STUDY ON AN EVALUATION METHOD OF INITIATION PROBABILITY OF DEBRIS FLOWS DURING HEAVY RAINFALL

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In an extreme climate event named “the Heavy Rain Event of July 2018,” prolonged and widespread heavy rainfall in western Japan caused several debris flows, which led the sediment to flow into rivers, causing further damage from sediment-flood inundation. For the existing landslide alert information, it is important to establish prediction methods that account for the amount of rainfall on individual mountain slopes and the topographic and geological information. The estimation of the probability of debris flow initiation and quantitative risk assessment have been challenging issues. In order to solve this problem, in this paper, the rainfall data of XRAIN with high spatial resolution and the features of the slope failure sites were examined during heavy rainfall events. This paper also discussed the reliability of rainfall index $R'$ to the heavy rainfall with strong long-term precipitation in July 2018, which is different from previous disasters due to the heavy rainfall with strong short-term precipitation, such as those in August 2014 and June 1999.

Key Words: debris flow, rainfall index, throughfall

1. INTRODUCTION

During June 28 and July 8, 2018, heavy rainfall occurred due to the influence of Typhoon 201807 (Prapiroon) and the seasonal rain front, mainly in western Japan. This event, named “the Heavy Rain Event of July 2018,” caused several debris flows, resulting in extensive damage from sediment-related disasters. According to an announcement made by the Ministry of Land, Infrastructure, Transport and Tourism on September 25, 2018, the event caused 769 debris flows, 55 landslides, and 1,688 slope failures. In Hiroshima Prefecture, on August 13, 2018, at 13:00, 624 sediment-related disasters were confirmed, mainly in the cities of Hiroshima, Kure, and Higashihiroshima⁵. In addition, considerable sediment transported by the debris flows accumulated in rivers, causing sediment-flood disaster. To reduce the damage caused by sediment-related disasters, it is important to establish prediction methods that account for the amount of rainfall on individual mountain slopes and the topographic and geological information.

This study aims to explain the characteristics of the Heavy Rain Event of July 2018 and investigate the method of assessing the probability of debris flow initiation through the rain index $R'$², ³, ⁴, using topographic and rainfall distribution data.
2. METHOD FOR ASSESSING THE RISK OF DEBRIS FLOW INITIATION USING RAINFALL INDEX R′

In this section, we explain the existing landslide alert information\(^5\), \(^6\). First, a graph is created by taking the value calculated from a three-serial tank model as the long-term rainfall index and hourly rainfall as the short-term rainfall index. Next, a baseline (called the “critical line”) is established for the risk of an earth-and-sand disaster based on the statistical data obtained from past earth-and-sand disasters, where the spot value and predicted value two hours ahead therefrom are shown. When the progress of the rainfall (called the “snake line”) exceeds these values, it is judged that there is an elevated risk of a debris flow disaster. At present\(^6\), a high-resolution distribution map of landslide or debris flow risk is published as a 1 km grid, with the critical line set according to the alert level\(^7\), \(^8\). However, as two rainfall indices are used, it is difficult to examine their relationship to the probability of debris flow initiation qualitatively.

Therefore, this study focuses on the rainfall index \(R'\)\(^2\), \(^3\), \(^4\), that assesses the risk of a sediment-related disaster caused by heavy rainfall. This index represents a comprehensive assessment of the risk of a debris flow occurrence based on the long- and short-term effective rainfall. It is calculated as shown in equations (1) and (2).

\[
R' = R_{fw0} - R_{fw} \quad (1)
\]

\[
R_{fw} = \sqrt{(R_1 - R_w)^2 + a^2(r_1 - r_w)^2} \quad (2)
\]

where \(R_w\) indicates the 72-h half-life effective rainfall (mm), \(r_w\) indicates the 1.5-h half-life effective rainfall (mm), \(R_1\) is the reference point on the abscissa \((R_1 = 600\ mm)\), \(r_1\) is the reference point on the ordinate \((r_1 = 200\ mm)\), \(a\) is a weighting factor \((a = 3)\), and \(R_{fw0}\) is the value of \(R_f\) when \(R_w = 0\) and \(r_w = 0\) \((R_{fw0} = 848.5\ mm)\). The two effective rainfall amounts \(R_w\) and \(r_w\) in equation (2) are calculated as shown in equation (3).

\[
D(t) = R(t)\Delta t + \alpha D(t - \Delta t) \quad (3)
\]

where \(D(t)\) is the effective rainfall at time \(t\), \(R(t)\) is the rainfall at time \(t\), and \(\alpha\) is a run-off factor expressed as \(\alpha = 0.5\Delta t/T\) using a half-life of \(T\). In this paper, equation (3) is calculated at 10-min intervals with \(\Delta t = 1\) hour and \(R(t)\) set to hourly rainfall depth. Appropriate weighting factors and other parameter settings are considered to vary depending on the topography and geology. In this case, we set the parameters proposed in the previous research based on the actual data from the “6.29 Disaster” (the torrential rain disaster of June 29, 1999, caused by a seasonal rain front)\(^2\), \(^3\), \(^4\).

\(R'\) combines a long-term rainfall index and a short-term rainfall index into a single index, which makes it easier to describe how the risk of a debris flow initiation changes over time on a map. Besides making it easier to visualize the spatial distribution of the risk, this index also makes it easier to investigate the relationships with other quantitative indices, such as the probability of debris flow initiation. Therefore, \(R'\) can be a simple and functional index that combines two different effective rainfall quantities, captures the characteristics of the critical line, and is scaled such that the slope of the critical line corresponds intuitively to the amount of rainfall. However, it is necessary to verify whether the index is suitable for evaluating the landslide or debris flow initiation risk for different rainfall characteristics. In the 6.29 Disaster, the debris flows were initiated at about \(R' = 125\ mm\), the hillside landslides (which can lead to debris flow) were initiated at about \(R' = 175\ mm\), and once the index rose above about \(R' = 250\ mm\), fluidization and debris flow began to occur\(^2\). They also succeeded to achieve a very good match between the prediction and the result of the Hiroshima heavy rainfall disaster of August 2014. Here, the 10-min rainfall data were used to estimate the risk of a sediment-related disaster, where the index reached \(R' = 175\ mm\) or greater in the affected areas prior to about 3:00 on August 20, when several debris flows began\(^4\). Table 1 compares the maximum values and times of occurrence of the 72-h half-life effective rainfall, the 1.5-h

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Table 1 Maximum values of effective rainfall and \(R'\) in previous disasters.

|                          | Effective rainfall (mm) | \(R'\) (mm) |
|--------------------------|-------------------------|-------------|
| Heavy Rain Event of      | 226.2mm (18:00)         | 379.1mm (17:10) |
| June 1999 Kure (weather station) |
| Heavy Rain Event of      | 280.5mm (4:30)          | 522.4mm (4:10) |
| August 2014 Shirakawa    | 190.1mm (4:10)          |             |
| observation point        |
| Heavy Rain Event of      | 351.8mm (6:20)          | 419.5mm (5:00) |
| July 2018 Kure (weather station) |

Fig. 1 Locations of ground observation points.
half-life effective rainfall, and $R'$ as measured by ground rain gauges in areas where sediment disasters occurred in the heavy rain events of June 1999, August 2014, and July 2018. The table shows that the Heavy Rain Event of July 2018 was comparable to the previous heavy rain events in terms of the magnitude of $R'$. However, an analysis of the effective rainfall values that constitute $R'$ indicates that the short-term effective rainfall in the Heavy Rain Event of July 2018 is smaller than those in the previous disasters. On the other hand, the long-term effective rainfall is larger, which increases the risk of landslides and debris flows initiation.

3. TEMPORAL AND SPATIAL VARIATIONS IN RAINFALL INDEX $R'$ DURING THE HEAVY RAIN EVENT OF JULY 2018

(1) $R'$ values using ground rainfall and XRAIN data

When using $R'$ to compare the rainfall characteristics on a per-mountain slope basis, XRAIN rainfall data are superior to ground-based rainfall data in terms of spatial resolution. However, the two types of rainfall data are known to exhibit variability\(^9\).

Prior to considering the distribution of $R'$, we first calculate $R'$ using XRAIN and ground rainfall, and then compare the changes over time in $R'$ in heavy rainfall to the amount of rainfall at that time. Figure 1 shows the locations of the ground observation points. Figure 2 compares $R'$, cumulative rainfall, and rainfall intensity in the Heavy Rain Event of August 2014, where the rain fell over a very short period in a small area. Data were collected at the Miirihigashi observation point and Miiri observation point, where the authors\(^10\) were conducting on-site observations. The sites are close to Takamatsuyama, where debris flows occurred during the Heavy Rain Event of August 2014. Figure 3 shows the same comparison for the Heavy Rain Event of July 2018. In this case, the locations were Agekurayama observation point, which is close to Mikumarikyou (Fuchu, Aki District, Hiroshima Prefecture), and Gohara observation point, which is close to Norogawa Dam (Yasura Town, Kure City, Hiroshima Prefecture). Both are locations where debris flows caused the sediment to flow into rivers, causing further damage from flooding. The XRAIN observation location closest to the ground rainfall gauge was used for comparison.

In the Heavy Rain Event of August 2014, there was a difference of more than 30 mm between the XRAIN and ground rainfall measurements, causing a misalignment in the peak $R'$ values.

Fig. 2 Rainfall index $R'$ (top) and cumulative rainfall (middle) over time and rainfall intensity (bottom) in terms of ground rainfall vs. XRAIN during the Heavy Rain Event of August 2014.
This may be because the XRAIN data were affected by rainfall attenuation in response to heavy rainfall intensity\(^9\). Furthermore, considering the peculiar characteristics of heavy rain falling in a very small area, it is possible that the slight difference in the distance between the ground rainfall station and the XRAIN rainfall station had a large effect on the observations.

In the Heavy Rain Event of July 2018, on the other hand, the instantaneous rainfall intensity was not as great and the rain fell for a longer period over a larger area. For this reason, although there is some variation in the instantaneous ground rainfall and XRAIN rainfall data, there is little difference in the cumulative rainfall amounts. Thus, the changes over time and maximum values of \(R'\) align quite well, which suggests that XRAIN rainfall distribution is useful in investigating debris flow initiation.

(2) Changes in the spatial distribution of \(R'\) over time and distribution of the maximum value of \(R'\)

Figure 4 shows the distribution of \(R'\) during the Heavy Rain Event of July 2018 every hour from 18:00 to 21:00 on July 6 and from 3:00 to 6:00 on July 7. Note that the \(R'\) values are calculated every 10 min, as explained above. From 18:00 to 20:00 on July 6, a clear pattern can be observed, where the high \(R'\) area moves from the southwest toward the vicinity of Mikumarikyou. At 21:00, that area begins to extend in the direction of the Norogawa dam (southeast direction). At 3:00 on July 7, a high-risk region of debris flow initiation appears in the southwest of Hiroshima Prefecture. Later, between 5:00 and 6:00, the distribution moves near Norogawa Dam.

Figure 5 shows the distribution of the maximum \(R'\) values in a 250 m\(^2\) grid during the Heavy Rain Event of July 2018. This figure shows that the high risk of debris flow initiation appears in the southwest of Hiroshima Prefecture. Several debris flows occur in Mikumarikyou, where the maximum value is about \(R' = 400\) mm, and in the vicinity of Norogawa Dam, where the maximum value is about \(R' = 450\) mm. In Takamatsuyama, where debris flows occurred during the Heavy Rain Event of August 2014\(^10\), no debris flow occurs in this most recent heavy rainfall event. As Fig. 5 shows, Takamatsuyama is located in an area where the maximum value reaches about \(R' = 300\) mm, on the outer edge of the area where the \(R'\) index predicts a high risk of debris flow initiation. There are several debris flows in areas with the highest \(R'\) values, which suggests that, for this most recent heavy rain event too, \(R'\) is an effective index of debris flow initiation. This will be discussed in detail in the next section. According to previous studies,\(^2\),\(^3\),\(^4\) the risk of debris flow initiation is elevated,
Fig. 4 Distribution of $R'$ (1-h increments).
starting at the level $R' = 250$ mm. The results of this most recent heavy rain event demonstrate that future data collection will be important for setting the lower limit for debris flow initiation.

4. LOCATIONS OF SOURCE HEADS AND PROBABILITY OF DEBRIS FLOW INITIATION

(1) Slope failure points during the Heavy Rain Event of July 2018 and channel network

This section describes a method for assessing the risk of debris flow initiation. Figure 6 shows the channel network of hill slope topography and locations of debris flow initiation superimposed on the maps of Mikumarikyou (Fuchu, Aki District, Hiroshima Prefecture) and the vicinity of Norogawa Dam (Yasuura Town, Kure City, Hiroshima Prefecture). The figure is prepared using the ArcGIS hydrological analysis tool based on pre-disaster topographic data (a 5-m grid, digital elevation model).

Figure 6 shows that “the source heads of debris flow”, which are defined as potential debris flow initiation points including the upstream ends or heads of each debris flow mark, slope failure and landslide, are located on the channel network created from the pre-disaster digital elevation data. Based on this result, we assessed the probability risk of debris flow initiation in the heavy rain on the channel network using the rainfall index $R'$. Specifically, we identified a drainage basin for each hillslope, superimposed the debris flow source heads and channel network over each basin, and then analyzed and calculated the probability of debris flow initiation. Next, we compared the maximum $R'$ values at the source heads of each debris flow. The method of calculating the probability of debris flow initiation is described later.

(2) Characteristics of debris flow source heads

To calculate the probability of debris flow initiation, it is necessary to determine the drainage basins area of the debris flow source head to be assumed. Figure 7 shows a histogram of the basins area for the source head where debris flows occurred in the heavy rain event. We used the ArcGIS hydrological analysis tool to create the channel network and the 100 m² grid elevation data to calculate the basin areas at each point from the accumulated flow rate at each cell in the grid. For the Heavy Rain Event of July 2018, 38 basins were identified, with a mode area of 1,100 m² and a median area of 1,400 m². Figure 7 also includes data from the Heavy Rain Event of June 1999. For the Heavy Rain Event of June 1999, 23 basins were identified, with a mode area of 6,000 m² and a median...
area of 6,000 m². For each of the two events, more than 90% of the source head on the channel network had a basin area of 10,000 m² or less. For the source head with a basin area of 40,000 m² or more, the correct source head might not have been captured by aerial photointerpretation, due to the presence of trees. Note that in the Heavy Rain Event of July 2018, the basins where the slope failures occurred tended to have smaller areas than in the Heavy Rain Event of June 1999.

Figure 8 shows a histogram of slope gradients on the source heads, where debris flows occurred. These are the same 38 locations shown in the histogram of the source head basin areas. The mode is 32.5° and the median is 32.1°. The larger the basin area, the smaller the slope gradient tends to be (Fig. 9). This is illustrated in Fig. 10, which compares the maximum $R'$ values and basin areas for source heads of different slope gradients. Note that the basin areas on the vertical axis are shown in log scale. These figures reveal no correlation between the basin areas or slope gradients and the maximum $R'$ values of the source heads of different slope gradients. It is necessary to further study this point in the future, but at this stage, we proceed under the assumption that the risk of debris flow initiation is independent of the basin area and slope gradient.

(3) Defining the probability of debris flow initiation

This section explains our method of calculating the probability of debris flow initiation using the Mikumarikyou area as an example. A 3D aerial photograph of Mikumarikyou is shown in Fig. 11, where the red dots indicate the locations of the source heads of slope failures that developed into debris flows and the yellow dots indicate the locations of the source heads of slope failures that resulted in hillside landslides but did not develop into debris flows. Using this map for identifying the slope failures and the channel network, we calculated the probability of debris flow initiation in a given basin by dividing the number of slope failure source heads where debris flows actually occurred (the number of red dots in Fig. 11) by the number of potential source heads on the channel network (number of upstream ends of the channel in Fig. 6). The probability of debris flow initiation varies depending on how the source head basin area is defined. In this study, based on the data shown in Fig. 7, we set the source head basin areas on the flow lines to 10,000 m². This is because, as mentioned earlier, most of the source heads where debris flow occurred were upstream of a
channel network with a basin area of 10,000 m². In this study, the probability of debris flow initiation was evaluated by determining whether debris flow occurred on each channel in the selected basin. We avoided setting the basin area to less than 10,000 m² because it would have considerably increased the number of potential debris flow source heads in the basin assessed at a given basin. To assess whether the debris flow occurred at a given source head, when multiple debris flows occurred upstream of the flow line source head, the source head was only counted once.

(4) Comparison of $R'$ and the probability of debris flow initiation

Figure 12 shows the relationship between $\bar{R'}_{\text{max}}$, which is calculated by averaging the maximum $R'$ values of source heads over a given basin, and the probability of debris flow initiation at that basin. The figure is based on Hayashi's graph comparing the landslide-area ratio to a rainfall index using daily rainfall. We used the basin average because it could help us to define the probability of debris flow initiation in each basin. In addition, we considered the basin average to be a sufficiently small scale for this most recent heavy rain event, which covered a wide area. To compare the probability of debris flow initiation across different sites, the horizontal axis of Fig. 12 shows dimensionless values that have been divided by 250 mm, which is the lower limit of debris flow initiation. Besides the Mikumakiyou and Norogawa Dam sites, we added data from the vicinity of Koyaura (Saka, Aki District), Hokotoriyama (Atocho, Aki Ward, Hiroshima), Kagamiyama (Hi-gashihiroshima City), and Shimmurayama (Ogawara, Asakita Ward, Hiroshima) from the Heavy Rain of July 2018. We also added data for Takamatsuyama (Kabe-cho, Asakita Ward, Hiroshima City) from both the Heavy Rain Event of August 2014 and the Heavy Rain of July 2018. The locations are shown in Fig. 5.

In Fig. 12, the total basin area is shown underneath the name of each observation site. This value is calculated by multiplying the area on the 100 m² grid by the accumulated flow rate at the downstream end with ArcGIS. Norogawa Dam has several basins, so the values are averaged. The number of channels evaluated for each basin (which is a number of possible debris flow source heads to calculate the probability of debris flow initiation) is shown in parentheses to the right of each site. Although the number of data points is small at present, the figure suggests that when $R'$ exceeds a certain value, the probability of debris flow initiation (risk level) increases sharply.

Fig. 13 compares the 72-h half-life effective rainfall and the probability of debris flow initiation, and Fig. 14 compares the 1.5-h half-life effective rainfall and the probability of debris flow initiation. These figures show that in Takamatsuyama, where debris flows occurred as a result of the Heavy Rain Event of August 2014, the long-term rainfall index is the smallest and the short-term rainfall index is the largest, compared to the other sites, which all experienced debris flows in the Heavy Rain Event of July 2018. A comparison of these figures with Fig. 12 suggests that $R'$ can be a single index to assess the risk of debris flow initiation that accounts for the distinct rainfall characteristics of the Heavy Rain Event of August 2014, which had heavy short-term rainfall, and the Heavy Rain Event of July 2018, which had heavy long-term rainfall.
5. CONCLUSIONS

In this paper, we described the characteristics of the Heavy Rain of July 2018, and then investigated a method of assessing the probability of debris flow initiation from XRAIN rainfall distribution data and the digital elevation data obtained by aerial laser surveying prior to the disaster.

In the Heavy Rain Event of July 2018, the long-term effective rainfall value was very high compared to the previous Heavy Rain Event, and it rained uniformly over a wide area. Comparing the rainfall measured with ground-based rain gauges to XRAIN, we observed some variation in their measurements of instantaneous rainfall. However, the rainfall index $R'$ exhibited good agreement with both measurements in terms of temporal variation and maximum values. This suggests that XRAIN rainfall data are useful for obtaining a detailed view of the rainfall at debris flow sites.

We confirmed that the distribution of changes in $R'$ over time could represent the likelihood of slope failure, which changed temporarily in each cell of the grid. We also demonstrated that $R'$ could be used to explain the probability by comparing the averaged maximum $R'$ values at source heads over a given basin with the probability of debris flow initiation at that basin. Finally, we demonstrated that $R'$ could be a single index to assess the probability of debris flow initiation that took into account the distinct rainfall characteristics of the Heavy Rain Event of August 2014, which had heavy short-term rainfall, and the Heavy Rain Event of July 2018, which had heavy long-term rainfall. This paper proposes a method for assessing the risk of debris flow initiation at a small scale from the rainfall distribution and catchment characteristics of mountain slopes (water flow lines created from digital elevation data). This assessment method depends on the topographic characteristics of the source heads at the sites where debris flows occurred. However, at present, there are many uncertainties about how parameters, such as the basin area and slope of the source head, are related to slope failure. Further study of the physical interpretation of $R'$ is, therefore, required.

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