A study of critical rainfall and landslide occurrence

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ABSTRACT

Landslide hazards have caused loss of human lives, failure of structures, damage to agricultural lands and the natural environment. Rainfall-induced landslides constitute a major proportion of landslides in different parts of the world. Efforts are make to understand the mechanism that triggers landslide due to rainfall. One often cited trigger factor of rainfall-induced landslides is critical rainfall. The critical rainfall can vary in duration from 1 hour to antecedent rainfall of several days. However, such critical rainfall is obtained from observation at a particular location and may not be used or extrapolated to other locations. This paper collates case studies of rainfall-induced landslides that occurred in different parts of the world. Information collated includes location, soil type, permeability, slope angle, slope height, average annual rainfall of that area and the critical rainfall responsible for the landslide. The relationships between critical rainfall and other variables are examined critically. The study found that only soil type, slope angle and critical rainfall were useful. The study shows that 1-hour and 1-day critical rainfall increases with slope angle. It appears that the critical rainfall has an exponential relationship with slope angle. For coarse-grained soils, the 1-hour critical rainfall exponential relationship with slope angle can be used as the trigger rainfall for slope failures. For fine-grained soils, the 1-day critical rainfall exponential relationship with slope angle can be used as the trigger rainfall for slope failures. However, the findings are based on limited case studies. These relationships should be further validated with more case studies.

Keywords: critical rainfall, landslides, rainfall threshold, slope failure.

1 INTRODUCTION

Rainfall-induced landslides pose a substantial risk to people and infrastructure. As a result of rainfall events and subsequent infiltration into the subsoil, the regime of pore-water pressures can be profoundly altered: decrease of suction in the unsaturated soil layers, increase in pore-water pressures in the saturated layers. The direct consequence of these effects is the reduction of resisting forces for the stability of a slope. For this reason, there has been numerous studies to understand the landslide mechanism. One often cited trigger factor of rainfall-induced landslides is critical rainfall. The critical rainfall can vary in duration from one hour to antecedent rainfall of several days. However, such critical rainfall is obtained from observations at a particular location and may not be used or extrapolated to other locations. This paper collates case studies of rainfall-induced landslides that occurred in different parts of the world. Information collated includes locality, type of soil, slope angle, slope height, average annual rainfall of that area and the critical rainfall responsible for the landslide. The relationships between critical rainfall and other variables are examine critically in this study.

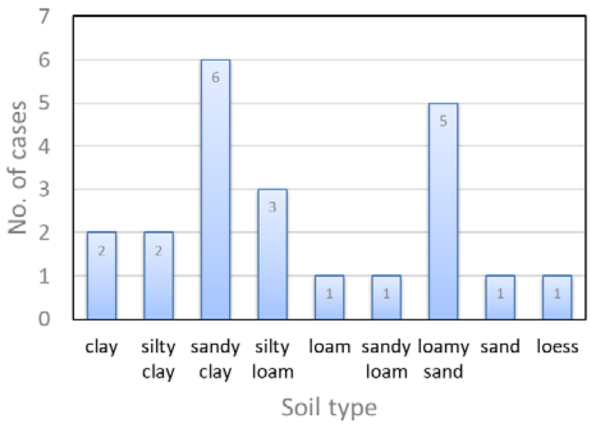


Fig. 1. Histogram depicting number of collated cases versus soil type.

2 DESCRIPTION OF SOME CASE STUDIES

A total of 22 cases of rainfall-induced landslides that occurred in different parts of the world were collated as shown in Table1. Information collated includes country, slope angle, critical rainfall responsible for the failure and the soil type.

Table 1. Collated cases of rainfall-induced landslides.

No	Countries	Slope angle (°)	Critical rainfall	Soil type	USCS
1	China	65	53 mm/h	Sandy clay	SC
2	Fiji	55	258 mm/d	Sandy clay	SC
3	Philippines	53	175 mm/d	Sandy clay	SC
4	India	50	48 mm/d	Sandy clay	SC
5	Slovenia	50	32 mm/h	Sandy clay	SC
6	India	40	32 mm/h	Sandy clay	SC
7	Czech Republic	21.2	11 mm/h	Loamy sand	SM
8	Japan	35 - 42	235 mm/d	Loamy sand	SM
9	Nigeria	42	270 mm/30 d	Loamy sand	SM
10	Slovenia	60	45 mm/h	Loamy sand	SM
11	Switzerland	28	20 mm/h	Loamy sand	SM
12	Brazil	45 - 65	100 mm/4 d	Sandy loam	SM
13	Portugal	75	20 mm/d	Sand	SP
14	China	26	80 mm/d	Loess	
15	Singapore	29	90 mm/d	Clay	CH
16	Slovenia	70	53.2 mm/h	Clay	CH
17	Philippines	40	100 mm/d	Silty clay	CH
18	Slovenia	46	6.1 mm/h	Silty clay	CH
19	Scotland	16	40 mm/d	Loam	CL
20	Bolivia	55	40 mm/h	Silty loam	ML
21	Japan	35 - 45	6 mm/h	Silty loam	ML
22	Japan	40 - 45	8 mm/h	Silty loam	ML

The soil type given is usually in terms of the classification used in agriculture. Hence, the soil type was also matched with the Unified Soil Classification System according to García-Gaines and Frankenstein (2015). Three typical rainfall-induced landslide cases are briefly explained below.

2.1 Fiji - Viti Levu Island (Ram et al. 2018)

While granular soils tend to drain quickly for intense rainfall of short duration, the typically clay dominated Fiji soils were particularly sensitive to prolonged rainfall. Shallow landslides in Fiji are often triggered during rainstorms. On Viti Levu Island, one such slope failure was caused by 258 mm of rainfall in one day after 30 days of antecedent rainfall totaling 482mm. This caused rapid increase in the pore-water pressure. Evidence of recurring slips on the slope as shown in Fig. 2 indicates that soil instability is caused by elevated pore-water pressure during high intensity rainfall events in the clay dominated soils.

Fig. 2. Evidence of recurring slips (from Ram et al. 2018)

2.2 Japan-Boso Peninsula (Matsuhi and Matsukura, 2007)

The study area is located in the south-west of the Boso Peninsula, Central Japan. The study area experienced episodic landslide events caused by heavy rainstorms.

Permeable sandstone hillslope has a greater critical rainfall and hence a longer recurrence interval than the impermeable mudstone hill slope. This implies a lower potential for land sliding in sandstone hillslope (leading to lower landslide activity). This case demonstrates the effect of geology on rainfall-induced landslides.

The critical mean intensity of a 10 hour rainfall is 9 mm/hour for mudstone slopes whereas a sandstone slope requires 15-20 mm/hour for the same duration. The rainstorms caused slides mainly in the mudstone slopes. In the sandstone slopes, the landslides only occurred on the steep lower parts of hillslopes adjacent to major valleys.

2.3 Nigeria, Iva Valley (Igwe et al. 2014)

Iva Valley is at the outskirt of Enugu town, the capital territory of Enugu State, Nigeria. The Iva Valley landslide volume is estimated at 7,875 m^3 and reached a distance of about 150 m. The elevation of the source area was 420 m. Slope height and inclination were 67 m and 42° respectively. The depth of slip surface was less than 2 m.

The average distribution of the soils associated with the landslide showed they contain 75% sand, 16% silt and 9% clay. Based on the soil textural triangle, the soil is loamy sand. The area receives more than 2,000 mm annual rainfall. These slopes frequently fail during short, intense rainfalls at the beginning of rainy season. The shallow translational slides are triggered by water infiltration in slopes with high topographic gradient where unconsolidated sand overlies less permeable claystone. Most landslides occur at the beginning of the rain because infiltrating water reduces the suction in the slopes.

3 INFLUENCING FACTORS

Table 1 only shows the most important factors that influenced the critical rainfall: slope angle and soil type. These factors are further analysed in detail below.

3.1 Slope angle

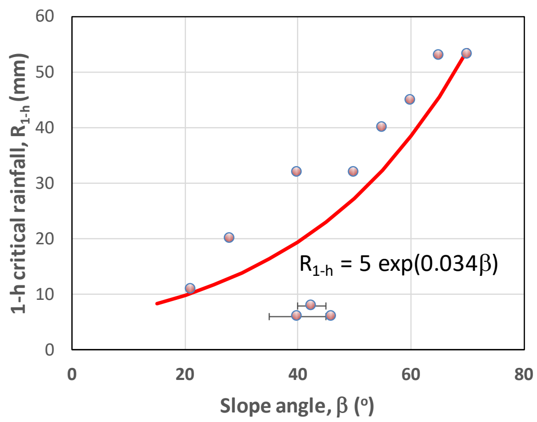
The critical rainfall for different locations is different in terms of duration and amount. Most of the cases in Table 1 have critical rainfall durations of one hour (1-h) and one day (1-d). Hence, 1-h and 1-d critical rainfalls versus slope angle are plotted in Figs. 3a and 3b, respectively. Some of the data are shown with horizontal error bars for cases where failed slopes have a range of slope angles. Figure 3 shows that the critical rainfall increases with slope angle and it appears that there is an exponential relationship between the critical rainfall and slope angle β as indicated in the plots. The exponential relationship shown by the curve indicates that critical rainfall above the curve will be unsafe for the slope. However, there are some data that fall below the curve indicating that the exponential relationship may be too simplistic and did not consider other influencing factors.

3.2 Soil type

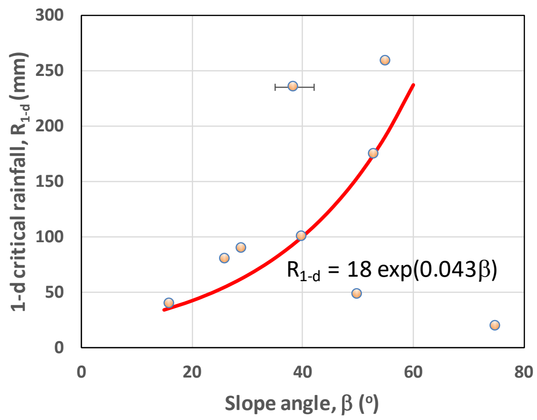
From Table 1, the data can be refined further by separating them into the different soil types. The soil types have been mapped into the USCS classification which allows the separation of soil types into coarse-grained (SC, SM, SP) and fine-grained soils (CH, CL, ML). The 1-h and 1-d criticals rainfall versus slope angle for coarse-grained are plotted in Figs. 4a and b, respectively. The 1-h and 1-d critical rainfalls versus slope angle for fine-grained soils are plotted in Figs. 5a and b, respectively.

Figure 4a shows that exponential relationship of the 1-h critical rainfall with slope angle is able to describe the data for coarse-grained soils but not the 1-d critical rainfall (Fig. 4b). In other words, the 1-h critical rainfall can be used as the trigger factor for stability of coarse-gained soil slopes under rainfall.

Figure 5b shows that exponential relationship of the 1-d critical rainfall with slope angle is able to describe the data for fine-grained soils but not the 1-h critical rainfall (Fig. 5a). In other words, the 1-d critical rainfall can be used as a trigger factor for the stability of fine-gained soil slopes under rainfall.



(a) 1-h critical rainfall



(b) 1-d critical rainfall

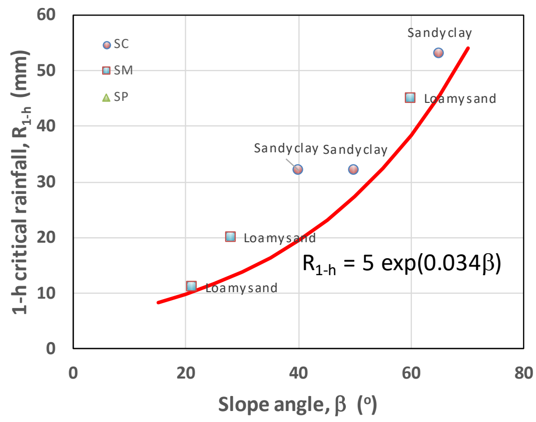
Fig. 3. Relationship between critical rainfall and slope angle.

In summary, it appears that the following equations can be used to define the critical rainfalls for coarse-grained soils ($R_{1\text{-}h}$) and fine-grained soils ($R_{1\text{-}d}$), respectively:

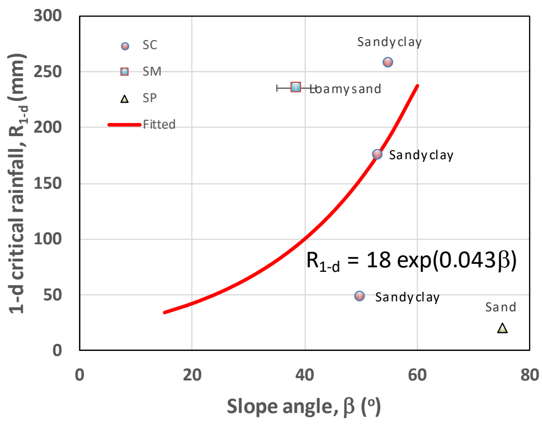
$$R_{1\text{-h}} = 5\exp(0.034\beta) \quad \text{mm} \tag{1}$$

$$R_{1\text{-d}} = 18\exp(0.043\beta) \quad \text{mm} \tag{2}$$

where β is slope angle in degrees.



(a) 1-h critical rainfall

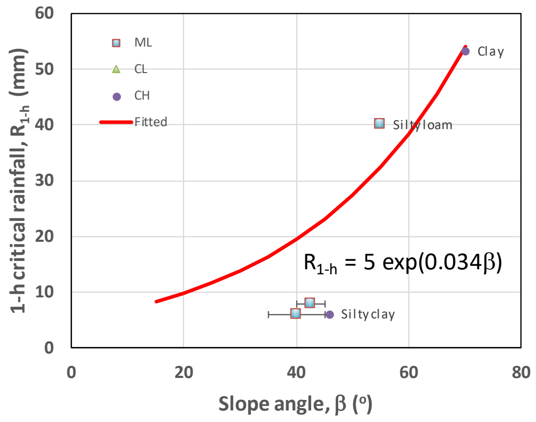


(b) 1-d critical rainfall

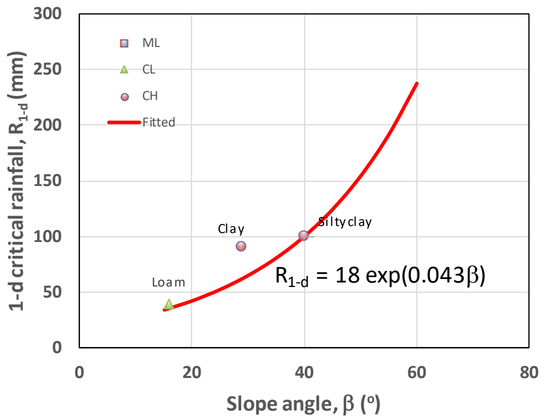
Fig. 4. Relationship between critical rainfall and slope angle for coarse-grained soils.

4 CONCLUSION

Rain is a major cause of landslides around the world. Critical rainfall has been used as the trigger factor for landslides. However, the critical rainfall is location-based and is difficult to extrapolate to other locations. This study found that the 1-h and 1-d critical rainfalls have an exponential relationship with slope angle. The 1-h critical rainfall may be used as the trigger factor for coarse-grained soil slopes and the 1-d critical rainfall may be used as the trigger factor for fine-grained soil slopes. However, only 22 cases studies were examined and the range of slope angles examined is between 20º and 60º. Further studies are needed to provide validation of the critical rainfalls found in this study.



(a) 1-h critical rainfall



(b) 1-d critical rainfall

Fig. 5. Relationship between critical rainfalls and slope angle for fine-grained soils.

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