hill collapse forming multiple falling blocks at Kampung Kubang Rusa, Merapoh, Pahang (New Strait Times 2020)

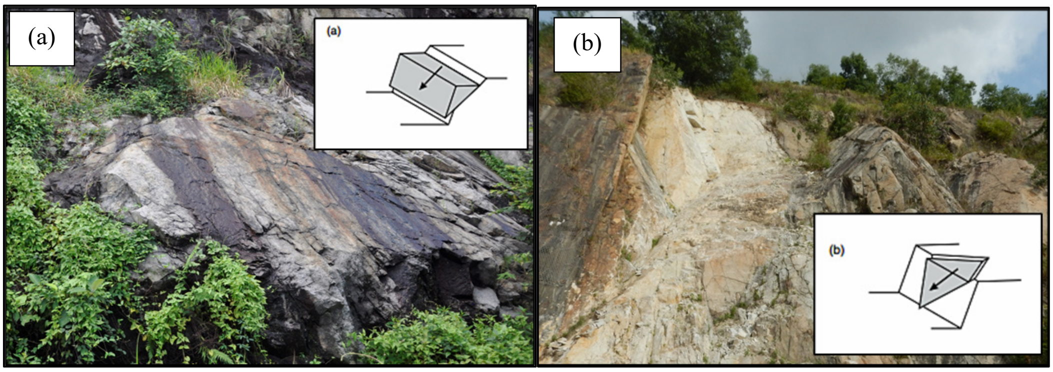

FIGURE 2. Observed sliding failure on rock slope by the author, including planar sliding on an abandoned quarry (a), and wedge sliding on a road cut slope

PRACTITIONERS AND REGULATING BODIES

Rock slope assessments historically was done by engineers and geologists. Establishment of *Akta Ahli Geologi* or Geologist Act (Act 689) in 2008 has specifically clarified that the 'Engineering Geology' field is to be under geologists' jurisdiction. The geologists, are in turn, regulated by Board of Geologists (BoG). There are several other supporting bodies including Institute of Geology Malaysia (IGM), Geological Society of Malaysia (GSM), and Society of Engineering Geology and Rock Mechanics Malaysia (SEGRM) which provides a medium for engineering geologists to interact including on rock slope assessment practice. Mineral and Geoscience Department Malaysia (JMG) acts as a government agency, and may conduct rock slope assessments on government's behalf.

To date, the only guide for rock slope assessment in Malaysia is restricted for limestone hills (Mineral and Geoscience Department Malaysia 2013) and not for systematic rock slope assessment in general. That means, any assessment is based on the geologist's knowledge, competency, and experience. Nevertheless, multiple case studies and several works to introduce assessment methods in Malaysia have been published.

GENERAL TREND OF ROCK SLOPE ASSESSMENT PRACTICE IN MALAYSIA

There are several types of rock slope assessment conducted in Malaysia, namely locally developed ratings system, Rock Mass Ratings (RMR) and its derivatives, kinematic analysis, and numerical analysis. Historically, traditional kinematic analysis and general Slope Assessment Systems (SAS) method was the primary technique. By early 2010s, use of rating systems (RMR) gained popularity and more methods were introduced. There are other different approaches including use of remotely sensed data, but such practices are rare and often used for academic purposes. Each method has its own advantages and disadvantages. By acknowledging this (advantage and disadvantage), use of the most accurate method for each rock slope stability assessment can be achieved.

LOCALLY DEVELOPED SLOPE ASSESSMENT SYSTEMS

Among early published rock slope assessments were done using locally developed Slope Assessment Systems (SAS), with successive systems that were developed by Public Works Department (PWD) of Malaysia for assessment including rock slopes. Singh et al. (2014) has provided a thorough review of existing systems. They are: Slope Maintenance System (SMS) (PWD 1996), Slope Priority Ranking System (SPRS) (Hussein et al. 1999), Slope Information Management System (SIMS) (JICA & PWD 2002), and Slope Management and Risk Tracking Systems (SMART) (PWD 2004). A relatively recent SAS system was also developed by Huat and Jamaludin (2005) for use in roads underlain by granitic rocks. It is worth noting that those systems were not developed specifically for rock slope stability assessment, but as a method for man-made slope inventory system. They contain varying degree of rock slope parameters as input, as they were intended for use in rock, soil and mixture of rock-soil slopes. Table 2 shows parameters included in each system.

The resultant number from the combination of parameters stated in Table 2 are often referred as 'hazard level' of the slope. Although they were not developed exclusively for the purpose of rock slope stability assessment, the systems do cover rock slopes as part of its slope inventory and thus, should be able to assess the stability of rock slopes. However, the input for rock slopes-related parameters into the systems are generally less significant and sometimes neglected. For example, none of them considered rock material strength, and only two of them took geological structure into account. The influence of geological structure also varies, as SPRS merely noted the presence of discontinuities, while SIMS considered the nature of geological structures (formation of daylighting block).

As such, these systems are rarely used in published documents for rock slope stability assessments. Some notable works on its application for slope inventory uses are done by Jamaludin and Nadzri (2006), Jamaludin, Huat dan Husaini (2006), and Kaamin et al. (2016). For comparison, the Landslide Hazard and Risk Assessment System (LHRA) by Fiener (1999) covers a more comprehensive parameters applicable to rock slope stability. This system goes into depth for slope mass' lithology, weathering, and structural geology (discontinuity spacing, width and continuity of joints). This system is capable for better assessment of rock slopes as part of its slope inventory.

Due to its nature as a tool for slope inventory system and landslide hazard mapping, these assessment systems (SMS, SPRS, SIMS, SMART, New SAS, and LHRA) are less suitable for detailed rock slope stability assessment. Therefore, any rating or hazard level assigned to the rock slopes shall not be treated as the final assessment for rock slopes. For a conclusive assessment including for mitigation measure design purposes, it is recommended to conduct kinematic analysis and/or Slope Mass Rating (SMR) assessment. If geotechnical parameters are available, suitable numerical analysis are highly recommended.

TABLE 2. Comparison of different parameters for each slope assessment system in Malaysia

Parameter	SMS (PWD 1996)	SPRS (Hussein et al. 1999)	SIMS (JICA & PWD 2002)	SMART (PWD 2004)	New SAS (Huat & Jamaludin 2005)
Slope morphology	✔	✔	✔	✔	✔
Lithology	✔	-	-	-	-
Weathering profile	-	✔	-	✔	✔
Structural geology (Discontinuities)	-	✔	✔	-	-
Rock material strength	-	-	-	-	-
Groundwater	✔	✔	✔	✔	✔
Existing mitigation structures	✔	-	✔	✔	✔
Vegetation / slope cover	✔	✔	✔	✔	✔
Erosion	✔	✔	✔	-	✔

ROCK MASS RATING AND ITS DERIVATIVES

In contrast to SAS which covers both rock and soil slopes, Rock Mass Rating (RMR) (Bieniawski 1989, 1976) and its resultant Slope Mass Rating (SMR) (Romana 1985) are developed specifically for rock mass and rock slope assessment. Therefore, it is more easily and widely applied for rock slope stability assessment in Malaysia. Generally, they cover the following major parameters; intact rock strength, Rock Quality Designation (RQD) (Deere 1964), discontinuities spacing, discontinuities condition and groundwater, with readjustments for potential instability induced by discontinuities orientation.

However, their application for rock slope stability assessment in Malaysia is still relatively recent. They are often applied in cut rock slope stability assessment (Goh & Afiq 2016; Rasyikin et al. 2019; Tonnizam & Vahid 2011), and in natural rock slopes especially for limestone hills (Ainul et al. 2018; Goh et al. 2016b; Norazliza & Tajul 2016; Nur Amanina et al. 2016; Figure 3(a); and Goh et al. 2018 (Figure 3(b)). Their usages are often accompanied with kinematic analysis for SMR input. SMR application in rock slope stability assessment in Malaysia is gaining attention due to its relatively quick yet comprehensive assessment and classification with suggested mitigation measures.

In certain unique cases, modification of existing rating system is done to suit for local use. For example, Ismail (2015) proposed a modified SMR (M-SMR) to suit the heterogenous Crocker Formation rocks. Nevertheless, more local case studies are needed to establish the efficiency of RMR and resultant ratings systems in assessing rock slope stability in Malaysia. Incorporation of weathering profile which almost always present in any rock slope in tropical climate including Malaysia into such rating systems is a good subject to be examined.

Application of other published rock slope rating systems (not derived from RMR) are largely limited and relatively new in Malaysia. Geological Strength Index (GSI) (Hoek & Marinos 2001; Hoek Marinos & Benissi 1998) application have been recorded in several studies involving heterogenous rock masses such as Crocker Formation (Norbert et al. 2016) or in cases where its use in Hoek-Brown failure criterion is needed (Goh et al. 2016a). Generally, its use has been utilized in conditions where SMR rating can be inaccurate especially in heterogenous and intensely jointed rock masses. Q-system (Barton 1976) was developed specifically for tunneling purposes and hence, was not applied to rock slopes in Malaysia. Its derivative, Q_{slope} system (Barton & Bar 2015) has yet to be applied widely in Malaysia (Afiq & Goh 2019). Exploratory studies for newer rock slope rating systems are recommended to be examined to assess their effectiveness for rock slope assessments in Malaysia.

It is important to acknowledge the limitations for such rating systems. They treat the slope/section as one whole mass, which means such assessment generalize the stability of the whole slope/section. This is true if the instabilities within the slope mass are uniform throughout, but in most cases, the instabilities are often limited to several unstable blocks. This condition results in inaccurate depiction of 'unstable slope' where overdesign or insufficient design of mitigation structures may occur. Competency of engineering geologist involved in such assessment plays an important role.

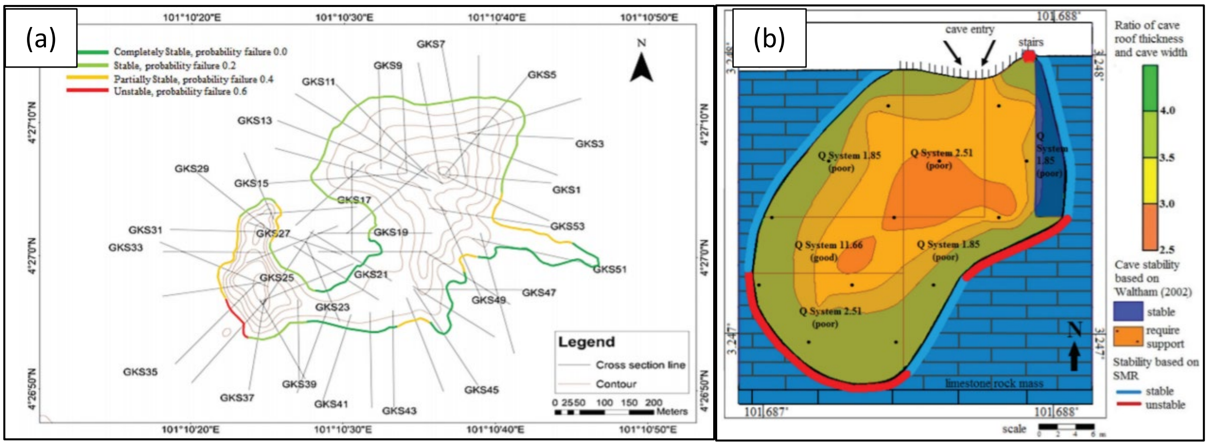

FIGURE 3. Uses of SMR system in limestone hill for mapping of its outer rock face (a) by Ainul et al. (2018), and for the cave's interior (b) by Goh et al. (2018)

KINEMATIC ANALYSIS

Kinematic analysis in this rock slope stability assessment review refers to stereograph use to plot discontinuity planes and identify potential failure geometries (Hoek & Bray 1981; Markland 1972). This technique is common and has become a fundamental method for rock slope stability assessment in Malaysia. This technique aims to establish the geometry of potential failure from discontinuity sets within the rock mass.

Earliest published works using kinematic analysis were by Aziman and Husaini (2001), Tajul (1991), Tajul and Nizam (2001), Tan (1994), and Tan and Tajul (2000). Such rock slope assessments were predominantly for roadside cut rock slopes (Abd 2005; Haswanto & Ghani 2008a; Mustaffa et al. 2006; Tonnizam & Vahid 2011), but applications were also made for ex-quarries (Mustaffa & Tajul 2004), development areas (Tajul & Nizam 2001; Tan 2004) and natural rock slopes (Goh et al. 2016b; Norazliza & Tajul, 2016; Nur Amanina et al. 2016).

Case studies involving the use of kinematic analysis are abundant, and its use have been ubiquitous in any rock slope stability assessment in Malaysia. Despite slight differences in their methodology for discontinuities sampling, the outputs have been almost uniform throughout the years - A stereograph plot showing the potential failure geometry identified on the rock slope (Figure 4). While use of stereograph plot would be an accurate tool to visualize the geometry of potential failure, most of the published kinematic analysis did not detail on the size of identified potential failure or specified (marked) on location of instabilities on slope. Although some of the studies did exhibit areas of interest for stabilization on slope (Mustaffa & Tajul 2004), most of them did not do so. Such output will be challenging for engineers to design any mitigation measures, as they could not gauge the size or location of instabilities which require any stabilization.

Haswanto and Ghani (2008a, 2008b) introduces the use of block theory (Goodman 1995) application for determining unstable block in a rock slope in Malaysia. This theory utilizes kinematic analysis and site observations for identifying the so-called key block. The theory has the potential to be applied more widely in practice.

There are multiple ways to improve the communication on identified rock slope instabilities. A more common method to visualize the data is to sketch or mark identified instabilities upon studied rock slope. In contrary to being a common method to visualize data by geologist, published rock slope assessments in Malaysia rarely delivers the data in sketches and models. Showing the identified instabilities on rock slope is important to help other parties involved in designing mitigation measures to get the big picture of situation on site. Another method to visualize the identified issues from kinematic analysis is to reconstruct the model of jointed rock mass in 2D or 3D manner (Figure 5).

A common practice in rock slope assessment in Malaysia is to end the analysis at kinematic analysis. Kinematic analysis answers on how the rock slope potentially fail, especially its geometry, but does not quantify the likelihood of failure or any forces influencing the potential failure. Therefore, a numerical analysis on calculating the stability of identified potential failure is needed to provide a comprehensive assessment.

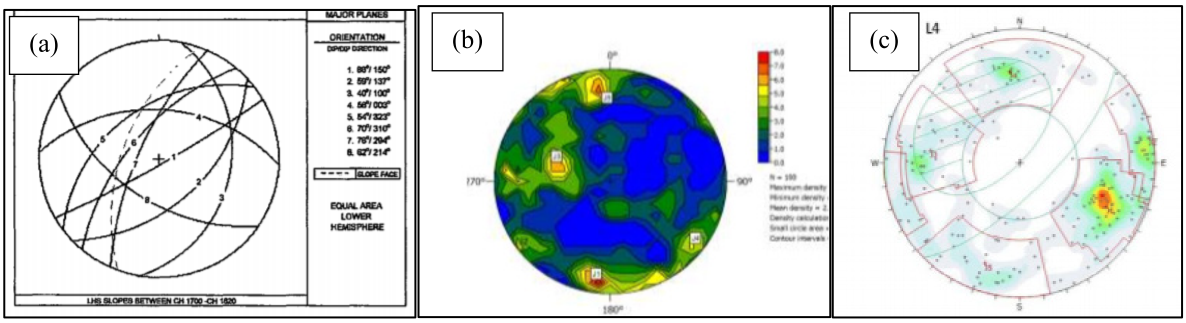

FIGURE 4. Use of stereographic plot to visualize the discontinuities pattern and its interpreted geometry of potential failure by (a) Abd (2005), (b) Goh et al. (2016b), and (c) Afiq et al. (2019)

NUMERICAL ANALYSIS IN ROCK SLOPE ASSESSMENT

Numerical analysis for rock slope stability assessment in Malaysia is quite uncommon compared to soil slope stability assessment where numerical analysis is a routine. This issue is partly due to qualitative-centric nature of local engineering geologist in conducting assessments. However, in good practice, stability of potential failures needs be calculated (McMillan, Harber & Nettleton 2011) to achieve a more conclusive assessment.

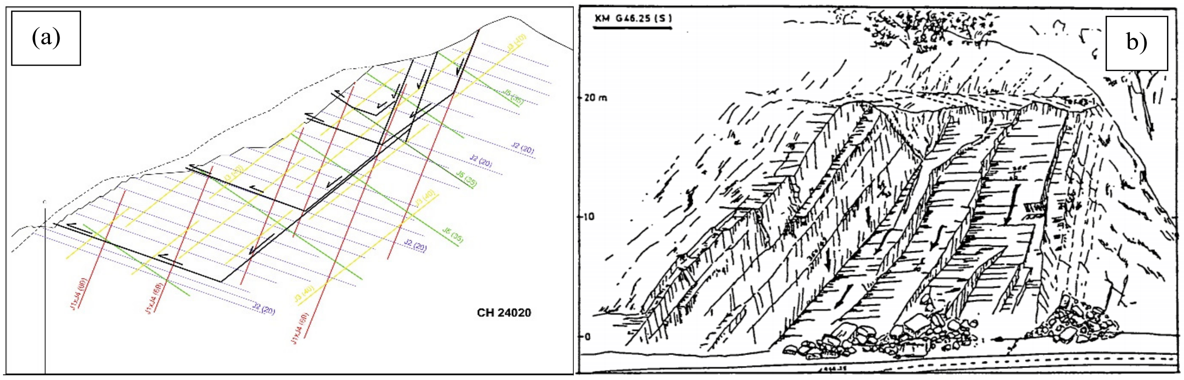

FIGURE 5. Example of modelling the jointed rock mass forming the slope in 2D (a) and 3D (b). It is crucial to get the properties of discontinuities right in this model; its orientation, length and spacing to reflect the site condition. (a) is 2D model of Gunung Pass failure (Asbi et al. 2005) and (b) is 3D sketch of rock slope failure along East-West Highway (Tajul 1991)

Nevertheless, the awareness of the importance of numerical analysis as part of rock slope assessment is slowly gaining attention in local practice. A more common method is static analysis in form of Limit Equilibrium Method (LEM) to calculate the Factor of Safety (FOS). Its application for rock slope stability analysis has been recorded for cut slopes either in 2D (Afiq & Goh 2019; Ismail & Raffee 2017) or in 3D (Nagendran & Ismail 2020). Application for probabilistic analysis to achieve probability of failure (PF) in Malaysia was also published (Afiq et al. 2019; Mat Radhi et al. 2008) but its use is relatively new and more study in this area is required. Another method is via Finite Element Method (FEM), but is even less common and its application has been more for academic purposes (Al-Bared et al. 2015; Kuraoka et al. 2016).

Utilizing the numerical analysis provides a wider prospective, including the dynamic analysis. The dynamic analysis of rock slope stability assessment has not been widely practiced in Malaysia. This is a potentially an important field to look into, as Malaysian climate means rock slope stabilities often deteriorate over time from intense rainfall. Effect of seismic vibration on rock slopes is another interesting topic. Despite the fact that only one case of devastating seismic activities has been recorded in almost 100 years (Mt. Kinabalu incident), vibrations induced by quarrying activities may deteriorate rock slopes within and nearby the quarry areas.

Generally, numerical analysis in rock slope stability assessment is relatively new and not widely practiced in Malaysia. This issue needs to be addressed, where numerical analysis should be included to achieve a comprehensive assessment. Any numerical analysis must adhere to rock mass behavior identified via kinematic analysis, especially on the effect of discontinuities. This will help in identifying potential criterion best describing the movement, for example; Mohr-Coulomb in soil mass, Hoek-Brown in heavily fractured mass (Hoek & Brown 1980), Barton-Bandis in joint-controlled sliding failures (Barton 1976; Barton & Bandis 1990), or other criteria deemed suitable for each case.

UTILIZATION OF NEW TECHNOLOGIES

Utilization of new technology for rock slope assessments in Malaysia has been primarily for assisting in discontinuities sampling, or for rock mass modelling. Their usage was usually to reduce time taken for assessment, provide better coverage of rock slope, reduce human error, and assisting in providing a comprehensive overall assessment.

Terrestrial Laser Scanning (TLS) (Figure 6) is a popular method in automating the discontinuities sampling and slope morphology. By scanning the rock slope in intense pulses of lasers, it can recreate the rock mass in 3D cloud space, including the discontinuities presence. Another advantage is its capability to penetrate light vegetation making its use very convenient in tropical countries. It has been utilized for cut slopes (Khairul 2012) and natural rock slopes (Hellmy et al. 2019). Another method capable of recreating the rock slope model in 3D is photogrammetry (Figure 7), which drawn successful uses (Nagendran, Ismail & Wen 2019; Wen, Nagendran & Ismail 2018) despite being less popular for practical use in Malaysia.

Use of remotely sensed technique to acquire discontinuity data must be approached with caution. While software can automatically extract exposed discontinuity surfaces from TLS or photogrammetry-generated point clouds, it may miss trace joints (i.e.: joints embedded within rock mass, observed as joint lines on rock surface, with little to no exposed facet) or misinterpret non-discontinuities feature (planar man-made structures) as rock mass discontinuities. This has been demonstrated by Hellmy et al. (2019) where several discontinuities set identified via TLS was not reported by Goh et al. (2016b) (Figure 8) who acquired the data via scanline method (use of compass and clinometer) and vice versa, even though both of them were working on the same rock mass (Gunung Lang, Ipoh).

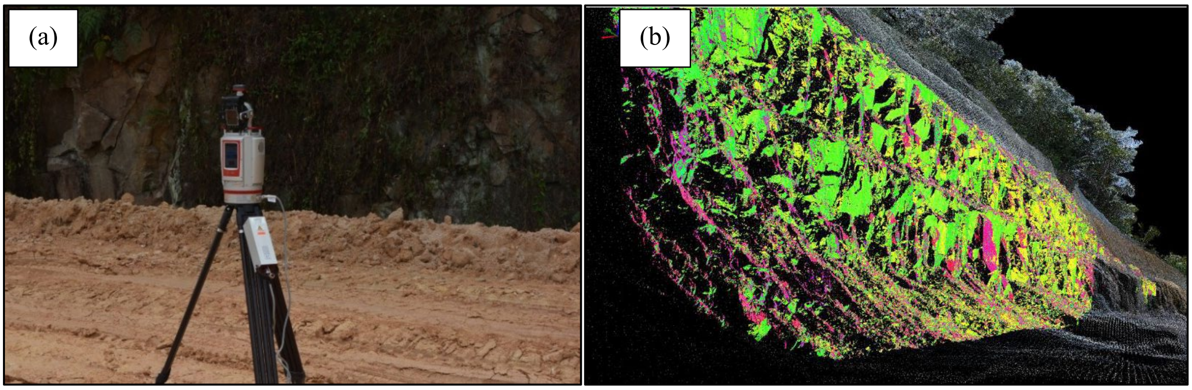

FIGURE 6. Example of TLS data acquisition upon a rock slope (a) and extracting discontinuity planes (b) from TLS-acquired point cloud

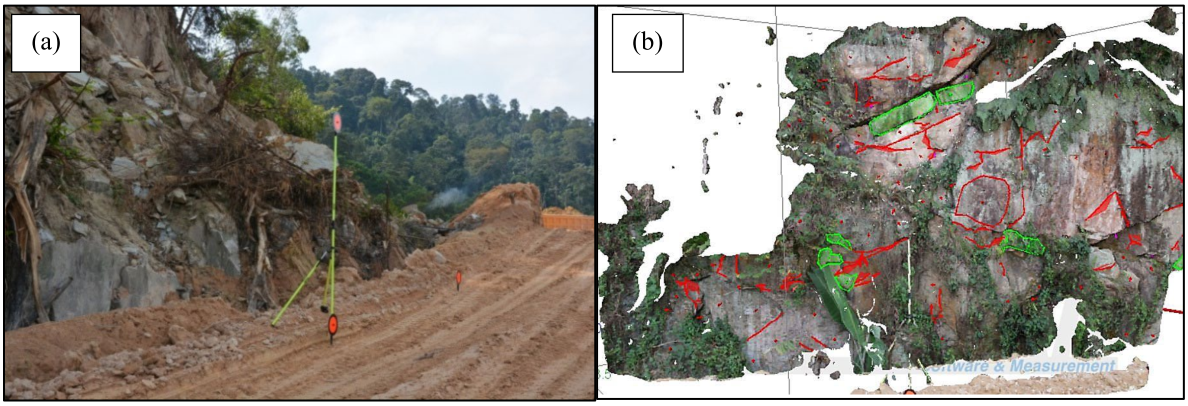

FIGURE 7. Photogrammetry data acquisition on site requires a reference point (a), which would later aid in identifying orientation of discontinuities from mesh model generated from photogrammetry (b)

This issue was also reported by Faruq et al. (2019) who were working on a mine pit wall, where interpretation from TLS data did not correlate well with scanline method data. These issues if not addressed, will greatly reduce the credibility of TLS as a mean of obtaining discontinuity data from rock mass. To overcome this issue, any discontinuity data acquisition via remotely sensed method must be confirmed with site observations.

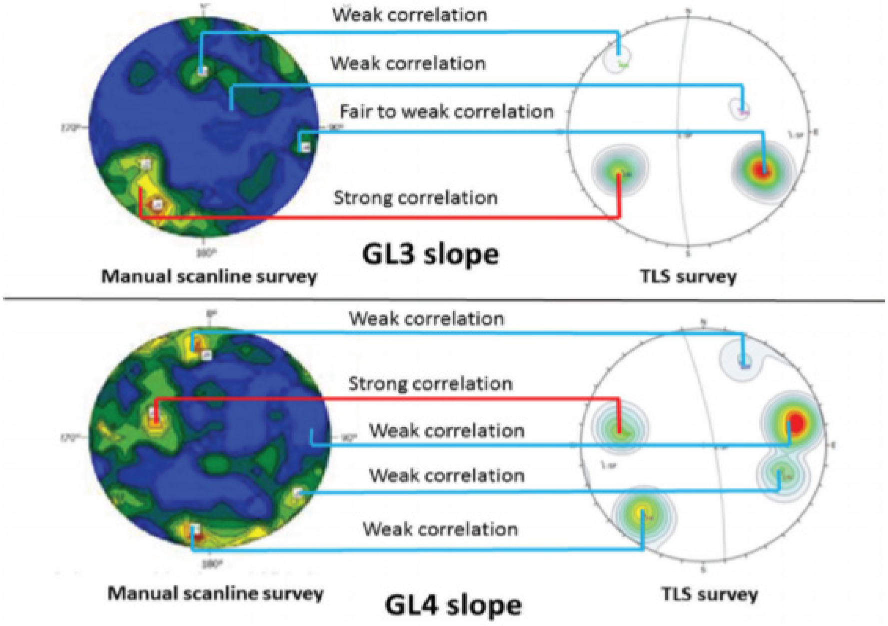

FIGURE 8. Comparison by Hellmy et al. (2019) between TLS-derived data in his study (right) with data obtained by Goh et al. (2016b) with scanline method (left), showing multiple weak correlation with only one strong correlation at each slope despite obtaining the data from the same rock slope

This will ensure the data is fit for further analysis and does not potentially overlook instabilities which defeats the assessment purposes. An engineering geologist should conduct or supervise data cleaning and filtering, including discontinuities extraction process to prevent any useful data from inadvertently being lost during the process.

RECOMMENDED IMPROVEMENTS FOR ROCK SLOPE ASSESSMENT

In a bigger picture, rock slope assessment practice in Malaysia has considerably improved over the years, with increasing awareness in approaching rock slopes especially after 2003 Bukit Lanjan incident. However, there are much room for potential improvement in general rock slope assessment practice. The proposed improvements are establishment of local systematic good practice guidelines, incorporation of numerical analysis into standard practice and the influence of seismic impact and improving utilization of new technologies for tropical weathering slopes.

ESTABLISHMENT OF LOCAL SYSTEMATIC GOOD PRACTICE GUIDE IN ROCK SLOPE ASSESSMENT

As new technologies and development of new techniques are introduced into local practice, they have undeniably improved the speed and accuracy of recent assessments. However, at the same time, rock slope assessments have become very decentralized lately, with several methods used concurrently. While in academic practice, it is useful to discover new methods of assessment and validate existing ones, it has become somewhat incoherent for practical use. It may lead to different interpretation or assessment towards a same problem (rock slope stability), and conflicting opinions among practitioners.

Therefore, a suitable guide for practitioners which has been made suitable for use in Malaysia would be useful in such situations. It does not necessarily be binding for any practitioner to follow, and they would still have the liberty to conduct assessments in their own preferred method. The document, instead, would suggest the good practice on rock slope assessment in line with international practice including recommendations by International Society for Rock Mechanics (ISRM). One example of such document published is 'Rock engineering guides to good practice: rock slope remedial and maintenance work' (McMillan, Harber & Nettleton 2011).

The establishment of local good practice in rock slope assessment would improve the local practice up to international standards. This document should have been updated regularly with new improved methods and lessons from case studies. To do so, a working group comprising of professional geologists can be set up to produce such good practice guide.

INCORPORATION OF NUMERICAL ANALYSIS INTO STANDARD PRACTICE

In this review, numerical analysis for rock slope stability assessments have been observed to be primarily conducted for academic purposes. Its application in practical use has been largely limited due to qualitative-centric nature of assessment by engineering geologists. It must not be confused with use of rating systems - a semi-qualitative method - which have been used widely in Malaysia.

Numerical analysis in this subtopic refers to the kinetics of movements involved in identified potential failures including its forces. To put it simply, to calculate the stability of potential failures. One of widely used method is the Limit Equilibrium Method (LEM). The objective of this analysis was to calculate the Factor of Safety (FOS) of potential failure block. Parameters for LEM may vary depending on criterion of choice, but a competent engineering geologist shall be able to understand the mechanics behind its movement. For example, Mohr-Coulomb model may suit homogenous and isotropic mass, while Barton-Bandis model suits jointed rock mass where sliding along discontinuities are expected, and Hoek-Brown criterion for intensely jointed and weak rock mass where mass failure is expected. Use of LEM greatly helps in mitigation design, especially in determining suitable countermeasures to increase its resisting force to get desirable FOS.

LEM analysis can be employed deterministically (one set of parameters to cater specific conditions) or probabilistically (ranges of parameters to cater varying conditions). Probabilistic analysis of FOS value will yield Probability of Failure (PF).

For a more thorough assessment, Finite Element Method (FEM) or Discrete Element Method (DEM) models can be employed. They can be suited for a more accurate model in complex engineering geological problem (rock slopes). Dynamic analysis can be conducted for rock slopes exposed to seismic vibrations and stability deterioration over time due to water influence. All analysis, however, must be done in adherence to the rock mass behavior, where discontinuities influence must be considered if present.

Engineering geologists should be equipped with fundamentals of rock mechanics to conduct numerical analysis of rock slopes. At times, cooperation with geotechnical engineer in assessments is vital to conduct such analysis accurately. Nevertheless, use of numerical analysis should be made as a standard practice in rock slope assessments to complement the findings from kinematic analysis.

IMPROVING UTILIZATION OF NEW TECHNOLOGIES

Despite its current limitations especially on accuracy of extracted data, it is undeniable that use of TLS and photogrammetry greatly reduces time and improves coverage in discontinuity mapping for rock mass. For example, cut rock slopes in highways may well exceed 5 berms in height (around 30 m) and greater than 200 m in length. For humans to be able to manually map the discontinuities using standard scanline method, it will be very lengthy, and some areas may be inaccessible or extremely dangerous to access. Use of TLS or photogrammetry with suitable extracting and processing software will be especially useful in such situation.

As stated earlier, such use of remotely sensed data acquisition may be inaccurate and results in erroneous assessment if not processed, filtered, and extracted properly. But in most cases, the need for such tool outweighs its limitations. Therefore, studies on methods to improve its accuracy in delivering quality data output should be conducted. Improvements on method and output of these new technologies would not only hasten rock slope assessment process, but also improve the quality of assessment.

TROPICAL WEATHERING AND ROCK SLOPE STABILITY

Rock masses in Malaysia are known to undergo intense tropical weathering associated with hot and humid weather. The result of such environment is thick and sometimes complex weathering profile. Rock slopes are often accompanied by slightly to moderately weathered rock mass (Grade II-III) and *in-situ* soil mass (Grade IV-V) where geological structures remain intact. Geotechnical properties of the same rock material experiencing different level of weathering differs (Goh, Abdul & Hariri 2012) where it is expected to weaken as weathering progresses. Issues with weathering on Malaysian slopes have been advocated by Tajul (1991) and Tajul and Muhammad Fauzi (2000). They argued that geological structures (discontinuities) still had an influence on slope stability even in highly weathered mass (Grade IV-V).

Assessments on such rock slopes are complicated, and in favorable scenario should not be similarly approached like fresh rock slopes. Research in establishing suitable methodology to assess weathered rock slope is recommended, especially in tropical conditions experienced in Malaysia. Another effect of tropical weathering experienced in Malaysia is deterioration of rock slope stability over time. Although the excavated rock slope may appear fresh, the tropical climate may physically and chemically weather fresh rock mass into weathered rock and soil mass. Geotechnical properties of the rock mass also deteriorate along with weathering, changing the stability of rock slope.

Limestone slopes, for instance, experience low rate of dissolution upon contactwith water. Tropical climate experienced in Malaysia ensures near-constant water flow all year long which contribute to prolonged dissolution of limestone slopes. This results in deterioration of slope stability especially along discontinuities where dissolution rate is the most. In some cases, differential weathering between different strata (often seen in sedimentary rocks) for example in sandstone-shale results in failure years after completion of rock slope excavation. This occurred despite stable FOS calculated in designing the slope. Therefore, deterioration of rock slope stability over the years due to weathering is another interesting aspect to look into in rock slope stability assessment.

INCORPORATION OF SEISMIC INFLUENCE

Incorporation of seismic influence is crucial in seismically active regions. Based on Department of Standards Malaysia (2017), areas which are more susceptible to seismic hazards includes Bukit Tinggi, Temenggor, Tasik Kenyir and Lumut in Peninsular Malaysia, Niah and central Sarawak in Sarawak, and Ranau, Lahad Datu and Kudat in Sabah. Rock slope stability analysis in these areas must take seismic influence into analysis. This is a relatively new field in Malaysia with few published studies. One of notable study was done by Abdullah et al. (2019) for slope stability related to 2015 Sabah Earthquake event.

DISCUSSIONS AND CONCLUSIONS

A total of 39 published case studies for rock slope assessments in Malaysia were examined in this review. They are shown in chronological order in Table 3. Based on Table 3, it is evidence that earlier rock slope stability assessments were limited to kinematic analysis but use of stability ratings become more popular in 2010s followed by incorporation of numerical methods post 2015. Recent studies are more liberal in choice of methodologies, but still anchored by kinematic analysis that forms the fundamental of the assessments. Diversification of methodologies gives out various type of output on rock slope stability assessment.

TABLE 3. List of case studies examined in this review, arranged in chronological order

No.	Source	Slope Type	Lithology	Location	Assessment Method: Kinematic Analysis	RMR and derivatives	Locally developed rating systems	Other stability rating systems	Numerical Analysis	Notes
1	Tajul (1991)	Cut slope	Granite and meta-sedimentary	Gerik, Perak and Jeli, Kelantan	✓					Intensive use of sketch to describe failure
2	Tan (1994)	Cut slope	Clastic sedimentary	Sarikei and Julau, Sarawak	✓					
3	Tan & Tajul (2000)	Cut slope	Granite	Ampang, Selangor	✓					
4	Tajul & Fauzi (2000)	Cut slope	Slate	Kota Tinggi, Johor	✓					Emphasis on weathering influence
5	Aziman & Husaini (2001)	Cut slope	Granite and Schist	PosSelim, Perak	✓					
6	Tajul & Nizam (2001)	Cut slope	Granite and Schist	Cameron Highlands, Pahang	✓					For EIA preparations

7	Tajul (2004)	Cut slope for dam	Clastic sedimentary	Bintulu, Sarawak	✓					Discontinuity data not presented in stereographic plot due to unusual failure pattern
8	Mustaffa & Tajul (2004)	Cut slope	Granite	Cheras, Selangor	✓					Mitigation suggested
9	Tan (2004)	Cut slope	Granite	Penang, Selangor	✓				✓	Emphasis on weathering influence
10	Abd (2005)	Cut slope	Granite	Senai, Johor	✓					
11	Jamaludin, Huat & Husaini (2006)	Cut slope	Granite	Peninsular Malaysia			✓			
12	Jamaludin & Nadzri (2006)	Cut slope	Granite and clastic sedimentary	Sandakan, Sabah and Gerik, Perak			✓			
13	Mustaffa, Samsudin & Mazlan (2006)	Cut slope	Shale, schist, and quartzite	Gerik, Perak and Jeli, Kelantan	✓					Emphasis on weathering influence
14	Haswanto & Ghani (2008a)	Cut slope	Granite	Bukit Fraser, Pahang	✓					Block theory application
15	Haswanto & Ghani (2008b)	Cut slope	Granite	Kajang, Selangor	✓					Block theory application
16	Mat Radhi, Mohd Pauzi & Omar (2008)	Cut slope	Granite	Perak					✓	Probabilistic analysis of rock slope stability
17	Tonnizam & Vahid (2011)	Cut Slope	Granite	Masai, Johor	✓	✓				
18	Ismail (2015)	Cut slope	Clastic sedimentary	Kota Kinabalu, Sabah		✓				Introducing M-SMR for Crocker Formation
19	Al-Bared et al. (2015)	Cut slope	Granite	Cheras, Selangor	✓				✓	Deterministic FOS from Hoek-Brown criterion
20	Kaamin et al. (2016)	Cut slope	Granite	Simpang Pulai, Perak			✓			
21	Goh & Afiq (2016)	Cut slope	Granite	Cheras, Selangor	✓	✓		✓	✓	Use of GSI and Hoek-Brown criterion
22	Norazliza & Tajul (2016)	Natural slope	Limestone	Ipoh, Perak	✓	✓				
23	Goh et al. (2016b)	Natural slope	Limestone	Ipoh, Perak	✓	✓				
24	Nur Amanina et al. (2016)	Natural slope	Limestone	Ipoh, Perak	✓	✓				

25	Norbert et al. (2016)	Cut slope	Clastic sedimentary	Sabah				✓		Use of GSI for Crocker Formation
26	Goh et al. (2016a)	Cut slope	Granite	Cheras, Selangor				✓	✓	Use of GSI and Hoek-Brown criterion
27	Kuraoka et al. (2016)	Cut slope	Schist	Pos Selim, Perak	✓			✓	✓	Use of GSI and Hoek-Brown failure criterion for displacement modelling.
28	Ismail & Raffee (2017)	Cut slope	Clastic sedimentary	Kota Belud, Sabah	✓				✓	Calculation of FOS using c and φ
29	Ainul et al. (2018)	Natural slope	Limestone	Gopeng, Perak	✓	✓				
30	Goh et al. (2018)	Natural slope	Limestone	Batu Caves, Selangor	✓	✓				
31	Wen et al. (2018)	Cut slope	Limestone	Perlis	✓					Use of photogrammetry to extract discontinuities
32	Rasyikin et al. (2019)	Cut slope	Granite	-		✓				
33	Afiq & Goh (2019)	Cut slope	Granite	Kajang, Selangor	✓	✓		✓	✓	Comparison between RMR, SMR, Q_{slope}& numerical using Barton-Bandis criterion
34	Afiq et al. (2019)	Cut slope	Granite	Kajang, Selangor	✓				✓	Deterministic and probabilistic FOS from Barton-Bandis criterion
35	Hellmy et al. (2019)	Natural slope	Limestone	Ipoh, Perak	✓					Use of TLS to extract discontinuities
36	Faruq et al. (2019)	Mining Pit	Slate and schist	Gerik, Perak	✓					Use of TLS to extract discontinuities
37	Abdullah et al. (2019)	Cut slope	Clastic sedimentary	Ranau, Sabah					✓	Dynamic analysis with seismic influence
38	Afiq (2020)	Cut slope	Granite	Kajang, Cheras and Rawang, Selangor	✓	✓		✓	✓	Use of RMR, SMR, Q_{slope}& numerical using Barton-Bandis criterion
39	Nagendran & Ismail (2020)	Cut slope	Limestone	Perlis	✓				✓	2D and 3D anisotropic numerical model of rock slope stability

While the differences shall be respected, it is recommended that a suggested good practice with systematic approach in local rock slope stability assessments can be proposed. The good practice itself should be improved from time to time based on newer case studies and established methodologies. Several suggestions can made to improve general practice of rock slope stability assessment in Malaysia; incorporation of numerical analysis, utilization of new technologies and further studies on relationship between tropical weathering and rock slope stability. The utilization of new technologies of this systematic approach shall integrate the knowledge of geospatial, geology, geophysics and engineering geology and finally provide adequate information for engineer in the rock slope design.

In conclusion, rock slope stability assessment practice in Malaysia has developed considerably over the last 20 years. This review observed that incorporation of multiple methods is becoming more popular recently without discarding fundamental methods such as the like kinematic analysis. Use of numerical methods also reflects increasing understanding of rock mechanics which is vital to rock slope stability assessment among local practitioners. Therefore, competent engineering geologists in Malaysia should be able to assess rock slope stability issues holistically, applying widely-accepted methods and customize them to Malaysian needs.

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