RAINFALL INDEX FOR WARNING AND EVACUATION AGAINST SEDIMENT-RELATED DISASTER: REEXAMINATION OF RAINFALL INDEX R_f , AND PROPOSAL OF R'

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ABSTRACT

Proper warning and evacuation are essential for mitigating sediment-related disasters during heavy rainfall. For this purpose, a scientific and rational rainfall index should be established in accordance with regional geological and topographical characteristics. A new rainfall index, named R' , is proposed through a revision of the Rainfall Index R_f . The effect of preceding rainfall prior to a disaster-inducing rainfall is taken into account in this newly-proposed Rainfall Index R' by utilizing the concept of “effective rainfall”. Rainfall records which were made during a serious disaster on June 29, 1999 and on September 15, 1999 in Hiroshima district were analyzed. Some other cases were also examined and taken to verify the effectiveness of this newly-proposed rainfall index. As a result of the study, it was found that R' is superior to R_f for judging the occurrence probability of a sediment-related disaster from on-going rainfall records. It has also been shown from several cases in the past that R' can identify not only area and time, but also mode and size of a disaster due to slope failures on Masado (decomposed granite soil) slopes which are widely spread around Hiroshima area.

Key words: Masado, rainfall, rainfall index, sediment-related disaster, slope stability, warning and evacuation (IGC: E6)

INTRODUCTION

Sediment-related disasters occur frequently in Japan almost every year, and have caused the loss of human lives and property. There are many recent cases where slope failures, hillside landslides and debris flows took place simultaneously at many sites in particular areas.

In Masado area in Hiroshima Prefecture, sediment-related disaster often occurs by heavy rainfall, where many residents live on a steep slope or on a past debris flow deposit. However, the critical values of rainfall for disasters occurrence are not higher than those in metamorphic rocks area and/or those in frequently rained area in Shikoku district (Hiura et al., 2004). Although the geological and topographical causes for occurrence of sediment-related disaster in these areas can be easily determined in relative, the degree of the inducing cause like heavy rainfall is still unsolved.

A serious sediment-related disaster occurred in Masado area in the western part of Hiroshima Prefecture on June 29, 1999 (hereinafter, “6.29 Disaster”), caused by heavy rainfall which concentrated in a fairly localized area. Adequate data that are needed to understand rainfall

situation in such a localized area was not available from neither AMeDAS (Automated Meteorological Data Acquisition System) nor rain gauges deployed by local governments at that time. After the 6.29 Disaster, Central Disaster-Prevention Council (2000) pointed out that the limitation of monitored rainfall data was a factor in exacerbating the damage.

On the other side, just after the 6.29 Disaster, Research Committee of the Chugoku Branch, JGS (2000) compiled the monitored hourly rainfall data during the disaster from 201 rain-gauge stations owned by several different organizations in Hiroshima Prefecture. The compiled data clearly show that the rainfall during 6.29 Disaster was localized and so concentrated that it could not be known from analysis of data obtained through dispersedly-deployed monitoring points used by AMeDAS.

Also, the Technical Committee on Countermeasures against the 6.29 Disaster, organized by Hiroshima Prefecture, proposed that rain-gauge stations should be more densely redeployed (1999a). Accordingly, the government deployed more than 300 rain-gauge stations in Hiroshima Prefecture, and began to open the rainfall data to the public through Internet. This tendency is now

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widespread in other regions of Japan. Today we can gather extensive and detailed rainfall data relatively quick.

However, the obtained rainfall data has not been fully utilized to mitigate sediment-related disasters due to the difficulty of evaluating the danger in particular areas from on-going rainfall data. It is hoped that proper rainfall indices to solve this difficulty can be developed.

In this study, a rainfall index proposed by some of the authors (Sasaki et al., 2001) was modified, and its validity was examined.

CRITICAL RAINFALL INDEX R_f AND ITS NECESSITY FOR MODIFICATION

It is a well-known fact that slope instability during a rainfall event is governed by both rainfall intensity and accumulated rainfall (Aboshi and Sokobiki, 1972; Senoo and Funazaki, 1973). Suzuki et al. (1979) showed that occurrence of sediment-related disaster could be expressed using the tank model method. Ministry of Construction (1984) introduced the effective rainfall which could express the influence of preceding rainfall with elapsed time, and proposed the combination of effective rainfall and an hourly rainfall as one of rainfall indices. Then Yano (1990) proposed the modified effective rainfall, which could be calculated continuously with time from on-going records of rainfall without segregating a time span. Ministry of Construction (1993) considered Yano's method and proposed the combination of long-term and short-term effective rainfall as one of the rainfall indices.

However, it is not so easy to express the rainfall situation in an arbitrary area with two indices. Okada et al. (2000) calculated the soil water index based on the tank model method, and displayed it on a map. Kaibori (2000) tried to illustrate the spatial distribution of accumulated rainfall by drawing rainfall intensity contours on a map.

Sasaki et al. (2001) proposed a new rainfall index R_f calculated from both quantities. R_f is defined by the equation below.

$$R_f = \sqrt{(R_1 - R)^2 + a^2(r_1 - r)^2} \quad (1)$$

where R and r are accumulated rainfall during a week prior to an arbitrary time and hourly rainfall during this time, respectively, and R_1 , r_1 , and a are constants having values of 600 mm, 100 mm, and 5, respectively. Using Eq. (1), governing properties of rainfall for slope failure which are expressed by two variables can be expressed by a single variable. This makes easy the drawing of spatial distribution of rainfall situation in a given area.

Sasaki et al. (2001) drew contour maps of R_f for the 6.29 Disaster at successive times using the rainfall records observed at 161 of the above-mentioned 201 rain-gauge stations. At these 161 rain-gauge stations, complete records were gained. The drawn maps showed that the spots of slope failure during the 6.29 Disaster were located within areas where $R_f < 450$ mm. This implies that

the proposed rainfall index R_f is useful to predict a possible sediment-related disaster from on-going rainfall records.

However, the proposed rainfall index R_f has some deficiencies:

- (a) Although accumulated rainfall and hourly rainfall are used to calculate R_f , the decrease with time due to the effects of preceding rainfall (the drainage effect) is not considered.
- (b) As rainfall condition where the decrease in rainfall index R_f corresponds to the increase of danger level, which is contrary to people's intuitions that the danger level increase with rainfall amounts.

To cope with above deficiencies, the authors devised a rainfall index R_{fw} in which the rainfall is replaced by "effective rainfall". And R_{fw} was transformed into a newly-modified rainfall index R' which increases in correlation to the danger level. The authors also attempted to verify the effectiveness of the newly-proposed rainfall indices R_{fw} and R' by analyzing the past sediment-related disasters.

NEW RAINFALL INDEX R'

Rainfall Index R_{fw}

The authors devised a rainfall index R_{fw} in order to take into account the decreasing effects of preceding rainfall and the passage of time. The rainfall index R_{fw} has the advantages of both the index R_f and the concept of effective rainfall proposed by Ministry of Construction (1993). Namely, the rainfall index R_{fw} is calculated similarly to Eq. (1) of the index R_f by using long-term effective rainfall instead of accumulative rainfall R , and by using short-term effective rainfall as the hourly rainfall r , as follows:

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

where R_w and r_w are long-term and short-term effective rainfalls (in millimeters), respectively, R_1 and r_1 are reference points on the abscissa and the ordinate, respectively, and a is a weighting factor.

As in the case of R_f , R_{fw} is the distance (in millimeters) from the reference point B (R_1 , ar_1) to a point A (R_w , ar_w) representing an arbitrary rainfall situation on an R_w - ar_w plane as shown in Fig. 1. Rainfall conditions having the same value of R_{fw} are represented by a circular arc whose center and radius are the reference point B (R_1 , ar_1) when R_{fw} is on the R_w - ar_w plane. If these rainfall conditions are plotted on R_w - r_w plane, the circular arc becomes an elliptical arc whose center is the reference point C (R_1 , r_1) and the major and minor-axis radii are R_{fw} and R_{fw}/a , respectively.

Since the values for R_w and r_w can be calculated continuously with time from on-going records of rainfall without segregating a time span, R_{fw} can also be calculated continuously. Therefore, R_{fw} is suitable for examining the danger level of sediment-related disaster in real-time manner during rainfall which is varying every moment.

 Fig. 1. Definition of rainfall index R_{fw}

Transformation into Rainfall Index R'

Rainfall index R' is defined so that it increases as the danger level increases using the rainfall index R_{fw} as shown by equation below:

$$R' = R_{fw0} - R_{fw} \quad (3)$$

where R_{fw0} is the distance from the origin 0 to a reference point B (R_1, ar_1).

By this transformation, R_{fw} is converted to an increasing rainfall index R' in accord with the accumulation of rainfall. A larger R' value indicates a higher probability for occurrence of sediment-related disaster.

Half-value Period, Reference Point, and the Weighting Factor

It is necessary to determine the half-value period, the reference point, and the weighting factor in consideration of the characteristics of the region. These coefficients should be selected with the case study occurred in Masado area around Hiroshima. Takahashi et al. (2000) considered some half-value periods in Yamaguchi Prefecture and reported that the value of 72 hours should be adopted appropriately for the granite area. Terada and Nakaya (2001) indicated that although the half-value period of long-term effective rainfall should be chosen according to regional characteristics, the effective rainfall of 1.5 hours half-value period can be used as short-term effective rainfall regardless of regional differences. Also in Hiroshima Prefecture, the combination of 72 hours and 1.5 hours half-value periods were applied in the calculation of effective rainfall (Honke and Ishiyama, 2003). Hence, half-value periods of 72 hours and 1.5

Table 1. Rainfall indices during past disasters

	R_w (72 h)	r_w (1.5 h)
1967-07-09 Kure Rain-Gauge Station	312.1 mm (19:00)	100.0 mm (18:00)
1988-07-21 Kake Rain-Gauge Station	271.3 mm (6:00)	117.6 mm (4:00)
1999-06-29 Toyama Rain-Gauge Station	327.2 mm (17:00)	114.5 mm (15:00)
1999-06-29 Kure Rain-Gauge Station	265.5 mm (18:00)	115.6 mm (17:00)

 Fig. 2. Relationship between R_w - r_w (Past cases in Kure city)

hours respectively for R_w and r_w have been selected.

In calculating R_{fw} , it is necessary to determine the reference point (R_1, r_1) and the weighting factor a . As for the reference point (R_1, r_1), both R_1 and r_1 must be larger than the largest rain in this area in the past. To determine values for these constants, past disasters that occurred in Hiroshima Prefecture, as shown in Table 1, were used to study the extreme value of effective rainfalls in this area. As the hourly rainfall records before July 7 were not available for the disaster on July 9, 1967 (hereinafter, "1967 Disaster"), the preceding rainfall before July 7, 1967 in Table 1 was calculated from daily rainfall. Referring to this table, values for R_1 and r_1 were adopted as 450 mm and 150 mm, respectively.

The weighting factor was determined from the past experiences of disasters in Kure City. Figure 2 shows the relations between long and short-term effective rainfalls R_w and r_w at different occasions of disasters in Kure City in 1967 and during the period from 1976 to 2003 (Hiroshima Prefecture, 1999a, 2003; Moriwaki, 2004).

In some cases where unknown damage features are included in the collected disasters shown in Fig. 2, it was found that the actual disasters in Kure City in the past

Fig. 3. Comparison of rainfall indices (R_f , R_{fw} , R') (June to September, 1999 Higashi-Hiroshima Rain-Gauge Station)

varied in size. These past disasters in Kure City are classified into the following three categories according to scale:

- Small-scale disaster with less than 100 slope-failures.
- Medium-scale disaster with 100 or more slope-failures.
- Large-scale disasters with serious damage such as the 1967 Disaster and 6.29 Disaster.

Here, numbers of slope-failures are obtained from the records of fire fighting department in the city.

The rainfall situations during the occasions of each disaster are shown in Fig. 2 and represented by the maximum value of R' . It is noticed from Fig. 2 that the critical rainfall conditions dividing each scale of disaster are different, and, by trial and error, the weighting factor a is found to be 3 for best fitting to these dividing arcs.

It is also found that small, medium and large-scale disasters start to occur when R' reaches 125 mm, 200 mm, and 400 mm, respectively.

Comparison of R' to R_f

The efficiency of R' was examined through the comparison with R_f .

In Higashi-Hiroshima City, debris flows occurred twice in 1999, on June 29 (6.29 Disaster) and before the dawn of September 15 (Typhoon 9916).

Figure 3 shows rainfall indices R_f , R_{fw} , and R' calculated from rainfall data recorded at Higashi-Hiroshima Rain-Gauge Station of Meteorological Observatory during the period from June to September 1999. As shown in Fig. 3, it is noticed that the danger level expressed by R' decreases gradually after the peak of each rainfall, while the danger level expressed by R_f decreases in stepwise pattern. This is due to the effects of preceding rainfall with time which are taken into account in R' through R_{fw} , whereas for index R_f , preceding rainfall is simply given as the accumulated rain in a week, and hence, all the effects of preceding heavy rainfall vanish instantly when a week

Table 2. Comparison of rainfall indices (R_f , R_{fw} , R') (June 29, 1999, Sep. 15, 1999, Higashi-Hiroshima Rain-Gauge Station)

	1999-06-29		1999-09-15	Range of fluctuation
	16:00-17:00	17:00-18:00	3:00-4:00	
R_f	386.5 mm	461.6 mm	546.3 mm	394.5 mm
R_{fw}	313.5 mm	311.2 mm	366.1 mm	325.2 mm
R'	322.9 mm	325.2 mm	270.3 mm	325.2 mm

passed. In fact, R_f rose suddenly one week after the rainfall reached its peak during the 6.29 Disaster.

Table 2 shows rainfall indices during the 6.29 Disaster and Typhoon 9916. The peak value of rainfall index R_f went down to 386.5 mm during 6.29 Disaster, while it rose to 546.3 mm at the time of Typhoon 9916; the difference being 159.8 mm. On the other hand, R' was 325.2 mm during 6.29 Disaster, while it was 270.3 mm at the time of Typhoon 9916; the difference being 54.9 mm. The deviation between the initial value and the peak value of R_f during the observation period was 394.5 mm, and that of R' was 325.2 mm, showing a relatively small difference between them; accordingly, it is known that the difference between the 159.8 mm and the 54.9 mm is not caused by this deviation.

When using the rainfall index R_f , it is noticed that the rainfall situations at the time of 6.29 Disaster and Typhoon 9916 are considerably different from each other. Since the calculated value for R_f was larger than the critical value of 450 mm at the time of Typhoon 9916, it is known that R_f cannot effectively express the dangerous situation in this case. On the contrary, the calculated value for R' reached above critical level of 250 mm during both occasions if the rainfall situation is expressed by R' . By using R' , it can be shown that the situation at the time of Typhoon 9916 was similarly as dangerous as the situation at the time of 6.29 Disaster. Since the amounts of damage on both occasions were similar to each other, it is known for the cases mentioned above that index R' is superior to R_f for evaluating the danger levels of rainfall situations.

The above difference comes from the difference in treatment of preceding rainfall in R_f and R' . If the preceding rainfall is heavy, as in the case of the 6.29 Disaster, R_f is liable to overestimate the danger. If the preceding rainfall is small, as in the case of Typhoon 9916, R_f is liable to underestimate the danger.

This tendency of R_f can also be seen at the time of rainfall on September 21, 1999, shown in Fig. 3. R_f on September 21 was smaller than that at the time of Typhoon 9916.

Furthermore, as shown in Table 2, R_f rose to 461.1 mm which is beyond the critical level of 450 mm during period of 17:00-18:00, though this period is only an hour after the rainfall peak, and it rained 24 mm during this period. However, the value of R' for both period of 16:00-17:00 and 17:00-18:00 indicate the same tendency of danger level. Therefore the newly-modified index gives more

Fig. 4. The locations of sediment-related disasters (June 29, 1999)

Table 3. Distances from disaster point to rain-gauge station

	Debris flow	Slope failure	Hillside landslide
Average	2.25 km	2.92 km	2.61 km
Maximum	7.62 km	8.37 km	8.05 km
Minimum	0.12 km	0.17 km	0.10 km

accurate results in evaluating the rainfall situation.

RAINFALL INDEX R' DURING THE 6.29 DISASTER

Spots of Slope Failure and Rain-Gauge Stations

The validity of R' was examined using the data of 6.29 Disaster. The data used in this study were based on both the results of an investigation by the Research Committee of the Chugoku Branch, JGS (2000) and the data reported by Hiroshima Prefecture (1999b).

The selected mass-movement spots are 118 spots of debris flows (the times of occurrence at 25 spots are known), 191 spots of slope failures (the times of occurrence at 35 spots are known), and 1,616 spots of hillside landslides identified from aerial photographs (see Fig. 4).

Monitored rainfall records for all the mass-movement spots were not obtained at their exact points. So firstly, the distances from each rain-gauge station to the mass-movement spots were examined, and it was revealed that the average distances were 2.25–2.92 km as shown in Table 3. As the rainfall records at distant places do not represent the rainfall situation near the damaged places, only the rainfall data at stations within 2.5 km distance from each damaged spot were regarded as the rainfall at this spot.

Rainfall Situations at the Occurrence Time of Disaster

In order to examine the rainfall situations at the times of debris flow disaster occurrences, R' values versus time

Fig. 5. Triggering times during rainfall for debris flow disasters at several rain-gauge stations (June 29, 1999)

are shown in Fig. 5. In this figure, 11 rain-gauge stations within 2.5 km from the disaster spots in which times of occurrence could be specified during 6.29 Disaster were chosen. Here, 18 streams are included.

In some cases, debris flows have occurred several times at the same locations. In these cases, the occurrence times of both the first and last debris flows are plotted.

From this figure, it can be seen that the debris flow disasters concentrate around the maximum value of R' (hereinafter, " R'_{max} ") at every rain-gauge station. Therefore, instead of the value for disaster occurrence time, sometimes R'_{max} is used in this paper.

Types of Disasters and Rainfall Index R'

Figure 6 shows the relationships between R_w-r_w with respect to debris flows, hillside landslides, and slope failures for 6.29 Disaster, corresponding to values of R'_{max} . From this figure, we can see that slope failures occurred first, followed by hillside landslides, and lastly, debris flows.

The minimum values of R' s at the times of occurrence of debris flows, hillside landslides, and slope failures were 274.1 mm (Hachihonmatsu Rain-Gauge Station of the Japan Highway Public Corporation), 184.4 mm (Gion Branch Office of the Fire Bureau of Hiroshima City), and 146.8 mm (Nukushina Branch Office of the Fire Bureau of Hiroshima City), respectively.

Histograms of R' for occurrence and non-occurrence of disaster against classes of R' by 25-mm interval are shown in Fig. 7. The lower bounds for each type of disaster occurrence are located in the class of 250–275 mm, 175–200 mm, and 125–150 mm. Debris flows start to occur when R' reaches 250–275 mm, and the frequency of occurrence increases as R' increases further. Moreover, it is understood that sediment-related disasters occur in all cases after R' exceeds 350 mm.

The curve for accumulated frequency of hillside landslides is similar to that of debris flows, but the former occurred faster than the latter by a smaller R' of 25–50

Fig. 6. Relationship between R_w - r_w (June 29, 1999)

mm (1–2 classes). On the other hand, the histogram for slope failures has a peak when R' is as small as 125–225 mm, and about 50% of the slope failures have already occurred when R' reaches 250–275 mm.

Slope failures under small R' s occurred in the vicinities of Nukushina Branch Office ($R'_{\max}=146.8$ mm), Naka Fire Station ($R'_{\max}=150.2$ mm), and Hesaka Branch Office ($R'_{\max}=167.9$ mm) of the Fire Bureau of Hiroshima City, and Hiroshima Rain-Gauge Station of Hiroshima Prefecture ($R'_{\max}=159.3$ mm).

These spots are all located in urbanized or residential area of Hiroshima City, and the reasons for occurrence of slope failures at small R' s are as follows:

- The spots of slope failures at the bottom of the hills are within 2.5 km from where the rain-gauge stations are located; accordingly, the rainfall conditions at the spots of slope failures may have been different from the rainfall conditions at the rain-gauge stations.
- The influence of rainwater flowing down from

hillside at the foot of hill is bigger than rainwater falling on flat-ground side.

- When a spot is filled with rainwater that came from mountainous and valley areas as surface-water and ground-water, the conditions at that spot become worse than the conditions when only rainwater was falling on the spot.
- In urbanized and residential areas, there is possibility for local concentration of surface water due to influence of road, ditches, etc.

Accordingly, rainfall with R' of 125 mm is likely to cause slope failures in areas such as residential area due to various factors. It appears that hillside landslides begin to occur when R' reaches 175 mm, and they develop into debris flows when R' rises over 250 mm.

DISTRIBUTION OF RAINFALL INDEX R' AND ITS MIGRATION

Rainfall indices currently in use are capable of evaluating the danger levels at individual locations of rain-gauge station, but are inappropriate for displaying the spatial distribution of danger levels over the locations. On the other hand, if R_f , R_{fw} , or R' , which are calculated from two rainfall indices, are used and contours are drawn on a map, the danger levels can be evaluated and the danger areas and their migrations with time can be shown on the map. By using the map, danger levels can be evaluated from on-going rainfall records. And importantly, it can be determined whether evacuation is necessary or not, and when to evacuate.

Figure 8 shows contour maps during the 6.29 Disaster. To draw these contour maps, monitored data obtained near the prefecture borders (some parts of Yamaguchi, Shimane, Tottori, Okayama, Ehime, and Kagawa Prefectures) were added to the rainfall data used for the

Fig. 7. The distribution of rainfall index R' (June 29, 1999)

analysis in Fig. 8. It was ascertained that the accuracy near the prefecture borders had been improved by adding the data (Kaibori et al., 2004).

The spots of debris flows and slope failures whose times of occurrence are known, are indicated on the maps. The maps show clearly the migration of dangerous areas (with large values of R') with time. The dangerous areas coincide well with the disaster-struck areas, proving that danger levels can be evaluated effectively by using the index R' .

It is apparent from Fig. 8 that all the debris flows whose occurrence times are known occurred when R' exceeded 250 mm, and all the slope failures whose occurrence times are known occurred when R' exceeded 200 mm.

As for all cases in Fig. 4, the critical values of R' for debris flows are estimated as $R'_c = 250$ mm, $R'_c = 175$ mm for hillside landslides, and $R'_c = 125$ mm for slope failures. The relationship between the size of slope failure and R' will be discussed later.

RAINFALL INDEX R' IN OTHER DISASTER CASES IN HIROSHIMA PREFECTURE

Disaster on July 21, 1988

On July 20–21, 1988, debris flows (hereinafter, “1988 Disaster”) occurred in areas of Kake Town, Togouchi Town, and Tsutsuga Village. Figure 9 shows the R' contour map during period of 3:00–4:00 on July 21 when R' reached the maximum of 425.1 mm at Kake Rain-Gauge Station, the center of disaster area.

By using the critical level of $R'_c = 250$ mm as mentioned in above discussion during the 6.29 Disaster, the area of debris flows could be expressed conveniently. As shown in Fig. 9, heavy rain hit in an extremely small concentrat-

ed area.

At the time of 1988 Disaster, the density of rain-gauge stations was low and hence, observed data of rainfall were limited. There were only four observation points in high intensity rainfall area available from AMeDAS, and by adding the data taken from six rain-gauge stations around the disaster area (Hiroshima Prefecture, 1988) to AMeDAS data, the accuracy of analysis was improved.

Disaster on Sept. 15, 1999 (Typhoon 9916)

In 1999, the same year of 6.29 Disaster, Typhoon 9916 brought heavy rainfall to a small area including Higashi-Hiroshima City before dawn of September 15, and debris flows occurred at about 10 spots in Higashi-Hiroshima City. Figure 10 shows R' contour map during the period of 3:00–4:00 when R' reached the maximum of 268.0 mm at Higashi-Hiroshima Rain-Gauge Station of Meteorological Observatory.

At that time, R' rose over 250 mm in a small area including Higashi-Hiroshima City and this corresponds well with the debris flows occurrence area.

Disaster on Aug. 1, 2004 (Typhoon 0410)

Typhoon 0410 caused heavy sediment-related disasters mainly in Shikoku area. On the other hand, small-scale slope failures occurred at several spots in hilly areas in Kure City of Hiroshima Prefecture. Figure 11 shows R' contour map during the period of 14:00–15:00 on Aug. 1, 2004. During this period, a relatively high intensity rainfall occurred around Kure City. However R' of the slope failures occurrence area did not exceed 200 mm. And in any district of Hiroshima Prefecture R' during this rainfall did not exceed 250 mm. Disasters due to debris flows caused by this typhoon were not reported in Hiroshima Prefecture.

(a) 1999-06-29, 14:00-15:00

(c) 1999-06-29, 16:00-17:00

(b) 1999-06-29, 15:00-16:00

From this case, it can be shown that small-scale slope failures can occur even during rainfall of relatively small R' of 125–150 mm, but debris flows do not occur unless R' reaches 250 mm.

APPLICATION TO DISASTERS THAT HAVE OCCURRED IN OKAYAMA PREFECTURE

Disaster on Oct. 21, 2004 (Occurred in Okayama; Typhoon 0423)

Typhoon 0423 caused heavy sediment-related disasters all over the country. On Oct. 20, 2004, several sediment-related disasters occurred in Tamano City of Okayama Prefecture which adjoins Hiroshima Prefecture. Five human lives and a large number of properties were lost in one of the debris flows which occurred in this area.

Although the hourly rainfall of 20–30 mm/hour was

Fig. 8. Spatial distribution of R' and its change with time (June 29, 1999, Hiroshima Prefecture)

○: Debris flow that has occurred during shown time
△: Slope failure that has occurred during shown time

Fig. 9. R' -distribution map (July 21, 1988, Hiroshima Prefecture)

not so large-scale for a usual debris flow, it turns out that the value of R' at disaster occurrence time around Tamano City exceeded $R'_c = 250$ mm due to the influence of preceding rainfall (see Fig. 12). This shows that debris flow occurrence can be well expressed by R'_c value. The usefulness of application by this method was also confirmed in Masado area of Okayama Prefecture adjoining Hiroshima Prefecture.

Past Rain in Tamano City (in Okayama Prefecture)

Tamano City is located in an area where little annual

Fig. 10. R' -distribution map (Sept. 15, 1999, Hiroshima Prefecture) Fig. 12. R' -distribution map (Oct. 20, 2004, Okayama Prefecture) Fig. 11. R' -distribution map (Aug. 1, 2004, Hiroshima Prefecture) Fig. 13. R' path (snake line) (1976-2004, Tamano Rain-Gauge Station)

rainfall is expected, the so-called typical Setouchi-style climate. Figure 13 shows the snake lines (paths of long and short-term effective rainfalls) of all rainfalls from 1976 to 2004 at Tamano Rain-Gauge Station of the Meteorological Observatory. It is understood that this area has had less rainfall compared with Kure City (which will be explained later).

However, there were two times of R' exceeding 250 mm in this period. One of them is Typhoon 0423 on Oct. 20, 2004, and another is Typhoon 8310 on Sept. 20, 1983.

It is recorded on data (SABO Technical Center, 1984) that sediment-related disasters also occurred in Tamano City because of Typhoon 8310 on Sept. 20, 1983.

In addition, there were four times of R' exceeding 200 mm in this period. One of them is Typhoon 0421, Sept.

29. Several sediment-related disasters were recorded in the southern part of Okayama Prefecture at that time. Although detailed locations are not known, there are several records of sediment-related disasters occurring at various places in Okayama Prefecture during these three times (Tanaka and Fujiwara 1988; SABO Technical Center, 1991).

CRITICAL RAINFALL IN KURE CITY

The recurrence frequency of R' values in Kure City were examined. For that purpose, the relations (snake lines) between long and short-term effective rainfalls for all rainfalls during the period from 1976 to 2003 at Kure

Fig. 14. R' path (snake line) (1976-2003, Kure Rain-Gauge Station)

Fig. 15. Distribution of rainfall index R' (1976-2003, Kure Rain-Gauge Station)

Rain-Gauge Station of the Meteorological Observatory are shown in Fig. 14.

For reference purpose, the data on 1967 Disaster (large-scale disasters in Kure City mostly due to debris flows) are also plotted in Fig. 14.

101 rainfalls with R' 's of 100 mm and larger were chosen out from above mentioned rainfalls. In Fig. 15, the horizontal axis is divided into interval of 25 mm, and the recurrence frequency of R' for each interval is shown.

As shown in Figs. 14 and 15, it can be seen that R' increases as recurrence frequency decreases. At the times of 6.29 Disaster and 1988 Disaster, R' was as large as 413.2 mm and 421.0 mm, respectively. During the 28 years from 1976 to 2003, there were nine rainfalls with R' 's of 200 mm and larger including the 6.29 Disaster,

Table 4. Relationship between sediment-related disaster and rainfall index R' (1991-2003, Kure Rain-Gauge Station)

Class of R' (mm)	Number of rainfall	Number of sediment disasters			Rate of occurring sediment disasters (%)		
		L*	M*	S*	L*	M*	S*
100-125	21	0	0	0	0	0	0
125-150	13	0	0	3	0	0	23
150-175	8	0	0	2	0	0	25
175-200	4	0	0	3	0	0	75
200-225	1	0	1	0	0	100	0
225-250	1	0	1	0	0	100	0
250-275	1	0	0	1	0	0	100
275-300	0	0	0	0	—	—	—
300-325	0	0	0	0	—	—	—
325-350	0	0	0	0	—	—	—
350-375	0	0	0	0	—	—	—
375-400	0	0	0	0	—	—	—
400-425	1	1	0	0	100	0	0

* L: Large scale disasters, M: Middle scale disasters, S: Small scale disasters

with probability of occurrence being about once every 3.1 years. On the other hand, there were 29 rainfalls with R' 's of 150 mm and larger (1.04 rainfalls per year on average), and 53 rainfalls with R' 's of 125 mm and larger (1.89 rainfalls per year on average).

The relations between the above rainfalls and the sediment-related disasters are interesting. According to the data on disasters occurring in Kure City in recent years (Hiroshima Prefecture, 1999a, 2003; Moriaki, 2004), eight out of nine rainfalls with R' 's of 200 mm and larger has caused sediment-related disasters.

Table 4 shows the relations between the rainfall index R' and the occurrence/non-occurrence of sediment-related disaster with regard to sediment-related disasters occurring during the period from 1991 to 2003. Same as the case in Fig. 2, disasters are classified into large, middle and small-scale disasters.

As shown in Table 4, the rainfalls with R' 's below 125 mm caused no sediment-related disaster in Kure City during the 13 years from 1991 to 2003. As R' increases from 125 mm toward 200 mm, the rate of occurrence of sediment-related disasters increases. All the rainfalls with R' 's of 200 mm and larger caused sediment-related disasters.

Because many houses are built on slopes in Kure City, potential risks of slope failures are high. By obtaining the total number of rainfalls with certain range of R' , and the number of disaster-causing rainfalls out of the total number, the probability of disaster occurrence within the range of R' can be obtained by calculating the ratio of latter number to former number.

In Kure City, the R' of rainfall that caused small-scale

disaster at a small probability (25% or less) was about 125–175 mm, and the R' of rainfall that caused small-scale disaster at a large probability (75% or more) was 175–200 mm and over. The R' of rainfall which caused middle and large-scale concentrated disasters was over 200 mm.

R' of 200 mm corresponds to the distribution range of slope failures with times of occurrence known during 6.29 Disaster, proving the validity of R' of 200 mm as a critical rainfall index for concentrated sediment-related disasters.

CONCLUSIONS

The authors attempted to revise the rainfall index R_f in order to overcome its deficiency, and proposed R' . Findings obtained through this study are as follows:

- Rainfall index R_f overestimates the effects of the preceding rainfall, whereas rainfall index R' is capable to solve the overestimation problem.
- Case analyses has proved that rainfall index R' is capable of expressing, without inconsistency, the disasters occurring in Masado (decomposed granite soil) area around Hiroshima Prefecture in recent years.
- Hillside landslides begin to occur when R' reaches about 175 mm while debris flows often occur when R' rises over 250 mm.
- Although slope failures including sporadic ones begin to occur when R' reaches about 125 mm, the critical R' for multiple simultaneous slope failures is about 200 mm.
- As the rainfall index R' increases, its occurrence frequency decreases. In Kure City, there is only one rainfall with R' of 200 mm or larger every three or four years, on average.

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