A Study on the Effect of Rainfall and Slope Characteristics on Landslide Initiation by Means
of Flume Tests

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Abstract

Landslide initiation has multiple preconditional, preparatory and triggering factors, including rainfall intensity, slope angle and slope moisture content. Previous literature only considers a singular variable in effecting failure. This study shows trends typical of previous literature whilst considering how an amalgamation of assorted variables collaborate to effect failure. To better understand the influences of these factors, a series of tests were conducted using a flume device, employed in the generation of modelled single soil layer slope failures. Experiments were performed in 3 series, determined by rainfall intensity (40, 70 and 100mm/h) and within these series alterations were made between slope angle (45-55°), and initial moisture content (5-12%). Failure times occurred once pore water pressure had peaked at positive values, as well as, moisture content equalised throughout the slope. Variations in failure time occurred when altering slope angle and initial moisture content. Increasing the initial moisture content created faster failures while slopes inclined 45° failed faster with the exception of 100mm/h intensity experiments. Initial failure times were summarised and used to develop an intensity-duration threshold function of $I = 80.065 D^{-0.596}$.

Keywords

Landslide initiation - Flume tests - Shear Strength - Pore Water Pressure - Intensity-Duration threshold

1. Introduction

Landslides are devastating natural disasters occurring worldwide every year, causing immense damage and loss of life (Sassa, 1974, 1984; Fourie, 1996; Corominas and Moya, 1999; Collins and Znidarcic, 2004; Chang and Chiang, 2009; Saito, 2010; Kim et al. 2013; Sassa et al, 2013; Shokouhi et al. 2013; Kim et al. 2014a, b; Peruccacci, 2017; Ravindran, 2018). An implemented method to understand the causes and mechanisms of failure for landslides is by means of a flume test. As landslides often occur without warning, it can be very difficult to predict where and when they may act. These natural disasters may be predicted through further understanding the causes and mechanisms of landslide failure to mitigate damage to infrastructure and life. A flume gives the ability to mimic landslide conditions through laboratory testing.

Investigations have shown landslide failures are often due to the angle of slope exceeding the critical angle of the saturated soil that the slope is comprised of (Terzaghi, 1925; Bishop, 1973; Brand et al. 1984; Larsen and Simon, 1993; Chien-Yuan et al. 2005; Dahal and Hasegawa, 2008.). This predominantly occurs due to high levels of rainfall increasing pore water pressures within the slope, which reduces effective stress in turn decreasing the shear strength of soil (Terzaghi, 1925; Bishop, 1973; Brand et al, 1984; Tsaparas et al, 2002; Craig, 2004). Once one area of a slope fails, it becomes increasingly difficult for the rest of the slope to hold together and progressive slides can occur (Wang and Sassa, 2001 & 2003). Relationships between pore water pressure and landslide occurrence show that an undrained soil layer has increased chance of failure if exposed to large amounts of rainfall. Although research has been performed on these relationships, knowledge on the topic of landslide prediction using flume testing is quite limited.

Wang and Sassa (2001), established an experimental rainfall-induced flowslide, using a small flume. Emphasis was placed on the examination of pore pressure generation in relation to sliding distance, through means of monitoring sliding distance and pore pressures. Alterations were made by changing initial dry density and sample thickness on silica sand within the flume, yielding results showing an optimal dry density for pore pressure build-up, where moving velocity and run-out distance were maximum. The optimal density was dependent on the sample thickness. Furthermore, tests carried out on silica sand - loess mixtures, investigated the effects of fine-particle content on flowslide motion, exhibiting different modes of flowslide motion dependent on fine-particle levels. Failure modes were believed to be affected by the differing rates of pore-pressure dissipation in the shear zone. The works carried out by Wang and Sassa (2001), laid the footing for future flume investigations for shallow landslides.

Flume experiments performed by Okura et al. (2002), Moriwaki et al. (2004), Olivares et al. (2009), Greco et al. (2010) investigated the failure generation of slopes with consistent experimental setups, while each differed the soil type tested. Olivares et al. (2009) and Greco et al. (2010) tested pyroclastic and volcanic ash soils respectively. Lourenco et al. (2006) continued the work performed by Wang (2003) investigating the hydrologic response of a two-layer system, with alterations made to the permeability of the slope. Investigations on debris flow and sediment discharge were performed by Acharya et al. (2009) through scale flume, while Fan et al. (2018) designed an experimental system in mountainous regions to observe landslides. Lastly, Ahmadi-adli et al. (2017) tested the influence of altering rainfall intensity

and relative density of slope material to observe influences on failure time. This was used to develop a rainfall intensity-duration threshold. These papers aimed to identify a slope characteristic's individual effect in determining their influences on initiation of slope failure. These characteristics range from rainfall intensity, soil permeability, slope angle, layer thickness, soil type etc. Due to setup time and costs required to perform flume investigations, these slope characteristics are seldom altered within the same series of tests, and therefore the information presented by each of these papers is stand-alone. As these factors have individually been proven to influence landslide initiation in previous literature, estimating landslide failure must incorporate different configurations of multiple slope characteristics. This paper proposes the testing of multiple triggering factors for landslide initiation, to observe their independent influences, as well as, how they influence landslide failure times when culminated, which has been previously untested.

This paper presents a series of flume tests that simulate rainfall induced landslides, under pre-determined rainfall rates and duration. Slope angle, rainfall intensity and initial slope moisture content were controlled to observe the movement of the landslide mass. Measurements were taken throughout to analyse the slopes reaction to the increase in pore water pressures and slope moisture content. Slope and rainfall characteristics were based on slopes observed in the Gold Coast region of south-east Queensland by Cogan et al. (2018). Slopes were found to typically range between 45-55°, with site investigation determining the undisturbed moisture contents of the failed areas were between 5-12%.

Soil Type

Experiments used one soil type: a coarse-grained sand. Details of mean grain size, uniformity coefficient and curvature coefficient are summarised in Table 1. Soil grain size distribution was determined in accordance with Australian standard (2009, AS 1289.3.6.1).

Table 1: Soil Properties

Mean grain size, D_{50} (mm)	0.25
Effective grain size, D_{10} (mm)	0.165
Uniformity coefficient, C_U (mm)	1.65
Curvature coefficient, C_C (mm)	0.84
Void ratio, e	0.53
Specific gravity, G_s	2.65

The sand was mixed to two separate moisture contents, 5% and 10% to represent field conditions observed by Cogan et al. (2018). This sand was then placed in 6 layers of 75mm thickness to make the slope homogenous. The sand itself differed from Cogan et al. (2018) due to difficulties collecting large enough testing samples.

2. Testing Program

2.1 Equipment and Flume Detail

The flume tank used for the experiments is detailed in Fig. 1 with dimensions 1.5m long, 0.83m high and 0.63m wide. The entirety of the tank was not filled, to observe how the sliding mass would impact the toe of the slope 0.8m in length and 0.45m in height. Visual observation was achieved through a plexiglass insert to witness the failure process internally. A drainage valve was installed to allow excess water to drain while still enabling full infiltration within the slope. A roll of geofabric was placed along the edge in front of the drainage valve to keep loss of fines at a minimum. The slope was outlined on the plexiglass to assist in the shaping as the sand was added. During the loading process both the moisture probes and pore pressure sensors were added into their indicated placements. For each setup, pore pressure sensors were placed to obtain an even spread of pressures, both in the full slope and the toe of the slope, and were placed nearer the front as this was the section likely to fail first. Sensors used were T5-7 to measure pore water pressure generation with capacity of -85kPa to 100kPa. Similarly, 4

moisture probes were inserted evenly within the slope (Fig. 1a) to gain an understanding of subsurface water movement. These probes were MP306 in make and came calibrated.

Figure 1: (a) Experimental apparatus arrangement for flume rainfall-induced slope failure, where; MS – Moisture Sensor, PS – Pore Pressure Sensor, (b) Flume tank model configuration, tilted 10° to establish the desired 55° slope

The sand was packed into the flume initially to a 45° slope, with the ability to tilt a further 10° by means of hydraulic lift to achieve the 55° slopes resembling Gold Coast field conditions observed by Cogan et al. (2018) (Fig. 1b). The sprinklers suspended over the tank were tested and calibrated to the rate of flow to achieve the desired rainfall intensities. Mist sprinklers were used to avoid surface erosion while still enabling full downward infiltration.

Data was recorded using 2 ICT International SDI-12 data loggers which were connected to the pore pressure sensors and moisture probes. All changes in pressure and moisture content were recorded throughout the duration of each test, with photographs taken every 10 minutes and a video recording throughout. Both the photo images and video recording were utilised in determining the initial surface movement of the slope and slope failure. The experiment was not concluded until a major failure had occurred.

2.2 Testing Procedure

2.2.1 Direct Shear Test

Direct shear tests were performed in accordance with Australian standard (1998, AS 1289.6.2.2), using a 60mm x 60mm shear box (sample height of 30mm). Shear box tests were performed on specimens with various moisture contents ranging from 0 – 25%. Consistency was maintained by preparing samples to the same void ratio of 0.53 by compacting soil in

layers into the shear box to achieve homogeneity. This void ratio was replicated in the flume test soil layering. Moist samples were prepared by mixing oven-dried soil with 10, 20 and 25% distilled water and sealed in bags to rest for 24 hours to achieve even saturation. Shear box specimens were consolidated for 24h under a 40 kPa normal stress, to simulate normal stress acting on a shear failure plane for an approximate 2m deep shallow slide. Data for horizontal displacement, vertical displacement and shear force were recorded. Specimens were sheared at a rate of 0.05 mm/min for a maximum of 10mm displacement to reach peak shear strength.

2.2.2 Flume Test

Experiments were performed with three variables: slope angle, rainfall intensity and initial slope water content. Intensity was altered using the suspended sprinklers above the slope to create artificial rainfall for downward infiltration, slope angle was controlled using a hydraulic lift attached to the tank (Fig. 1) and moisture content controlled through the mixing process previously mentioned. These alterations in slope characteristics made for a total of 12 experiments performed.

Table 2 details the initial conditions of each experiment. These initial conditions replicated observations in the field as closely as possible, with the intention to change one of the three interchangeable variables. Due to mixing large quantities of soil with water it was difficult to obtain exact same moisture content values per experiment.

Table 2: Testing constraints and slope failure times

Experiment No.	Rainfall Intensity (mm/h)	Slope Angle (°)	Initial Slope moisture content (%)	Initial failure (min)	Test Duration (min)
1	40	45	5.9	143	240
2		55	6.9	186	360
3		45	10.7	123	240
4		55	11.2	229	360
5	70	45	5.9	84	140
6		55	6.1	99	245
7		45	11.2	84	140
8		55	11.1	91	180
9	100	45	7.9	49	122
10		55	5.6	41	92
11		45	10.5	36	120
12		55	10.1	37	102

Failure was defined and determined through video footage, camera photography and visual observation as the slope deformed. Failure times correspond to the initial wash out of sand particles. Initial failures and total test durations are given in Table 2. Although experiments had some unique characteristics the general setup and properties of each experiment were the same. Trends are observed in the wetting process and eventual failure through subsurface water movement and pore pressure build-up. The main focus in analysis was put on observing initial failure times, subsurface water movement and the main failure process initiated by pore pressure generation.

3. Results and Discussion:

3.1 Shear Box results

Shear box test results were plotted in Fig. 2 as a shear stress - horizontal displacement relationship with comparisons between 0, 10, 20 and 25% moist samples. Peak shear stress values were shown to decrease up to 27.5% when sample moisture content was increased. The greatest shear strength was obtained for dry samples at 40kPa, where increasing moisture decreases shear strength to 29kPa. There was no notable difference in peak shear stresses for 20 and 25% moist samples. Such decreases in shear strength are known for contributing to mechanisms for failure of slopes during rainfall events.

Figure 2: Shear stress – displacement from direct shear tests at varying moisture content

3.2 Flume test results

Obtained results from flume experiments are (i) failure times expressed in Table 2, (ii) pore water pressure response to rainfall over time from test initiation (Fig. 3a), (iii) subsurface moisture content response to rainfall over time from test initiation (Fig. 3b) and (iv) tracking of failure surface and wetting front previously mentioned (Fig. 4 & Fig. 5). The time start for the experiments coincides with the application of rainfall, while experimental “failure” occurs when sand particles initially washout from the toe of the slope. Experiments continued after this first failure to track the progressive motion of collapse and to observe the pore water pressure and subsurface water content responses.

An example of general experimental results is provided in Fig. 3(a) and Fig. 3(b) from experiment No. 12. Pore water pressure response is recorded at the 4 different locations within the slope from time of rainfall initiation in Fig. 3(a). Initially, pore water pressure reads in the range of -4.4 to -3.3 kPa before rainfall. As the 100mm/h rainfall infiltrates the soil, over time the wetting front is increased from the base of the flume until it reaches the pore pressure transducers, at which point pore pressures begin to increase. PS1 and PS3 are the first sensors to be affected by the rainfall infiltration, with PS4 responding latest, as it is deepest within the slope. Pore pressure values tend to peak around -2 kPa for sensors PS1 and PS2 as the wetting front fails to reach the height of sensor placement, and only begins to increase again after slope collapse begins allowing infiltration horizontally from the sprinklers.

Figure 3: Time series of experiment No. 12 (a) Suction response after start of constant rainfall (100mm/h), (b) Subsurface water content response after start of constant rainfall (100mm/h)

Results displayed in Fig. 3(b) are key in assessing the progression of the wetting front over time, as well as, the use of plexiglass on the side of the flume tank. Direct shear testing determined water content in the range of 25-30% for this soil mixture was at maximums and therefore the wetting front is predicted with this conclusion. Moisture content values shown in Fig. 4 are derived from Fig. 3(b) at 25 min time intervals and the graph shows a link between

3 of the 4 sensors reaching 25-30% moisture content at the time of failure in the slope. Wetting front depth is estimated to roughly 15cm from the base of the flume at 37min when failure occurs. A detailed breakdown of the effect of altered slope variables shall be given in the following sections.

3.2.1 Wetting Front

The subsurface wetting process occurred similarly for each experiment. Slope wetting times varied between 20-90 min dependent on experimental setup, for subsurface water contents to increase greatly enough to onset failure. Wetting front progression of experiment No. 12 is detailed in Fig. 4. The progression of the wetting front is only an assumption based on the change in moisture content values at each sensor.

Figure 4: Progression of subsurface water movement in Experiment No. 12: (a) Potential water flow-paths based on observed moisture content build-up and details tank inclination (a), (b)-(d) Wetting front movement based on data from moisture content sensors and visual observations.

Typically, the moisture content would increase greatly in the earlier stages of experiments at MS1 and MS3 due to their close proximity to the sprinklers, with delay to the lower MS2 and MS4 sensors. In this experiment (No. 12), failure occurred at 37min when moisture content was 27.6% at MS2 (sensor closest to wetting front). This correlates with the assumptions made from shear box testing that shear strength is decreased greatly at 25-30% moisture content. This

furthermore coincides with peaking of pore water pressure and therefore results in failure. These values would then increase as the experiment progressed leading to larger failure. These trends are typical throughout all conducted tests.

3.2.2 Predominant Failure Type

The predominant failure mode was seepage erosion (visible through video and photography). This was caused by the dragging effect induced by water seeping through the granular sand material (Crosta and di Prisco 1998). In each experiment, regardless of time (from start) to initial failure, once pore water pressure and moisture content increased throughout the slope, excess water began to wash out the sand particles at the toe, and this gradually caused larger collapses to occur. As more sand eroded, larger sections of the slope slumped until major slope failure occurred. This failure type is primarily due to the susceptible nature of the granular sand which therefore made it more likely. Typical seepage erosion exhibited by 100 mm/h rainfall intensity is detailed in Fig. 5.

Figure 5: Failure mode summary (a) Erosion of slope as failure progresses (schematic). Images of failure progress at (b) 50 min, (c) 80 min, (d) 100 min, from Experiment No. 12.

3.2.3 Rainfall Intensity

To investigate the effects of rainfall, only the deepest pore pressure sensor (PS4) and moisture content sensor (MS4) were considered for comparisons, as these are most crucial to the knowledge of slope failure. Detailed in Fig. 6 is the progressive build-up of pore water pressure and moisture content over the duration of experiments 1, 5 and 9 until failure occurred.

Figure 6: Time series of pore pressure and moisture content for experiments 1, 5 and 9, altering rainfall intensity (I) (angle (α) = 45° , initial moisture content (IMC) = $\sim 5\%$). (a) Time series of pore pressure from initiation to failure. (b) Time series of moisture content from initiation to failure.

For Fig. 6(a) and 6(b) it is clear that increased rainfall intensity has a drastic effect on the build-up of pore water pressure and moisture content within the slope, resulting in quicker failure times progressively as the intensity increases. There is a large period of time in each experiment where pore pressure and moisture content remain relatively constant, due to the depth at which these focused sensors are placed. Once the wetting front increases towards these sensors spikes in measurements occur. The difference in time taken for initial spikes in pressure and moisture content varies between 18-50min and 18-65min respectively. Peak pore pressure and moisture content values were similar for each experiment ranging between, -0.0178 to 0.026 kPa and 27.3 to 32% respectively at times of failure. Due to the rapid progression of wetting front at increased rainfall intensities, pore pressure and moisture content increase at a faster rate, evident in the 100mm/h experiment No. 9 failing 66% sooner than 40mm/h (exp. No. 1) and 42% sooner than 70mm/h (exp. No 5). These similar trends are shown in all experiments where rainfall intensity is increased.

3.2.4 Slope Angle

Similar with alterations in rainfall intensity, pore pressure sensor PS4 and moisture content sensor MS4 shall be the focus for analysis of failure. The progressive build-up in both moisture

content and pore water pressure until failure is detailed in Fig. 7 for experiments 5 and 6. It is clear from both data sets that the lower angle of 45° fails 15mins before the steeper 55° . Although pore water pressure values reach roughly the same level, the build-up is delayed in experiment 6 with peaks in moisture content 8% below experiment 5. Overall at the rainfall intensity of 70mm/h in these 2 experiments the higher slope angle is believed to allow greater drainage and therefore cannot build a wetting front to instigate failure as rapidly.

Figure 7: Time series of pore pressure and moisture content for experiments 5 and 6, altering α ($I = 70\text{mm/h}$, $\text{IMC} \approx 5\%$). (a) Time series of pore pressure from initiation to failure. (b) Time series of moisture content from initiation to failure.

Similar to Fig. 7, experiments performed using the 40mm/h rainfall intensity yielded the same results, where 45° slopes failed faster than 55° slopes. However, Fig. 8 details the progression of pore water pressure and moisture content build-up for 2 100mm/h experiments (9 and 10), where the 55° slope fails quicker. As in Fig. 7, pore water pressure values peak at similar levels before slope failure, yet a 9% higher moisture content at failure for experiment 9 did not mean faster failure time.

Figure 8: Time series of pore pressure and moisture content for experiments 9 and 10, altering α ($I = 100\text{mm/h}$, $\text{IMC} \approx 5\%$). (a) Time series of pore pressure from initiation to failure. (b) Time series of moisture content from initiation to failure.

From this experimental data it is clear that at lower rainfall intensities (40 – 70mm/h), a 55° slope does not fail as quickly when compared with the results for 45° slopes due to ability to drain well. However, as the rainfall intensity increases to the tested upper limits of 100mm/h, increased water flow at a greater angle creates more rapid failure in the 55° slopes (exp. No 10).

3.2.5 Initial Moisture Content

Finally, in observation of slope moisture content alteration, PS4 and MS4 shall again be the focused sensors when identifying patterns in failure. Changes in pore water pressure and moisture content over experiments 1 and 3 are detailed in Fig. 9.

Figure 9: Time series of pore pressure and moisture content for experiments 1 and 3, altering IMC ($I = 40\text{mm/h}$, $\alpha = 45^\circ$). (a) Time series of pore pressure from initiation to failure. (b) Time series of moisture content from initiation to failure.

It is evident in Fig. 9(a) and 9(b), the heightened initial moisture content carries throughout the experiments leading to faster failure times. Pore pressure values peak between -0.233 to -0.178 kPa while moisture content is within the range of 27.3 to 33% comparable with all other experiments performed. Although the experiments are performed at the same 40mm/h rainfall intensity, it is evident from the graph that the initial increase in moisture content of experiment No. 3 flows through the duration of the test and is constantly higher at the same time stamp when compared with experiment No. 1. This leads to a 14% faster failure time when comparing experiment No. 3 with 4.8% higher initial moisture content to experiment No.1. This same trend was followed in the 70 and 100mm/h experiments where increasing the slopes initial moisture content made failure time decrease in all regards. Furthermore, when slope angle is increased to 55° the same effect is seen and failure occurs quicker with increased initial moisture content.

The following general summary of observations can be drawn based on the results:

- Shear strength of the specimens tested decreased 27.5% from 0 to 25% moist. Therefore, as experiments are prolonged moisture contents increase and the failure mechanism of decreased shear strength effects slope stability.
- After sudden increases in pore water pressure and an equalisation of moisture content throughout the slope due to increase in wetting front, failures would begin at the toe of the slope in the form of seepage erosion, until progressing to larger segmented failures.
- Increased rainfall intensity leads to quicker failures, with the same trend being typical when initial slope moisture content is increased as well.
- At lower rainfall intensities, a higher slope angle allows for better drainage and therefore failure time takes longer, however as the intensity is increased (100mm/h in this study) the heightened slope angle results in a faster failure.

3.3 Comparisons with previous works

Summarised in Table 3 are the experimental setups for previous flume investigations, with the inclusion of this study for comparisons to be drawn. In general, most previous flume investigations do not alter from their initial setup, and create repetitive experiments focusing on 1 to 2 contributing factors for landslide failure. This paper by no means sets out to discredit the previous work, but instead explores the scenario of variable slope characteristics and their influences on slope failure.

Table 3: Summarisation of Flume tests with comparisons to this study

	Initial Water content (%)	Packing	Slope angles	Soil Type	Drained or Undrained	Rainfall Intensity (mm/hr)
Wang and Sassa. 2001	5	2cm thick tamped layers (totalled 10 – 12cm)	30	Sandy silt / silt	undrained	102
Okura et al. 2002	-	Loosely filled by dropping from mobile hopper	10° toe, 32° upper slope	Sand (0.6% silt + clay)	undrained	100
Moriwaki et al. 2004	8	Packed in 40 cm layers and tamped with ‘foot-traffic’	10° toe, 30° upper slope	Sandy soil	drained	100
Olivares et al. 2009	50	Moist-tamping 0.5 cm thick layers	40°	Non-plastic silty sand	undrained	40
Acharya et al. 2009	7.2	packed in layers of 40 – 50 mm with mechanical hammer at 40 kPa pressure	10° toe, 30° upper slope	sandy soil	drained	50
Lourenco et al. 2006	4 tests deposited dry, 4 deposited moist (unclear on %)	Sand was dumped in 3 kg loads until 120 kg max. for both layers	30°	medium-grained and fine-grained sand	drained	no specific rates given for upper or lower infiltration
Greco et al. 2010	0.2 – 0.35	Moist-tamping 0.5 cm thick layers	40°	pyroclastic silty sand	drained	35 - 55
Ahmadi-adli et al. 2017	1.5	Tamping 5 cm thick layers with a steel plate	56.5°	fine sand (34 & 48 % D _r)	drained	18 - 64
Fan et al. 2018	15	Use of wooden compactor	60°	Gravel	drained	50
This Study	5 - 12	Moist packing of 6 layers 75mm thick	45 & 55°	Coarse-grained sand	drained	40, 70 & 100

Previous literature often only alters 1 or no variables in effecting failure. For instance, each previous flume investigation listed details of only one slope angle tested, whilst most investigations keep to very few rainfall intensities used. This study shows trends typical of previous literature whilst considering how an amalgamation of assorted variables collaborate to effect failure. For example, to compare a singular variable change of rainfall intensity from 40 to 70mm/h, a difference in failure time of 59min was recorded at a 45° inclination. However, altering the slope angle to a 55° inclination now creates a 44min difference recorded between 40 and 70mm/h intensity tests (alteration of 2 variables). This is one example of the wide variation in failure times recorded in this study when altering rainfall and slope characteristics.

4. Rainfall Intensity-Duration Investigation

A well-known influencer for landslide initiation is the duration and intensity of a rainfall event. Studies performed by Caine (1980) and Moser and Hohensinn (1983), explore the relationship between landslide susceptibility due to various rainfall events. Using published records for rainfall intensities and duration associated with shallow landslides, Caine (1980), developed the first rainfall intensity-duration (I-D) threshold, based on 73 cases, exhibiting the minimum-level line for triggering landslides. The threshold curve is presented as:

$$I = 14.82D^{-0.39} \quad (0.167 < D < 240) \quad (1)$$

Where D is in hours and I is expressed as millimetres per hour and is best defined for rainfall durations between 10 minutes and 10 days. Similar investigations performed by Larsen and Simon (1993), Chien-Yuan et al. (2005) and Dahal and Hasegawa (2008), explore the process of determining I-D thresholds by region due to differences in rainfall events and geological conditions. The investigations yielded substantially different I-D thresholds, leading to the conclusion that regional thresholds are preferred over the Caine (1980) original for their improved prediction of landslide susceptibility. Table 4 details these various regional I-D thresholds.

Table 4: Summary of Intensity-Duration thresholds of different regions worldwide with comparisons to this study

Paper	Region	Total Landslides	Rainfall (mm/h)	Duration (h)	Intensity-Duration threshold
Caine (1980)	Global	73	0.32-169	0.167-240**	$I = 14.82 D^{-0.39}$
Moher and Hohensinn (1983)	Austria	140	2-100	Up to 48	-
Larsen and Simon (1993)	Puerto Rico	42 Storms each responsible for 10s to 100s of landslides	3.3-192	2-312	$I = 91.46 D^{-0.82}$
Chien-Yuan et al. (2005)	Taiwan	61	0.5-127.5	6-239	$I = 115.47 D^{-0.8}$
Dahal and Hasegawa (2008)	Nepal Himalaya	193	2-12	5-720	$I = 73.9 D^{-0.79}$
Ahmadi-adli et al. (2017)*	Turkey (not region specific)	10	18-64	0.8-10.5	$I = 38.04 D^{-1.556}$ (34% D_r) $I = 134.9 D^{-1.431}$ (48% D_r)
This Study	Based on observed SEQ Landslides	12	40-100	0.5-4	$I = 80.07 D^{-0.6}$

*Note: this threshold was determined from flume investigation, not analytical investigation

**Note: For rainfall ranges and hour ranges, large rainfall corresponds to small hourly value and vice versa

4.1 Application of Flume Tests Results

A summary of the experimental failure times is presented graphically in Fig. 10, detailing time to failure against the rainfall intensity of the given experiment. It shows how each of the changing characteristics influence the time to failure. While it was intended to investigate the influence of angle and initial moisture content, as well as, rainfall intensity on the initiation of slope failure, this summary of data was further used in the construction of a rainfall intensity-duration threshold for slopes of these characteristics.

Figure 10: Data comparison of failure times by rainfall intensity, comparing alterations between angle (α) and initial moisture content (IMC).

A rainfall intensity-duration threshold was developed using this data and presented in Fig. 11. The function of this threshold is;

$$I = 80.065D^{-0.596} \quad (2)$$

Where, I = rainfall intensity (mm/h), D = duration (h)

Figure 11: Rainfall intensity-duration threshold from flume tests of this study compared with published thresholds.

To validate the data and the threshold a comparison was made with published rainfall intensity-duration thresholds for tropical regions with presence of soils similar to this area of study. These are presented in Fig. 11.

Comparisons show this study's threshold tends to underestimate intensities during shorter duration events and begins to overestimate intensities as duration increases. Factors that may play a role in these inaccuracies are: landslides observed to generate thresholds from the literature often occurred after longer rainfall durations than this study, they occurred in regions where rocks were present rather than just one soil type, and failed slopes were not all in the angle range of 45° and 55° . Comparisons between the threshold developed from this study of flume-based testing, and published literature of naturally occurring landslide correlate in some regard, however it does not encompass characteristics outside the scope of this study. These results are expected as a singular threshold is insufficient to extrapolate for all cases. The experimental findings however, do show promise in the use of flume testing to alter slope characteristics in a controlled environment and their effects on triggering landslides.

5. Concluding Remarks:

A series of tests were conducted on a coarse-grained sand, within a small flume, to identify the effects of varying triggering factors for rainfall-induced shallow landslides. The primary conclusions reached from this research can be summarised as follows:

- a) Typically, pore water pressure would increase to a peak, nearing positive values in some areas of the slope, as this occurred, the wetting front would increase throughout the slope creating increased moisture contents. Once moisture content was equalised throughout the slope, failure was quick to follow. Failure times ranged from between 36min to 229min based on the general intensity and setup of the experiments. Pore water pressure reached positive values at failure while moisture content reached 20-30% throughout the entirety of the slope before failure occurred.
- b) Increased rainfall intensity leads to substantially faster failure times in some cases.
- c) Variations in failure times were noted for different slope angles. For the tests with inclination of 45°, faster failure times occurred in the 40mm/h and 70mm/h series of tests, with difference in failures ranging from as little as 7min up to 106min. However, when the rainfall intensity was increased to 100mm/hr the 55° slopes quickened in failure time with one difference being negligible and the other now being 8min faster in favour of 55°.
- d) When altering initial moisture content, most cases tended towards failing faster in tests with higher initial water content, with a difference as great as 20min in the 40mm/h test for 45°.
- e) Initial failure times allowed the determination of a rainfall intensity-duration threshold based off observed Gold Coast field conditions to give a preliminary predictive method for determining the likelihood of failure for a slope. In comparison with previous literature, this studies threshold predicts values well in some cases, however was slightly inhibited by the difference in slope materials (presence of rocks) and bounds of duration and slope angles for functions created by Larsen & Simon (1993), Dahal & Hasegawa (2008) and Chien-yuan et al. (2005). As no one threshold is suitable for all cases, it is reasonable to conclude this study is applicable particularly to slides resembling the characteristics outlined in this paper.

These experimental findings help understand the influence of different slope characteristics affecting initial failure times in slopes imitating field observed landslides. Comparing the failure time differences whether by intensity, slope angle or initial moisture content shows large

variations on the time to failure. Previously the literature has only detailed 1 changing slope characteristic in experimentation, whereas this study has multiple combinations of 3 to develop a larger understanding of how they contribute to influence slope failure times. This indicates the importance of incorporating all variables to comprehensively understand slope failure.

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