

LANDSLIDES AND PRECIPITATION CHARACTERISTICS DURING THE TYPHOON LIONROCK IN IWATE PREFECTURE, JAPAN

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ABSTRACT: In August 2016, the typhoon Lionrock made landfall on Japan's northeastern coast and caused floods and landslides. Lionrock brought heavy precipitation to Japan, which Shimotokusari station (33201) recorded 24-hour rainfall amount over 200 mm and the peak rainfall intensity was approximately 65 mm/hr. The total cost of damage within the Iwate prefecture is over 700 million dollars, moreover, 20 lives were lost and 4 people missing. Therefore, the objective of this paper is to present the results of the post-disaster investigation, including, the back-analysis of landslides and precipitation due to the typhoon Lionrock. The rainfall and landslides relationship is significantly important for rainfall intensity-duration threshold. For this typhoon, the empirical rainfall intensity-duration threshold has been derived as $I = 20.24D^{-0.33}$. The slope failure could be broadly categorized into the debris flow, surficial erosion, and soil slide, moreover, occurred on slopes ranging from 19 to 58 degrees.

Keywords: Typhoon, Tropical Cyclone, Landslides, Rainfall, Intensity-duration threshold, Critical rainfall

1. INTRODUCTION

Landslides are one of the serious natural hazards and may lead to the occurrence of the large volumes of rock, wood or the other debris. The mechanism of intense rainfall due to the typhoon (tropical cyclone) induced landslides is well understood. Landslides can be caused by increased pore water pressure or groundwater table during intense storms [1]. Moreover, there are many contributing factors such as geological, geomorphological, or land use [2].

Numerous studies proposed the model that depicts the criteria and relationship between rainfall and landslides occurrence for early warning development or understanding behavior of rainfall-induced landslides such as empirical rainfall threshold, analytical rainfall infiltration-infinite slope model, and numerical models. The empirical rainfall threshold uses the correlation of critical daily rainfall and three-day antecedent rainfall for an early warning system, in addition, finding the correlation of rainfall intensity and duration of rainfall (I-D critical threshold) [3-6]. The analytical rainfall infiltration-infinite slope model has applied the infiltration model for finding rainwater infiltration volume and also applied the infinite slope model for a factor of safety calculation. The numerical model is a widely used analysis the rainfall seepage through

the hillslope.

In 2016, Iwate prefecture is located in the Tohoku region of Japan, experienced extreme events of the Typhoon. Typhoon Lionrock made landfall especially near the Ofunato city where is a city located in Iwate prefecture on 30 August 2016. This is a cause of flood, landslides, debris flow and the other in Iwate prefecture and vicinity. As a consequence, there are many serious infrastructure damages and loss of lives and property. This study aims to present a post-disaster damage investigation and back analysis of landslides and rainfall characteristic due to the Typhoon Lionrock in Iwate prefecture, Japan.

2. TYPHOON LIONROCK

Typhoon Lionrock was first observed on 15 August 2016 where it was located about 580 km to the west of Wake Island in the western Pacific Ocean. It developed into a tropical depression and was classified by the Japan meteorological agency (JMA) on 16 August 2017 that the wind speed is about 45 km/h. During August 20-21, the wind speed is increased to 65 km/h and became a tropical storm. The Lionrock developed into a severe tropical storm on August 23 and a tropical storm on August 24. The highest wind speed is 166 km/h on August 28. Table 1 shows the information of the Typhoon Lionrock. Fig. 1

shows the direction of the Typhoon Lionrock. JMA reported the Typhoon Lionrock made landfall near the city of Ofunato which this unusual typhoon to directly land in the Tohoku because of typhoons usually approach Japan from the south and southwest before moving northward across the archipelago.

Table 1 Information of the Typhoon Lionrock

Date (UTC)	Lat	Long	Winds (km/h)	Category
08/21 (12:00)	29.2	133.3	65	Tropical Storm
08/22 (12:00)	28.5	134.1	74	Tropical Storm
08/23 (12:00)	26.6	134	111	Severe Tropical Storm
08/24 (12:00)	24.4	131.8	148	Typhoon
08/25 (12:00)	23.5	130.8	157	Typhoon
08/26 (12:00)	23.2	132.1	148	Typhoon
08/27 (12:00)	24.5	134.6	157	Typhoon
08/28 (12:00)	28.5	138.8	166	Typhoon
08/29 (12:00)	32.3	143.4	138	Typhoon
08/30 (12:00)	41.3	140	111	Severe Tropical storm

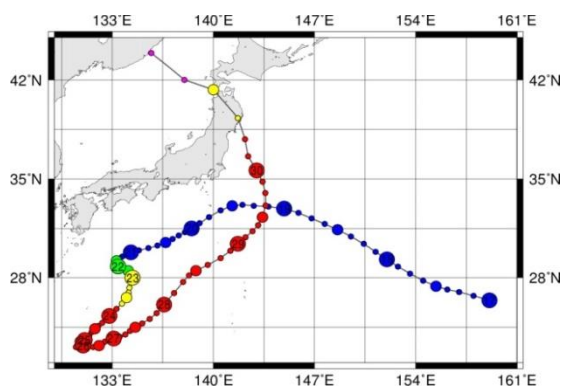


Fig.1 Direction of the Typhoon Lionrock [7]

3. CHARACTERISTICS OF RAINFALL AND LANDSLIDES DURING THE TYPHOON LIONROCK

3.1 Rainfall pattern and intensity

There were 50 rain gauges in Iwate prefecture which were used to measure the amount of rainwater in this the landslides and debris flow

event. Rainfall information for an event that triggered the landslides was collected from Automated Meteorological Data Acquisition System (AMeDAS) by the Japan Meteorological Agency and the rain gauges are operated by Iwate prefecture. The heavy rainfall started on August 30 and the 24 – hour rainfall was reached 220 mm that was observed at the Shimotokusari station in Kuji city, Iwate. Fig. 2 illustrates the intensity and distribution of rainfall on August 30 in Iwate prefecture. The Typhoon Lionrock produced the heavy rain covered Iwaizumi town, Tanohata city, Miyako city which the amounts of 24-hour rainfall in these areas were between 155 to 220 mm. This was a cause of the overflow of the riverbanks of Omoto River and landslides and debris flows. Fig. 3 shows the hourly rainfall of the five rain gauges in Iwaizumi town on August 30. Considering landslide triggering factors, the intensity and duration of rainfall are the main factors to consider.

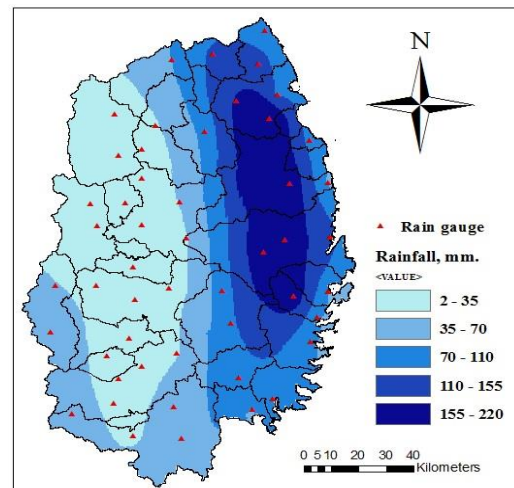


Fig.2 Distribution of rainfall on August 30, 2016, in Iwate prefecture

Therefore, intensity-duration thresholds (I-D critical thresholds), as the empirical threshold, using the rainfall intensity and duration data obtained from this landslide event. Intensity-duration thresholds are the most common type of landslide thresholds and have a general form as the following:

$$I = c + aD^{-\beta} \quad (1)$$

where I is the rainfall intensity (mm), D is rainfall duration (h), and c, a, β are the parameters obtained from the curve. Numerous researchers developed several I-D critical thresholds serves the landslide warning as shown in Table 2. Fig. 4 shows the comparison of I-D critical thresholds obtained from this event and the literature reviews. Fig 4 shows the intensity and duration of the gauge nearest the landslide areas.

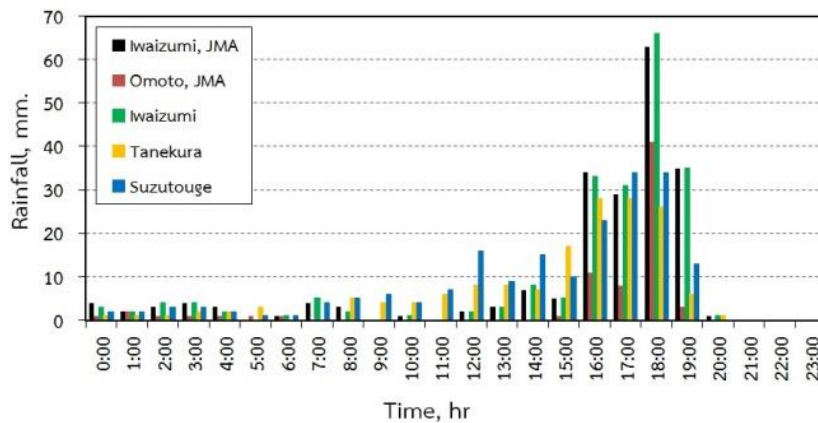


Fig.3 Hourly rainfall from five rain gauges in Iwaizumi town on August 30, 2016

Table 2 Intensity-duration threshold for landslides

No	Area	Equation	Range, h	Landslides type	Reference
1	World	$I = 14.82D^{-0.39}$	$0.167 < D < 500$	Shallow landslides, Debris flow	6
2	World	$I = 30.53D^{-0.57}$	$0.5 < D < 12$	Debris flow	6
3	World	$I = 10D^{-0.77}$	$0.1 < D < 1000$	Soil slip	6
4	World	$I = 0.48 + 7.2D^{-1.00}$	$0.1 < D < 1000$	Shallow landslides	6
5	Japan	$I = 39.71D^{-0.62}$	$0.5 < D < 12$	Debris flow	6
6	Japan	$I = 2.18D^{-0.26}$	$3 < D < 537$	Shallow landslides	4

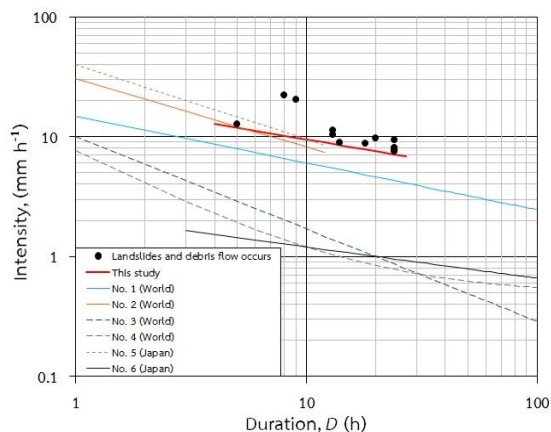


Fig.4 I-D critical threshold determined by this study and comparison with other I-D critical thresholds

According to the rainfall intensity and duration, the I-D critical threshold for this event can be presented in Eq. (1). This threshold is defined for the rainstorm durations range 5 to 24 hours. The type of failure of the landslide occurrence is to combine shallow landslides with the debris flows.

$$I = 20.24D^{-0.33} \quad (2)$$

As shown in table 2, the previous research studies proposed several I-D critical thresholds for world scale and country scale. Comparison the previous thresholds with the data obtained from this landslide event, it was found that most of all previous thresholds can serve this event, but only the threshold No. 5 is slightly higher than the one point of intensity and duration this event. Threshold No. 5 was developed to serve the debris flow failure type, but this event was to combine shallow landslides with debris flow that were observed and surveyed in the field by a team. Considering the threshold No. 6 for Japan, the I-D critical threshold is rather a conservative criterion.

In addition to the above mentioned, the relation between the 24-hour rainfall and cumulative soil moisture are also significantly useful for the establishment of the critical rainfall envelope. The 24-hour rainfall criterion can reflect a function of regolith thickness and porosity of soil mass and the antecedent precipitation index, as cumulative soil moisture, can refer a function of interception and evapotranspiration [8]. Fig. 5 indicates the plots between the 24-hour rainfall and antecedent precipitation index.

Fig. 5 presents the critical zone that is rainfall triggered landslides. The red dots are the 24-hour rainfall and the API that collected from the rain gauges surround the landslide areas. The blue dots are the 24-hour rainfall and the API in the non-

landslides occurrence time. The minimum critical 24-hour rainfall is approximately 130 mm and the minimum API is 220 mm.

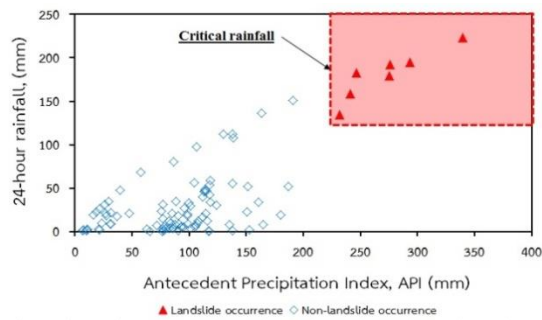


Fig.5 Critical rainfall envelope obtained from this landslides event

3.2 Landslides characteristics

The catastrophic landslide in Iwaizumi town and Tanohata village are located in Shimohei District, Iwate prefecture, Japan, were serious and large landslide induced Typhoon Lionrock. Geological conditions in these areas were formed an accretionary complex (Mesozoic and Palaeozoic) and some plutonic rocks [10]. Fig. 6 shows the bedrock layer of the landslide scar.



Fig.6 Bedrock layer of the landslide scar

The landslide scars data were obtained from Geospatial Information Authority of Japan and Google Earth website. Fig. 7 shows the landslide distribution and slope angle. The failures occurred on slopes ranging from 19 to 58 degrees. Field investigation revealed that the majority of the slope failures were of complex forms that could be broadly categorized into the debris flow, surficial erosion, and soil slide. Fig. 8 shows the debris

flow occurrence. Fig. 9 shows the aerial photos showing landslide scars in Iwate. Failure scars usually stretched from the stream banks to uphill at various distances and the depth of failure scars is about 0.5-1.5 meters. Consequences of failure brought the large amounts of debris such as rock, wood, or sediment, into the river or villages and got stuck on the bridge or a house. Fig 10 shows the woody debris trapped the rail bridge.

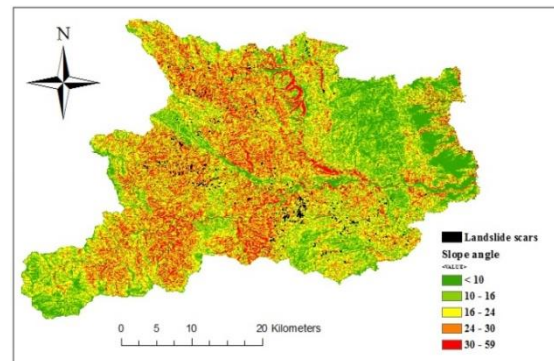


Fig.7 Landslides distribution and slope angle



Fig.8 Debris flow occurrence in Iwate prefecture on 30 August 2016



Fig.9 Aerial photos showing landslide scars in Iwate. [11]

4. REGIONAL RAINFALL THRESHOLD

As already discussed the characteristic of precipitation was the intensity-duration rainfall and

the antecedent rainfall condition as an empirical relationship including the characteristic of the landslide. Hence, the purpose of this section is to discuss the critical rainfall threshold at the regional scale which considers the physical properties such as soil permeability, soil strength, and failure mechanism, using the rainfall infiltration and infinite slope model. Conceptual of this critical rainfall threshold is to find the amount of rain that makes the factor of safety less than 1. The critical rainfall threshold is based on two main assumptions. The first assumption is the failure type of landslides is the infinite slope and the saturation of hillslope would destabilize a hillslope. The second assumption is the soil moisture initial condition prior to rainstorm is equal to the volumetric water content at field capacity (suction at 33 kPa).

The wetting front of the sloping surface is defined as:

$$z_w = \frac{I}{(\theta_s - \theta_f) \cos \beta} \quad (3)$$

Therefore,

$$I = z_w (\theta_s - \theta_f) \cos \beta \quad (4)$$

Therefore, the critical rainfall threshold is defined as:

$$I_{cr} = z_{cr} (\theta_s - \theta_f) \cos \beta \quad (5)$$

where z_w is the wetting front, I is the amount of rain infiltration, θ_s is the volumetric water content at saturation, θ_f is the volumetric water content at field capacity (33 kPa), I_{cr} is the critical rainfall threshold, z_{cr} is the critical depth, and β is the slope angle. The volumetric water content at field capacity and saturation can be estimated using a soil texture. [12] The soil texture is estimated by the soil classification and grain size distribution curve. The critical depth uses the infinite slope stability model. The factor of safety for an infinite slope model is based on the Mohr-Coulomb failure criterion is defined as:

$$Fs = \frac{c'}{\gamma_t z \sin \beta \cos \beta} + \frac{\tan \phi'}{\tan \beta} \quad (6)$$

where Fs is the safety factor, c' is the effective cohesion of soil, ϕ' is the effective friction angle,

γ_t is the total soil unit weight, and z is the depth.

Hence, from (5) and (6), the critical rainfall threshold can create a new form as follows:

$$I_{cr} = \left[\frac{c'}{[\gamma_t \sin \beta \cos \beta] \times \left[1 - \frac{\tan \phi'}{\tan \beta} \right]} \right] \times [(\theta_s - \theta_f) \cos \beta] \quad (7)$$

Jotisankasa [13] proposed the range of critical depth that is 2-5 meters for a large debris flow and soil slip and 0.7-1.2 meters for small soil slip and local failure. Generally, the critical depth is controlled by the natural soil strata and the other geological condition in each area. Following laboratory results, the type of soil was classified as a loamy sand (LSa), so, the volumetric water content at field capacity is 14% and the volumetric water content at saturation is 45%. Fig. 11 shows the regional critical rainfall threshold for Iwaizumi town and Tanohata village. Fig. 12 shows the rainfall distribution in Iwaizumi town and Tanohata village.

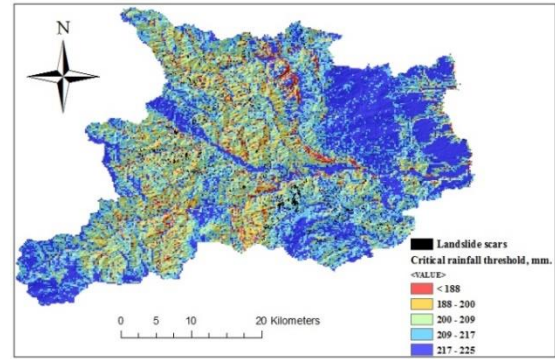


Fig.11 Regional critical rainfall threshold for Iwaizumi town and Tanohata village

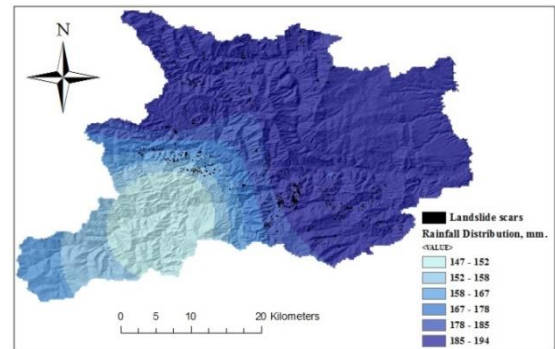


Fig.12 Rainfall distribution in Iwaizumi town and Tanohata village

According to the critical rainfall threshold map, the landslides occurred in the red and yellow zone that the critical rainfall is ranging 124 – 192 mm,

hence, compared with the rainfall distribution in that zone, it was found that the amount of rainfall is higher than the critical rainfall and the excess rainfall is about 5 to 25 mm.

5. CONCLUSION

Typhoon-triggered landslide is a serious natural disaster. Understanding the characteristics of rainfall and landslides are a very important method for developing the critical criterion of the landslide early warning. This study could be concluded that:

The past I-D threshold can be applied in this case, except the threshold No. 5 that the rainfall is considerably higher than the threshold. Moreover, we create the critical rainfall envelope using the 24-hour rainfall and antecedent precipitation index.

The majority of the failures were could be broadly categorized into the debris flow, surficial erosion, and soil slide, in addition, occurred on slopes ranging from 19 to 58 degrees. One of the consequences of the landslide is debris such as rocks, or woody that is the cause of property damage.

The region critical rainfall applies the infiltration process and the infinite slope analysis model that can apply in this case.

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