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Stability of man-made slopes: A numerical case study using an extreme rainfall distribution in Brunei Darussalam

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Abstract. The number of slope failure cases in Brunei Darussalam has been observed to increase during periods of intense rainfall, such as during the month with peak rainfall. Like other countries around this region, a recommended value of slope angle during earthwork and construction has been established. However, the apparent correlation between landslides and high rainfall intensity suggests that an investigation needs to be carried out to see whether the recommended value is appropriate for the current Brunei's climate condition, especially in relation to a potential reduction in the factor of safety due to rainfall infiltration. This study investigated the effect of the peak monthly rainfall distribution on the stability of different slope angles using the continuous rainfall data from December 2013 to January 2014 as a case example. A commercial software, GeoStudio2012, was used to carry out the numerical analysis of rainfall infiltration and limit equilibrium to evaluate the factor of safety of slopes. The study revealed that the current recommendations may not be appropriate for certain soil condition under the considered critical rainfall distribution. It also revealed that the daily highest intensity of rainfall did not necessarily result in a slope failure, but rather the accumulation of rainfall was a more significant factor to trigger slope instability.

1. Introduction

The stability of a man-made slope can be influenced by several factors including the height of the slope, angle of the slope, the strength of the soil, rainfall in the area, drainage over the slope, groundwater table, seepage of water, and vegetation on the slope. Due to the high number of these influencing factors, and the spatial variation of the soils, rainfall and vegetation, it is often difficult to generalise a design method that can evaluate the stability of all types of slope. This poses a challenge in specifying a general engineering design guideline for slope development.

Brunei Darussalam is a small country with a land area of 5765 km^2, located on the north of Borneo Island, next to the South China Sea and with land bordering Eastern Malaysia. Rainforest covers about 80 percent of Brunei's land and the country receives an average annual rainfall of 3200 mm. Official figures have shown that there were approximately 156 slope failure cases per year (2011 – 2016), and 86% of these cases have occurred in the most populated area of Brunei-Muara District [1]. A notable case example that supported the abundance of rainfall-induced slope failures can be found in January

2014 – a total monthly rainfall of 840 mm, that was 26% of total annual rainfall in 2014, was recorded together with over 150 reported landslides within the same month.

The slope development guideline of Brunei Darussalam [2] recommends an acceptable slope angle to be used during earthwork and construction of slopes. However, the apparent correlation between landslides and heavy rainfall suggests that an investigation is required to examine if the recommended values are appropriate during periods of intense rainfall. Therefore, it is the aim of this study to explore the effect of a peak monthly rainfall distribution on the stability of selected, representative slopes using numerical modelling. The investigation was conducted on representative configurations of model slopes with two different slope heights and three different slope angles. The rainfall distribution in the model followed the monthly rainfall data recorded from December 2013 to January 2014. Commercially available software, SEEP/W and SLOPE/W in GeoStudio 2012, was used for the numerical modelling.

2. Relationship between landslides and slope angles

Slope angle, slope height and slope surface play a vital role in determining the stability of slopes [3]. It has been shown that the initial slope angle might control the geometry of landslides, while the sizes of the landslide were controlled by complex factors, including peak soil strength and gravity [4]. It was suggested that in a landslide-susceptible geologically complex area, the most slope instability activities occurred at slope angles ranging from 19° to 34° [5]. In Hong Kong, soil slopes have shown to be generally stable when it is initially angled at less than 20°, and rock slopes at higher than 50° [6].

Recommended values of slope angle and procedures for earthwork and construction on slopes have been established in many guidelines for different locations around this region [2,7–9]. In Brunei Darussalam, the guidelines have recommended that a cut slope shall be maintained at a gradient of 1:2 to 1:2.5, a man-made slope shall be constructed at a gradient of 1:2.5 to 1:3, and development appears to only be permitted when the slope angle is less than 30° as any slope with an angle of above 30° are considered environmentally sensitive as it is prone to failures [2].

In contrast, in Pulau Penang, Malaysia, the guidelines have suggested that development shall not occur beyond 25° [8]. Therefore, there are some variations across this region on the recommended safe angle for slope design and construction. Regular review of these guidelines and new studies at the state or national level should be conducted to account for the different geological conditions, continuous environmental changes and changes to design standards and construction practice.

3. Previous studies on rainfall-induced slope failure

Rainfall is one of the major factors in causing landslides, as its occurrence can increase landslide vulnerability due to increasing infiltration rate in the soil. The infiltration rate caused by different rainfall intensity affects the pore water pressure and soil's strength – it was identified that at higher rainfall intensities, the critical slope angle is between 25° to 40° [10].

Moreover, numerical modelling [11] conducted to evaluate the stability of a shallow soil slope during high intensity and short duration rainfall have shown that 35° slopes have failed, while no failure was observed in 15° and 25° slopes. However, one experimental study [12] has revealed that varying slope angles with three different rainfall intensities – minimum, maximum and average – indicated that the steepness of the slope only provided a minor contribution to slope failure. Instead, it was the rainfall intensity that played a significant role in determining the infiltration rate of rainfall into the soil. For steep slope, the surface runoff was found to be higher, while for gentle slope, the infiltration rate was higher, thus resulting in slope instability.

Currently, for Brunei Darussalam, there is not enough evidence to suggest that the recommended value of slope angle [2] is suitable for the current rainfall condition in Brunei. Hence, this study aims to contribute towards addressing this concern to ensure that the recommended value is acceptable even under the selected case of extreme monthly rainfall conditions.

4. Model configurations

Three slope angles of 25°, 30° and 35° at two different slope heights of 5 m and 10 m were selected for the study. The two-dimensional models consisted of homogenous soils overlying an impermeable hard rock. One example of the slope models is shown in Figure 1. The model consisted four boundaries that need to be considered, i.e. the ground surface, the soil/rock interface, the left- and right-side boundaries of the slope model. To minimise the influence of the flow boundaries during seepage analysis, the left- and right-side boundaries were set to be 20 m away from the toe and the crest of the slope, while the soil/rock interface was located at 15 m below the toe of the slope. The water level was set at a depth of 2 m below the toe of the slope by using the steady state condition before rainfall was applied on the ground surface.

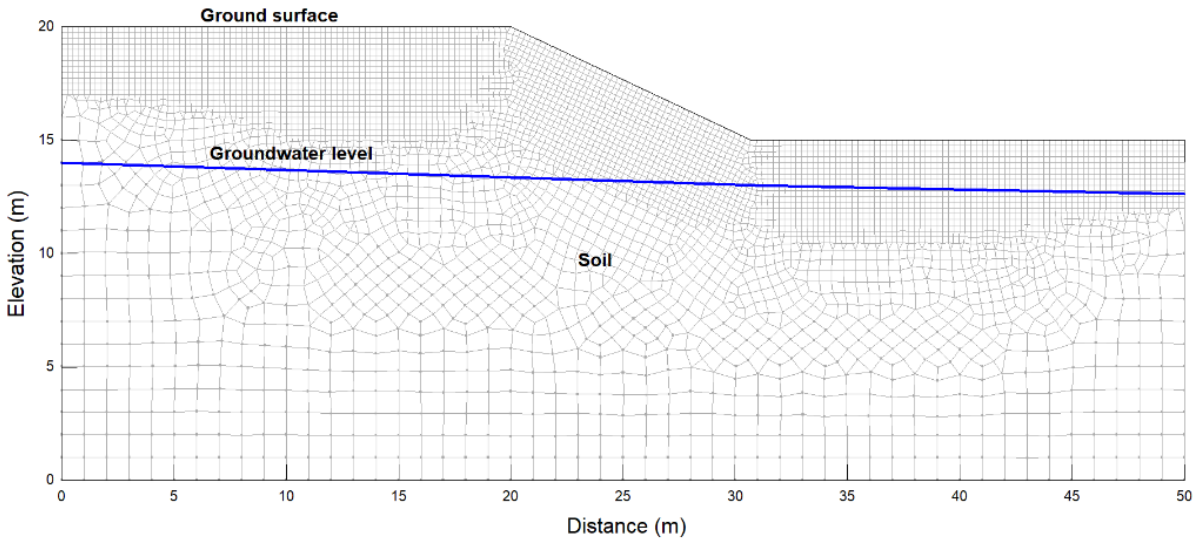

Figure 1. Slope geometry of 25° angle at 5 m high.

4.1. Mesh design and boundary condition

The finite element mesh of the model was designed to avoid unstable solutions during transient analyses. The mesh had a combination of small quadrilateral elements near the ground surface, underlain by coarser elements. The reason for combining different sizes of elements was to reduce the total number of nodes and thus the analysis time required for each simulation.

The configuration has included four boundary conditions: a unit flux boundary condition, two constant head boundary conditions and a no-flow boundary condition. The unit flux boundary was applied on the ground surface to allow rain water infiltration into the soil, while a constant head was used on the upstream and downstream to maintain a constant ground water level. It was assumed that there was a no-flow boundary at the bottom of the model, as the groundwater will not be able to infiltrate into the impermeable layer of rock.

4.2. Initial pore water pressure condition

As stated earlier, the initial groundwater level was determined by steady state analysis. This was conducted using SEEP/W as it has the ability to run the analysis until it reached the steady state condition. Initially, two different head boundary conditions were applied along the left and right edges of the model in order to define the initial groundwater level and the initial pore water pressure profile. During this process, the groundwater started to flow from left to right (see Figure 1) – a few adjustments were subsequently made on the head values so that the groundwater level remained at 2 m below the toe of the slope to ensure that large part of the model was unsaturated before the rainfall.

The resultant condition of pore water pressure distribution and groundwater level were used as the initial condition of the subsequent slope stability analysis study.

4.3. Soil parameters

Two sets of soil parameters were used for the study. The first set of data was needed to run the numerical analysis of water seepage. The upper part of the model, which was above the groundwater level, was considered unsaturated and assigned with unsaturated soil hydraulic properties during the analysis. The saturated hydraulic conductivity, K_s and other parameters, including the saturated volumetric water content, θ_s and curve fitting parameters, a, n, and m, from the relationship between the water content and negative pore water pressure, i.e. soil water retention curve (SWRC) in unsaturated soil [13,14] were also used in the analysis. One of the limitations of the work was that the soil hydraulic parameters for unsaturated soil that were needed for this study have not previously been obtained experimentally for Brunei's soil condition. Hence, these parameters have been adopted from other studies [15–19] and it was suggested that a study in Singapore [18–20] would give the closest approximation as Singapore has similar climate conditions and hence assumed to have similar soil properties as some areas in Brunei Darussalam.

The second set of parameters described the shear strength properties of the soil for limit equilibrium analysis. A Mohr-Coulomb soil model was used in this analysis [21] and the soil parameters, including dry unit weight γ_d, saturated unit weight γ_s, effective cohesion c', and effective angle of shear resistance ϕ', were obtained by interpretations from existing soil investigation data from Public Work Department, Brunei Darussalam and other previous studies [18–20]. One additional parameter that was used in the study is the effective angle of shear resistance ϕ'_b due to matric suction (u_a - u_w). This parameter was included because Brunei's soil is considered to be tropical and residual, and hence largely existed in an unsaturated environment. The soil hydraulic and shear strength parameters for the study are summarised in Table 1. These soil parameters were kept constant for all models so that the factor of safety of the slope was only influenced by the slope angle and slope height.

Table 1. Soil parameters.

Soil hydraulic parameters :	K_s = 1 x 10^{-5} m/s; a = 0.1 kPa; n = 2; m = 0.5 and θ_s = 0.53
Soil shear strength parameters :	$\gamma_s = \gamma_d$ = 20 kN/m^3 ; c' = 1 kPa ; ϕ' = 25° and ϕ'_b = 24°

4.4. Rainfall

Rainfall in Brunei Darussalam occurs throughout the year and the heaviest rainfall typically occurs between October and January. The seasonal rainfall pattern is heavily influenced by the North East Monsoon between November and March, and the South West Monsoon between May and September. In January 2014, 150 slope failures were officially reported in the Brunei-Muara district during which a total of 840 mm monthly rainfall was recorded [1]. Therefore, in order to observe the effect of rainfall on the stability of slopes during this month, the daily rainfall throughout a period of December 2013 – January 2014 were applied on the surface of the models. The daily rainfall distribution for a 62-day period from 1 December 2013 to 31 January 2014 is illustrated in Figure 2. Figure 2 indicates that the highest daily rainfall with a total amount of 189.8 mm was received on 22 January 2014 (Day 53).

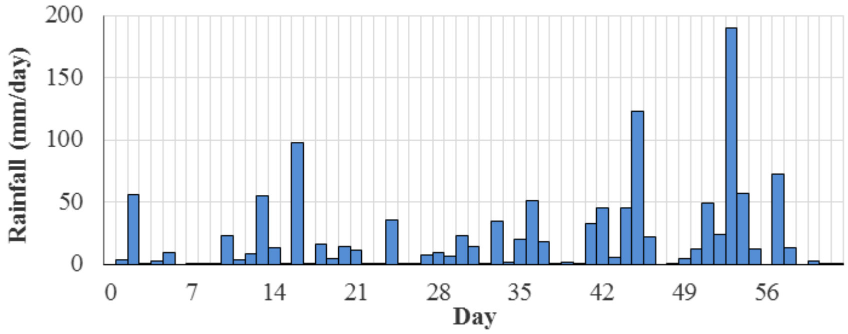

Figure 2. Daily rainfall over a 62-day period from 1 December 2013 to 31 January 2014.

4.5. Limitation of the study

At this stage, there is a lack of field study data available to validate the numerical study and some of the soil parameters used in this analysis were estimated from other sources due to the unavailability of a complete set of input data. There were some factors that have not been investigated in the models, such as vegetation and drainage system which would influence the infiltration and evaporation, and hence the pore water pressure distribution and slope stability. However, the current slope configurations without surface cover and drains may be considered as the worst-case scenario.

Despite these limitations, the results from the numerical models have indicated the effect of the extreme rainfall event on the stability of slopes of different geometries given a specific soil type with properties given in Table 1. The results have provided an understanding of the relationship between pore water pressure distribution during rainfall and slope stability and have given a useful insight into whether there is a need to consider revisiting and refining the current recommended values of slope angle in Brunei Darussalam.

5. Effect of extreme rainfall distribution on slope stability

The changes in the factor of safety (FoS) for the 5 m and 10 m high slopes at three different slope angles are plotted in Figure 3 and Figure 4 respectively. For the 5 m high slopes at 25°, 30° and 35° angles, before rainfall was applied, the FoS were 2.31, 2.21 and 2.12 respectively.

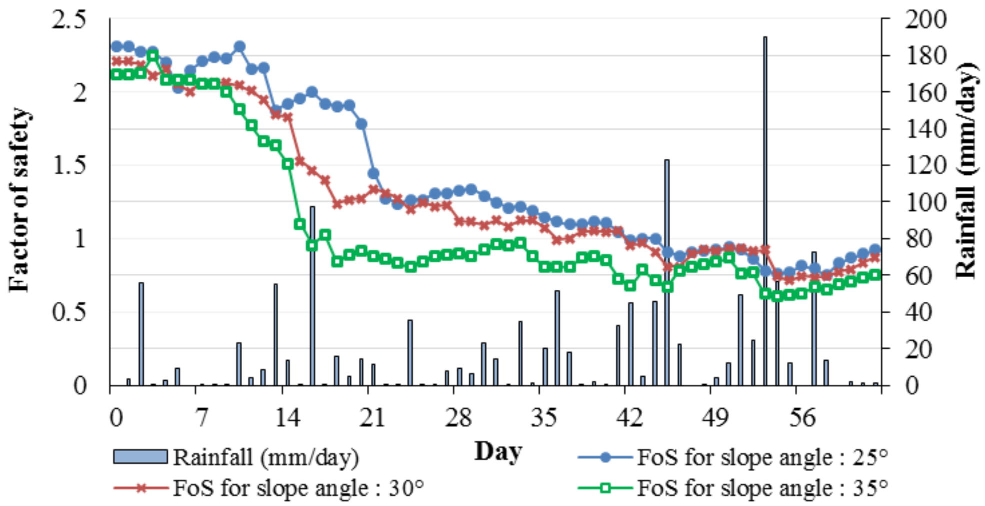

Figure 3. Changes in factor of safety (FoS) for 5 m high slope.

Based on conventional geotechnical design principles, slope failure would occur due to an inadequate factor of safety of less than 1. From the simulation, it appeared that the 35° slope started to fail at the end of Day 16 with FoS = 0.95, while the FoS for the other two slopes remained above 1.0 on the same day. The slopes at 30° and 25° angles only began to fail at FoS = 0.99 at the end of Day 36 and Day 42 respectively. The result suggested that a 5 m slope with at least 25 degree angle that consists of the same soil type as stated in Table 1, would also fail during the 62-day rainfall.For the case of 10 m high slopes, the FoS at the initial condition were 1.88, 1.8 and 1.66 for slopes at angles of 25°, 30° and 35° respectively. From the analysis, it appeared that the 35° slope started to fail only at the end of Day 25 with FoS = 0.80, and for the 30° slope, it began to fail at the end of Day 44 with FoS = 0.94. The factor of safety for the 25° slope remained above 1.0 throughout the analysis. The results suggested that a 10 m slope that consists of the same soil type as stated in Table 1, would fail during the 62 days rainfall simulation if the slope angle was at 30 and 35 degree. It also appeared that slopes at 10 m high tend to remain stable for a longer period of time when compared with slopes at the height of 5 m.

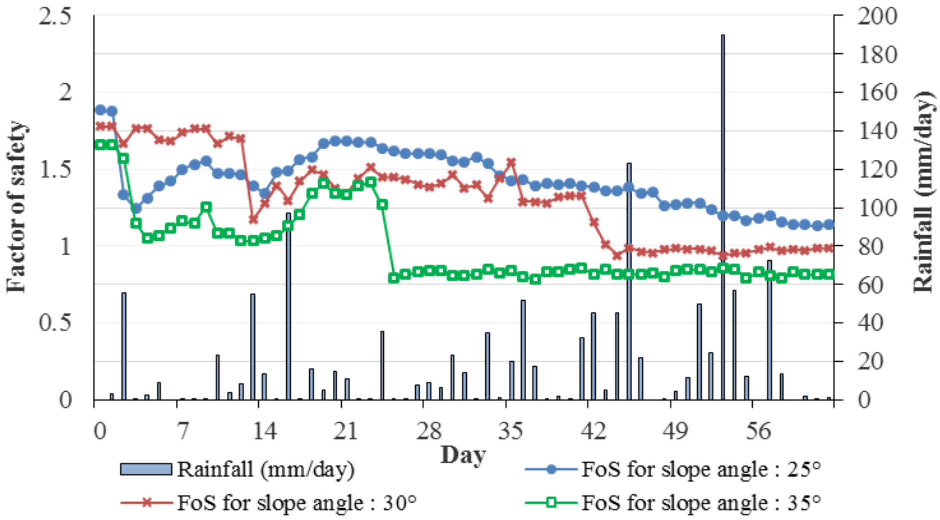

Figure 4. Changes in factor of safety (FoS) for 10 m high slope.

The results from this study do not support the findings from a previous study [12] that steeper slopes will result in reduced infiltration and hence the slope will be more resilient to rainfall-induced failure. In contrast, the present results indicate that the steeper slope fails at an earlier time with less accumulation of rainfall. The study also reveals that high daily rainfall intensity over a short duration does not necessarily result in slope failures, but rather the accumulation of rainfall is a more significant factor that triggers slope instability.

6. Conclusion

In relation to the guideline considered in this study [2], the findings from this study supports the recommendation that a slope with an angle of more than 30° could be considered sensitive to failure if no precaution is considered during construction. However, the agreement is only applicable to a 10 m high slope that has similar soil condition as stated in Table 1. The recommended values appear to be underestimated for the 5 m high slope as all analysed models have failed under rainfall within the simulation period. However, in terms of the influence of height to slope stability, the results appear to contradict with other guidelines [7,9] which suggest that slope at a higher height should be classified as more susceptible to landslides than slope at a lower height. The study has concentrated on a specific configuration and soil type. A more comprehensive case study covering typical ground conditions in Brunei Darussalam incorporating layered soil types, calibrated using experimentally-determined soil properties, would improve the quality and validity of the analysis. The outcomes of the study should

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also be validated using physical models and field data. Nevertheless, the numerical models provide a preliminary understanding on the effect of an extreme rainfall event on slope stability. A more in-depth study is recommended to investigate the suitability of the current recommended slope angle for a range of soil types and slope heights.

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References

[1] Rahman E K A Ratnayake U Tan S J Mahri A R H Tan A E H Othman D H Sabtu A N H and Hamzah H H H 2018 *7th Brunei International Conference on Engineering and Technology (BICET 2018)* (IET) pp 1–4

[2] Town and Country Planning Department 2012 *Planning guidelines and standards for earthwork development: Focus on developments in environmentally sensitive areas* (Department of Town and Country Planning, Ministry of Development, Brunei Darussalam)

[3] Chaulya S K and Prasad G M 2016 *Sensing and Monitoring Technologies for Mines and Hazardous Areas : Monitoring and Prediction Technologies* ed S K Chaulya and G M B Prasad (Elsevier)

[4] Chen X L, Liu C G, Chang Z F and Zhou Q 2016 The relationship between the slope angle and the landslide size derived from limit equilibrium simulations *Geomorphology* **253** 547–50

[5] Donnarumma A Revellino P Grelle G and Guadagno F M 2013 Slope angle as indicator parameter of landslide susceptibility in a geologically complex area *Landslide Science and Practice: Landslide Inventory and Susceptibility and Hazard Zoning* vol 1, ed C Margottini, P Canuti and K Sassa (Berlin, Heidelberg: Springer) pp 425–33

[6] Kwong A K L Wang M, Lee C F and Law K T 2004 *Eng. Geol.* **76** 27–39

[7] Ministry of Public Works and Transport 2008 *Slope maintenance manual* (Ministry of Public Works and Transport, Laos)

[8] Penang Town & Country Planning Department 2012 *Safety guideline for hillsite development* (Town & Country Planning Department, Penang Malaysia)

[9] Geotechnical Engineering Office 1984 *Geotechnical manual for slopes* (Geotechnical Engineering Office, Civil Engineering and Development Department, The Government of the Hong Kong Special Administrative Region)

[10] Li Z and Fang H 2016 *Earth-Science Rev.* **163** 94–117

[11] Egeli I and Pulat H F 2011 *Sci. Iran.* **18** 1179–87

[12] Ismail M A M and Hamzah N H 2017 *AIP Conf. Proc.* **1865** 90005

[13] Genuchten M T van 1980 *Soil Sci. Soc. Am. J.* **44** 892–8

[14] Fredlund D G and Xing A 1994 *Can. Geotech. J.* **31** 521–32

[15] Gasmo J M, Rahardjo H and Leong E 2000 *Comput. Geotech.* **26** 145–65

[16] Schaap M G Leij F J and van Genuchten M T 2001 *J. Hydrol.* **251** 163–76

[17] Lu N and Likos W J 2004 *Unsaturated soil mechanics* (Wiley)

[18] Tsaparas I Rahardjo H Toll D G and Leong E C 2002 *Comput. Geotech.* **29** 1–27

[19] Tsaparas I and Toll D G 2002 *The Proceedings of the 3rd International Conference on Unsaturated Soils (UNSAT 2002)* ed J F T Jucá, T M P de Campos and F A Marinho (Recife, Brazil) pp 755–62

[20] Gasmo J M Rahardjo H and Leong E 2000 *Comput. Geotech.* **26** 145–65

[21] Fredlund D G and Rahardjo H 1993 *Soil Mechanics for Unsaturated Soils* (John Wiley & Sons)