Landslides (2021) 18:3875–3889
 DOI 10.1007/s10346-021-01758-7
 Received: 19 May 2021
 Accepted: 13 August 2021
 Published online: 4 October 2021
 © The Author(s) 2021

Suman Panday · Jia-Jyun Dong

Topographical features of rainfall-triggered landslides in Mon State, Myanmar, August 2019: spatial distribution heterogeneity and uncommon large relative heights

Abstract Continuous 5-day (August 4–9, 2019) torrential rainfall in the monsoon season triggered more than 90 landslides on north-west-southeast extended mountain range of Mon State, Myanmar. In this study, remote sensing images, DEM, and limited fieldworks were used to create the landslide inventory. The topography features of these landslides are analyzed via ArcGIS. The largest one occurred on 9 August 2019 and caused 75 deaths and 27 buildings were damaged. This landslide occurred on gentle topography (slope angle, 23°) with long run-out, in which the angle of reach was relatively low (10°). The volume was 111,878 m³ was mainly composed of weathered granite and red soil and the sliding depth was approximately 7.5 m. Topographic characteristics including the relative slope height, angle of reach, and slope angle of source area of 35 landslides with areas > 4000 m² were analyzed. The spatial distribution characteristics and topographic features of the 35 landslides below are distinguished: (1) the concentration of most of landslides on southwest-facing slopes showing the heterogeneous spatial distribution of landslide; (2) an uncommon landslide distribution in which more than half of landslide originates from upper slope; (3) the range of the angle of the source area (17°–38°) compatible with the internal friction angle of soils in tropical regions (17°–33°); and (4) the tangent of the angle of reach is generally smaller than 0.5 (angle of reach < 27°) shows a relative high mobility and the relation between landslide mobility and the slope angle of the landslide source area is similar to the one of earthquake-triggered landslides, even though the triggering mechanism, landslide type, and landslide volume are dramatically different.

Keywords Landslides · Rainfall · Slope angle of source area · Angle of reach

Introduction

Landslides play a significant role to reshape the earth's surfaces and lead to hazards. Interactions between boundary conditions such as geology, geomorphology, hydrology, and triggering factors like weathering, rainfall, and human activity enhance their complexity. Myanmar is a mountainous country that contains two major ranges of mountains, the Western Ranges and the Eastern Highlands. The topography of mountain regions may influence rainfall patterns because mountains usually act as barriers to wind blows and enhance rainfall on the windward side (Kozo 1980; Parish 1982; O'Connor et al. 1994; Bougeault et al. 2001; Medina and Houze 2003). Infiltration during continuous torrential rainfall elevates pore pressure or destroys the capillary tension forces of soils and rocks and reduces the shear strength of slopes (Iverson 2000; Pailha and Pouliquen 2009; Rahardjo et al. 2010; Marino et al. 2020). Human

activities in the mountainous regions of Myanmar related to modern infrastructure such as roads and buildings also have a significant role to increase landslide activities. Yearly, substantial life and socioeconomic losses in Myanmar caused by landslides are a major hazard affecting the country due to the geological, topographical, geomorphological, and meteorological conditions (ADPC 2009; Aung et al. 2017).

This study mainly focuses on the landslides triggered by heavy rainfall during the monsoon season of 2019 in Mon State, Myanmar. In total, 90 landslides were identified and an inventory was produced and documented. The influence of slope aspects that are relevant to meteorological conditions on the landslide concentration was explored. Among them, the sloping relief of the 35 landslides having an area larger than 4000 m² was analyzed. The geological features (e.g., lithology and weathering conditions) relevant to the largest, catastrophic one, Thae Phyu Kone landslide which occurred on 9 August 2019, were illustrated and the causative factors related to this landslide were discussed in depth.

Background of the study area

Site location

The study area lies in Paung County, Mon State, in the eastern region of Myanmar, and 270 km away from the southeast of Yangon (Fig. 1a). The coastal region of the Gulf of Martaban (Fig. 1b) is approximately 5–10 km west of these ranges, which directly controls the climatic variability of the area. Hilly mountain ranges with flat terrain cover this area. The Mawlamyine Highway connecting Yangon passes through the area along the foothill side (Fig. 1b, c). The area contains a relatively low thin mountain extending from the northwest to the southeast (Fig. 1c). Landslides are spatially distributed along the southern section of the low relief hill (Fig. 1c, d).

Geological settings

Myanmar lies continuously as Indo Myanmar Ranges in Eastern Himalayan Syntaxis of a continental collision of the Indian and Eurasian plate extended southwards to the north from the Indonesian Arc System to the Eastern Himalayan orogenic belt (Khin et al. 2017; Sloan et al. 2017). Northern Myanmar consists of exposed Indian Plate with various slices of faults also overlain by the Naga hills. Nevertheless, the active subduction of the Indian plate develops transcurrent faults, whereas the pre-collision margin of the Indian Eurasian plate can be evidenced by the most prominent Magok metamorphic belt (Searle et al. 2007; Khin

Fig. 1 Location of the study area. (a) The global position of Myanmar with neighboring countries and the yellow region with a red boundary is Mon State. (b) The location of Paung township in Mon State. (c) More specifically, Paung township is in the location of the study area in the blue boundary, where the blue curve is the ridge of the north-south extended mountain. Thaton, Hpa-an, and Mawlamyine

are three rainfall stations. The brown boundary is the study area enlarged in d. (d) Detailed study area showing the distribution of landslides in red polygons; the red line is the Mawlamyine Highway passing through the study area, and blue curve is ridge of north-south extended mountain

et al. 2017; Sloan et al. 2017), which mainly composed of the oldest rock units in Myanmar, and lies in the major tectonic structural belt. The Magok metamorphic belt (Fig. 2a) mainly composed of gneiss, schist, phyllite, graywacke, dolomite, limestone, and meta-sedimentary rocks (Mitchell et al. 2012). Intruded igneous rocks are common within this belt. This region frequently experiences landslides and mass wasting due to steep slopes with soils or highly weathered rock masses and torrential monsoons (ADPC 2009).

The study area (red square of Fig. 2b) lies in the Magok metamorphic belt where the carbonate sedimentary rocks and intruded granitic bodies outcrop. The carbonate rocks of phlogopite and diopside marbles are Carboniferous to Devonian time. Between these rocks, intruded granitic/pegmatitic body can be observed. The age of the slightly foliated granite is 70.0 ± 0.9 Ma (Searle et al. 2007). Slightly elongated pegmatitic nodules of quartz-tourmaline-garnet rock with an abundant leucocratic outer zone indicate foliation forming after the granite.

Precipitation

Myanmar is a country with a highly complex spatial hydroclimatic phenomenon with variation in multiple topographical influences of the environment. Mon State, Myanmar, is situated in the tropical monsoon climate region. The temperature is not varied significantly. July and August are the peak of monsoon season and heavy rainfall hit the study area during this period. Since the largest landslide in the study area occurred on 9 August 2019, 8:00 a.m., we illustrate 5-day (4–9 Aug.) daily rainfall records of three rainfall stations (Thaton, Hpa-an, and Mawlamyine stations, Fig. 1c) in Mon State (Fig. 3). According to the Department of Metrology and Hydrology (Myanmar), these daily rainfall events were collected during the previous 24 h up to 9:30 a.m. each day. The Mawlamyine station is the closest station to the study area and shows a high rainfall amount (356 mm) from 9:30 a.m., 8 August, to 9:30 a.m., 9 August, which was immediately before the occurrence of the largest landslide event. Thaton and Hpa-an stations in the northern part of the study area recorded relatively

Fig. 2 (a) Regional geological map of Myanmar (Chapman et al. 2015). (b) Geological map near the studied area (modified after Earth Sciences Research Division (1977))

low rainfall compared to the rainfall recorded at Mawlamyine station, which shows strong daily rainfall recorded heterogeneity.

Landslide inventory

Spatial distribution of the identified 90 landslides

A landslide inventory is a detailed description of the spatial distribution, location, and type of landslides (Ayalew et al. 2004; Alessio et al. 2005; Korup 2005; Devoli et al. 2007). We mapped the areal extension of 90 landslides (Fig. 4) that were identified from Google Earth Pro images of 2019/9/26. Landslides were mapped as polygons in kmz format (Online Resource 1). Most of the identified landslides were concentrated on the slopes along the uphill side (northeastern side) of the Mawlamyine Highway. We considered that all of these landslides occurred along with heavy rainfall from the 4th to 9th of August due to lack of landslide activity in past Google Earth images. Most of the landslides in this study area were shallow, debris slides with long transportation paths (Fig. 5). Landslide mapping is not difficult because this disrupted landslide type can be identified easily from the vegetation cover condition. However, human distortions for agriculture and other activities should be carefully excluded. The landslides in this study were mapped at a fixed eye elevation about 500 m. The mapped landslide polygons were further analyzed using ArcGIS software. It should be noted that separating the source, transportation, and deposition areas precisely is difficult because

the landslides are small. The size distribution of the 90 landslides is illustrated in Fig. 6. Among them, the topography features of 35 landslides that have areas larger than 4000 m² were characterized and will be introduced in Section “Topography features of the 35 landslides with areas > 4000 m².” The largest Thae Phye Kone landslide was studied via field investigation and will be introduced in more detail in Section “Thae Phye Kone landslide”.

Topography features of the 35 landslides with areas > 4000 m²

Topographical factors account for the instability of slopes (Montgomery and Dietrich 1994; Talebi et al. 2008; Hess et al. 2017; Cogan and Gratchev 2019). Understanding the topographical factors of the studied shallow landslides is significantly important. The 35 landslides, whose areas were larger than 4000 m², are illustrated in Fig. 7. The topography features including slope aspect, relative slope height, angle of reach, and slope angle of the landslide source area were analyzed. The 30*30-m pixel SRTM (Shuttle Radar Topography Mission) was used for the topographical analysis. The topographical parameters used in this study are presented in Fig. 8. The relative slope height (h/H) is the slope height (h) divided by the elevation difference between the ridge, top, and the valley floor (H) deals with the topographical position (Lee 2013). Angle δ represents the slope angle of landslide source area. The angle connecting from the top of the source area to the bottom of the deposition area is termed the angle of reach (β) (Heim 1932), which evaluates the mobility of landslides (Hsu 1975; Iverson 1997; Okura et al. 2003).

Fig. 3 Five-day (a) accumulated rainfall; (b) daily rainfall amounts in Mon State close to the deadly Thae Phye Kone landslide, which occurred on 8:00 a.m. on 9 August 2019, rainfall data of each day

recorded by 9:30 a.m. of last 24 h. The Mawlamyine station recorded the highest rainfall from 9:30 a.m., 8 August, to 9:30 a.m., 9 August, which is significantly close to the study area (DMH 2019)

Relative slope height (h/H)

The main common feature of rainfall-induced landslides is a favorable location on the lower slope, which can be characterized by a small value of relative slope height (Lee 2013). Herein, the landslides are analyzed via relative slope height (Fig. 9). Less than half of the 35 landslides were concentrated at the lower slope ($h/H < 0.5$). There were still many landslides located at the upslope even near the ridges of slopes, which was not expected.

Distribution of slope angle of landslide source area (δ) and angle of reach (β)

The most important topographic factor that dominates the initiation of shallow landslides is the slope gradient (Mulder and Alexander

2001). The distribution of the slope angle of the landslide source area (δ) of the 35 landslides is illustrated in Fig. 10a. The determined δ ranged from 17° to 38° with a mean value of 27° (Online Resource 2).

The angle of reach of landslides is influenced by the debris properties, geometry of the flowing path, and presence of obstacles (Corominas 1996). Figure 10b shows the distribution of the angle of reach β of the 35 landslides. The smallest angle of reach β of the studied landslide (the largest the Thae Phye Kone Landslide) is 10° , which will be introduced later. The angles of reaches are 31° , 31° , 34° , and 34° for landslides IDs 22, 25, 28, and 33, respectively (Fig. 7). The transportation paths of these landslides were roughly perpendicular to the main creek and the runouts were largely constrained, accounting for the high angle of reach. The angle of the source area was relatively higher than the angle of reach (Fig. 9a, b).

Fig. 4 Distribution of 90 landslides triggered in early August 2019, identified from Google Earth Pro images from 2019/9/26. The landslide polygons were documented in Online Resource 1 in kmz format

Thae Phye Kone landslide

On 9 August 2019, at approximately 8:00 a.m., after long-lasting heavy rainfall (Fig. 3), a massive landslide hit Thae Phye Kone village ($16^{\circ}33'40.95''\text{N}$ latitude and $97^{\circ}34'46.22''\text{E}$ longitude), north of Mottama, Mon State. Thirty buildings were damaged, and a total of 75 people were killed due to this slope failure, together with debris

slides of red soil and rock fragments (Fig. 11a, b). The huge mass of debris on the highway buried several vehicles and passengers. Twenty-seven buildings were damaged by sliding debris (BBC 2019).

Based on the satellite images, pre-event SRTM, and site investigations, the features of the Thae Phye Kone landslide were characterized (Table 1). The Thae Phye Kone landslide is a weathered

Fig. 5 Photograph showing shallow, debris slides (red boundary) in densely vegetated areas, with small source areas but long transportation paths. The locations of landslide near the top of slope. The photo is shot to the northeast direction from the Mawlamyine Highway

Fig. 6 Size distribution of 90 landslides in the study area

Fig. 7 Map showing 35 landslides with an area greater than 4000 m² in which the topographic features were analyzed (details in Online Resource 2). Landslide no. 3 is the Thae Phye Kone landslide triggered on August 9, 2019. This landslide was investigated via field investigation which will be described in Section “Thae Phye Kone landslide”

Fig. 8 Definitions of studied geomorphological features. The relative slope height (h/H) is the ratio of height of landslide (h) and whole landslide existing slope height (H). The slope angle of the landslide source area is denoted by δ . The angle of reach (β) is the angle representing the tip of landslides to end (bottom) of deposits

rock/soil slide. The weathered rock fragments and residual soils slid down from the ridge of the hill to the toe of the slope. Soils and weathered rock debris spread widely on flat areas where the vehicles on the road and buildings were buried suddenly. A pagoda located on the lower part of the slope was badly damaged by the big boulders (Fig. 12). Based on the pre- and post-satellite images, the landslide covered 48,558 m². The area was calculated by pixel counting via ArcGIS of the polygon-based projected area. The maximum projected length of this landslide was approximately 400 m, and the maximum projected width is approximately 170 m.

The large boulders in the deposition area are mainly composed of granite with different weathering degrees. The soils are red in color and clay-rich, which came from the thick residual soils on the top of a ridge (Fig. 12).

The whole landslide area is subdivided into three different parts based on slope geometry and material properties. The crown (point c), source area (points c to b), and deposition area (points b to a) of the Thae Phye Kone landslide were identified and marked in Fig. 13a. The deposition area with large rock fragments was also marked. The profile of the Thae Phye Kone landslide is illustrated in Fig. 13b. The exposed source area is close to the slope top, and the relative slope height is 0.7. The exposed source area was 5922 m², and the slope angle of the landslide source area was 23°. Since part of the source could still be buried by the rock fragments, the true source area could be larger than the exposed source area. We define a transitional/depositional area, together with the rock fragment area (Fig. 13a), which means that the area includes erosion but is covered by moving debris. The transitional/depositional area (5912

Fig. 9 Distribution of the relative slope height (h/H) of 35 landslides

m²) and rock fragment area (3132 m²) cover 9044 m², and the total source area could be approximately 14,966 m².

A weathered granitic rock mass with several vertical and inclined joints can be observed on the landslide crown. Spheroidal weathering could dominate the mass wasting process. The large boulders of rock fragments near the source area are mainly the rock cores of the spheroidal weathering process. The angle of repose of the rock fragments is approximately 20°, and the rock to debris slide is presumed. The deposition area lies on the toe part of the landslide and the angle of reach is only 10°. The deposition area is approximately 33,619 m², and the average thickness is estimated approximately 3 m from the height of buried buildings. The details of the depth estimation and volume calculation are presented in Table 2. If the deposition depth of the transitional/deposition area (5912 m²) is 3 m too and the deposition depth of the rock fragment area (3132 m²) is 5 m, the deposition volume (after expansion) of this landslide is approximately 134,253 m³. Since the estimated source area is 14,966 m², the average sliding depth is approximately 7.5 m if an expansion ratio of 1.2 (Guzzetti et al. 2009) is assumed (i.e., the landslide volume before expansion is 111,878 m³).

Discussion

Heterogeneity of rainfall and landslide spatial distribution

In the study area, a thin mountain extending from northwest to southeast (Fig. 14; green line is a ridge separating the southwest- and northeast-facing slopes) could induce rainfall heterogeneity and dominate the spatial distribution of landslides. In total, 77 out of 90 landslides were located on the southwest side of the ridge (Fig. 14). We suggest that this spatial distribution of rainfall-induced landslides can be correlated with rainfall pattern heterogeneity in the study area.

Fig. 10 Distribution of (a) slope angle of the landslide source area (δ); (b) the angle of reach (β) of the 35 landslides

High temporal and spatial heterogeneity in rainfall can be observed in Fig. 3, wherein stations Thaton and Hpa-an recorded lower daily rainfall (61 and 69 mm, respectively) than the Mawlamyine station (356 mm) during the last 24 h before 9:30 a.m. on August 9, 2019. This temporal and spatial rainfall heterogeneity is observed clearly from radar data (Fig. 15a–d). Figure 15a shows that rainfall only accumulated on the northern and southern sides of the study area at 18:48 p.m. on August 7, 2019. At 15:51 p.m. on August 8, 2019, the rainfall area concentrated more to the study area (Fig. 15b). The rainfall started to increase near the study area at 18:47 p.m. on August 8, 2019 (Fig. 15c), and the rainfall intensity reached approximately 100 mm/h on the southwestern side of the study area at 7:03 a.m. on August 9, 2019, which was approximately 2 h before the deadly Thae Phye Kone landslide events. It can be observed that the rainfall intensity is lower on the northeastern side.

Rainfall patterns globally and locally are spatially heterogeneous due to topography effects (Smith 1979). The topographical

conditions in the study area include sequences of mountain ranges, and valleys lie very close to the Gulf of Martaban and Bay of Bengal. In southern Myanmar, the direction of monsoon wind in this region is from southwest to northeast (Aung et al. 2017). On the windward side, higher rainfall due to the lifting of air masses releases an increase in rainfall but decreases the precipitation on the other side of mountain ranges (Smith 1979; Hill 1983). Mountains act as a barrier to wind flow and automatically facilitate the rainfall process. This type of barrier mountain range is found in many other regions of the entire world and is termed the orographic effect (Pierrehumbert and Wyman 1985; Smith 1989). The enhanced rainfall on the windward side can percolate more into the subsurface of slopes and reduce the stability of slopes (Parish 1982; McCauley and Sturman 1999; Houze 2012). However, it is difficult to conclude that the spatial distribution features of the studied landslides are due to orographic effects

Fig. 11 Google Earth image (a) pre-event (2018/3/17); (b) post-event (2019/9/26) showing the Thae Phye Kone landslide

Table 1 Characteristics of the Thae Phyu Kone landslide studied via site investigations

Property	Description
Landslide name	Thae Phyu Kone
Location	Paung County, Mon State
Coordinates	Latitude: 16°33'40.95"N Longitude: 97°34'46.22"E
Elevation range (m)	10–70
Length (m)	400
Width (m)	170
Area (m ²)	48,585
Slope angle of source area (°)	23
Angle of reach (°)	10
Relative slope height	0.7
Parent rock type	Granite
Soil type	Residual, clay-dominated
Landslide type	Slide, shallow
Landslide volume (m ³)	111,878
Sliding depth (m)	7.5

due to the lack of dense precipitation station arrays near the study area.

High relative slope height, gentle slope angle of the landslide source area, and high mobility

As shown in Section “Topography features of the 35 landslides with areas > 4000 m²,” the distinct topographic features (Figs. 9 and 10) of the 35 landslides included (1) high relative slope height (h/H),

(2) gentle slope angle of the landslide source area (δ), and (3) high mobility (small angle of reach; β):

(1) High relative slope height (h/H): Rainfall-induced landslides are favorably located on the lower slope (Lee 2013) because the groundwater table upslope is generally deeper than that of the downslope. It is interesting to find that almost half of the studied landslides out of 35 (area having > 4000 m²) are located near the top of the slope ($h/H > 0.5$). Among them, 4 started from the top of the slope (Fig. 9), which is not common for rainfall-triggered landslides.

(2) Gentle slope angle of the landslide source area (δ): The slope angle of the landslide source area δ ranged from 17 to 38°, with a mean value of 26° (Online Resource 2). This relatively gentle slope angle of the landslide source area (δ) is correlated to the high relative slope height (h/H). Generally, the slope angle near the ridge is relatively gentle. Therefore, soil erosion was minimized near the ridge because the slope-steepness factor and slope-length factor (factors in USELE) are low (Wischmeier and Smith 1978; Renard et al. 1997). Thick weathered regolith can therefore accumulate easily at gentle topography near the ridge, although the soil production rate will decrease when the soil depth increases (Heimsath et al. 1999).

The slope angle of the landslide source area positively correlates to the friction angle of the sliding surface of landslides. Rigo et al. (2011) collected the residual shear strength of tropical soil throughout the world, including Southeast Asia, Africa, and South America, from different studies. The internal friction angle of the migmatitic, micaceous saprolitic soil of South America ranges from 17° to 33°. The main lithology are migmatitic granites of the study area, and the documented internal friction angles are compatible with the slope angle of the landslide source area in the study area (ranging from 17° to 38°).

(3) High mobility (small angle of reach; β): A $\tan \beta$ roughly equals 0.5 for saturated, poorly sorted debris flows along unconfined paths (Iverson 1997). Among the 35 studied landslides, 28 landslides had $\tan \beta$ (angle of reach) less than 0.5 ($\beta < 27^\circ$) (Online Resource 2). The angle of reach of the studied landslides was generally smaller than the angle of the landslide source area (δ) (Fig. 9a,

Fig. 12 Photograph showing the Thae Phyu Kone landslide. The weathered regolith outcrops on the source area. The landslide deposits are composed of highly to slightly weathered rock fragments (maximum 5 m in diameter), mixed with clay-rich soils. The angle of repose of the rock fragments is approximately 20

Fig. 13 The scarp, source, and deposition area of Thae Phye Kone landslide. (a) Plan view; (b) profile. The areas are divided using Google Earth images (Fig. 11b) and a digital elevation model. Two more areas were identified: transitional/deposition area and rock fragment area, where the source area could be covered by debris or rock fragments

b). The angle of reach of the Thae Phye Kone landslide was the lowest (10°) among the 35 studied landslides. This high mobility causes catastrophic consequences.

Based on the three features observed, possible explanations are discussed. First, the angle of the source area is relatively higher than the angle of reach (Fig. 9a, b), implying that the role of fluid (runoff mixed with debris) is significant (Iverson et al. 1997). The low angle of reach (10°) of the Thae Phye Kone landslide could be related to the low strength of weathered clay-rich soils mixed with runoff or groundwater. This promotes the rock (debris) to slide into

debris (soil) flow with long run-out. The mechanism of undrained loading lowering the angle of reach due to an increase in pore water pressure (Hutchinson and Bandhary 1971; Sassa et al. 1991) can be another explanation of the observed long run-out.

Second, for dry slopes without cohesion, the critical slope angle equals the drain friction angle of the sliding debris for infinite slope instability. When the groundwater table is identical to the slope surface and the groundwater flow is parallel to the slope surface, the critical slope angle will be half of the drain friction angle of the sliding debris (Lambe and Whitman 1969).

Table 2 Details of the volume estimation of the Thae Phye Kone landslide

Landslide parts	Area (m^2)	Depth (m)	Volume (m^3)	References for depth estimation
Depositional area	33,619	3	100,857 ^I	Almost all buildings are buried and take the average height of a building approx. 3 m
Rock fragments area	3,132 ^a	5	15,660 ^{II}	Maximum boulder sizes are 5 m
Transitional/depositional area	5,912 ^b	3	17,736 ^{III}	Same with deposition area
Exposed source area	5,922 ^c	-	-	-
Total erosional area (a + b + c)	14,966	-	-	-
Total deposition volume (I + II + III, after expansion)			134,253	-
Landslide volume (deposition volume divided by volume expansion ratio 1.2)			111,878	-

Fig. 14 Southwest-facing slopes (green line is the ridge separating the southwest- and northeast-facing slopes) have a higher concentration of landslides

Fig. 15 Radar images showing spatial and temporal heterogeneity in rainfall intensity (J-BIRDS, JRC-Brilliant and Intelligent Radar Dialogic System) from 7 to 9 August, (a) 18.48 p.m. August 7; (b) 15.51 p.m. August 8; (c) 18.47 p.m. August 8; (d) 7.03 a.m. August 9, 2019 (modified from DMH 2019)

The slope angle of the landslide source area compatible with the documented friction angle of saprolitic soil suggests that the failure of the studied landslides cannot be caused by fully saturated slopes with strong seepage force.

Finally, rainfall-triggered landslides usually originate from an increase in the groundwater table (pore pressure elevation). The groundwater table near the top of the slope is generally low, and the pore pressure rise due to the elevated groundwater table is not a good explanation for the occurrence of landslides upslope, as observed in this study. Alternatively, during infiltration, wetting front migration on unsaturated upslopes reduces matrix suction, and upslopes that become unstable are frequently observed in tropical areas (Fredlund et al. 1978; Fredlund and Rahardjo 1993; Rahardjo et al. 1995), even though the sliding surface is well above the groundwater table. The thick weathered regolith accumulated on gentle topography near the ridge can enhance infiltration during rainfall. We speculate that the saturation of thick weathered regolith from the slope surface due to rainfall infiltration in the study area could episodically promote shallow landslides on the top of slopes. However, this argument has not been well constrained, and convincing evidence could be obtained via further detailed site investigation and monitoring projects, which is out of the scope of this study.

Relation between the slope angle of the landslide source area and angle of reach (landslide mobility)

The mobility of landslides is critical and complex phenomena from the viewpoint of landslide hazard mitigation. Landslide mobility is mainly controlled by topographical and morphological factors such as volume of the sliding mass, properties of debris, motion mechanism, pore water pressures, geometry or regularity of the traveling path, and presence of obstacles such as vegetation and boulders (Heim 1932; Hsu 1975; Coraminas 1996; Hunter and Fell 2003). Zhan et al. (2017) presented a positive correlation between the tangent of the angle of reach and the slope angle of the landslide source area ($\tan \delta$) of 38 channelized rock avalanches induced by the 2008 Wenchuan earthquake. The data points and regression line are shown in Fig. 16 (red circles and straight line). Similarly, rainfall induced 35 Myanmar landslides in Fig. 16 (blue circles) which suggests that the tangent of the angle of reach ($\tan \beta$) correlated positively with the tangent of the slope angle of the landslide source area. Landslide mobility is decreased (the angle of reach increases) with an increasing slope angle in the landslide source area reflecting the fact that the slope angle of the landslide source area correlates the friction angle in sliding debris positively (Okura et al. 2003; Zhan et al. 2017). This illustrated that the kinetic energy of the sliding mass

Fig. 16 Relationship between the tangent of the angle of reach ($\tan \beta$ or H/B) and tangent of the slope angle of landslide source area ($\tan \delta$) where red circles are data of earthquake-induced landslides

(Zhan et al. 2017), and blue circles are data on rainfall-induced landslides (this study)

consumed by internal friction is positively correlated to the slope angle of the landslide source area (Iverson 1997). The data scattering in Fig. 16 implies that the angle of reach could be controlled by other factors, such as strength heterogeneity and local topography aside from the valley rather than slope gradient, which could be an obstacle for the mobility of landslides and increase the angle of reach. Another possible reason are obstructions by dense vegetation and boulders for shallow landslides (Hunter and Fell 2003). It is interesting to find that the data points of earthquake-induced and rainfall-induced landslides are quite similar in Fig. 16. Notably, the landslide volumes of these two datasets are dramatically different. This issue deserved more study in the future.

Conclusions

We created an inventory of a total of 90 landslides triggered by heavy rainfall during the monsoon season of 2019 in Mon State, Myanmar. Among them, 35 landslides with areas > 4000 m² were carefully analyzed using Google Earth imagery and SRTM with ArcGIS software. The topographic characteristics of these 35 landslides, including the relative slope height, angle of reach, and angle of the source area, were documented. The biggest and most catastrophic Thae Phye Kone landslide was studied via field investigations, and the characteristics were documented in more detail. The critical findings can be summarized in the following headings:

1. On 9 August 2019, the biggest Thae Phye Kone landslide, triggered by long-lasting heavy rainfall (more than 3 days with approximately 100 mm rainfall per day) killed 75 people and 27 buildings were damaged. The landslide was mainly composed of weathered granite and residual soils in red, located on a gentle slope (slope angle 23°) near the slope top (relative height = 0.7). The volume was approximately 111,878 m³, and the average sliding depth is approximately 7.5 m. The angle of reach was quite low (~10°), indicating the high mobility of this catastrophic landslide.

2. A highly heterogeneous rainfall pattern from August 4 to 9 was observed. The mountain range extending from northwest to southeast could contribute to rainfall heterogeneity. In total, 77 out of 90 landslides located on the southwest side of the ridge showed strong spatial distribution heterogeneity of landslide occurrence, which could be related to the heterogeneous rainfall pattern.

3. More than half of 35 landslides with area > 4000 m² were located on the upper slopes (relative height > 0.5) including 4 landslides on the slope top, which is uncommon for rainfall-triggered landslides. The slope angle of the source area ranges from 17° to 38°, which is compatible with the internal friction angles of saprolitic soils in tropical regions (17°–33°). The groundwater table rise or seepage force caused by groundwater flow in saturated soils fails to account for the observations.

4. The tangent of the angle of reach is generally smaller than 0.5 (angle of reach < 27°), which indicates a relatively high mobility. The relation between $\tan \beta$ (angle of reach) and $\tan \delta$ (slope angle of source area) of the studied rainfall-triggered landslides surprisingly resembles the relation of earthquake-induced landslides, although the triggering mechanism, landslide type, and landslide volume are dramatically different.

Acknowledgements

The authors would like to thank Myanmar Engineering Council (MEC) Dr Charlie Than, President, who invited the corresponding author to visit the landslide sites and U Tin Latt, Joint General Secretary of MEC, who made all of the arrangements of site survey. The authors would like to thank colleagues who joined the site survey including Federation of Myanmar Engineering Societies, Myanmar, U Ko Ko Gyi, Vice President; Calvin Chang, PE, GM; Mingte Hong, PE; Khin Maung Than, AGI (Asia Geotechnique International) Myanmar & Taiwan; Myo Min Aung, Chief Engineer, Myat Mi Ba Construction, Myanmar. The Calvin Engineering, Myanmar & Taiwan, provided accommodations which are highly appreciated.

Funding

This research was supported by Taiwan Ministry of Science and Technology (MOST108-2638-E-008-001-MY2 and MOST107-2116-M-008-001-MY3). This work was also financially supported by Earthquake-Disaster & Risk Evaluation and Management Center (E-DREaM) from The Featured Areas Research Center Program within the framework of the Higher Education Sprout Project by the Ministry of Education (MOE) in Taiwan. The Calvin Engineering, Myanmar & Taiwan, provided the travel funds.

Declarations

Conflict of interest The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Alessio C, Lanteri L, Ramasco M, Troisi C (2005) Systematic GIS-based landslide inventory as the first step for effective landslide-hazard management. *Landslides* 2:291–301. <https://doi.org/10.1007/s10346-005-0025-9>
- ADPC (Asian Disaster Preparedness Center) (2009) Hazard profile of Myanmar. Asian Disaster Preparedness Center (ADPC). Yangon, Myanmar. <http://dpanther.fiu.edu/dpService/dpPurlService/purl/F113042445/00001>
- Aung LL et al (2017) Myanmar Climate Report. Climate Record and Research Section, Department of Metrology and Hydrology (DHM) Yangon, Myanmar. <https://www.scribd.com/document/422145423/Myanmar-Climate-Report-Final-11-Oct-2017>
- Ayalew L, Yamagishi H, Ugawa N (2004) Landslide susceptibility mapping using GIS-based weighted linear combination, the case in Tsugawa area of Agano River, Niigata Prefecture, Japan. *Landslides* 1:73–78. <https://doi.org/10.1007/s10346-003-0006-9>
- BBC (2019) Myanmar landslide death toll rises to 59. BBC News. www.bbc.com/news/world-asia-49329280. Accessed 13 Aug 2019
- Bougeault P, Binder P, Buzzi A, Dirks R, Houze R, Kuettner J, Smith R, Steinacker R, Volkert H (2001) The map special observing period. *Bull Am Meteor Soc* 82:433–462. [https://doi.org/10.1175/15200477\(2001\)082%3c0433:TMSOP%3e2.3.CO;2](https://doi.org/10.1175/15200477(2001)082%3c0433:TMSOP%3e2.3.CO;2)

- Chapman H, Bickle M, Thaw S, Thiam H (2015) Chemical fluxes from time series sampling of the Irrawaddy and Salween Rivers Myanmar Chemical Geology 401. <https://doi.org/10.1016/j.chemgeo.2015.02.012>
- Cogan J, Gratchev I (2019) A study on the effect of rainfall and slope characteristics on landslide initiation by means of flume tests. Landslides 16:2369–2379. <https://doi.org/10.1007/s10346-019-01261-0>
- Coraminas J (1996) The angle of reach as mobility index for small and large landslides. Can Geotech J 33:260–271. <https://doi.org/10.1139/t96-005>
- Devoli G, Strauch W, Chávez G, Høeg K (2007) A landslide database for Nicaragua: a tool for landslide-hazard management. Landslides 4:163–176. <https://doi.org/10.1007/s10346-006-0074-8>
- DMH (2019) Department of Metrology and Hydrology (Myanmar). <https://www.facebook.com/dmhmoezalanaypyitaw>. Accessed 4–9 Aug 2019
- Earth Sciences Research Division (1977) Geological map of the Socialist Republic of the Union of Burma, 1:1000,000 scale, Rangoon
- Fredlund DG, Morgenstern NR, Widger RA (1978) The shear strength of unsaturated soils. Can Geotech J 15:313–321. <https://doi.org/10.1139/t78-029>
- Fredlund, DG, Rahardjo H (1993) Soil mechanics for unsaturated soils. Wiley, Canada. <https://onlinelibrary.wiley.com/doi/book/https://doi.org/10.1002/9780470172759>
- Guzzetti F, Ardizzone F, Cardinali M, Rossi M, Valigi D (2009) Landslide volumes and landslide mobilization rates in Umbria, Central Italy. Earth Planet Sci 279:222–229. <https://doi.org/10.1016/j.epsl.2009.01.005>
- Heim A (1932) Der Bergsturz und Menschenleben. Fretz und Wasmuth Verlag, Zürich 218 (English translation by Skermer NA (1989) Landslides and human life. BiTech Publishers. Vancouver BC
- Heimsath AM, Dietrich WE, Nishiizumi K, Finkel RC (1999) Cosmogenic nuclides, topography, and the spatial variation of soil depth. Geomorphology 27(1–2):151–172
- Hess DM, Leshchinsky BA, Bunn M, Benjamin Mason H, Olsen MJ (2017) A simplified three-dimensional shallow landslide susceptibility framework considering topography and seismicity. Landslides 14:1677–1697. <https://doi.org/10.1007/s10346-017-0810-2>
- Hill FF (1983) The use of average annual rainfall to derive estimates of orographic enhancement of frontal rain over England and Wales for different wind directions. J Climatol 3:113–129
- RA Houze (2012) Orographic effects on precipitating clouds. Rev Geophys 50. <https://doi.org/10.1029/2011RG000365>
- Hsu KJ (1975) Catastrophic debris streams (sturzstroms) generated by rockfalls. Geol Soc Am Bull 86(1):129–140
- Hunter G, Fell R (2003) Travel distance angle for “rapid” landslides in constructed and natural soil slopes. Can Geotech J 40(6):1123–1141. <https://doi.org/10.1139/t03-061>
- Hutchinson JN, Bandhari RK (1971) Undrained loading, a fundamental of mudflow and other mass movements. Geotechnique 22:353–358
- Iverson RM (1997) The physics of debris flows. Rev Geophys 35:245–296
- Iverson RM, Reid ME, LaHusen RG (1997) Debris-flow mobilization from landslides. Annu Rev Earth Planet Sci 25(1):85–138
- Iverson RM (2000) Landslide triggering by rain infiltration. Water Resour 36(7):1897–1910. <https://doi.org/10.1029/2000WR900090>
- Khin Z, Win S, Barber AJ, Crow MJ, Yin Yin N (2017) Chapter 1: Introduction to the geology of Myanmar Geological Society, London, Memoirs 48:1.1–17. <https://doi.org/10.1144/m48.1>
- Korup O (2005) Distribution of landslides in southwest New Zealand. Landslides 2:43–51. <https://doi.org/10.1007/s10346-004-0042-0>
- Kozo TL (1980) Mountain barrier baroclinicity effects on surface winds along the Alaskan Arctic coast. Geophys Res Lett 7:377–380. <https://doi.org/10.1029/GL0071005p00377>
- Lambe TW, Whitman RV (1969) Soil mechanics. John Wiley & Sons, New York
- Lee CT (2013) Re-evaluation of factors controlling landslides triggered by the 1999 Chi-Chi Earthquake. In: Ugai K, Yagi H, Wakai A (eds) Earthquake-induced landslides. Springer, Berlin, Heidelberg, 213–224. https://doi.org/10.1007/978-3-642-32238-9_22
- Marino P, Peres D, Cancelliere A, Greco R, Bogaard T (2020) Soil moisture information can improve shallow landslide forecasting using the hydrometeorological threshold approach. Landslides 17:2041–2054. <https://doi.org/10.1007/s10346-020-01420-8>
- McCauley MP, Sturman AA (1999) A study of orographic blocking and barrier wind development upstream of the Southern Alps, New Zealand. Meteorol Atmos Phys 70:121–131. <https://doi.org/10.1007/s007030050029>
- Medina S, Houze RA (2003) Air motions and precipitation growth in Alpine storms. Q J R Meteorol Soc 129:345–371. <https://doi.org/10.1256/qj.02.13>
- Mitchell A, Chung S-L, Oo T, Lin T-H, Hung C-H (2012) Zircon U-Pb ages in Myanmar: magmatic–metamorphic events and the closure of a neo-Tethys ocean? J Asian Earth Sci 56:1–23. <https://doi.org/10.1016/j.jseaes.2012.04.019>
- Montgomery DR, Dietrich WE (1994) A physically based model for the Topographic controls on shallow landsliding. Water Resour Res 30:1153–1171
- Mulder T, Alexander J (2001) The physical character of subaqueous sedimentary density flow and their deposits. Sedimentology 48:269–299. <https://doi.org/10.1046/j.1365-3091.2001.00360.x>
- O'Connor WP, Bromwich DH, Carrasco JF (1994) Cyclonically forced barrier winds along the Transantarctic Mountains near Ross Island. Mon Weather Rev 122:137–150
- Okura Y, Kitahara H, Kawanami A, Kurokawa U (2003) Topography and volume effects on travel distance of surface failure. Eng Geol 67:243–254. [https://doi.org/10.1016/S0013-7952\(02\)00183-7](https://doi.org/10.1016/S0013-7952(02)00183-7)
- Pailha M, Pouliquen O (2009) A two-phase flow description of the initiation of underwater granular avalanches. J Fluid Mech 633:115–135. <https://doi.org/10.1017/S0022112009007460>
- Parish TR (1982) Barrier winds along the Sierra Nevada Mountains. J Appl Meteorol 21:925–930
- Pierrehumbert RT, Wyman B (1985) Upstream effects of mesoscale mountains. J Atmos Sci 42:977–1033
- Rahardjo H, Lim T, Chang MF, Fredlund D (1995) Shear-strength characteristics of a residual soil. Can Geotech J 32:60–77. <https://doi.org/10.1139/t95-005>
- Rahardjo H, Li X, Toll D, Leong E (2010) The effect of antecedent rainfall on slope stability. Geotech Geol Eng 19:371–399. <https://doi.org/10.1023/A:1013129725263>
- Renard KG, Foster GR, Wessies GA, McCool DK, Yoder DC (1997) Predicting soil erosion by water: a guide to conservation planning with the revised universal soil loss equation (rusle). United States Department of Agriculture (USDA), 703:384. https://www.ars.usda.gov/arsuserfiles/64080530/rusle/ah_703.pdf
- Rigo M, Pinheiro R, Bressani L, Bica A, Silveira R (2011) The residual shear strength of tropical soils. Can Geotech J 43:431–447. <https://doi.org/10.1139/t06-015>
- Sassa K, Kukuoka H, Lee JH, Zhang DX (1991) Measurement of apparent friction angle during rapid loading by high speed high stress ring shear apparatus-interpretation of the relationship between landslide volume and the apparent friction during motion. 6th International Symposium on Landslides 1:545–552
- Searle MP, Noble SR, Cottle JM, Waters DJ, Mitchell AHG, Hlaing T, Horstwood MSA (2007) Tectonic evolution of the Mogok metamorphic belt, Burma (Myanmar) constrained by U-Th-Pb dating of metamorphic and magmatic rocks Tectonics 26. <https://doi.org/10.1029/2006tc002083>
- Sloan RA, Elliott JR, Searle MP, Morley CK (2017) Chapter 2-Active tectonics of Myanmar and the Andaman Sea. Geological Society, London, Memoirs, vol 1. <https://doi.org/10.1144/m48.2>
- Smith RB (1979) The influence of mountains on the atmosphere. Adv Geophys 21:87–233
- Smith RB (1989) Hydrostatic airflow over mountains. Adv Geophys 31:1–41
- Talebi A, Uijlenhoet R, Troch PA (2008) Application of a probabilistic model of rainfall-induced shallow landslides to complex hollows. Nat Hazard 8:733–744. <https://doi.org/10.5194/nhess-8-733-2008>
- Wischmeier WH, Smith DD (1978) Predicting rainfall erosion losses: a guide to conservation planning. United States Department of Agriculture (USDA), 537. <https://naldc.nal.usda.gov/download/CAT79706928/PDF>
- Zhan W, Fan X, Pei X, Li W (2017) Empirical prediction for travel distance of channelized rock avalanches in the Wenchuan earthquake area. Nat Hazard 17:833–844. <https://doi.org/10.5194/nhess-17-833-2017>

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1007/s10346-021-01758-7>.

Suman Panday · Jia-Jyun Dong (✉)

Graduate Institute of Applied Geology, National Central University,
Zhongli, Taiwan
Email: jjdong@geo.ncu.edu.tw

Jia-Jyun Dong

Earthquake-Disaster & Risk Evaluation and Management Center,
National Central University, Taoyuan 32001, Taiwan