A simple method to estimate the amount of rainfall required for a natural landslide dam to overflow

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Many landslide dams breach when they begin to overflow [*Schuster et al*., 1986]. Estimation of the water level of a dam reservoir is important information when planning an evacuation. Often, however, in the early stages of a disaster insufficient data are available to estimate water levels because landslide dams tend to occur in remote mountainous areas, where in many cases the rainfall and runoff data are insufficient. This paper introduces a simple method for estimating the amount of rainfall required to fill a dam reservoir by using rainfall and reservoir water level data. The method is based on the relationship between total rainfall and total loss of rainfall proposed by Endo [1983], which has been applied to 164 basins in Japan [*Uchida et al.*, 2013]. A case study applying this method to landslide dams that occurred in the Kii Mountains has been reported [*Chiba*, 2013]. Here, we report a second case study, in which this method was applied to a landslide dam in the Republic of Indonesia, which occurred in July 2012 and breached in July 2013. Although only approximate, we were able to estimate the total rainfall resulting in overflow in this case. The method is useful in the initial stage of landslide dams and for mountain regions where it is difficult to collect sufficient data.

Key words: natural landslide dam, dam breach, rainfall-runoff relation

1. INTRODUCTION

Many landslide dams occur in Japan. Most recorded landslide dams breached when the reservoirs overflowed [*Schuster et al*., 1986], causing floods downstream. Therefore, knowledge of when a landslide dam reservoir will become full is necessary to plan for evacuation and other emergency work.

Since the volume of a dam reservoir increases with run-in flow resulting from rainfall, the relationship between the amounts of rainfall and run-off is important for predicting when a dam reservoir will reach capacity. This relationship has been studied in mountainous areas, for which several models have been developed. These models are accurate and have been applied to many basins, but in many models, parameters must be identified from reliable long-term data. Often, there are insufficient data on the rainfall and flow rates in mountainous regions, such as in the Kii Mountains, where several landslide dams occurred in 2011. In the disaster, Ministry of Land, Infrastructure, Transport and Tourism and Kinki Regional Development Bureau predicted the water levels of the landslide dam reservoir by using a storage routing model, but were unable to predict them accurately [*Kitagawa et al*., 2013]. In addition to the lack of data, prediction must be made in a limited time frame to plan the initial countermeasures.

Therefore, we introduce a simple method of predicting the amount of rainfall needed to fill a landslide dam reservoir for use in the initial emergency preparations at the time the landslide dam occurs. We report a case study of the application of this simple method to a landslide dam that occurred at Ambon, in the Republic of Indonesia, in July 2012.

2. METHOD

2.1 Relationship between rainfall and outflow

In mountainous areas, the proposed relationship between total rainfall and total loss of rainfall is:

$$L=a\times(1-\exp(-R\times b)) \qquad (1)$$

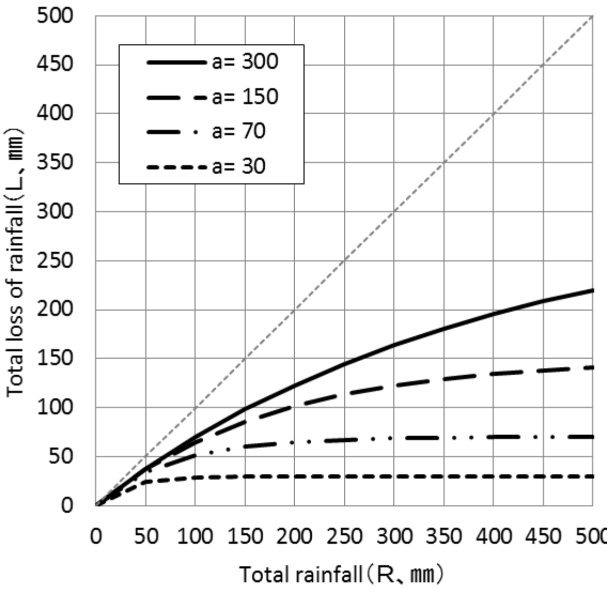

Fig. 1 Difference in the relationship between total rainfall and total loss of rainfall for different values of *a*.

Fig. 2 Location map

where L (mm) is the total loss of rainfall, R (mm) is the total amount of rainfall in a rainfall event, and a and b are coefficients [*Endo*, 1985; *Fujieda*, 2007]. Some studies have applied this relationship to rivers in Japan and reported values of a and b. For example, $b = 1.231 \times a^{(-1.044)}$ for the basins of five landslide dams that occurred in the Kii Mountains in 2011 as a result of Typhoon Talas [*Mizuyama et al*., 2013]. *Uchida et al*. [2013] applied this relationship to 164 basins in mountainous areas of Japan, and found that $b = 1.422 \times a^{(-1.073)}$. The value of b differed in these two studies; we cannot explain why b was smaller in the Kii Mountains. However, we concluded that we can use $b = 1.4 \times a^{(-1.1)}$ for many areas in Japan. Therefore, in **Eq. 1**, we replace b by $1.4 \times a^{(-1.1)}$ and propose the following relationship:

$$L=a(1-\exp(-R \times 1.4 \times a^{(-1.1)})) \qquad (2)$$

Uchida et al. [2013] showed that a = 30–300 for 90% of 164 rivers, and 70–150 for 40%. Based on this difference, the relationship between total rainfall and total loss of rainfall calculated with **Eq. 2** is shown in **Fig. 1**.

2.2 Simple method for estimating the amount of rainfall that will cause a natural dam to overflow

The available capacity of a landslide dam is determined by the water level. If we consider the water leakage from the reservoir of a landslide dam to be 0, the water level increases and the available capacity of the landslide dam decreases with run-in flow. During a period of rainfall, the amount of run-in flow equals the amount of rainfall minus any loss of rainfall. Therefore, the available capacity of a landslide dam required to fill the reservoir in any period is determined by the total rainfall minus the total loss of rainfall for that period. So that:

$$V=(R-L) \times S \times 10^{-3} \qquad (3)$$

where V (m^3) is the available (vacant) capacity of the dam and S (m^2) is the basin area of the river dammed by the landslide. Determining V and S will give the relationship between the amount of rainfall in a period and the unused capacity of the dam using **Eqs. 2 and 3**, and allow an estimate of the amount of rainfall that will be dangerous according to the water level at that time.

We have applied this method to landslide dams that occurred in the Kii Mountains [*Chiba et al*., 2013]. In that study, we estimated that the total rainfall amount required was about 85 mm in Akadani when the water level was 5 m less than the total capacity. In fact, the actual rainfall was 135 mm.

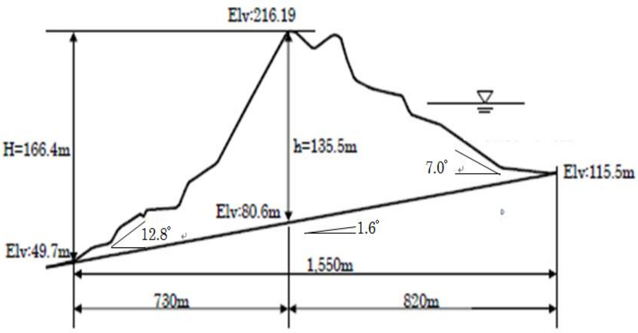

Fig.3 The shape of the landslide dam based on *Watanabe* [2013].
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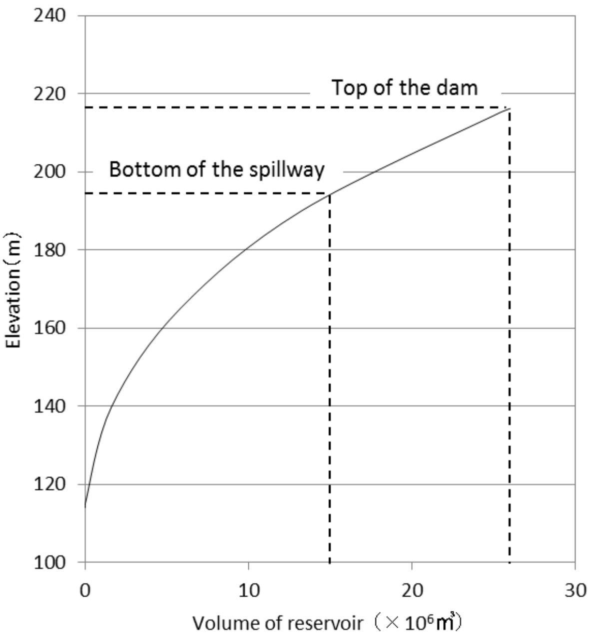

Fig. 4 The relationship between the volume and elevation of the landslide dam reservoir based on *Watanabe* [2013].

3. CASE STUDY

On July 12, 2012, a large landslide occurred at Ambon (**Fig. 2**) in the Republic of Indonesia and formed a landslide dam on the Way Ela River. The dam was 166.4 m high and 1550 m long (**Fig. 3**). The area of the dammed river basin was 11,500,000 m^2.The landslide damming the river was about 900 m long and 450 m wide. A village with about 5000 residents 2 km downstream was in danger if the landslide dam breached.

No data were available for any rainfall event around the time of this disaster, and it is possible that an earthquake occurred 2–3 days before the landslide [*Ishizuka*, 2013]. The volume of the landslide dam reservoir was about 25,000,000 m^3. **Fig. 4** shows the relationship between the water level and the volume of water in the reservoir [*Watanabe*, 2013]. The Ministry of Public Works of the Republic of Indonesia worked on a drainage system and a plan for evacuation. At 17:20 on 24 July, 2013, the water level of the landslide dam reached the level of the spillway, which was at an elevation of 194 m, overflowed a temporary coffering at 5:15 on July 25, and then breached [*Ishizuka*, 2013]. There was damage to downstream infrastructure and 470 houses were swept away, but human casualties were limited to three missing persons [*JICA*, 2013].

The Public Works Research Institute (PWRI) of Japan, the Directorate General of Water Resources (DWRM), and the Research Center for Water Resources (RCWR) of the Ministry of Public Works of the Republic of Indonesia had measured the water level of the reservoir using buoys transported by rafts. For some reasons, the water level was not

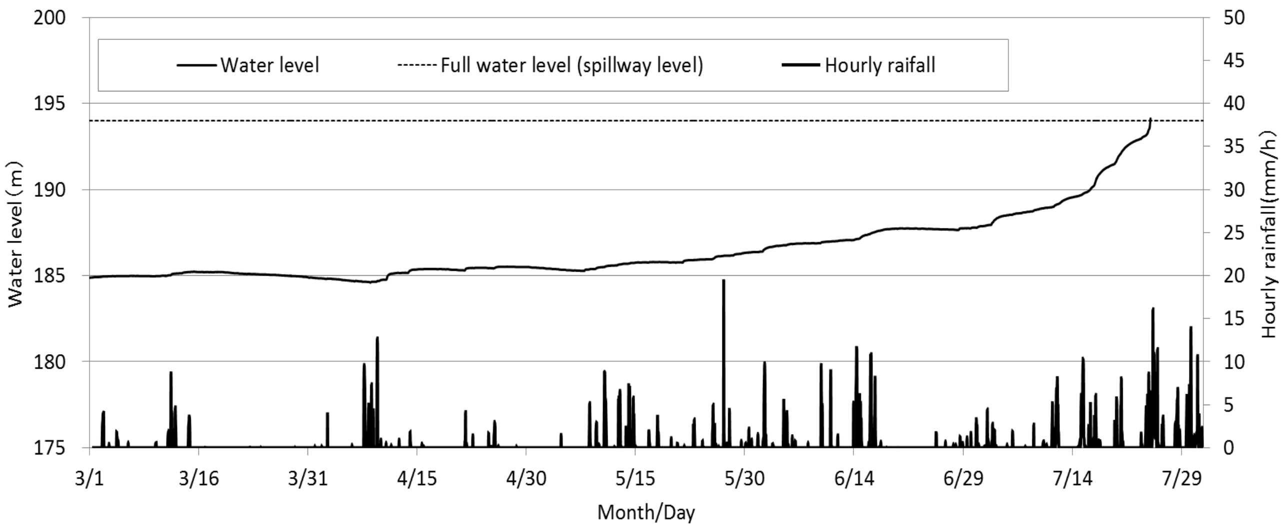

Fig. 5 Relationship between rainfall and water level of the landslide dam

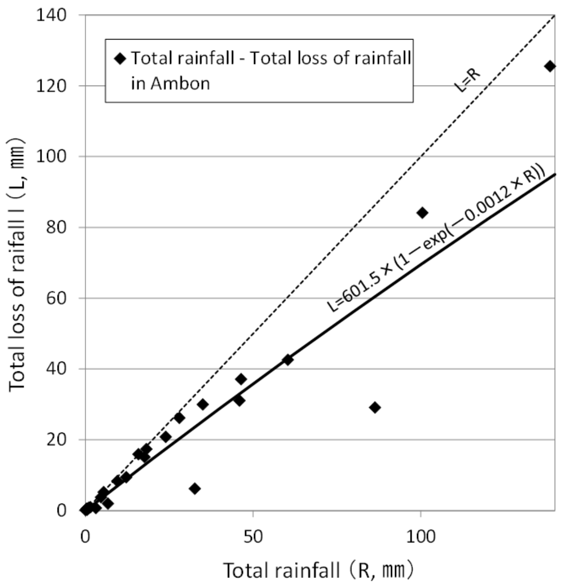

Fig. 6 The relationship between total rainfall and total loss of rainfall at Ambon.

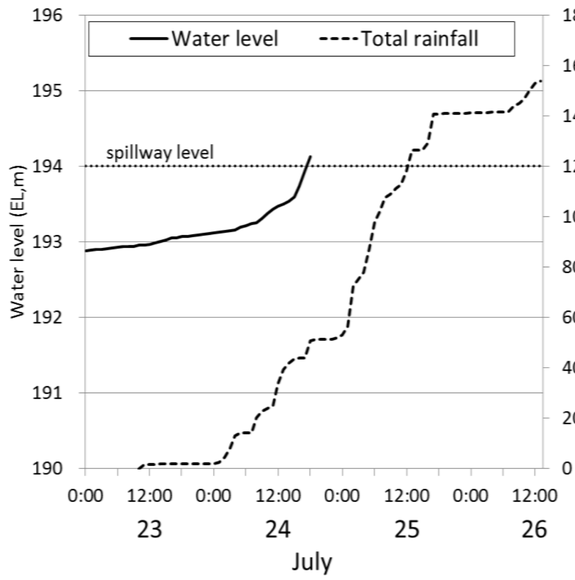

Fig. 8 Total rainfall and water level in around breach of the landslide dam

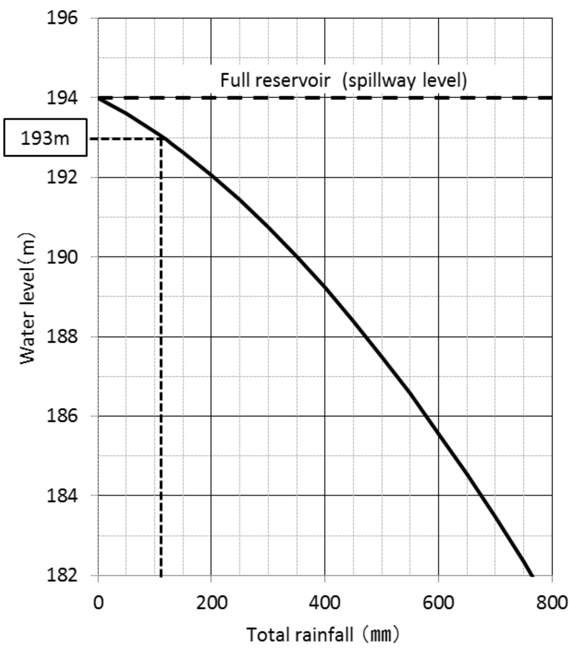

Fig. 7 Estimated rainfall amount causing overflow.

measured after 18:50 on July 24. The PWRI collected hourly rainfall data based on satellite data from the Global Satellite Mapping of Precipitation Rainfall production in Near-real-time [*Okamoto et al.*, 2005] produced by the Japan Aerospace Exploration Agency (JAXA) and the Earth Observation Research Center (EORC). In this study, we used these data of the water level of the landslide dam and the rainfall from 1 March to 24 July 2013. **Fig. 5** shows the hourly rainfall and the water level of the landslide dam. In Fig. 5, we regarded the water level of the full reservoir to be the level of the spillway, which was at an elevation of 194 m.

First, we calculated the total loss of rainfall as the total rainfall minus the added water volume of the reservoir resulting from one rainfall event (**Eq. 4**).

$$L = R - (V(s) - V(e+24)) / S / 10^{-3} \qquad (4)$$

where *V(s)* (m) is the water volume of the reservoir when the rainfall started and *V(e+24)* (m) is the water volume of the reservoir 24 h after the rainfall ended. The water volume was calculated by the water level of the reservoir. We regarded a single rainfall event as the period between 24-h periods without rainfall before and after the event. In this case, several decreases in water level were evident. Therefore, we believe that water leakage from the landslide dam occurred. However, we did not include the effect of water leakage in this calculation. As a result, we identified 42 rainfall events. The total rainfall of these events ranged from 0.05 to 142.77 mm. We used 27 rainfall events in this period, as the range of the total amounts of these events was identical to that for all 42 events.

Fig. 6 shows the relationship between the total rainfall and the total loss of rainfall. From the relationship in **Fig. 6**, *a* was calculated to be 601.5 in this case, so **Eq. 2** becomes:

$$L = 601.5(1 - \exp(-R \times 0.0012)) \qquad (5)$$

Fig. 7 shows the estimated rainfall amount that causes overflow by **Eq. 3** and **Eq. 5**.

We considered the water level of the landslide dam reservoir when the reservoir was full to be 194 m, which was the elevation of the spillway of the landslide dam. The water level was 193 m at 11:00 A.M. on 23 July 2013, when the last rainfall started before it became full. Therefore, from **Fig. 7**, we can calculate the total amount of rainfall required to fill the dam to have been about 100 mm. In fact, the dam reached 194 m (the elevation of the spillway) at 17:20 on 24 July 2013. The rainfall amount during the period from 11:00–18:00 on 23 July was 51 mm. The total rainfall of the one period of rain (11:00 on 23 July to 13:00 on 26 July) was 153.7 mm (**Fig. 8**).

4. DISCUSSION

We applied our simple method to the landslide dam at Ambon. In this case, we were able to use total rainfall and water level data from about 5 months; therefore, it was easy to determine the relationship between the total rainfall and total loss of rainfall. The reservoir became full after about 51 mm of rainfall, whereas we had estimated that about 100 mm would be required. Therefore, the reservoir would not fill following rainfalls of 20 mm or less, such as occur often in Ambon (**Fig. 5**). This simple method cannot estimate when a landslide dam will breach, but it can estimate the total amount of rainfall needed to fill a landslide dam reservoir. This is important information when making plans for an emergency.

Many of the landslide dam disasters that occur are in mountainous areas where data on the relationship between rainfall and runoff are not available. Therefore, we will consider values of *a* from 30 to 300. **Fig.1** shows that the difference in the results using different *a* becomes clearer as the total rainfall increases. The greater the total rainfall is, the more the rainfall intensity affects the direct runoff [*Fukushima et al*., 1986]; rainfall intensity also affects the infiltration rate of unsaturated soil [*Ogawa*, 1995]. In this study, we did not consider rainfall intensity. Nevertheless, a warning of a possible breach must be issued when the total rainfall is high. Therefore, further studies must examine the effects of rainfall intensity on the total rainfall loss and a means of identifying the nature of *a*. Such data will enable use of this method to estimate the amount of rainfall required to cause a landslide dam to overflow.

We believe that we can propose a practical use for rainfall and runoff data that are now being collected in many areas. Collected data can be used to determine the relationship between the total rainfall and total loss of rainfall. When a landslide dam occurs, data for nearby areas can be used if information regarding that specific basin is not available.

The estimation can be affected by the relationship between rainfall and runoff, the volume of the reservoir, and water leakage from the landslide dam. For the landslide dam that occurred in the Kii Mountains in 2011, the impact of the data of the volume of reservoir and water leakage on the total loss was not significant [*Chiba et al*., 2013]. However, the impact may differ for other landslides and the data will vary with time. Therefore, it is important to collect such data to take appropriate measures to deal with landslide dams.

5. CONCLUSION

Although only approximate, the method outlined above can be used in the early stages of landslide dam measurements, when plans regarding the handling of a possible emergency must be made but there are often insufficient data. In comparison with other models for estimating the rainfall-runoff relationship in mountainous areas, this method estimates only the total amount of rainfall needed to fill the landslide dam reservoir, but it is rapid. The accuracy of the estimates was acceptable for practical use in this case study.

In Japan, many landslide dams occur in mountainous areas. In such mountainous areas it is difficult to set up and maintain rain gauges, flow meters, and other instruments to make observations. This method will be useful in such areas because it uses available data. We plan to apply this method to other landslide dams and investigate appropriate methods of formulating emergency plans for landslide dams.

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REFERENCES

Chiba, M., Mizuyama, T. (2013): Estimation of the rainfall causing overflow by use of water level of natural dams (Case study of natural dams occurred by typhoon No.12 at 2011), Jour. of Japan Society of Erosion Control Engineering, Vo.65, No.5, pp.50-55 (in Japanese)

Endo, T. (1985): Theoretical meaning of experimental equation showing the relation between a rainfall and basin water loss, Bulletin of the Forestry and Forest Products Research Institute. No. 332, pp.12-19 (in Japanese with English abstract)

Fujieda, M. (2007): Water-holding capacity and basin storage at forest catchments in Japan, Bulletin of the Forestry and Forest Products Research Institute. No. 403, pp.101-110 (in Japanese with English abstract)

Fukushima, Y., Suzuki, M. (1986): Hydrologic cycle model for mountain water sheds and its application to the continuous 10 years records at intervals of both a day and an hour of Kiryu Watershed, Shiga Prefecture, Bulletin of the Kyoto University Forests, No.57, pp.162-185

Ishizuka, T. (2013): Research and measurement about the landslide dam occurred in Ambon, Indonesia, lecture papers of PWRI (in Japanese)

Japan International Cooperation Agency (JICA) (2013) "Responding to the Potential Risks of the Natural Dam in Ambon: JICA Dispatches an Expert Team to Support the Government of Indonesia " (press release, 16 August 2013)

Kitagawa, S., Kinoshita, A. (2012): Study on a prediction about a water level of landslide dams occurred by Typhoon No.12, 2011, Proceedings of Ministry of Land, Infrastructure and Transport Kinki Regional Development Bureau Conference 2013, Department of disaster prevention and conservation, No.08, pp.1-6 (in Japanese)

Mizuyama, T., Mori, T. and Chiba, M. (2013): Prediction of landslide dam breach for Kii-Mountains in 2011, Jour. of Disaster Research, Vo.8, No.1, pp.159-160

Ogawa, S. (1995): "Hydrologic Effects of a Changing Forest", Forest Hydrology, Tsukamoto, Y. (Ed.), Bun-eido press, pp.268-270. (in Japanese)

Okamoto, K.., Iguchi, T., Takahashi, N., Iwanami, K. and Ushio, T. (2005): The Global Satellite Mapping of Precipitation (GSMaP) project, 25th IGARSS Proceedings, pp. 3414-3416.

Schuster, Robert L., Costa, John E., (1986): " A Perspective on Landslide Dams", LANDSLIDE DAM PROCESSES, RISK, AND MITIGATION, Robert L. Schuster. (Ed.), American Society of Civil Engineers, pp.1-20

Uchida, T., Hayashi, S., Okamoto, A., Tomomura, M., Sato, Y., Asano, Y. (2013): Studies on runoff characteristic of the mountainous basins, Abstracts of JSEC Annual Conference 2013, Japan Society of Erosion Control Engineering, pp.B2-B3 (in Japanese)

Watanabe, Y., Mori, T., Watanabe, F., Chiba, M., Yoshino, K., (2013) Simulation about overflow-erosion breach of the landslide dam ~a study on landslide dam occurred in Ambon, Indonesia~, Abstracts of JSEC Annual Conference 2013, Japan Society of Erosion Control Engineering, pp.B64-B65 (in Japanese)