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Mechanisms of Shallow Rainfall-Induced Landslides from Australia: Insights into Field and Laboratory Investigations

Ivan Gratchev, Sinnappoo Ravindran, Dong Hyun Kim, Chen Cui, and Qianhao Tang

Abstract

This paper presents and discusses the mechanisms of rainfall-induced shallow landslides that commonly occur in South East Queensland (SEQ) and northern New South Wales (NSW), Australia. The major factors causing the formation of landslide mass such as geology, weathering, and rainfall patterns were discussed. Results from field surveys and laboratory testing of rock/soil material from landslide masses were presented, and relationships between the material strength and landslide occurrence were drawn. It was found that most of shallow slides were related to sandstone deposits. Those failures occurred on natural slopes and road cuts with the inclination of the failure plane being in the range of 35–45°. For natural slopes where the landslide mass mostly consisted of coarse-grained soil, the relationship between the soil strength and water content was established. In addition, the relationship between rainfall patterns such as intensity and duration, and the landslide occurrence was presented. Based on the data from field work and laboratory results including a series of flume tests, the mechanism of shallow landslides triggered by rainfall events was identified and discussed.

Keywords

Shallow landslides • Rainfall-induced landslides • Soil strength • Suction • Geology • Weathering

1 Rainfall-Induced Landslides in Australia

Rainfall-induced landslides are a common natural disaster that occur in all states and territories of Australia, leading to environmental degradation as well as millions of dollars in damage to infrastructure and land. Although large catastrophic landslides such as the 1997 Thredbo landslide (18 fatalities and \$25 million damage) always draw national attention (Middelmann and Mazengarb 2007), it is the overwhelming number of relatively shallow (1–3 m deep) landslides occurring annually which has led the National Research Council (2004) to declare that landslides are responsible for considerably greater socioeconomic losses than generally recognized. For example, Geoscience Australia recorded 963 landslides nationwide within 20 years between 1990 and 2010, yet this number is believed to be largely underestimated as several local landslides may not be captured by the national database. Although it seems rather difficult to estimate the landslide cost across the whole country, a study on landslide risk in New South Wales (Osuchowski and Roberts 2011) indicated that the cost of landslide remediation may vary from \$1 to 3.5 million, and it can greatly increase by several times when landslides happen to affect important transportation infrastructure. National recognition of the landslide problem resulted in several guidelines for landslide susceptibility, hazard and risk management published by Australian Geomechanics Society (2007a, b) and Australian Building Codes Board (2015). These guidelines were adopted by City Councils across the country to evaluate landslide hazards, identify areas with a high landslide risk, and develop strategies for landslide hazard management. These strategies are mostly oriented at

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avoiding dangerous sites and stabilizing unstable slopes; however, with the development of civil and mining infrastructure, slope stability is expected to become a larger issue for the safety of local communities, and thus more advanced methods will be required to deal with this natural disaster. Unfortunately, there are many uncertainties in forecasting the time and rate of landslide movements, and for this reason, it cannot be performed reliably at present. Better understanding of landslide mechanisms is required to develop more reliable hazard assessment and risk management strategies and achieve more accurate forecasting of landslide movements.

The literature contains several well-documented world case-studies (for example, Wang et al. 2003; Gratchev and Towhata 2011; Gratchev et al. 2011); however, most of them investigated the mechanisms of large-sized catastrophic failures associated with a number of fatalities and considerable economic loss. The mechanisms of such landslides were found to be rather complex, involving the process of soil–water interaction, including changes in soil strength as landslide mass becomes saturated during rainfall. In comparison, limited research into the mechanism of relatively shallow rainfall-induced slides (1–3 m deep) in Australia has been conducted to date. The available data (Abeykoon et al. 2018; Cogan et al. 2018; Cogan and Gratchev 2019; Ravindran et al. 2019) indicate that the mechanism of shallow slides is associated with the behaviour of unsaturated soils, three-phase (soil, water, and air) interaction, and soil suction.

Unfortunately, experimental data on the properties of unsaturated soils remains limited as such studies are costly, time-consuming, and difficult to conduct.

In the past several years, a research group from Griffith University, Australia, has conducted extensive studies on shallow landslides that occurred in South East Queensland (SEQ) and northern New South Wales (NSW) (Fig. 1). This included field surveys of landslide sites and lab testing of landslide material. This generated important data on landslide characteristics, mechanisms, factors affecting it, and properties of rock and soil from the landslide mass. The large study area has also provided a variety of geology, geomorphology, and soil conditions which were found to be the key factors causing the formation of landslides. This work provides a detailed account of major findings which will be of interest to the international reader as well. This paper first discusses the geological settings of typical landslide sites and the effect of geology and geological structures on the landslide occurrence. The influence of rock mass discontinuities and weathering are shown through the analysis of test results obtained for fresh, weathered, and jointed rocks. This paper also provides data on rainfall patterns prior to landslides and describes the rainfall intensity threshold that can be used for landslide hazard assessment. The mechanisms of shallow landslides are analyzed using



Fig. 1 Location of the study area: South East Queensland (SEQ), and northern New South Wales (NSW)

experimental data on properties of soil from landslide masses, with the focus on relationships between the shear strength and water content. In addition, insights from a series of flume tests conducted to simulate the soil mass behavior under different rainfall patterns are presented and discussed.

2 Factors Causing Landslides

2.1 General Characteristics of Landslides

Several shallow rainfall-induced slope failures were studied in SEQ and northern NSW in the past several years. Despite the different locations, those landslides had several similarities that can be described as follows:

1. There were two common types of failures such as slides in jointed rock mass and failures of heavily weathered rock material.
2. Many slope failures in rock mass were associated with geological features such as bedding planes and folds. The rock mass in such structures was affected by sets of discontinuities that created pockets of weathering and accumulation of water which significantly undermined the strength of natural slopes and road cuts (Shokouhi et al. 2013; Kim et al. 2015a). Figure 2a gives an example of slope failure that occurred in the layered formation of sandstone alternated with argillite/shale. Steep inclinations of the bedding planes also had an adverse effect on slope stability.

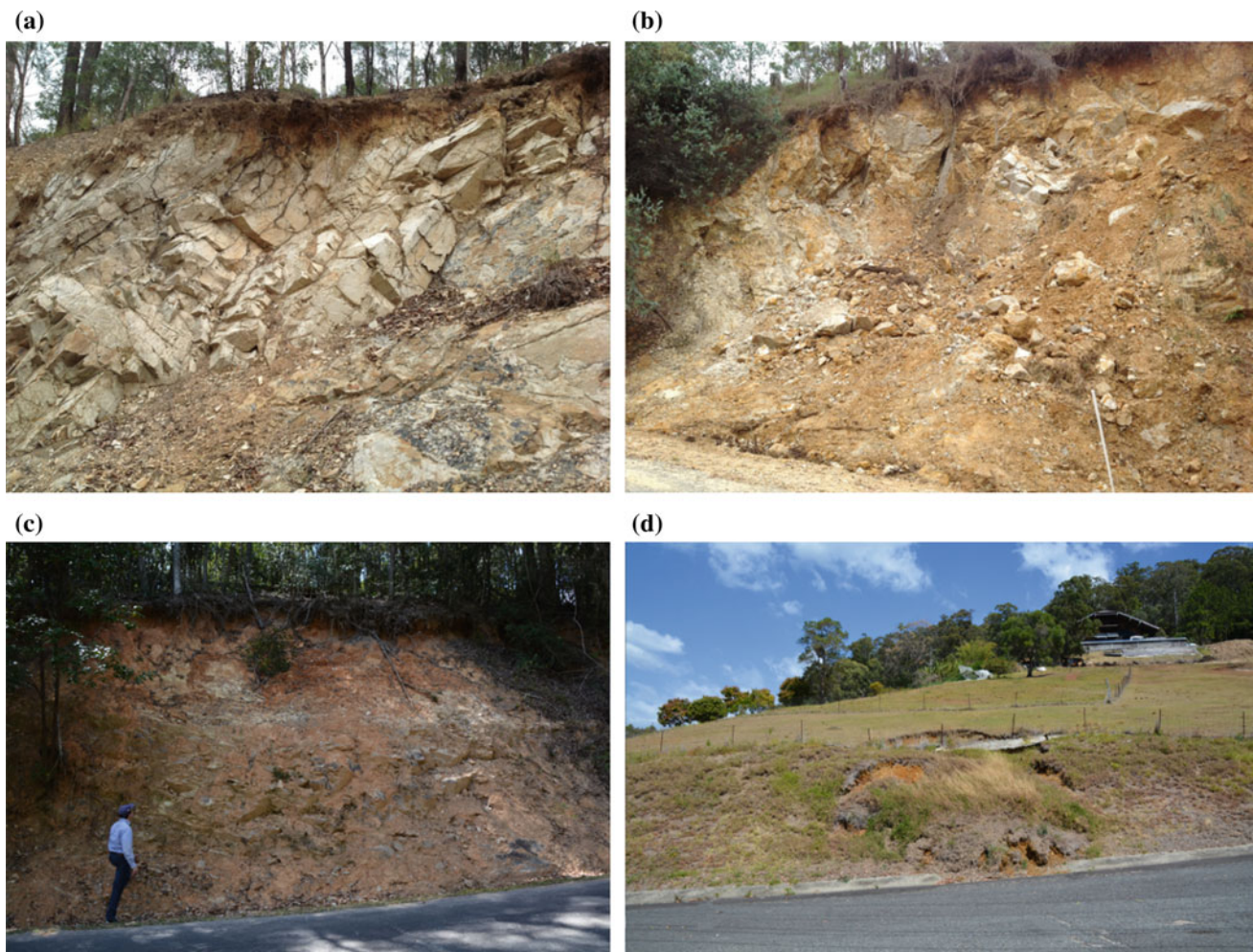


Fig. 2 Examples of rainfall-induced landslides: **a** failure in rock mass of the Neranleigh–Fernvale Beds formation. The bedding planes of sandstone and argillite are steeply inclined, producing an adverse effect

on rock mass stability, **b** landslide in heavily weathered volcanic deposits, **c** shallow slide of heavily weathered material caused by the Cyclone Debbie in 2017, **d** shallow landslide in weathered material

3. On several occasions, the landslide mass was the product of weathering of sedimentary rocks such as sandstone or slightly metamorphized sedimentary rocks such as greywacke and argillite. Kim et al. (2013, 2015b) reported that, despite the different location, most of landslides had similar geological features such as the relatively soft weathered material overlaying relatively hard bedrocks (Fig. 2c). In addition, the bedrock was also deeply weathered while the bedding structure associated with the sets of discontinuities was significant factor contributing to the failure.
4. A few slope failures occurred in weathered igneous rocks as shown in Fig. 2b, where the landslide mass formed in heavily weathered volcanic deposits.
5. The failure plane inclination was found to be in the range of 35 to 45°. This was related to slope cuts along roads and the bedrock inclination. As shown in Fig. 2c, d, the shallow landslide mass (about 1 m deep) was a heavily weathered material, which formed on the slope cut next to a road. The strength of rock/soil has deteriorated over time under environmental conditions.
6. Landslide mass consisted mostly of coarse-grained material such as sand or gravely sand, only few landslides occurred in low plasticity fine-grained soils.
7. The mechanism of such shallow landslides is related to suction. While being stable during dry periods, natural slopes may experience stability issues during a rainfall event as the shear strength of soil tends to decrease with decreasing soil suction (Ravindran and Gratchev 2020, 2021). In several cases, a significant decrease in soil strength was observed as the moisture content of soil greatly increased.

2.2 Geology and Rock Weathering

Geology plays an important role in slope stability as it determines the strength properties of rock. Rock slopes are considered stable when rock strength is high, which is mostly the case for fresh and slightly weathered material. Figure 3 presents a geological map of the Gold Coast area as an example that would relatively well represent the geological conditions in SEQ. Several landslides formed in the Neranleigh–Fernvale Beds formations (Willmott 2010; Gratchev et al. 2013; Shokouhi et al. 2013), which are widely spread in SEQ and northern NSW. The Neranleigh–Fernvale Beds composed of metasediments which are commonly presented as layered argillite (shale) and greywacke (sandstone). Argillite, which is hardened and slightly recrystallized shale, is fined-grained rock, bedding, and fractured in many surface exposures. Greywacke is a typically dark color, low grade metamorphic rock containing fragments that formed a detrital matrix. In some areas, greywacke is replaced with sandstone which is mostly coarse-grained sediment with dark brown color (Kim et al. 2015a, b, c). In many road cuts and natural slopes, where these rocks are exposed on the surface, they are found to be heavily weathered, folded, and steeply inclined.

Towards the continent's inland, there is a large area of sedimentary rocks formed at the end of the Triassic period (Bundamba group, Marburg subgroup). This group consists primarily of planar to cross-bedded, medium to coarse, quartz sandstones interbedded with grey shales and/or siltstones (Willmott 1981).

Volcanic rocks such as basalt, rhyolite, and tuff are found in the mountainous part of the area, and they are remnants of Cainozoic volcanic lava flow deposits. With a relatively high

strength when fresh, these rocks become relatively weak when heavily weathered.

Figure 4 shows the results of unconfined compression tests on fresh samples of basalt, argillite, and sandstone from the Gold Coast area. Rock specimens with a height of 100 mm and diameter of 50 mm were tested in unconfined compression, following the relevant Australian Testing Standard. It is evident from this figure that basalt has the greatest strength compared to different types of sandstone. Four types of sandstone (S1–S4) of the Marburg subgroup were collected at different depths from borehole explorations. It was observed that the strength of sandstone specimens (S1–S4) depended on their porosity. Figure 5 plots the average values of porosity and unconfined compressive strength (USC) for all four types. It is clear that the strength tends to decrease with increasing porosity.

Analysis of over 100 landslides that occurred in northern NSW from 2009–2017 showed that the majority of slides originated in weathered sedimentary rocks (mostly sandstone); however, several slides also occurred in weathered igneous rocks (Ravindran et al. 2019). The reason is that sedimentary or slightly metamorphized sedimentary rocks are widely spread in the northern NSW, and when compared to igneous rocks (for example, basalt), they have relatively low strength.

Weathering. Weathering significantly contributes to the formation of landslides in the study areas. When rock is exposed to environmental conditions, its strength deteriorates over time, resulting in a relatively thick (1–2 m) mass of weathered rocks. A study on the strength of common rock types from SEQ at different levels of weathering was conducted by Gratchev and Kim (2016) and Gratchev et al. (2019). Table 1 summarizes that data from point load tests

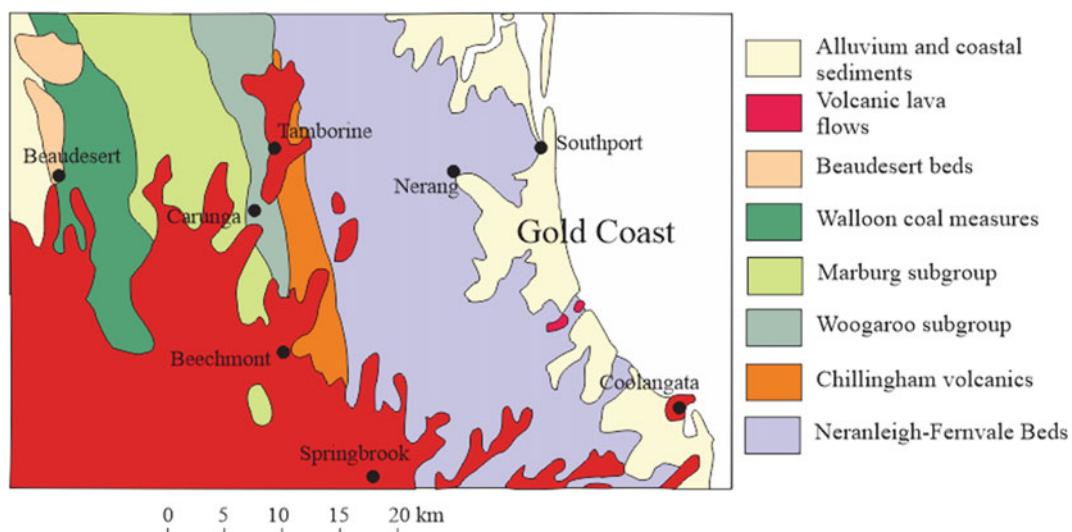


Fig. 3 Geological map of the Gold Coast area (part of SEQ) showing the major geological units

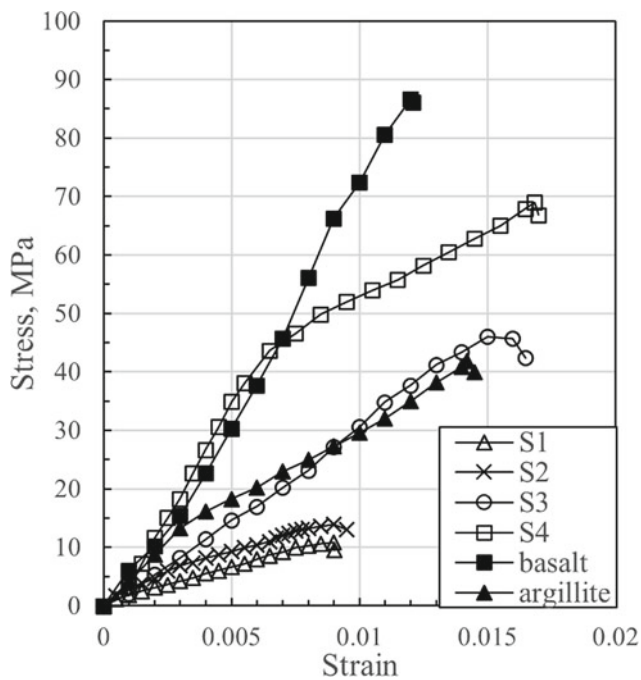


Fig. 4 Results of unconfined compression tests on common types of rock from the Gold Coast area. S1–S4 denote four different types of sandstone from the Marburg subgroup

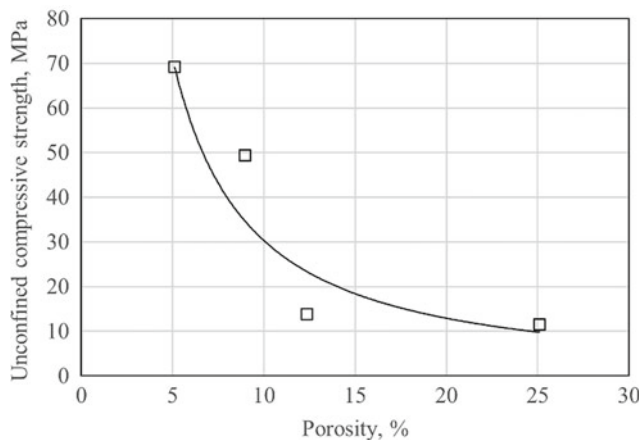


Fig. 5 Results of unconfined compression tests on four different types of sandstone plotted as the unconfined compressive strength (UCS) against rock porosity

conducted on six different rock types, which gives an idea about changes in the rock strength caused by weathering. Visual examination of rock samples was conducted according to the ISRM (1981) guidelines to determine the weathered grade.

It can be inferred from this table that the strength of sedimentary rocks (sandstone and shale) is relatively low compared to the metamorphic greywacke and argillite and

igneous rocks. Also, for all rock types, there is a significant difference between the strength of fresh specimens and heavily weathered ones.

In summary, the relatively low strength of sandstone, compared to other geological units, and its wide distribution in the study area seem to be the major factors for the large number of landslides that occurred in sandstone or sandstone-related material.

2.3 Rock Mass Discontinuities and Strength of Jointed Rock

Another important factor that must be considered in slope stability assessment is joints and discontinuities that affect the stability of rock mass (Gratchev 2019). Rock mass often contains sets of discontinuities that generally undermine the overall strength and create planes of weakness (potential failure zones), and it is thus important to estimate the strength of jointed rock mass (Cui and Gratchev 2020). As several slope failures were associated with sandstone, a series of shear box tests were conducted on jointed and intact core samples of sandstone (Cui et al. 2019) to study the effect of joints on rock strength. For the jointed rock specimens, the surface roughness described by the joint roughness coefficient (JRC) before and after each test was recorded and compared.

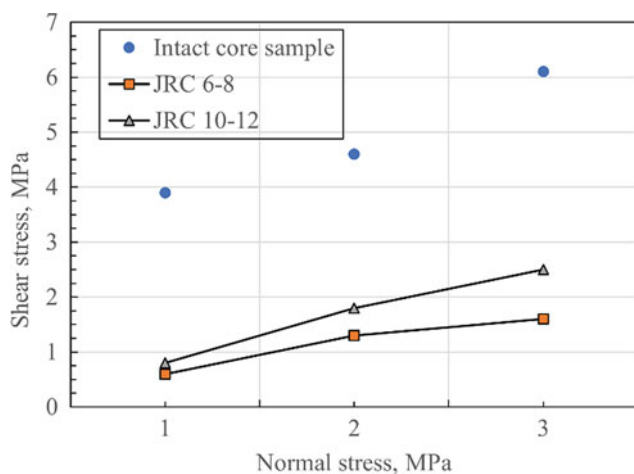
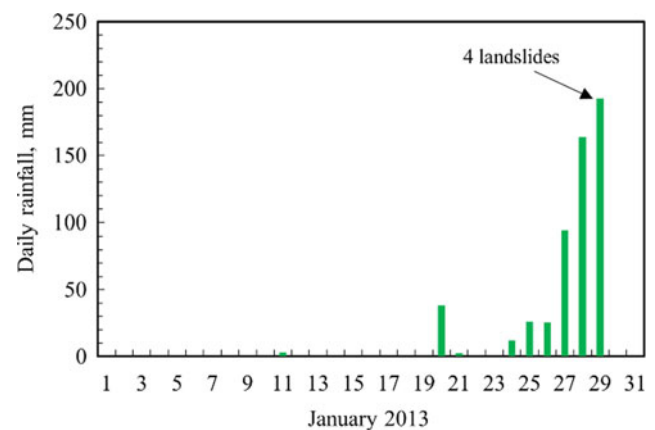
Figure 6 shows typical results from those tests that indicate the effect of joints and joint surface roughness on rock shear strength. The intact rock pieces exhibited much greater strength (almost twofold) compared to the jointed specimens. It is interesting that the specimens with a rougher surface (JRC of 10–12) exhibited greater shear strength compared to the specimens with a relatively low JRC of 6–8. The importance of JRC on the strength of jointed rock mass was discussed by Kim et al (2013, 2015b) who showed, through a series of numerical analysis, that when the JRC increased, the slope stability safety factor also increased.

2.4 Rainfall Patterns Prior to Landslides

Bordoni et al. (2015) noted that landslide occurrence can be related to rainfall characteristics such as rainfall duration and intensity. There have been a few studies where the rainfall threshold associated with landslides has been reported by researchers for different areas. Similar type of analysis was conducted by Ravindran et al. (2019) for the mountain passes in northern NSW where the rainfall data prior to landslides in the period of 2009–2017 was collected and analyzed. Figure 7 presents an example of the rainfall data

Table 1 Change in rock strength with weathering grade (WG). F–fresh, SW–slightly weathered, MW–moderately weathered, HW–highly weathered

Rock	WG	Point load index $I_s(50)$, MPa				
		Test no	Min	Max	Mean	SD
Sandstone	F	4	1.25	2.50	1.72	0.54
	SW	10	1.10	2.20	1.53	0.42
	MW	12	0.60	1.40	1.01	0.24
	HW	8	0.30	0.80	0.58	0.17
Shale	F	2	1.57	2.26	1.92	0.49
	SW	3	1.20	1.67	1.37	0.26
	MW	3	0.86	1.20	0.99	0.19
	HW	5	0.21	0.95	0.63	0.28
Greywacke	F	5	3.47	6.10	4.73	0.99
	SW	8	3.52	4.20	3.83	0.23
	MW	6	2.90	3.50	3.21	0.22
	HW	6	1.80	2.50	2.21	0.26
Argillite	F	4	4.10	5.40	4.54	0.51
	SW	7	2.50	3.42	2.95	0.33
	MW	18	1.22	4.00	2.12	0.77
	HW	6	0.20	0.80	0.48	0.21
Basalt	F	5	7.50	9.10	8.38	0.62
	SW	7	5.00	6.40	5.32	0.49
	MW	8	3.10	4.60	4.00	0.45
	HW	9	1.13	2.50	1.79	0.46
Tuff	F	1	–	2.40	–	–
	SW	2	1.40	2.04	1.72	0.45
	MW	–	–	–	–	–
	HW	3	0.28	0.85	0.64	0.32

**Fig. 6** Results of shear box tests on intact and jointed specimens of sandstone. The core samples with a diameter of 50 cm were used. Note that JRC is the joint roughness coefficient**Fig. 7** Rainfall data prior to the occurrence of 4 landslides in the Gibraltar range area in NSW

obtained before the occurrence of four landslides in the Gibraltar range area of NSW in 2013. Analysis of several rainfall events revealed that most of landslides (about 88%) occurred when the cumulative rainfall was between 100 to 600 mm, and it was then suggested the cumulative rainfall amount greater than 300–500 mm would be sufficient to trigger landslides in northern NSW (Ravindran et al. 2019).

Further analysis of the rainfall threshold revealed the relationship between the rainfall intensity and duration as given in Eq. 1.

$$I = 22.6D^{-0.554} (48 < D < 432 \text{ hrs}) \quad (1)$$

where, I is the rainfall intensity (mm/hrs), D is the duration of rainfall (hrs).

Through analysis of flume test results that simulated different slope and rainfall conditions, combined with the analysis of published data on the rainfall intensity and duration prior to the landslide occurrence in tropical regions, Cogan and Gratchev (2019) suggested the rainfall-intensity threshold that can be used for SEQ Australia conditions as given in Eq. 2

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

It is noted that although these relationships provide useful tools for landslide hazard assessment, they are considered as general estimations, and thus engineering judgement must be exercised while using them.

2.5 Characteristics of Soils from Landslide Sites

Soil samples were collected from several landslide sites to study the index properties and strength of soil material. As reported by Ravindran and Gratchev (2020), most of soil samples were classified as coarse-grained material, predominantly sand. Only small amount of fines (usually less than 5%) were present in the tested soil samples.

Several triaxial tests on saturated soil specimens were conducted to estimate the undrained strength of soil under loads (Ravindran and Gratchev 2021). In addition, a series of shear box tests on soil specimens at different values of water content were carried out to investigate the effect of moisture on soil strength.

Figure 8 presents the results of undrained triaxial tests conducted on coarse-grained soil specimens plotted as the effective stress path. It is clear from these graphs that the excess pore water pressure generated in the specimens under loads (i.e., a decrease in p'); however, the amount of excess pore water pressure wasn't sufficient to cause liquefaction (note that the liquefaction conditions would likely occur when p' drops to almost 0). These typical results suggest that the failure in shallow landslides may not be triggered by the

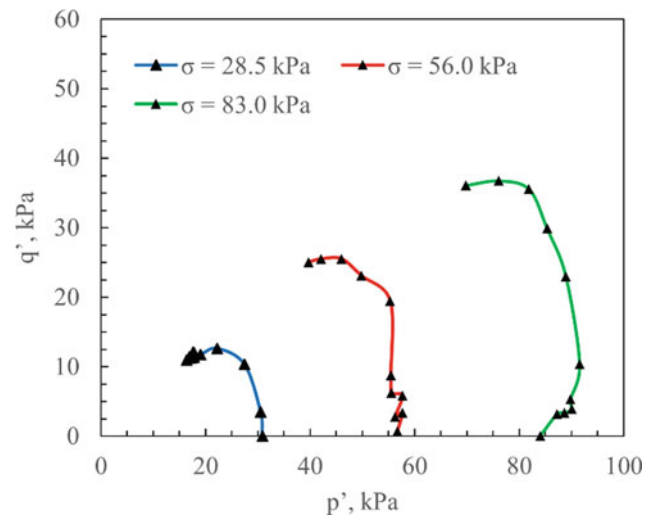


Fig. 8 Results of undrained triaxial tests on coarse-grained soil from a landslide site presented as the effective stress path for different confining pressures

extremely large values of pore water pressure. In fact, as suggested by Krahn et al (1989), shallow slope failures generally occur during rainfall due to the loss of suction.

The test results from a series of shear box tests on 15 different soils from several landslide sites in northern NSW showed that the shear strength of soil decreased as the initial water content of the shear box specimens increased (Fig. 9). It was found that although the friction angle of soil remained almost the same in spite of the increasing amount of moisture in the soil, the apparent cohesion drastically decreased. The experimental data in Fig. 10 indicated that for the range of water content used, there was a pronounced decrease in the apparent cohesion with an increase in water content. This change in the apparent cohesion was mainly attributed to soil

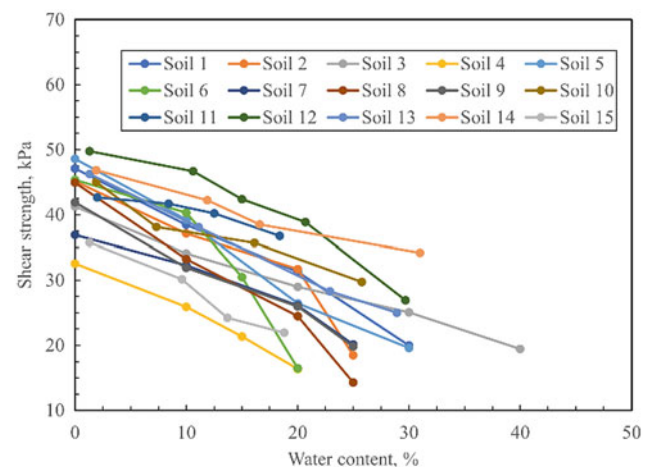


Fig. 9 Results from shear box tests on soils from landslide sites in the northern NSW plotted as the shear strength against the initial water content

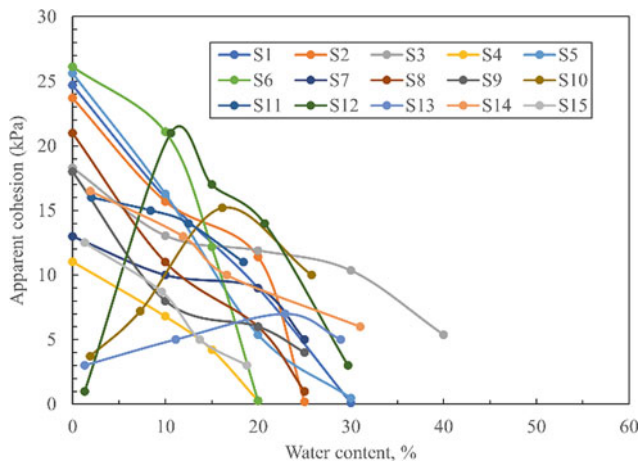


Fig. 10 Results from a series of shear box tests plotted as the apparent cohesion against the initial water content

suction, which was the greatest at a low range of water content and then dropped to zero when the soil specimens became saturated (or very close to saturation) (Fig. 11).

This data has been utilized to draw a relationship between the values of apparent cohesion and water content (Eq. 3) which can be used to estimate changes in strength for similar soil types. Note that Eq. 3 was obtained for the range of water content of 0–30%, and the effective vertical stress of 28.5 kPa.

$$c/c_o = 1.1 - 4.7\theta + 5.9\theta^2 \quad (3)$$

where, c is the apparent cohesion at any water content between 0 and 30%; c_o is the cohesion at zero water content; and θ is the water content.

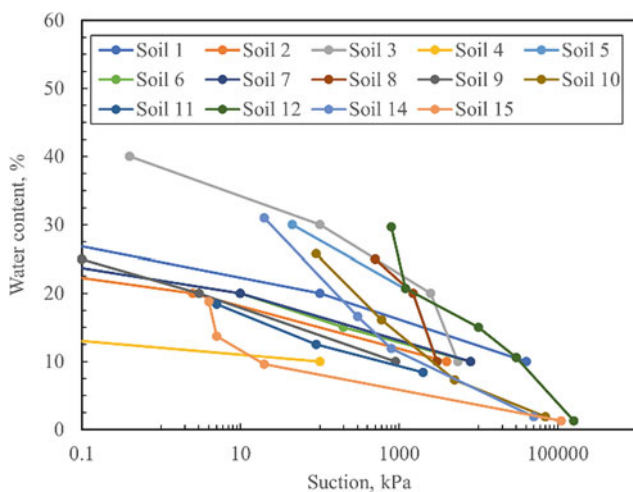


Fig. 11 Results from a series of suction tests showing the relationship between the water content of soil specimens and suction

3 Mechanisms of Shallow Rainfall-Induced Landslides

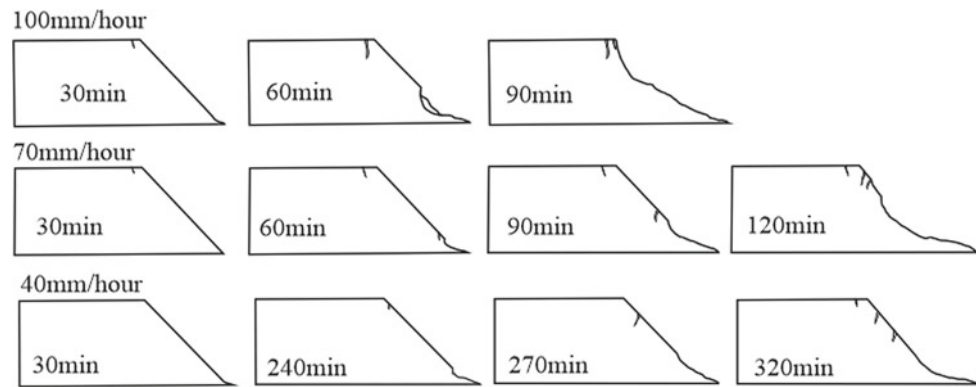
Flume tests provide great opportunities to study the mechanism of rainfall-induced shallow landslides by controlling important factors that contribute to failure. In such tests, it is possible to vary soil types, initial soil conditions, slope geometry, and rainfall intensity. Cogan and Gratchev (2019) conducted a series of flume experiments on sandy slopes with various surface inclinations and rainfall rates, and provided insights into the mechanism of landslide initiation and development. Those tests were equipped with a range of sensors that allowed changes in soil water content, suction, pore water pressure, and displacements to be accurately measured and monitored. It has been found that at a relatively high rainfall intensity, the wetting front formed at the base of the flume. The soil suction decreased as the water content of soil mass increased, resulting in the development of excess pore water pressures through the slope. The pore water pressures then gradually increased until failure. According to visual observations reported by Cogan and Gratchev (2019), at high pore water pressures, the excess water began to wash out the soil particles at the toe, which gradually caused larger collapses to occur.

Rainfall intensity plays an important role in slope stability. It was experimentally observed that an increase in rainfall intensity could lead to more rapid failure. Figure 12 shows the behaviour of a sand slope under different rainfall rates. For 100 mm/hour, failure at the toe occurred about 60 min from the beginning of the experiment while a somewhat similar outcome occurred in the slope after 90 min when the rainfall rate decreased to 70 mm/hour. At a rate of 40 mm/hour, no failure occurred, even after 320 min (with the exception of some minor soil particle erosion at the toe). At this relatively low rainfall intensity, the drainage of water along the slope surface was sufficient to keep the excess pore water pressure at a low value, at which no failure could occur.

3.1 Discussion

Analysis of experimental data from shear box and flume tests reveals the strong influence of water content on soil strength. At a low range of water content, the shear strength of soil appears to be relatively high, and thus sufficient to keep the soil mass stable. Soil suction developed in the soil mass, as evident from the suction and shear box tests, seems to provide the additional strength component in terms of the apparent cohesion. As the water content increases during a rain event, the apparent cohesion along with the total shear

Fig. 12 Changes in the slope geometry over time for different rainfall intensities observed in a series of flume tests



strength of soil begin to decrease. If the rainfall intensity is relatively high, greater amounts of water will permeate the slope and cause the development of a wetting (moisture) front. As the wetting front expands across the soil mass, generating excess pore water pressures, the stability of soil mass will decrease. A relatively low rainfall intensity may not be sufficient for this purpose as the water drainage on the slope surface may exceed the water influx in the slope. In the former case, the slope may become unstable, resulting in the occurrence of landslide. In the latter case, the slope mass can still retain its strength and no slope failure will occur.

4 Concluding Remarks

The paper has summarized and discussed the major findings obtained by the authors in relation to the mechanisms of common landslides in SEQ and northern NSW, Australia, and factors that affect them. The following major conclusions can be drawn:

- Geological factors such as rock type, bedding planes and their inclination, discontinuities of rock mass, and weathering play an important role in the formation of landslides in the study area. It was found that most of the slides were related to jointed, bedded, and weathered sandstone deposits.
- The rainfall intensity and duration have significant effects on slope stability. Cumulative rainfall of greater than 500 mm might be associated with the landslide occurrence. The rainfall threshold described in this study can provide engineers and decision makers with an important tool for more accurate landslide hazard assessment.
- The strength of soil from the landslide mass depends on water content. The apparent cohesion existing in the soil at a low range of water content due to suction tends to disappear when the water content increases towards soil saturation. This correlates with a drop in shear strength of soil, a process that leads to slope instability.

- Considering the results from flume tests, the mechanism of shallow rainfall-induced landslides can be attributed to the formation of wetting (moisture) front, increases in water content, and the excess pore water pressure generation.

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