Three slope failures in Malaysia: lessons learned and suggestions for the future

Ali A. Mahmood[1*] and Mohamad Zularif Ayup[2]
[1]Advanced Studies Research Centre, 2365 rue Cardin, Drummondville, Quebec J2C 6J6, Canada
[2] Petronas Dagangan Berhad, Kuching, Sarawak, Malaysia
**Corresponding author (email: ali@asrcentre.com)*

ABSTRACT
Slope failures are one of the most studied type of hazards due to the amount and extent of losses incurred and their usual proximity to residential areas and highways. Many studies have been devoted to the theoretical and experimental analysis of slope failures in their different forms and soil conditions. This study analyzed three slope failures in the states of Johor, Kelantan and Selangor in Malaysia. Global slope stability analysis indicated that, in general, these slopes had a factor of safety above one. Consequently, an analysis of other factors potentially involved in the initiation of the landslides was undertaken. Suggestions are put forward to mitigate this type of slope failures including the addition of a system of gabions-soil nails on the front face of the slope and geogrid-geosynthetic combinations and water pressure dissipation channels on the back face of the slopes. This is suggested in order to eliminate potential slope failures and to increase the factor of safety against failure, taking into account local soil conditions and the steepness of slopes. A conceptual risk analysis procedure is further proposed before actual slope reinforcement design takes place. The risk analysis should encompass, among others, all possible critical failure surfaces, the frequency of severe rain storm events and the non-homogeneity in subgrade soil conditions.

RÉSUMÉ
Les ruptures de pente sont l'un des types de risques les plus étudiés en raison de la quantité et de l'étendue des pertes subies et de leur proximité habituelle avec les zones résidentielles et les autoroutes. De nombreuses études ont été consacrées à l'analyse théorique et expérimentale des ruptures de talus sous leurs différentes formes et conditions de sol. Cette étude a analysé trois ruptures de talus dans les états de Johor, Kelantan et Selangor en Malaisie. L'analyse globale de la stabilité des pentes a indiqué qu'en général, ces pentes avaient un facteur de sécurité supérieur à un. Par conséquent, une analyse des autres facteurs potentiellement impliqués dans l'initiation des glissements de terrain a été entreprise. Des suggestions sont avancées pour atténuer ce type de ruptures de talus notamment l'ajout d'un système de clous gabions-sol sur la face avant du talus et de combinaisons géogrille-géosynthétiques et de canaux de dissipation de la pression d'eau sur la face arrière des talus. Ceci est suggéré afin d'éliminer les ruptures de pente potentielles et d'augmenter le facteur de sécurité contre la rupture, en tenant compte des conditions locales du sol et de la pente des pentes. Une procédure d'analyse conceptuelle des risques est en outre proposée avant que la conception réelle du renforcement des talus n'ait lieu. L'analyse des risques devrait englober, entre autres, toutes les surfaces de rupture critiques possibles, la fréquence des épisodes de fortes pluies et la non-homogénéité des conditions du sol de fondation.

1 INTRODUCTION

Slope failures are one of the most common types of failures that take place in Malaysia and elsewhere. Several investigations took place to analyze and to discern their different aspects in order to shed light on possible remediation or mitigation methods. Examples are the works of Liew et al. (2003), (Gue and Wong 2009), (Liew et al. 2010), (Kazmi et al. 2016), (Kazmi et al. 2017) and (Zabidi et al. 2021) who investigated several slope failures in Malaysia and came up with general recommendations and possible mitigation methods. However, it seems that a comprehensive global stability analysis using the Ordinary Method of Slices is missing from these studies. This research, hence, is an attempt to further investigate three slope failures that took place in the Malaysian states of Selangor, Johor and Kelantan. A few details on these slopes were mentioned in the paper by Liew et al. (2004). However, several index parameters of the soils are missing. Therefore, it is desired to find these parameters to perform a rigorous global slope stability analysis using the Ordinary Method of Slices. Findings of this study will shed further light on possible causes and remediation methods for these and similar slopes in tropical rainy environments using a global slope stability analysis.

2 EXPERIMENTAL PROCEDURE

In order to perform the slope stability analysis, it was decided to use the Ordinary Method of Slices (Das and Sobhan 2012). It is thought that this method is widely used in practice for this purpose. Since soil parameters will be needed to perform the analysis, a literature search was conducted to determine the relevant index parameters for the three slopes in Selangor, Johor and Kelantan.

2.1 Index Parameters

Residual soils in the Kenny Hill formation in peninsular Malaysia, were previously studied by Kong and Miasin (2005). They reported two distinct lithologies: Phyllite and Quartzite, according to their source rock. These soils are predominant in the Klang valley in the Malaysian state of Selangor, the first subject of the slope stability analysis. Phyllite soils are generally fine-grained in nature with clay contents ranging from 41-60%, with silt contents ranging from 20-45%. Their sand content is generally below 30%, with the exception of a sample that showed a sand content of 39% (Kong and Miasin 2005). Quartzite residual soils, on the other hand, show higher sand contents ranging from 37-67% and lower clay contents that range from 6-43% and generally lower than 20% (Kong and Miasin 2005).

Gasmo (1997) who investigated residual soils in the Jurong formation, predominant in Johor, where the second slope failure occurred, reported soils classified as clays with low plasticity (Leong et al. 2002).

While Liew et al. (2004) indicate that the Kelantan area of the third slope failure investigated is underlain by shell facies consisting of mudstone and siltstone. Hence the soil for the former is hardened mud, which is a mix of clay and silt particles, and for the latter it is soil with more than half its composition silt-sized particles (Geologyscience.com 2018).

2.1.1 Selangor Slope

According to Pushparajah and Amin (1977) (as cited in Huat et al. (2004), residual soils from sand-stones have a bulk density, ρ_{bulk} of 1.3 g/cm^3. Thus, it was assumed that the unit weight of the residual soil is 12.8 kN/m^3. The shear strength parameters of the soil are c' = 2 kPa and φ' = 32°, as retrieved from Liew et al. (2004) who interpreted peak shear strength from the subsurface investigation at a filled slope in Selangor.

2.1.2 Johor Slope

According to Leong and Rahardjo (1995) (as cited in Huat et al. (2004) and Sharma et al. (1999) (as cited in Huat et al. (2012), residual soils from the Jurong formation have a bulk density ranging from 1.8 to 2.2 g/cm^3. Based on this an average value of ρ_{bulk} = 1.9 g/cm^3 was selected in this study, for the Johor slope. Accordingly, the unit weight of the residual soil was assumed to be 18.6 kN/m^3. The shear strength parameters of the soil were c' = 3 kPa and φ' = 29°, as retrieved from Liew et al. (2004) who interpreted laboratory critical state strength of a landslide failure at a construction site in Johor.

Knowing that Liew et al. (2003) performed geotechnical investigation and monitoring work of a landslide failure in southern peninsular Malaysia where Johor is located, the construction drawings in their study were used as a reference to perform the Ordinary Method of Slices slope stability analysis.

2.1.3 Kelantan Slope

Based to the analysis performed by Liew et al. (2004) of the global slope stability of the Gua Musang, Kelantan highway slope, the unit weight, γ of the Grade V, Grade IV and Grade III soils were found to be 19.5 kN/m^3, 22.5 kN/m^3 and 22.5 kN/m^3 respectively. And according to the same authors, the cohesion, c of the Grade V, Grade IV and Grade III soils were 5 kPa, 50 kPa and 30 kPa respectively. Also, the friction angle, φ of the Grade V, Grade IV and Grade III soils were found to be 33°, 33° and 39° respectively (Liew et al. 2004). In order to represent a worst-case scenario, the lowest of these parameters was used in the current study. As such, density was assumed to be 19.5 kN/m^3, cohesion 5 kPa and the angle of internal friction 33°.

2.2 The Ordinary Method of Slices

The analysis using the Ordinary Method of Slices proceeded, as a first step, for each of the three slopes by varying the radius of the potential failure circle to get the lowest and highest factor of safety, as shown in Figure 1. Subsequently, another analysis was performed using two radii that were determined in the first step; the radius with the lowest factor of safety surpassing one, and that with the highest factor of safety. This was done to further investigate the possible worst-case scenario by varying the locations of these two radii, in one-meter intervals, while keeping their lengths constant, as shown schematically in Figure 2. This procedure was applied for the three slopes. To the Selangor slope, however, was added another radius retrieved by analysis from the paper by Liew et al. (2004).

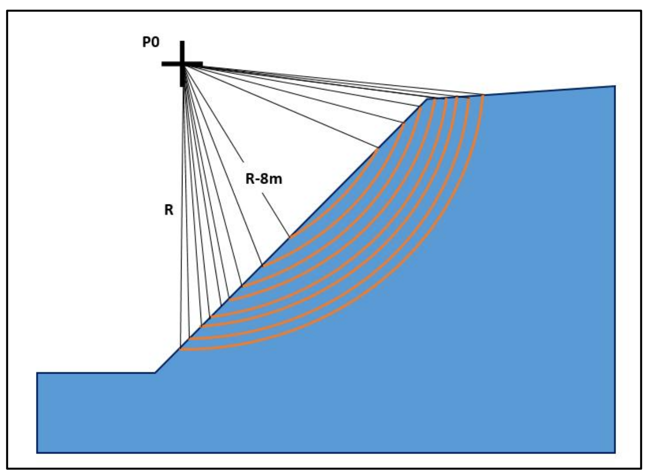

Figure 1. Different radius, constant point stability analysis using the Ordinary Method of Slices.

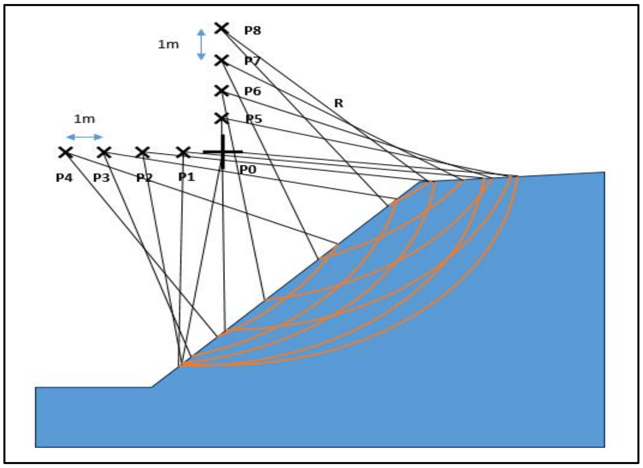

Figure 2. Constant radius, different point stability analysis using the Ordinary Method of Slices.

3 RESULTS AND DISCUSSION

A report by the Malaysian Work Department (Jabatan Kerja Raya), as referenced by Kazmi et al. (2016), shows that the major causal factor that contributed to slope failures in Malaysia was improper design (58%) while rainfall was the main triggering factor (58%) (Kazmi et al. 2016). In light of this, this study investigated three different slope failures using the Ordinary Method of Slices, in an attempt to shed some light on their failure mechanism. This particular failure mechanism governs by virtue of a factor of safety analysis. Figures (3), (4), (5) and (6) show the results of the analysis performed.

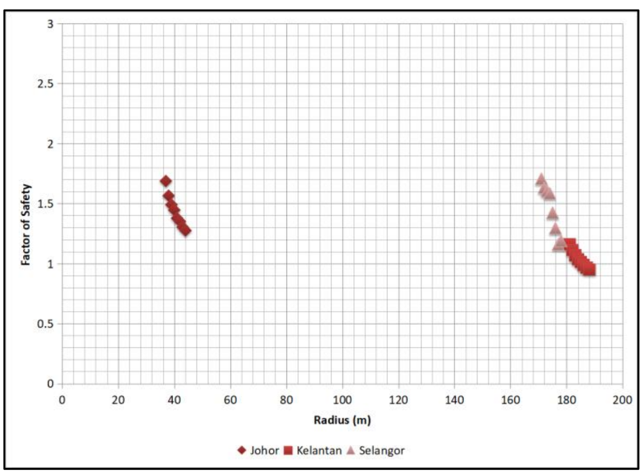

Figure 3. Global stability analysis using the Ordinary Method of Slices, performed on the three slopes in Johor, Kelantan and Selangor, as a function of failure radius.

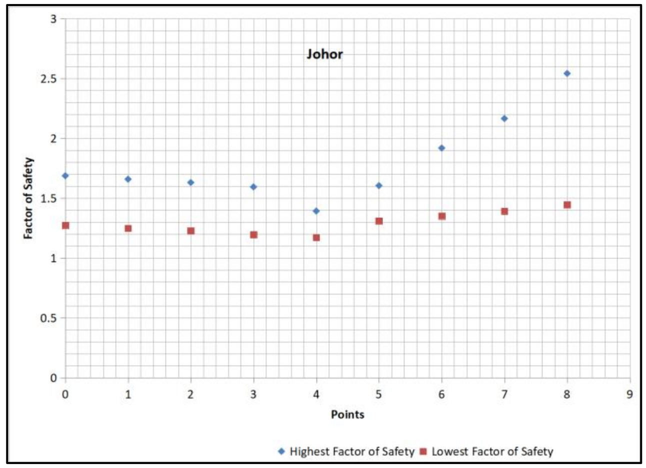

Figure 4. Global stability analysis using the Ordinary Method of Slices, performed on the slope in Johor, as a function of position, for the two extreme factors of safety.

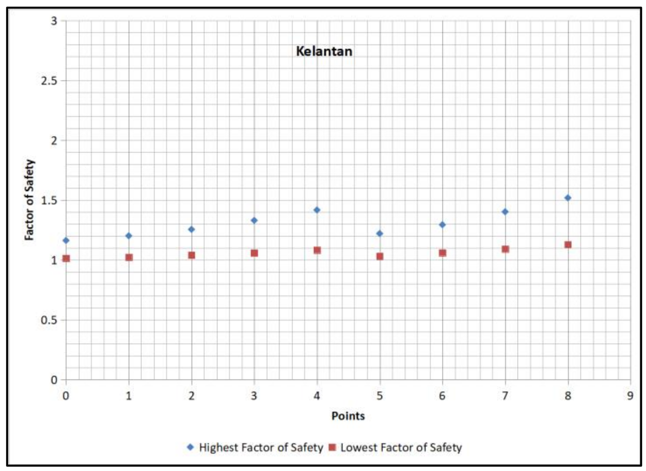

Figure 5. Global stability analysis using the Ordinary Method of Slices, performed on the slope in Kelantan, as a function of position, for the two extreme factors of safety.

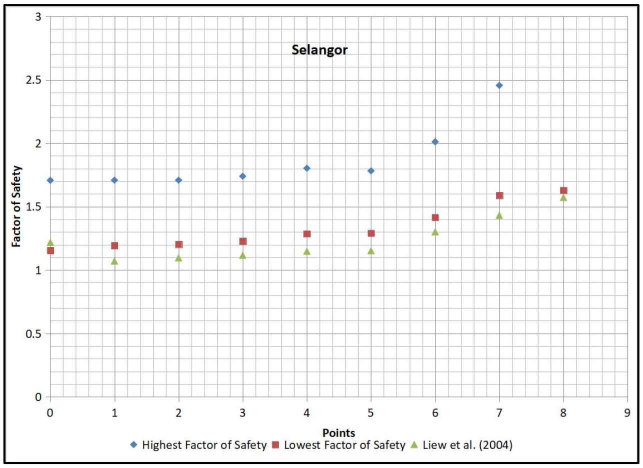

Figure 6. Global stability analysis using the Ordinary Method of Slices, performed on the slope in Selangor, as a function of position, for the two extreme factors of safety plus the radius retrieved from the paper by Liew et al. (2004).

The global slope stability analysis conducted on the three slope failures in the Malaysian provinces of Selangor, Johor and Kelantan suggest the existence of potential slip surfaces with low factors of safety that border on one or below. This is shown in the three Kelantan slopes in Figure (3). However, most of the analysis conducted on the slopes showed factors of safety above one. Variations in the range of radii, shown in Figure (3), for the three slopes is an indication of the different types of soils encountered within each slope. Based on the investigation by Liew et al. (2004), and as indicated therein, static groundwater conditions were assumed when performing the slope stability analysis.

It is thought, that strengthening the said slopes to produce higher factors of safety is essential in order to avoid future failures. Based on this understanding, the following suggestions are put forward:

(1) it is suggested to strengthen the soil by using reinforcement to penetrate the slip circles with the lowest factor of safety. Soil and groundwater conditions vary for each of the three sites, as indicated in Liew et al. (2004); hence each site has unique slip circles' location. Since most of the analyses conducted showed factors of safety above one, it is thought essential to adopt another type of reinforcement to strengthen the said slopes. Additionally, it is thought that the slopes constructed are too steep for the types of soils involved and therefore it is advised to flatten the slopes to reduce the hazard associated with a landslide.

(2) Although soil nailing and shotcrete is a widely used practice in slope construction in Malaysia, it is suggested that a system of gabions-soil nails be instrumented in these and similar slopes to eliminate potential slope failures. This design should take into account local soil conditions and steep slopes. Soil nailing application will have to consider these unique features. It is thought that the addition of gabions adds more stability to slopes notably at the toe, where potential slope failures would occur (Liew et al. 2010). It is also advised to extend the soil nails into the rock layer beneath, if it exists. Gabions have been shown to provide stability to retaining walls and other structures in other parts of the world (Nakazawa et al. 2019). Geogrid-geosynthetic systems add further reinforcement to the back face of the slope, and it is advised to install them penetrating potential critical slip surfaces

(3) Using deep root vegetation

(4) Installing water pressure dissipation channels to prevent water pressure buildup at the back and heel of the slope surface

(5) The assumption of a circular failure profile, according to the Ordinary Method of Slices, may not always be accurate especially in non-homogeneous soils

(6) A conceptual risk analysis is proposed as shown in Figure (7), to analyse the potential failure risk for slopes exposed to torrential rain events in tropical terrains:

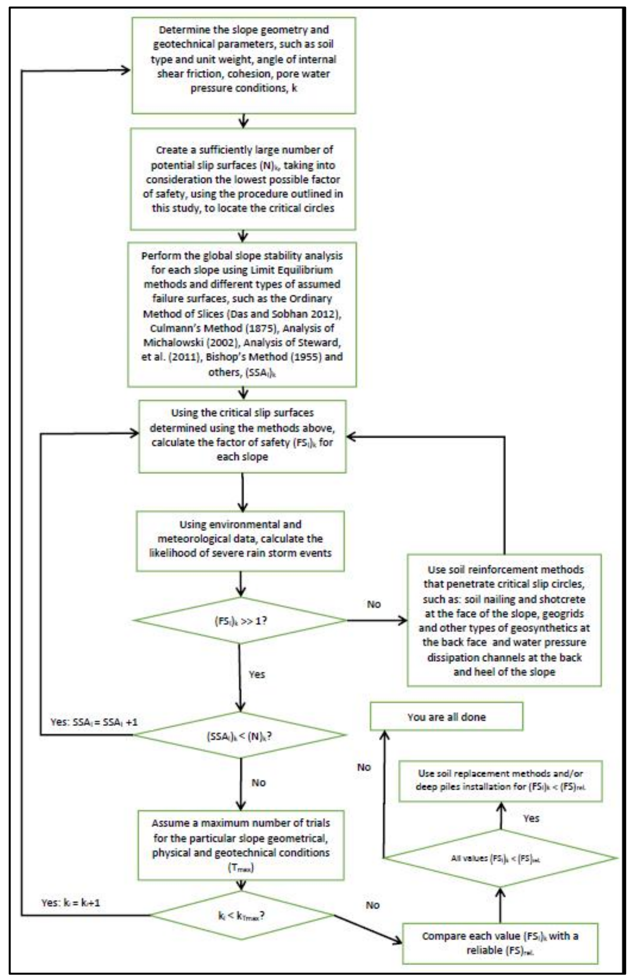

Figure 7. Flow chart showing the proposed conceptual risk analysis procedure.

(7) In extreme cases, where soft soils and extreme rain storm events are encountered, soil replacement

methods and deep piles installation, should be assumed as the final solution, pending budget constraints

In the end, trial slopes with the suggested modifications will ultimately determine the relevance of these strengthening methods in a Malaysian climate environment.

4 CONCLUSION

Global stability analysis using the Ordinary Method of Slices, performed on three slopes in the Malaysian states of Johor, Selangor and Kelantan revealed that the factor of safety for most scenarios analyzed was above one. Three Kelantan slope analyses, however, showed a factor of safety marginally below one. It is suggested, therefore, that in order to increase the factor of safety, additional layers of protection against rainfall infiltration should be added. For example, it is advised to install a system of gabion-soil nails that infiltrate the potential slip circles with the lowest factor of safety. Preferably the nails should extend to the rock layer below, if permissible. Geogrid-geosynthetic systems, installed on the back face of the slope penetrating potential critical slip surfaces, should add more protection in cases of severe tropical rain storm evens. Installing water dissipation channels at the back slope to prevent water pressure buildup, is equally important. And, deep root vegetation, should be used as a back up strategy. Therefore, encompassing all these and more, a conceptual risk analysis procedure is proposed in this study before the actual design of the slope reinforcement takes place. The risk assessment, should take into consideration all potential slip surfaces (circular and non circular), the frequency of severe tropical rain storm events in the study area and the non-homogeneity of subgrade soil layers.

5 REFERENCES

Bishop, A.W. (1955). The Use of Slip Circle in the Stability Analysis of Earth Slopes, *Geotechnique*, 5(1): 7-17.

Culmann, C. (1875). *Die Graphische Statik*, Meyer and Zeller, Zurich.

Das, B.M. and Sobhan, K. 2012. *Principles of Geotechnical Engineering*, 8th ed., Cengage Learning, 200 First Stamford Place, Suite 400, Stamford, CT 06902, USA.

Gasmo, J.M. 1997. *Stability of Unsaturated Residual Soil Slopes as Affected by Rainfall*, master's thesis, Nanyang Technological University, Singapore.

Geologyscience.com. 2018. https://geologyscience.com/rocks/sedimentary-rocks/mudstone/, accessed 8 March 2022.

Gue, S.S. and Wong, S.Y. 2009. Slope Engineering Design and Construction Practice in Malaysia, *CIE-IEM Joint Seminar on Geotechnical Engineering*, Yilan, Taiwan.

Huat, B.B.K., Gue, S.S. and Ali, F.H. 2004. *Tropical Residual Soils Engineering*. 258 pp. CRC Press. UK.

Huat, B.B.K., Toll, D.G. and Prasad, A. 2012. *Handbook of Tropical Residual Soils Engineering.* 536 pp. CRC Press. UK.

Kazmi, D., Qasim, S., Harahap, I.S.H., Baharom, S., Imran, M. and Moin, S. 2016. A Study on the Contributing Factors of Major Landslides in Malaysia, *Civil Engineering Journal,* 2(12): 669-678.

Kazmi, D., Qasim, S., Harahap, I.S.H. and Vu, T.H. 2017. Analytical Study of the Causes of the Major Landslide of Bukit Antarabangsa in 2008 Using Fault Tree Analysis, *Innovative Infrastructure Solutions*, 2(1): 1-11.

Kong, T. B. and Miasin, S. F. E. 2005. Physico-chemical Properties of Residual Soils of the Kenny Hill Formation in the Shah Alam Area, Selangor, *Annual Geological Conference*, 51: 13-17 Seremban, Negeri Sembilan, Malaysia.

Leong, E. C., He, L. and Rahardjo, H. 2002. Factors Affecting the Filter Paper Method for Total and Matric Suction Measurements, *Geotechnical Testing Journal*, *GTJODJ*, 25(3): 321–332.

Leong, E.C. and Rahardjo, H. 1995. Typical Soil - Water Characteristics Curves for Two Residual Soils From Granitic and Sedimentary Formations, *1st International Conference on Unsaturated Soils*, Paris, France, Vol. II: 519-524.

Liew, S.S., Gue, S.S. and Liong, C.H. 2003. Geotechnical Investigation and Monitoring Results of a Landslide Failure at Southern Peninsula Malaysia (Part 1: Investigating Causes of Failure), *International Conference on Slope Engineering*, Hong Kong.

Liew, S.S., Lim, W. and Lau, L.S. 2010. Investigation of Soil Nailed Slope Distress at Fill Ground and Remedial Solutions, *The 17th Southeast Asian Geotechnical Conference*, Taipei, Taiwan.

Liew, S.S., Liong, C.H. and Low, C.L. 2004. Four Landslide Investigations in Malaysia, *15th SEAGC*, Bangkok, Thailand.

Michalowski, R.L. (2002). Stability Charts for Uniform Slopes, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 128(4): 351-355.

Nakazawaa, H., Nishi, T., Kurihara, H., Suetsugu, D. and Hara, T. 2019. Basic Study on Deformation Evaluation of Steel Wire Mesh for Rational Gabion Structure Design, *EPI International Journal of Engineering*, 2(2): 109-115.

Pushparajah, E. and Amin, L.L. 1977. *Soils Under Hevea and Their Management in Peninsular Malaysia*, 188 pp. Rubber Research Institute of Malaysia, Kuala Lumpur, Malaysia.

Sharma, J., Chu, J., Zhao, J. 1999. Geological and Geotechnical Features of Singapore: An Overview. *Tunneling and Underground Space Technology*, 14 (4): 419-431.

Steward, T., Sivakugan, N., Shukla, S.K., and Das, B.M. (2011). Taylor's Slope Stability Charts Revisited, *International Journal of Geomechanics,* ASCE, 11(4): 348-352.

Zabidi, M.D., Hadi, B.A., Amir, K.R., Keria, R., and Derahman, A. 2021. A Preliminary Study on the Slope Failure at Highlands in Peninsular Malaysia.

International Journal of Academic Research in Business and Social Sciences, 11(4): 585-594.