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# FACTORS CONTROLLING RAINFALL-INDUCED SLOPE INSTABILITY OF NATURAL SLOPES IN NORTH MALENY, QUEENSLAND

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**ABSTRACT:** Rainfall infiltration is a significant triggering factor of slope failures as major landslide events have occurred during or immediately after rainfall. The rainfall-induced slope instability is governed by a complex interaction of topographical, hydrological and geological conditions of the slopes; hence these properties are critical parameters in determining slope stability under rainfall. The slopes in reservoirs catchments areas are constantly subjected to heavy rainfall with high intensity; thus, investigating the effect of rainfall on slope failures is vital to mitigate the adverse consequences. In this study, two critical slopes were identified based on high rates of erosion, sediment run-off, and elevated risk in Eden Road and Newsham in Lake Baroon Catchment, North Maleny, Queensland, Australia. The effect of slope geometry was analyzed by parametric analysis with the parameters; of soil's initial moisture content, rainfall intensity, and intermittent rainfall on landslide initiation in these two critical slopes by employing seepage and slope stability. The stability of the slopes was evaluated by the factor of safety, based on the produced seepage conditions from seepage analyses. The outcomes of the parametric studies are involved in identifying critical slope regions and rainfall conditions to mitigate the potential risk of rainfall-induced slope failures on Baroon Pocket Dam, Queensland.

*Keywords: Rainfall-induced landslides, Slope stability, Parametric analysis*

## 1. INTRODUCTION

More than 60% of Australian drinking water comes from surface water run-off, such as streams, rivers, and reservoirs filled by rainfall. Potable water reservoirs are critically important as they provide reliable, high-quality water to communities, particularly when other water resources are not operational due to extreme drought or flooding. Most water reservoirs are in steep terrains with significant annual rainfall, thus allowing sufficient and efficient water accumulation within small catchment areas. The nature of such landscapes makes them prone to high rates of erosion, sediment run-off, and elevated risk of rainfall-induced slope failures [1, 2].

Rainfall-induced slope instability is governed by a complex interaction of the topographical, hydrological, and geological conditions of the slopes [3, 4]. Therefore, relative evaluation of controlling factors; slope geometry, initial moisture content, soil properties, rainfall intensity, antecedent rainfall, and intermittent rainfall are critical in determining the stability of a slope [4-7].

Numerous parametric studies have been conducted on slope geometry to evaluate the effect of slope angle and height on the vulnerability of slope failures [8-10]. Many studies have concluded that the higher the slope angle lower both the initial and minimum factors of safety [5, 11, 12]. In contrast, the reduction of the factor of safety in gentle slopes is higher than that of steeper slopes at heavy rainfall [13-15]. According to [5], under a short-term rainfall (i.e. less than 24 hours (h)), slopes with gentle inclination are failed only if the saturated permeability is higher than $10^{-5}$ m/s and the rainfall intensity is extremely high. Their results [5] confirmed that the slopes with an inclination less than $32^0$ are theoretically stable even at extreme rainfall conditions. Further, it proved that a slope with a lesser saturated coefficient of permeability (i.e., less than $10^{-6}$ m/s) and steeper slope inclinations up to $63^0$ would not fail under short-term extremely high rainfall intensities [16, 17].

This study focused on the evaluation of rainfall-induced slope instability of two critical slopes in Lake Baroon Catchment, North Maleny, Queensland, Australia (26.72 °S, 152.87 °E). Baroon Pocket Dam is located there and slope failures in the catchment area adversely affect the Baroon Pocket Dam. The selected slopes are Eden Road and Newsham which are in the Mapleton - Maleny plateau in Southeast Queensland (SEQ). This area has been documented since the mid - 1950's as a highly susceptible region for rainfall-induced slope failures [18-21]. Further, the region consists of expansive soil [22-24] which undergoes a significant volume change when drying and wetting. This soil needs to be stabilized before when lightweight structures such as roads, and residential houses are placed [25-28]. In order to analyze the effect of slope geometry, a parametric study was conducted to evaluate the effect of rainfall intensity and duration, antecedent rainfall and slope angle and height. Parametric studies are widely employed in solving practical problems with a proper understanding of soil behaviors [15, 29-31]. The current parametric study includes finite element method based transient seepage analyses and limit equilibrium method-based slope stability analyses. Two software packages in the GeoStudio software cluster were used: SEEP/W and SLOPE/W, for seepage and stability analyses respectively. The stability of the slope is quantified by the factor of safety (FS). The outcomes of the parametric studies are involved in identifying critical slope regions and rainfall conditions to mitigate the rainfall-induced slope failures in Lake Baroon Catchment area.

## 2. RESEARCH SIGNIFICANCE

This study was based on a parametric analysis of rainfall-induced slope failures. The developed numerical model was validated by real-time monitoring data which obtained from a reservoir catchment area in Southeast Queensland, Australia. Therefore, the outcomes are significant to apply for identification of critical slope regions by considering the factors employed in the analysis: slope geometry, initial moisture content, soil properties, rainfall intensity, antecedent rainfall, and intermittent rainfall. Consequently, remedies can be introduced to mitigate the rainfall-induced slope failures when there is a complex interaction of aforementioned factors.

## 3. DESIGN OF PARAMETRIC STUDY

Comprehensive parametric studies are required for early detection of rainfall-induced landslides due to the complexity of the governing factors [15, 32, 33]. The slope stability was assessed in terms of FS and factors were varied to simulate the field conditions in the Lake Baroon Catchment. The rainfall intensity and intermittent rainfall conditions (i.e., the distribution of major rainfall events), the antecedent rainfall prior to the major rainfall event, initial moisture content (initial pore-water pressure), slope angle and slope height were employed as the variable parameters. The parametric study series were performed on the typical slope geometry depicted in Figure 1. It was assumed that the slope was composed of homogenous isotropic soil to simplify the problem domain, isolating the influence of complex hydrogeological conditions on the seepage analysis. Table 1 [34-36] depicts the soil properties used for the seepage and, stability analyses and the boundary conditions employed for seepage analyses are summarized in Table 2. The shear strength parameters and saturated unit weight were kept constant for each soil throughout parametric studies to eliminate the effects of shear strength properties to ensure that the alterations in slope stability under varied rainfall conditions are primarily due to the changes in pore-water pressures rather than the changes in shear strength properties of the slope material [37, 38].

The initial pore-water pressure condition for the parametric studies was determined as a hydrostatic condition with a limiting pore-water pressure of “-25 kPa”, based on the initial depth of the water table to avoid the generation of unrealistic pore-water pressures during the seepage analyses [39, 40].

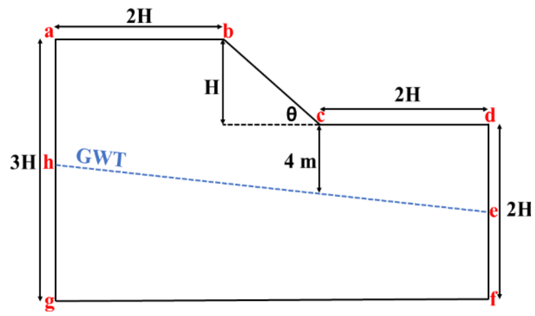



Fig.1 Slope geometry for homogeneous soil slope used in the parametric study

Table 1 Summary of the soil parameters

| Parameter | | Eden road soil | Newsham soil |
|---|---|---|---|
| SWCC parameters | a | 30 | 300 |
| | m | 0.2 | 0.34 |
| | n | 2.9 | 1.22 |
| | $\theta_s$ | 0.57 | 0.57 |
| Saturated hydraulic conductivity | $K_s$ | $2.4 \times 10^{-11}$ m/s | $2.0 \times 10^{-11}$ m/s |
| Effective cohesion | $c'$ | 53.2 kPa | 66.2 kPa |
| Effective angle of friction | $\phi'$ | $17.17^0$ | $16.42^0$ |
| Angle of internal friction related to matric suction | $\phi^b$ | $7.6^0$ | $6.3^0$ |
| Saturated unit weight | $\gamma_{sat}$ | 20.72 kN/m$^3$ | 20.64 kN/m$^3$ |

Rainfall intensities ranging from 0.05 mm/h to 40 mm/h and the event duration of 120 hours (5 days) were used in the parametric studies, considering the historical rainfall data triggered shallow landslides in SEQ.

It considered five antecedent rainfall scenarios based on a distribution over a 5-day period, as summarized in Table 3. For the scenario 1 and 2, the corresponding rainfall intensities were distributed over 6 h period for every 24 h, for 5 days. Similarly, for the scenarios 3 and 4, it was over 12 h period for every 24 h, for 5 days. In scenario 5, the antecedent rainfall was distributed as 60 h, a single rainfall event within the 5-day period. For all the five scenarios, a major rainfall event of 20 mm/h was considered after the distribution of antecedent rainfall. Additionally, in each case, the rainfall period was followed by a 5-days dry period to study the negative pore-water pressure recovery process.

As shown in Table 3, five series of parametric studies were performed to analyze the impact of rainfall intensity, antecedent rainfall distribution, slope angle and height and, major rainfall duration for Eden Road and Newsham soils.

Table 2 Boundary conditions

| Boundary | Boundary condition type | Boundary condition |
|---|---|---|
| ab, bc, cd | Water flux | Rainfall as a function of time |
| ab, bc, cd | Land-climate interaction | Air temperature, relative humidity, wind speed, net radiation as a function of time |
| ah, de, fg | Water flux | Q = 0 $m^3/s/m^2$ (No flow boundary) |
| ef, hg | Water total head | Total head at each side |

Table 3 Summary of parameter combinations for each series of parametric study

| Study series | Rainfall intensity, I (mm/h) | Major rainfall duration (h) | Slope height, H (m) | Slope angle, θ (Degrees) |
|---|---|---|---|---|
| 1 | (0.05, 0.1, 0.2, 0.5, 1, 5, 10, 20) | 120 | 8 | (26.6, 36.7, 45, 63.4, 71.6) |
| 2 | 20 | 120 | 8 | (26.6, 36.7, 45, 63.4, 71.6) |
| 3 | 20 | 120 | 8 | (26.6, 36.7, 45, 63.4, 71.6) |
| 4 | 20 | 120 | 2, 4, 6, 8, 10 | 45 |
| 5 | (0.05, 0.1, 0.2, 0.5, 1, 5, 10, 20) | (24, 48, 72, 96, 120, 144, 168) | 8 | 45 |

### 3.1 Transient Seepage Analysis

Based on the determined finite element mesh size, seepage analyses were performed for each parametric study as the initial step. The movement of water flow was analyzed in SEEP/W and fed into slope stability analyses to determine the FS of the slopes. Figure 2 shows a slope section in the parametric study with the employed boundary conditions and the position of the initial groundwater table.

### 3.2 Slope Stability Analysis

The pore-water pressures determined from the transient seepage analysis were incorporated in the slope stability analysis to evaluate the stability of each slope in terms of FS. The shear strength equation utilized in the slope stability analysis was the unsaturated shear strength equation to incorporate the negative pore-water pressure contribution [41, 42]. Morgenstern – Price analysis was adopted in the parametric study, which satisfies both moments and forces equilibrium and accounts for both interslice shear and normal forces [43]. The half-sine interslice function was used in determining FS during each parametric study. Moreover, in order to facilitate the visualization of the extent and the range of trial slip surfaces, the entry and exit method that defines the location where the trial slip surfaces enter the ground surface and exit was incorporated.

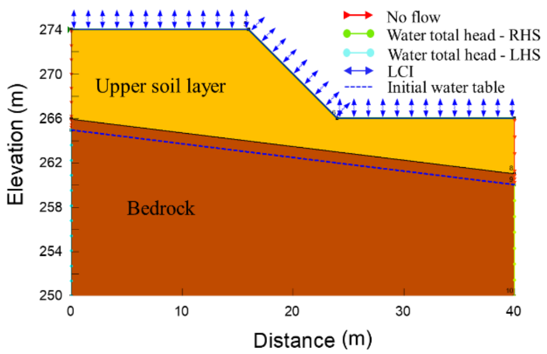



Fig.2 Boundary conditions in seepage analysis

## 4. RESULTS AND DISCUSSION

### 4.1 Parametric Study 1 – Effect of Rainfall Intensity

The analysis was conducted over a 240 h period, allowing the slopes to drain after the rainfall and the antecedent rainfall conditions were not considered.

Figure 3 shows the drop of FS with rainfall intensity for slope angle $45^0$. The magnitude and the rate of FS reduction are proportional to the applied rainfall intensity for a particular slope angle. Therefore, higher the applied rainfall intensity is higher the rate of FS reduction. Further analysis showed that with the initiation of the rainfall event, FS drops regardless of the slope angle, the soil type or the applied rainfall intensity. However, the initial FS of the slope decreased with increasing the slope angle.

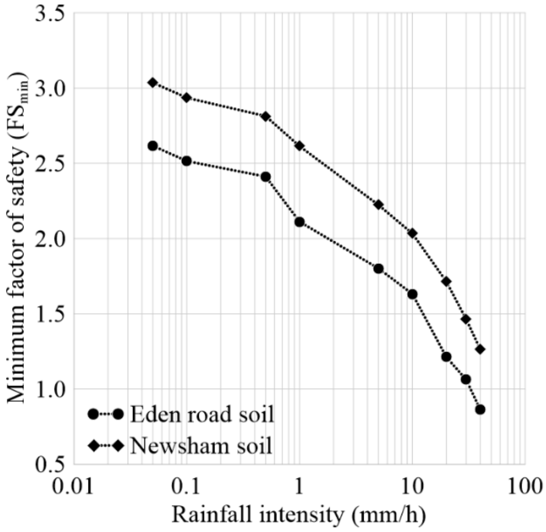



Fig.3 Relationship between rainfall intensity and minimum FS for the slope inclination $45^0$

In summary, no rainfall intensity leads to a FS lower than 1.0 (i.e., critical FS – $FS_{cri}$) for the slopes with inclinations $26.6^0$ and $36.7^0$ for Eden Road soil and slopes with inclinations $26.6^0$, $36.7^0$ and $45^0$ for Newsham soils. Rainfall intensity 40 mm/h leads to $FS_{cri}$ in $45^0$, $63.4^0$ and $71.6^0$ slopes, while rainfall intensity 30 mm/h results in FS values below $FS_{cri}$, in $63.4^0$ and $71.6^0$ slopes for Eden Road soil. Further, the rainfall intensity of 20 mm/h leads to $FS_{cri}$ in the steepest $71.6^0$ slope of Eden Road soil. On the contrary, the Newsham soil, which has higher shear strength, reaches $FS_{cri}$ only under 40 mm/h rainfall intensity in $63.4^0$ slopes and under 30 mm/h and 40 mm/h rainfall intensity in $71.6^0$ slope.

### 4.2 Parametric Study 2 – Effect of Antecedent Rainfall

The major rainfall was applied for 120 h period while each analysis was conducted for a 360 h period, allowing an additional 120 h period for the slopes to drain and allowing for the recovery of the negative pore-water pressures.

Temporal variation of FS with different antecedent rainfall values was investigated for all the slope angles. The results presented in Figure 4 only for Eden Road soil to illustrate the pattern of variation of FS with elapsed time at different scenarios. The antecedent rainfall distributions of the study were selected to replicate typical rainfall events that triggered slope failures in SEQ. The scenarios 1, 2, 3, 4, and 5 in Figure 4 represent 150, 300, 300, 600 and 300 mm of total rainfall and 5, 10, 5, 10, 5 mm/h rainfall intensities respectively. The development of FS depicted that the antecedent rainfall distribution can significantly influence the stability of the slopes [44]. Especially with similar major rainfall distribution (i.e., 20mm/h major rainfall for 120 h period), only the steepest $71.6^0$ slope of Eden Road soil reached the $FS_{cri}$ as presented in section 4.1. However, with the addition of antecedent rainfall, the FS dropped below $FS_{cri}$ for the "scenario – 4" in $45^0$, $63.4^0$ and $71.6^0$ slopes in Eden Road soil and $63.4^0$ and $71.6^0$ slopes in Newsham soil. Further, in regard to the slopes with $71.6^0$ of inclination, all antecedent rainfall distributions except "scenario – 1" extended to FS below $FS_{cri}$ in Eden Road soil, while "scenarios 3, 4 and 5" reached FS below $FS_{cri}$ in Newsham soil.

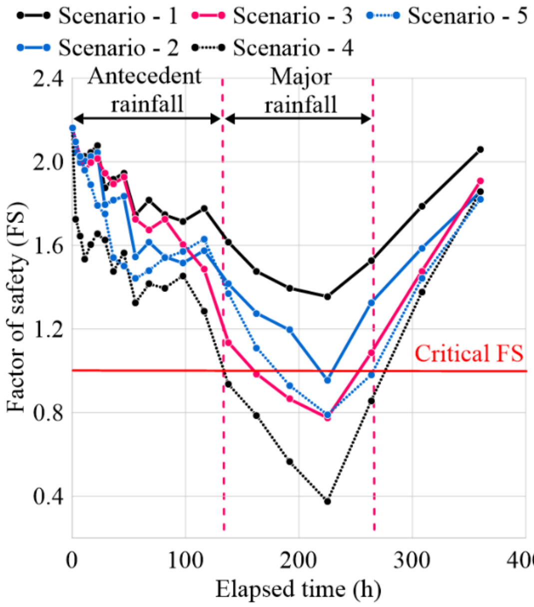
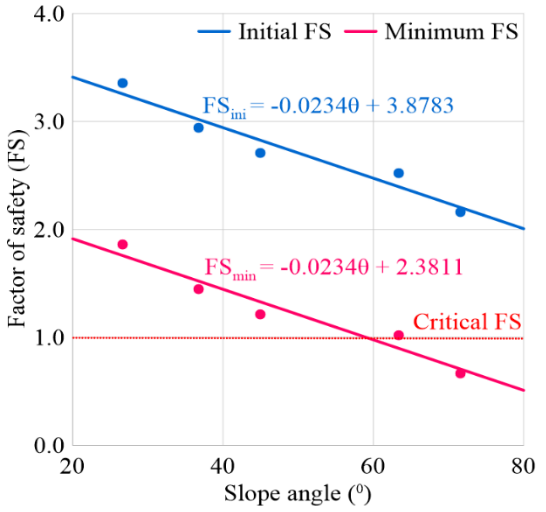



Fig. 4 Effect of rainfall intensity on temporal variation of FS for slope angle $71.6^0$ in Eden Road

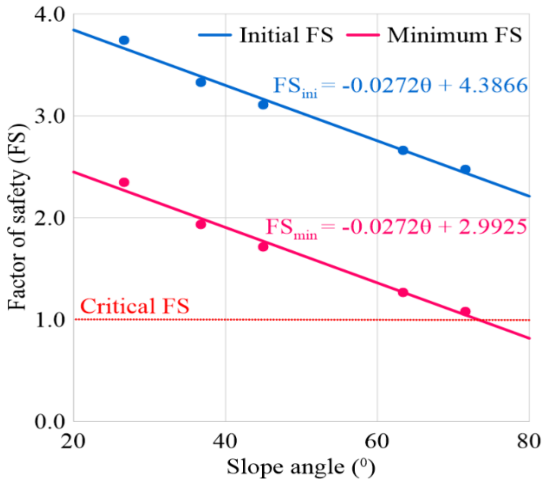
### 4.3 Parametric Study 3 – Effect of Slope Angle

The major rainfall intensity was kept constant at 20 mm/h and did not apply the antecedent rainfall in parametric study 3. An additional 120 h period was considered for the slopes to drain after a major rainfall, allowing for the recovery of the negative pore-water pressures.

All the model slopes depicted a reduction of stability during rainfall infiltration and an increase of FS during the recovery of negative pore-water pressure. As the slope angle increases, the minimum FS decreases, highlighting steep slopes yield lower FS compared to a flat slope under initial conditions and during rainfall. Only the steeper model slopes of Eden Road soil with inclinations $63.4^0$ and $71.6^0$ reached critical FS during the application of 120 h rainfall with the intensity 20 mm/h. All the remaining model slopes were stable under the applied rainfall conditions, mainly due to the lower permeability of the test material. These observations agree with previous parametric studies on the effect of slope angle on rainfall-induced slope stability [4, 5, 45]. Further, these observations emphasize that slopes with angles below $35^0$ (i.e., approximately twice of soil's friction angle) are theoretically safe under typical rainfall intensities in Queensland. Moreover, due to the low hydraulic conductivities, such slopes are potentially stable even under short term extreme rainfall intensities of 40 - 60 mm/h.




(a)




(b)

Fig.5 Relationship between initial and minimum FS with slope angle for (a) Eden Road (b) Newsham soil for slope height 8 m

The comparison of the results of Section 4.2 and 4.3 accentuates the significance of long duration or antecedent rainfall conditions in triggering slope failures in soils with lower hydraulic conductivities, such as Eden Road and Newsham soils. Especially with 600 mm total rainfall spread over a 5-day period with a maximum intensity of only 10 mm/h resulted in critical FS for an Eden Road slope with an inclination of $45^0$, while a solitary major rainfall of 20 mm/h did not destabilize the same slope.

Figure 5 summarizes the relationships of initial FS and the minimum FS with the slope angle for both types of soils. As expected, both initial and minimum FS bear a negative relationship with slope inclination with regard to stability under precipitation. The negative linear relationships between initial and minimum FS with the slope angle ($\theta$) were presented in linear regression equations as depicted by Figure 5 (a) and (b).

### 4.4 Parametric Study 4 – Effect of Slope Height

The antecedent rainfall scenarios were not considered for this phase of the parametric study, and an additional 120 h period was considered for the slopes to drain after the major rainfall, allowing for the recovery of the negative pore-water pressures. Investigation of temporal variations of FS for different slope heights depicted decrease of stability during rainfall infiltration and an increase of FS during the recovery of negative pore-water pressure. As the slope height increases, the minimum FS decreases, highlighting greater slopes yield lower FS compared to a small slope under initial conditions and during rainfall. Only the larger model slopes of Eden Road soil with heights 8 m and 10 m reached critical FS during the application of 120 h rainfall with an intensity 20 mm/h. All the remaining model slopes were stable under the applied rainfall conditions, mainly due to the lower permeability of the soil.

As shown in Figure 6, the initial FS depict an exponential reduction with the slope height. The relationship between initial FS and slope height emphasize that the higher slopes have a greater potential of failure due to the low initial FS. In contrast, relatively lower slopes (i.e., slope with height 4 m and 6 m) are stable during the applied rainfall conditions as none of those model slopes reaches critical FS value. Also, the reduction of FS during the rainfall infiltration is less and reduces at a slower rate compared with lower slopes. Even though Figure 6 extends only to 4 m to 10 m extended graph, it shows that the gradient of the exponential fit curves decreases with the increasing the slope height.

For all the slopes in the current study, a perched water table was observed regardless of the slope height. However, based on the given trend of the position of the water table of the simulated model slopes, it can be deduced that when the slope height goes higher than 20 m leads to a reduction of matric suction due to the rainfall infiltration in the unsaturated zone above the water table [37, 46].

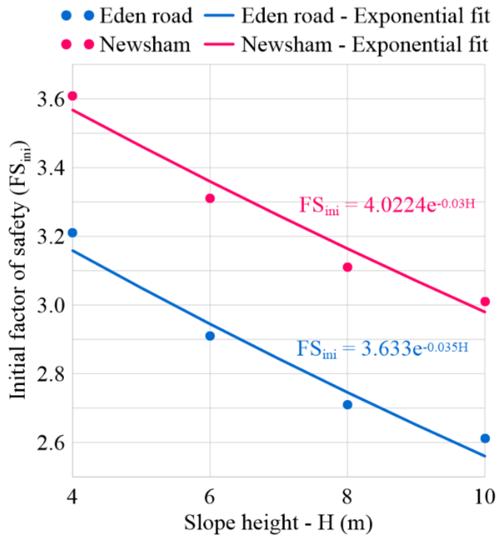



Fig.6 Relationship between initial FS and the slope height for slopes with inclination $45^0$

### 4.5 Parametric Study 5 – Effect of Major Rainfall Duration

This analysis was conducted for a 240 h period, allowing the slopes to drain 120 h after the major rainfall to recover the negative pore-water pressures. Moreover, no antecedent rainfall conditions were considered.

The minimum FS value decreased with the increase of major rainfall duration and rainfall intensity in all cases. The Eden Road model slopes with $45^0$ slope inclination destabilized for major rainfall durations of 144 h and 168 h under the intensity of 30 mm/h and for major rainfall durations of 120 h, 144 h and 168 h under the intensity of 40 mm/h while none of the Newsham slopes reached critical FS values even for 7-day rainfall with 40 mm/h intensity. Given the same initial conditions for both Eden Road and Newsham slopes, the initial FS values were the same for each soil type. Hence the reduction of FS to the minimum value increased with the increase in rainfall duration and intensity [37].

A negative linear relationship was identified between the major rainfall duration and the minimum FS for a particular rainfall intensity in Eden Road and Newsham soil slopes with slope angle $45^0$. Based on the outcomes of the linear regression analysis, relationships were formulated for both soil types, to determine the major rainfall duration required to reach critical FS (i.e., FS=1) for a slope with inclination $45^0$ and shown in Figure 7. The time to reach critical FS decreases exponentially with the rainfall intensity. The relationship highlights approximately 99 h, 40 mm/h rainfall is required to trigger slope failure in Eden Road soil with an inclination of $45^0$ while 152 h similar rainfall condition is required for Newsham slopes.

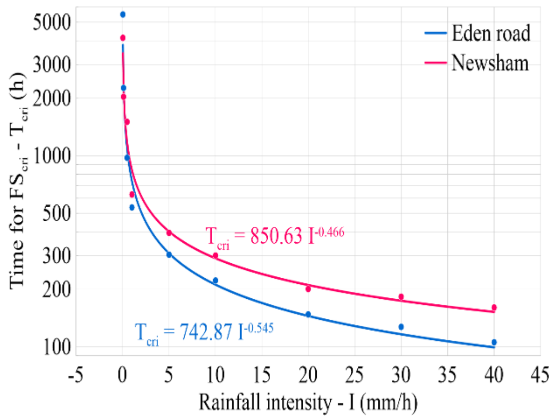



Fig.7 Relationship between rainfall intensity and the time to reach critical FS for slopes with inclination $45^0$

## 5. CONCLUSION

- Model slopes with lower slope angle (< $45^0$) and lower slope height (< 8 m) did not lead to slope instability for the applied rainfall intensities and durations due to the low saturated permeability.
- Eden Road soil is slightly more susceptible to slope failures compared to the Newsham soil, primarily due to the higher hydraulic conductivity and lower shear strength.
- The study depicted a threshold rainfall intensity for the least minimum FS value, and the threshold was higher for Eden Road soil relative to Newsham material.
- The slope height, angle and initial position of the water table make a significant impact only on the initial FS, and the applied rainfall conditions greatly determine the vulnerability of slope failure.
- The entire parametric study is consistent with the actual slope failures in Eden Road and Newsham sites, as discussed in [31]. This agreement includes not only the properties of slope geometry and the rainfall conditions that lead to landslides in the two study regions but also the behavior of the water table during rainfall triggered slope failures.

## 6. REFERENCES

[1] Guzzetti F., Peruccacci S., Rossi M., Stark C.P. Rainfall thresholds for the initiation of landslides in central and southern Europe. Meteorology and Atmospheric Physics. 2007, Vol. 98, pp. 239-67.

[2] Brand E.W., Premchitt J., Phillipson H.B. Relationship between rainfall and landslides in Hong Kong. In: Proceedings of the 4th Int.

Symp. on Landslides, Toronto, 1984, pp. 377-84.
[3] Sorbino G., Nicotera M.V. Unsaturated soil mechanics in rainfall-induced flow landslides. Engineering Geology. 2013, Vol. 165, pp. 105-32.
[4] Gallage C., Abeykoon T., Uchimura T. Instrumented model slopes to investigate the effects of slope inclination on rainfall-induced landslides. Soils and Foundations. 2021, Vol. 61, pp. 160-74.
[5] Rahardjo H., Ong T.H., Rezaur R.B., Leong E.C. Factors Controlling Instability of Homogeneous Soil Slopes under Rainfall. Journal of Geotechnical and Geoenvironmental Engineering. 2007, Vol. 133, pp. 1532-43.
[6] Souliyavong T., Gallage C., Egodawatta P., Maher B. Factors affecting the stability analysis of earth dam slopes subjected to reservoir drawdown. Proceedings of the 2nd Int. Conf on GEOMATE, Japan, 2012, pp. 507-12.
[7] Gallage C., Jayakody S., Uchimura T. Effects of slope inclination on the rain-induced instability of embankment slopes. Proceedings of the 2nd Int. Conf. on GEOMATE, Japan, 2012, pp. 196-201.
[8] Gallage C., Abeykoon T., Uchimura T. Failure processes of rainfall-induced flow slides using a large-scale model slope. Australian Geomechanics Journal. 2021, Vol. 56, pp. 33-42.
[9] Garcia E., Gallage C., Uchimura T. Function of permeable geosynthetics in unsaturated embankments subjected to rainfall infiltration. Geosynthetics International. 2007, Vol. 14, pp. 89-99.
[10] Gallage C., Uchimura T. Investigation on parameters used in warning systems for rain-induced embankment instability. In: Proceedings of the 63rd Canadian Geotechnical Conf., Calgary, 2010, pp. 1025-31.
[11] Suryo E.A., Zaika Y., Gallage C., Trigunarsyah B. A non-destructive method for investigating soil layers of an individual vulnerable slope. International Journal of GEOMATE. 2020, Vol. 18, pp. 1-8.
[12] Suryo E., Gallage C., Trigunarsyah B. A method for predicting rain-induced instability of an individual slope. Proceedings of the 9th Annual Int. Conf. of the Int. Institute for Infrastructure Renewal and Reconstruction, Australia, 2015, pp. 118-27.
[13] Suryo E., Gallage C., Trigunarsyah B., Rachmansyah A. The effects of deep cracks on the rain-induced instability of slopes: A case study. Proceedings of APSEC 2012 and ICCER 2012, Malaysia, 2012, pp. 537-42.
[14] Hakim Sagitaningrum F., Bahsan E. Parametric study on the effect of rainfall pattern to slope stability. MATEC Web Conf. 2017, Vol. 101, p. 05005.
[15] Towhata I., Uchimura T., Gallage C. On Early Detection and Warning against Rainfall-Induced Landslides (M129). Landslides: Risk Analysis and Sustainable Disaster Management, Springer Berlin Heidelberg, 2005, pp. 133-9.
[16] Gallage C., Kodikara J., Uchimura T. Laboratory Measurement of Hydraulic Conductivity Functions of Two Unsaturated Sandy Soils During Drying and Wetting Processes. Soils and Foundations. 2013, Vol. 53, pp. 417-30.
[17] Udukumburage R.S., Gallage C., Dawes L., Gui Y. Determination of the hydraulic conductivity function of grey Vertosol with soil column test. Heliyon. 2020, Vol. 6, p. e05399.
[18] Ellison L., Coaldrake J.E. Soil Mantle Movement in Relation to forest Clearing in Southeastern Queensland. Ecology. 1954, Vol. 35, pp. 380-8.
[19] Willmott W.F. Slope Stability and Its Constraints on Closer Settlement on the Mapleton-Maleny Pateau, Southeast Queensland, Geological Survey of Queensland, 1983.
[20] Zhu C., Thambiratnam D., Gallage C. Inherent Characteristics of 2D Alluvial Formations Subjected to In-Plane Motion. Journal of Earthquake Engineering. 2019, Vol. 23, pp. 1512-30.
[21] Abeykoon T., Gallage C., Murray J., Trofimovs J. The Relationship of Landslide Initiation and Rainfall Thresholds in South-East Queensland. Proceedings of the Int. Conf. on Geotechnical Engineering ICGE Colombo, Sri Lanka, 2020, pp. 453-8.
[22] Udukumburage R.S., Gallage C., Dawes L. Oedometer Based Estimation of Vertical Shrinkage of Expansive Soil in a Large Instrumeted Soil Column. Heliyon. 2019, Vol. 5, p. e02380.
[23] Jayalath C.P.G., Gallage C., Miguntanna N.S. Factors Affecting the Swelling Pressure Measured by The Oedemeter Method. International Journal of GEOMATE. 2017, Vol. 11, pp. 2397-402.
[24] Shannon B., Gallage C., Kodikara J. Experimental Modelling of Coupled Water Flow and Associated Movements in Swelling Soils. Proceedings from the 3rd Int. Conf. on Problematic Soils, Singapore, 2010, pp. 295-302.
[25] Gallage C., Tehrani K., Williams D. Instrumented large soil-column to investigate climate-induced ground deformation in expansive Soil. In: 19th Int. Conf. on Soil Mechanics and Geotechnical Engineering, Seoul, South Korea, 2017.

[26] Suryo E., Gallage C., Trigunarsyah B., Mochtar I., Soemitro R.A. Application of Electrical Resistivity Method to Detect Deep Cracks in Unsaturated Residual Soil Slope. Proceedings of the 5th Asia-Pacific Conf. on Unsaturated Soils, Thailand, 2011, pp. 901-6.

[27] Udukumburage R.S., Gallage C., Dawes L. Investigation of the Effect of Initial Water Content and Surcharge on Volume Change Behaviour of Compacted Grey Vertosol. In: Proceedings of the 13th Australia New Zealand Conf. on Geomechanics Australia, 2019, pp. 1029-33.

[28] Udukumburage R.S., Gallage C., Dawes L. Loaded Swell Tests to Estimate the Heave of the Expansive Soil in Instrumented Soil Column. In: Proceedings of the 8th Int. Conf. on GEOMATE Japan, 2018, pp. 390-5.

[29] Abeykoon A.G.T.B.B., Gallage C., Trofimovs J. Optimisation of Sensor Locations for Reliable and Economical Early Warning of Rainfall-Induced Landslides. Proceedings of the 9th Int. Conf. on GEOMATE, Japan, 2019, pp. 69-74.

[30] Abeykoon A.G.T.B.B., Gallage C., Trofimovs J. Unsaturated Shear Srength of Expansive Soils from Natural Slopes in Queensland. Proceedings of the 10th Int. Conf. on GEOMATE, Japan, 2020, pp. 284-9.

[31] Gallage C., Dareeju B., Trofimovs J., Wang L., Uchimura T. Real-time Monitoring and Failure Prediction of a Slope due to Rainfall - Case Study. Proceedings of the 9th Int. Conf. on Sustainable Built Environment 2018, Sri Lanka, 2018, pp. 12-8.

[32] Wang L., Fukuhara M., Uchimura T., Gallage C., Abeykoon T. An EWS of Landslide and Slope Failure by MEMS Tilting Sensor Array. In: Understanding and Reducing Landslide Disaster Risk: Volume 3 Monitoring and Early Warning, Springer Int. Publishing, Cham, 2021, pp. 295-305.

[33] Wang L., Fukuhara M., Uchimura T., Gallage C. Case Studies of Early Warning System of Unstable Slopes Using Tilting Sensor Array. In: 20th Int. Conf. on Soil mechanics and Geotechnical Engineering 2022, Sydney Australia, 2022.

[34] Priddle J., Lacey D., Look B., Gallage C. Residual soil properties of South East Queensland. Australian Geomechanics Journal. 2013, Vol. 48, pp. 67-76.

[35] Gallage C.P.K., Uchimura T. Effects of Dry Density and Grain Size Distribution on Soil-Water Characteristic Curves of Sandy Soils. Soils and Foundations. 2010, Vol. 50, pp. 161-72.

[36] Udukumburage R.S., Dawes L., Gallage C. A Practical Approach to Determine the Temperature Correction for WC-5 Moisture Sensors Embedded in Vertosol. Proceedings of the 10th Int. Conf. on GEOMATE, Japan, 2020, pp. 253-8.

[37] Gallage C.P.K., Uchimura T. Effects of Wetting and Drying on the Unsaturated Shear Strength of a Silty Sand Under Low Suction. In: Unsaturated Soils 2006, 2006, pp. 1247-58.

[38] Udukumburage R.S., Gallage C., Dawes L. An Instrumented Large Soil Column to Investigate Climatic Ground Interaction. Int. Journal of Physical Modelling in Geotechnics. 2021, Vol. 21, pp. Article number: 1900007 55-71.

[39] Kodikara J., Rajeev P., Chan D., Gallage C. Soil Moisture Monitoring at the Field Scale Using Neutron Probe. Canadian Geotechnical Journal. 2014, Vol. 51, pp. 332-45.

[40] Chan D., Rajeev P., Gallage C., Kodikara J. Regional Field Measurement of Soil Moisture Content with Neutron Probe. Proceedings Volume 1 of The Seventeenth Southeast Asian Geotechnical Conf., Taiwan, 2010, pp. 92-5.

[41] Gallage C., Uchimura T. Direct Shear Testing on Unsaturated Silty Soils to Investigate the Effects of Drying and Wetting on Shear Strength Parameters at Low Suction. Journal of Geotechnical and Geoenvironmental Engineering. 2016, Vol. 142, p. 04015081.

[42] Fredlund D.G., Morgenstern N.R., Widger R.A. The Shear Strength of Unsaturated Soils. Canadian Geotechnical Journal. 1978, Vol. 15, pp. 313-21.

[43] Ltd G.I. Heat and Mass Transfer Modeling with GeoStudio 2020. Calgary, Alberta, Canada2020.

[44] Gallage C., García E., Uchimura T. Use of Soil-Water Characteristics Curve in Determination of Stability of Embankments During Drying and Wetting Processes, Advanced Experimental Unsaturated Soil Mechanics. Proceedings of the Int. Symp. on Advanced Experimental Unsaturated Soil Mechanics, Trento, Italy, 2005.

[45] Gallage C., Mostofa M.G., Vosolo D., Rajapakse J. A New Laboratory Model of a Slaking Chamber to Predict the Stability of On-Site Coal Mine Spoils. International Journal of GEOMATE. 2016, Vol. 10, pp. 2065-70.

[46] Abeykoon A., Udukumburage R.S., Gallage C., Uchimura T. Comparison of Direct and Indirect Measured Soil-Water Characteristic Curves for a Silty Sand. International Journal of GEOMATE. 2017, Vol. 13, pp. 9-16.