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# RAINFALL THRESHOLDS FOR DEEP-SEATED RAPID LANDSLIDES

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## ABSTRACT

Soils and weathered bedrock have been known to slide simultaneously, with the resulting landslides sometimes moving rapidly and triggering debris flows. In this study, we refer to these landslides as deep-seated rapid (catastrophic) landslides (hereafter, DCLs). DCLs can result in serious damage, although the frequency of such disasters is generally low. Therefore, early warning systems and the construction of countermeasures for DCLs are important tools for disaster risk reduction. We analyzed the characteristics of recent storms that triggered DCLs in Japan. We found that several of these storms triggered multiple DCLs (multi-DCL events), although most triggered only a single DCL (single-DCL events). For short-term (<24 h) rainfall intensity, there was no significant difference in maximum rainfall intensities between storms that triggered single and multiple DCLs. Conversely, for long-term (48 or 72 h) rainfall amounts, storms that triggered multiple DCLs exhibited considerably higher rainfall amounts than storms that triggered no DCLs or a single DCL. In particular, more than 90% of storms that triggered multiple DCLs recorded rainfall of more than 600 mm per 48 h. Our results suggest that the 48-h or 72-h rainfall amounts were effective for assessing temporal changes in DCL susceptibility, but not the 1-h to 24-h rainfall amounts. This indicates that the occurrence of DCLs is strongly controlled by long-term rainfall amounts but less strongly by short-term rainfall intensity.

***Key words**: deep-seated catastrophic landslide, rainfall threshold, early warning*

## INTRODUCTION

In steep mountainous regions, soils and weathered bedrock have been known to slide simultaneously (e.g., Jitosono *et alii*, 2008; Uchida *et alii*, 2011). These landslides sometimes move rapidly and trigger debris flows (e.g., Nishiguchi *et alii*, 2012), and such landslides can have serious impacts on human lives and infrastructure (e.g., Evans *et alii*, 2007; Jitosono *et alii*, 2008; Taniguchi, 2008; Shieh *et alii*, 2009). In this study, we refer to these landslides as deep-seated rapid (catastrophic) landslides (hereafter, DCLs). This study excludes slow, mall displacement, failures, such as slower deep-seated landslides, including earthflow, slump (e.g., Sidle & Ochiai, 2006), deep-seated gravitational slope deformation (e.g., Agliardi *et alii*, 2009), or rock flow, which are distinct from DCLs.

It has been proposed that early warning systems and the development of countermeasures for DCLs are important tools for disaster risk reduction. Accordingly, Uchida *et alii* (2011) recently proposed a method for mapping the susceptibility of a landscape to DCLs. In fact, the Japanese government initiated a nationwide survey to map susceptibility to DCL using this method (Uchida *et alii*, 2012).

In 2005, the Japanese government also initiated a new nationwide early warning system for disasters associated with landslides and debris flows. The system primarily involves setting a criterion for the occurrence of debris flows and shallow landslides based on several rainfall indices (e.g., Osanai *et alii*, 2010). Moreover, many studies have been conducted to clarify rainfall thresholds for use in the prediction of landslide occurrence (e.g., Caine, 1980; Guzzetti *et alii*, 2008; Saito *et alii*, 2010). However, since the frequency of DCLs is low, it is very difficult to collect a large quantity of data describing the characteristics of rainfall-triggered DCLs. Consequently, the rainfall threshold for DCLs has not yet been clarified. In this study, we compiled rainfall data and landslide inventories to clarify the rainfall threshold for DCL occurrence. Additionally, we examined several rainfall indices to select the most effective rainfall indices for assessing temporal changes in DCL susceptibility.

## METHODS

### *LANDSLIDE DATA*

We used a database of DCLs in Japan, published by the volcanic and debris flow team of the Public Works Research Institute (PWRI). The PWRI compiled landslide information from the existing literature, including journals, conference proceedings, and event and technical reports. Most of the literature used was written in Japanese. The PWRI included only landslides triggered by rainfall or snowmelt and those that occurred after 1868 (the beginning of the Meiji era). Thus, the database excluded earthquake-triggered landslides and volcanic landslides. The PWRI confirmed areas of landsliding using current topographic maps, current and historical aerial photographs, and field surveys, and did not include landslides that could not be confirmed.

Landslides with volumes greater than $10^6$ $m^3$ or areas greater than $10^5$ $m^2$ were compiled in the database. The PWRI excluded slow failures of a more chronic nature (such as slower deep-seated landslides, deep-seated gravitational slope deformation, and rock flow) from the database, similarly to Korup *et alii* (2007). Landslides that turned into debris flows (Fig. 1a) and slid in many fragments (Fig. 1b) were also included in the database. Moreover, if more than half the volume of landslide runout from landslide scar, this landslide was included in the database (Fig. 1c). Around 150 deep catastrophic landslides were included in the database. For each landslide,

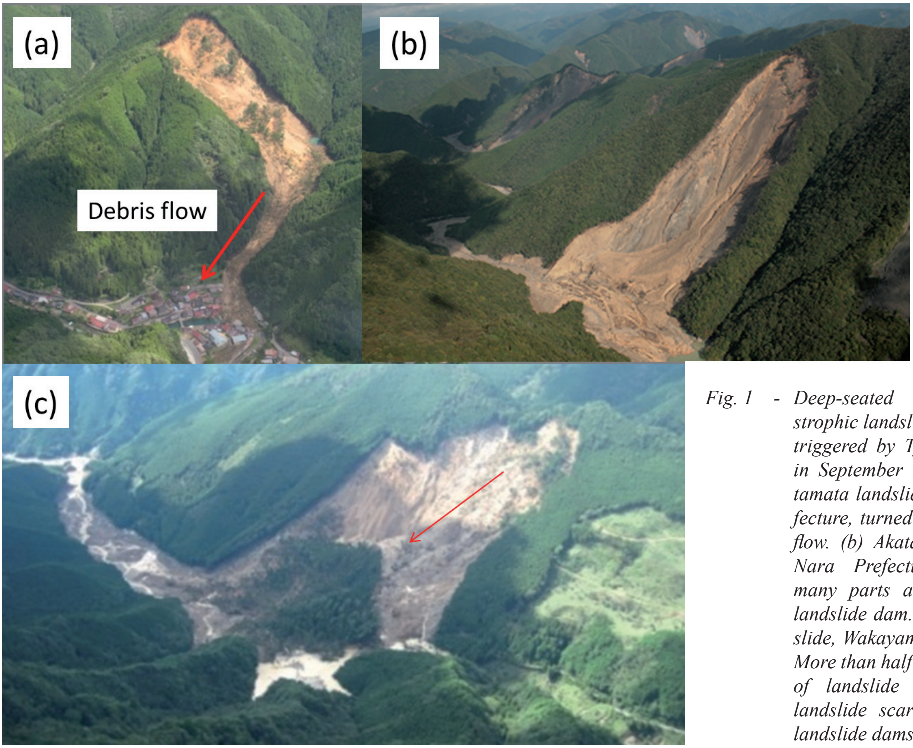

*Fig. 1 - Deep-seated rapid catastrophic landslides in Japan, triggered by Typhoon Tales in September 2011. (a) Kitamata landslide, Nara Prefecture, turned into a debris flow. (b) Akatani landslide, Nara Prefecture, slid in many parts and caused a landslide dam. (c) Iya landslide, Wakayama Prefecture. More than half of the volume of landslide runout from landslide scar and caused landslide dams*

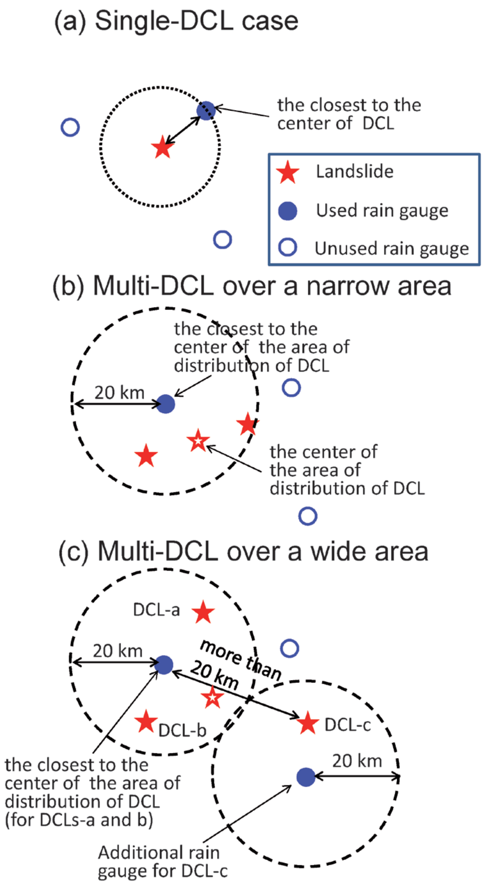

Fig. 2 - *Schematic illustration describing location of analyzed rainfall gauges*

the information stored includes the following: (i) geographical location; (ii) landslide geometrical properties, including length, width, depth, area, and volume; (iii) date of occurrence; and (iv) triggering phenomena (e.g., snowmelt, rainfall). Since DCLs that occurred in 2011 were not included in the database, we added these DCLs for our study.

## RAINFALL DATA

Because it is difficult to obtain rainfall data for old landslides, we used information for landslides that occurred after 1976. We used rainfall data from the Automated Meteorological Data Acquisition System (AMeDAS), operated by the Japan Meteorological Agency (JMA). AMeDAS was developed in 1976, and has around 1,700 rain gauges; therefore, the mean density of rain gauges is approximately one per 220 km$^2$. We used hourly rainfall data.

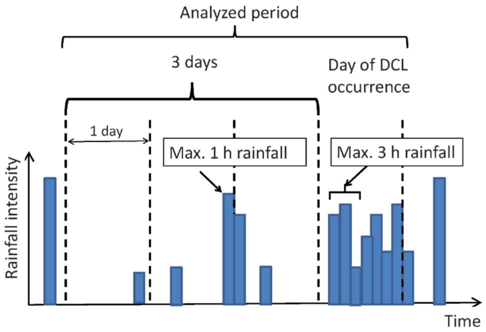

Fig. 3 - *Schematic illustration describing the periods used for calculation of rainfall indices*

## DATA ANALYSIS

If a single DCL was known to be triggered by a given storm, we collected rainfall data for the rain gauge closest to the landslide (Fig. 2a). Conversely, if several DCLs were triggered by a single storm, we collected data at a rain gauge located around the center of the area of landslide distribution (Fig. 2b). If a DCL occurred more than 20 km away from the rain gauge closest to the center of area landslide distribution, we collected additional rain gauge data for the DCL,apart from more than 20 km (Fig. 2c). So, we collected two sets of rainfall data 20 km apart In the latter case, we assumed the DCL to be triggered by two (or more) distinct events.

Consequently, we analyzed data from 43 rainfall events. Thirteen of these rainfall events triggered more than two DCLs; hereafter, we refer to these rainfall events as multi-DCL events. Conversely, 30 rainfall events triggered only one DCL; hereafter, we refer to these as single-DCL events. Moreover, eleven of these single-DCL events, but no multi-DCL events, occurred in snowmelt season.

We analyzed rainfall data for four days: the day of landslide occurrence, and the three days prior (Fig. 3). We refed these four days as "analyzed period", Several rainfall indices have been proposed for assessing temporal change in landslide susceptibility (e.g., Osanai *et alii*, 2010). Here, we simply varied the calculated total rainfall amount for a given duration to search for effective rainfall indices to assess temporal changes in DCL susceptibility. In this study, we used seven durations (1, 3, 6, 12, 24, 48, and 72 h) for calculation. Using hourly rainfall data, we calculated total rainfall amount for a given duration, such as 1, 3, 6, 12, 24, 48, and 72 h, for every hour. Then, we searched for the maximum total rain-

| Calculated duration | 1 h | 3 h | 6 h | 12 h | 24 h | 48 h | 72 h |
|---|---|---|---|---|---|---|---|
| Rainfall amount (mm) | > 10 | > 10 | > 25 | > 25 | > 50 | > 100 | > 100 |
| | > 20 | > 20 | > 50 | > 50 | > 100 | > 200 | > 200 |
| | > 30 | > 30 | > 75 | > 75 | > 150 | > 300 | > 300 |
| | > 40 | > 40 | > 100 | > 100 | > 200 | > 400 | > 400 |
| | > 50 | > 50 | > 125 | > 125 | > 250 | > 500 | > 500 |
| | > 60 | > 60 | > 150 | > 150 | > 300 | > 600 | > 600 |
| | > 70 | > 70 | > 175 | > 175 | > 350 | > 700 | > 700 |
| | > 80 | > 80 | > 200 | > 200 | > 400 | > 800 | > 800 |
| | > 90 | > 90 | > 225 | > 225 | > 450 | > 900 | > 900 |
| | > 100 | > 100 | > 250 | > 250 | > 500 | > 1000 | > 1000 |
| | > 110 | > 110 | > 275 | > 275 | > 550 | > 1100 | > 1100 |

*Tab. 1 - Criteria for counting numbers of rainfall events and DCLs*

fall amount for a given duration in the analyzed period for each rainfall event (Fig. 3).

Moreover, we used all of the rainfall data in AMeDAS from 1976 to 2011 to calculate the numbers of rainfall events for each criterion. Criteria are summarized in Tab. 1.

## RESULTS AND DISCUSSIONS

Figure 4 shows the relationships between duration and maximum rainfall amount for each rainfall event. For single- DCL events, the maximum rainfall amounts increased with increasing duration if the duration was shorter than 24 h. Conversely, if the duration was longer than 24 h, the maximum rainfall amounts of most single-DCL events remained almost constant (Fig. 4a). In contrast, the maximum rainfall amounts for multi-DCLs events increased with increasing duration, at least when the duration was shorter than 72 h (Fig. 4b). The maximum rainfall amounts were generally very small for single-DCL events affected by snowmelt (Fig. 4c).

There was no clear difference in maximum 1-h rainfall amount between single-DCL and multi-DCL events (Fig. 5a). Approximately half of the 1-h rainfall values for single-DCL events were larger than the lowest 1-h rainfall value for multi-DCL events (20 mm/h). Generally, the difference in rainfall amount between single-DCL and multi-DCLs events became more pronounced with increasing duration. Thus, if the calculated duration was shorter than 24 h, the difference between rainfall amounts for single-DCL and multi-DCL events was minor (Fig. 5b-5d). Conversely, the 48-h rainfall amounts for multi-DCL events were clearly larger than those for single-DCL events (Fig. 5f). Although 48-h rainfall was less than 400 mm for one of the multi-DCL events, the remaining twelve multi-DCL events involved rainfall of more than 600 mm. Moreover, all 48-h rainfall amounts of single-DCL events involved rainfall of less than 600 mm. There were also clear differences between single-DCL and multi-DCLs events for the maximum 72-h rainfall (Fig. 5g).

Figure 6 shows the relationship between the number of storms in 1976-2010 and the number of DCLs for each criterion (see Tab. 1). For example, around 230 storms had 48-h rainfall greater than 600 mm, while around 90 DCLs occurred during such events (Fig. 6). The plot in the upper left of Figure 6 indicates the ratio of number of DCLs to number of rain storms , which satisfied the criterion, likes 600 mm/48-h, was high, indicating that that if rain storms satisfied such criteria, there was high probability of DCL occurrence. Conversely, the plot in the lower right of Figure 6 indicates that even if rain storms satisfied these criteria, likes 50 mm/1-h, there was low probability of DCL occurrence. This figure also suggests that, for a set number of rainfall events, the numbers of DCLs occurring increases with increasing duration. Moreover, if the number of rainfall was the same, multi-DCLs event increased with the increase of calculated duration (from brawn plots to light blue plots in Fig. 7). We found no clear differences

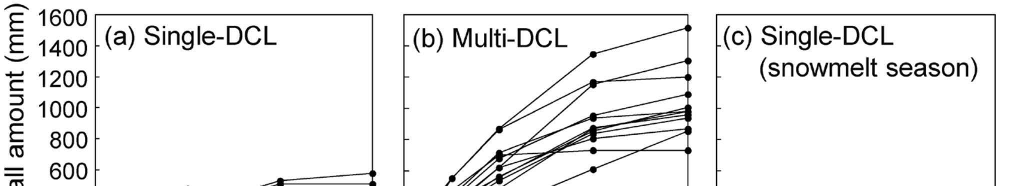

*Fig. 4 - Relationship between calculated duration and maximum rainfall amounts for analyzed periods: (a) single-DCL events, (b) multi-DCL events, (c) single-DCL events affected by snowmelt*

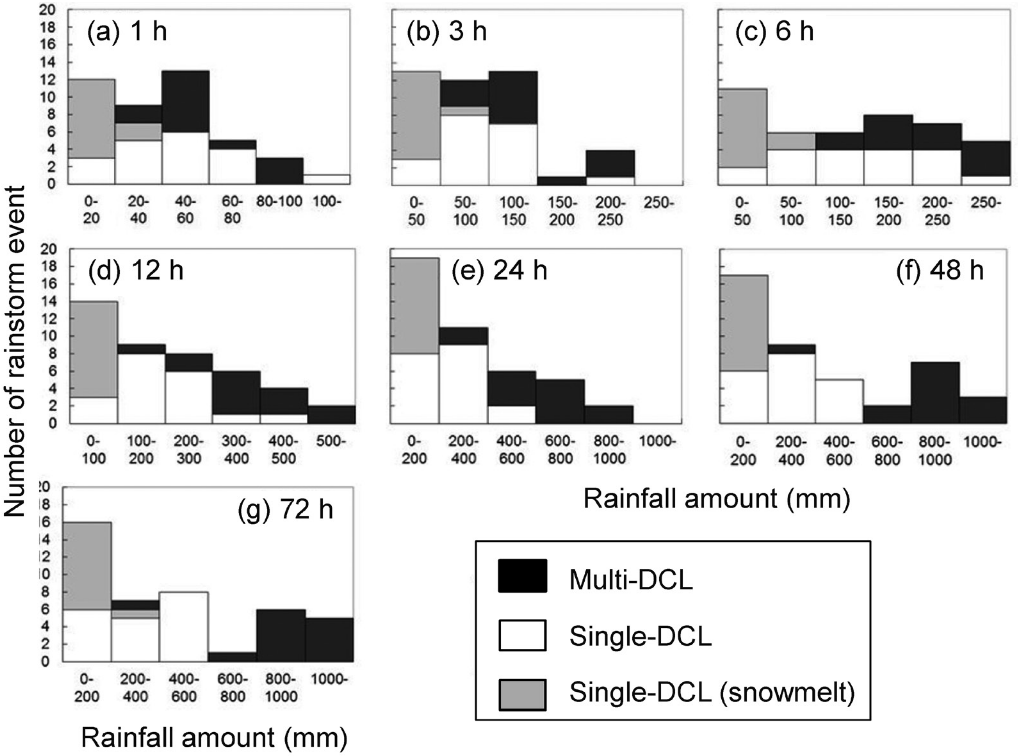

*Fig. 5 - Numbers of rain storm events triggerd DCL according to maximum rainfall amounts for (a) 1 h, (b) 3 h, (c) 6 h, (d) 12 h, (e) 24 h, (f) 48 h, and (g) 72 h*

in these relationships between the 48-h and 72-h rainfall amounts; this suggests that using 48-h or 72-h rainfall amounts, but not 1-h to 12-h amounts, can provide an opportunity to assess the probability of single- and multi-DCL events occurring. These results indicate that the occurrence of DCLs is strongly controlled by long-term rainfall amounts, but not short-term rainfall intensity. This agrees with existing evidence, which suggests that DCLs tend to occur near the ends of storms.

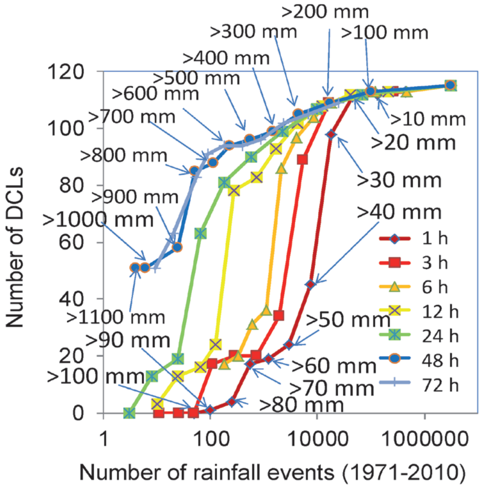

*Fig. 6 - Relationship between number of rainfall events (from 1976 to 2010 in Japan) and number of DCLs for each criterion*

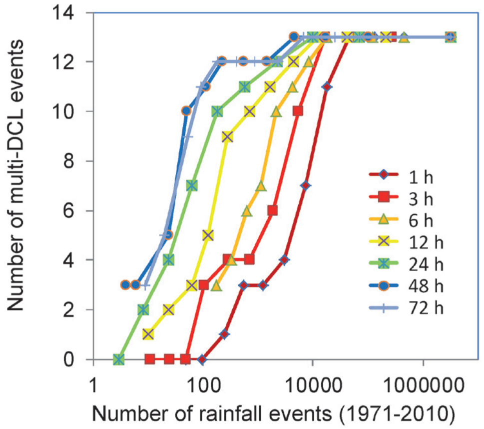

*Fig. 7 - Relationship between number of rainfall events (from 1976 to 2010) and number of multi-DCL events for each criterion*

As shown in Figure 8, the probability of occurrence of multi-DCL events is not particularly high, even when the 48-h rainfall is used to assess temporal changes in DCL susceptibility. For example, if we set 600 mm in 48 h as a threshold value for DCL occurrence, the probability of DCL occurrence is less than 3%. This indicates that most rainfall events will not trigger any DCLs, even if total rainfall exceeds the threshold. Therefore, to establish an effective early-warning system for DCLs, it is necessary to combine rainfall information with other tools, such as susceptibility mapping (e.g., Uchida *et alii*, 2011), hydrological and sediment transport monitoring (e.g., Fujita *et alii*, 2010; Okamoto *et alii*, this issue), and seismic wave observation (e.g., Yamada *et alii*, 2012).

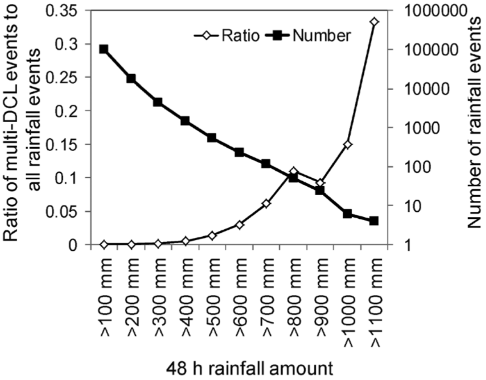

*Fig. 8 - Relationship between 48 h rainfall amounts, ratio of multi-DCL events to all rainfall events from 1976 to 2010, and number of all rainfall events from 1976 to 2010*

## CONCLUSIONS

We investigated the rainfall threshold for the occurrence of deep-seated rapid (catastrophic) landslides (DCLs) by studying around 50 rainfall events that triggered DCLs in Japan. We found that 48-h or 72-h rainfall are more effective in assessing temporal changes in DCL susceptibility 1-h to 24-h rainfall amounts. Our results suggest that the occurrence of DCLs is strongly controlled by long-term rainfall amounts, but not by short-term rainfall intensity.

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