Applying a Method for Assessing Deep-Seated Rapid Landslide Susceptibility in Jember District, East Java Province, Indonesia

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A deep-seated rapid (catastrophic) landslide is a phenomenon that may cause serious damage due to the large amount of sediment movement, such as the formation of a landslide dam and debris flows. In Japan, a method for estimating deep-seated rapid (catastrophic) landslide susceptibilities for many small catchments (ca. 1 km\textsuperscript{2}) over relatively large areas (ca. hundreds of km\textsuperscript{2}) was proposed in 2008. In the present study, we applied the Japanese method to the northern part of Jember, East Java, Indonesia, where a debris flow disaster occurred due to the collapse of a landslide dam formed by a deep-seated rapid (catastrophic) landslide in 2004. Although there were several limitations related to data availability, we successfully assessed susceptibility to deep-seated rapid landslides.

Key words: deep-seated rapid landslide, geology, Indonesia, Jember, small catchment

1. PREFACE

Indonesia is a country with a high potential for natural disasters. Because of geographical and geomorphological factors that vary widely throughout the region, landslides have become one of the most deadly kinds of disasters in Indonesia.

Similar to many other countries and regions in the Pacific Rim, Indonesia has a variety of types of landslides. Deep-seated rapid (catastrophic) landslides, which can move a volume of material \(\geq 10^5 \text{ m}^3\), have occurred frequently, as in neighboring countries and regions. This type of landslide can cause major damage when the material blocks the flow of a river and forms a natural dam that leads to flash floods.

Recently, a method for estimating deep-seated rapid (catastrophic) landslide susceptibilities for many small catchments (ca. 1 km\textsuperscript{2}) over relatively large areas (ca. hundreds of km\textsuperscript{2}) has been proposed [Tamura et al., 2008; Uchida et al., 2011]. Uchida et al. [2011] successfully demonstrated the applicability of this method using data from Mount Wanitsuka, Japan, where deep catastrophic landslides occurred during a typhoon in 2005. Additionally, Takezawa et al. [2012] confirmed the applicability of the method in a mountainous area around Mount Kurikoma, Japan, where a number of co-seismic deep-seated rapid landslides were triggered by an earthquake in 2008.

A variety of detailed data, such as high-resolution aerial photographs, LiDAR data, etc., are available in Japan. However, these data are often not available in many of the countries and regions of the Pacific Rim. Nevertheless, satellite data have recently become available for the entire world. Thus, if satellite data can be used effectively to apply the method proposed by Uchida et al. [2011], the method could be used widely to estimate spatial patterns of susceptibility to deep-seated rapid landslides.

Here, we report a project in which the method proposed by Uchida et al. [2011] (hereafter referred to as the “proposed method”) was applied to...
estimate spatial patterns of susceptibility to deep-seated rapid landslides in Jember District, East Java Province, Indonesia.

2. RESEARCH AREA

We conducted this study in Jember District, East Java Province, Indonesia (Fig. 1), which has a topography that is particularly vulnerable to landslides. In 2006, a large flash flood disaster occurred in this region. This disaster was caused by the collapse of a natural dam upstream that had formed from material derived from a deep-seated landslide that closed the flow of a river [Watanabe et al., 2006; Ito et al., 2009].

We divided the research area into 1 km × 1 km square grids (Fig. 2), which were used as the unit for assessing landslide susceptibility. Additionally, Uchida et al. [2011] indicated that their method can be applied to an adjacent area with similar climatic and geological conditions. Hence, we also selected the northern areas of Jember District as a research area because these areas have similar geological and climatic characteristics (Figs. 3 and 4).

3. METHODS

Uchida et al. [2011] proposed a method for assessing the susceptibility to deep-seated rapid landslides for many small catchments (ca. 1 km²) over relatively large areas (ca. hundreds of km²). They proposed three criteria for determining a susceptible catchment:

1. the presence of old deep-seated rapid landslide scars;
2. the presence of faults or landforms caused by long-lasting mass movements;
3. the presence of many steep slopes with large upslope contribution areas.

Moreover, they proposed that the susceptibility of a given catchment increases with the number of these criteria that are satisfied.

According to the proposed method, we examined the roles of landforms, geologic structures, and topography on deep-seated rapid landslide occurrence. First, we identified grids with old deep-seated rapid landslide scars interpreted from satellite images. Then, we calculated the hit ratio \( P_i \) and cover ratio \( C_i \) for each landform, geologic structure, or topographic condition using equations 1 and 2:

\[
P_i = \frac{N_{L,i}}{N_i}, \quad (1)\]
\[
C_i = \frac{N_{L,i}}{N_{L}}, \quad (2)
\]

where \( N_{L,i} \) is the number of landslide grids with landform, geologic structure, or topographic condition element \( I \); \( N_i \) is the number of grids with landform, geologic structure, or topographic condition element \( I \); and \( N_L \) is the number of landslide grids in the research area.

4. DATA PREPARATION

Two groups of datasets, namely primary data and derivative data, are needed to assess deep-seated rapid landslide susceptibility through the proposed method. The derivative data are the data obtained through the processing of the primary data.

Primary data included:
- Satellite image data (raster data, in color, with a minimum resolution of 2.5 m)
- Topographic data (contour data; polyline vector data)
- Geological map
- Climate map

Then, we prepared the following derivative data.
- Old deep-seated rapid landslide scars map: We interpreted old deep-seated rapid landslide scars from the satellite image.
• Geologic structure map: We digitized active faults and lineaments (geological faults) from the geological map.
• Landform distribution map: We mapped old deep-seated chronic landslides (such as slower deep-seated landslides, deep-seated gravitational slope deformations, and rock flows) and circular arc cracks from satellite image and field survey. Uchida et al. [2011] and Takezawa et al. [2012] used more detailed landform maps, included gentle crest slopes, mass rock creep, etc., through interpretation of more detailed aerial photographs, but because we used satellite images, only the two landform types could be interpreted.
• Triangulated irregular network (TIN) and digital elevation model (DEM) data: We produced these from the topographic data (contour data). Using the TIN and DEM data, we calculated local slope gradient and upslope contributing area for each 50-m grid as follows:

5. RESULTS

5.1 Assessing deep-seated rapid landslide susceptibility based on old landslide scars
Deep-seated rapid landslides often occur near locations of previous deep-seated rapid landslides [e.g., Yokoyama et al., 2012]. Hence, the probability that a deep-seated rapid landslide will occur is high in areas close to such locations [Uchida et al., 2011]. The method used to identify these unit grids was to overlay old deep-seated rapid landslide scar polygons interpreted from the satellite images (i.e., landslide grids). Figure shows the spatial pattern of landslide grids in the research area.

5.2 Assessing deep-seated rapid landslide susceptibility based on geologic structures and landforms
Geologic structures are considered to play an important role in the generation of deep-seated landslides [e.g., Agliardi et al., 2009]. Additionally, there is a high probability that landforms such as rock creep or linear depression contours represent deformation of the rock, which is considered to be a signal that a deep-seated landslide will occur [e.g., Iwamatsu and Shimokawa, 1986; Wang et al., 2003].

First, a unit grid with overlain geological and landform data was identified. In the case of the northern area of Jember District, we could use four types of data, including active faults, lineaments (geological faults), circular arc cracks, and old deep-seated chronic landslides.

Fig. 3 Geological and lithological characteristics of the northern area of Jember District.
Fig. 4 Predicted rainfall for the northern area of Jember District.

Fig. 5 Landslide potential map of the northern area of Jember District based on past landslide events.
Then, we calculated the hit ratio and cover ratio based on equations 1 and 2. Figure 6 shows the calculated values of the hit ratio and cover ratio for each element. The results show that the old deep-seated chronic landslides and the circular arc cracks have the highest values of both hit and cover ratios.

Finally, we tested the effectiveness of the combined elements for assessing landslide susceptibility through the method proposed by Uchida et al. [2011]. Figure 7 shows that the combined index of old deep-seated chronic landslide is best correlated with old deep-seated rapid landslide scars. From the results, it was concluded that if at least elements of old deep-seated chronic landslides or circular arc cracks exist in a given grid, the grid could be evaluated as prone to landslides based on geologic structures and landforms. Figure 8 presents the results.

5.3 Assessing deep-seated rapid landslide susceptibility based on topography

Table 1 lists the grids with different combinations of local slope angle and upslope contribution area. Table 2 lists the grids intersecting with old deep-seated rapid landslide scars. Table 3 lists the ratios of the number of grids overlaying landslide scars to the number of all grids resulting from combinations of local slope angle and upslope contribution area. The total number of topographical factor points from Table 2 divided by that from Table 1 yields an average ratio, which in this case is about 0.0042.

Next, similar to the proposed method, we identified categories with landslide ratio values at least twice the average ratio (Table 4). Thus, the ranges of highly susceptible grids in terms of topography were defined as shown by the grids marked in Table 4.

According to the proposed method, we examined the relationship between highly susceptible grids and old deep-seated rapid landslides by considering the hit ratio and cover ratio at different threshold numbers of highly susceptible grids (Fig. 9). Thus, we identified grids exceeding a given threshold as highly susceptible grids and calculated the hit ratio and cover ratio for these grids using equations 1 and 2. The cover ratio decreased with increasing threshold number, whereas the hit ratio increased. We subsequently defined grids with values >50 as
Table 1 Calculation of the number of topographical factor points based on data of small catchments (the entire research area).

| Slope  | 3.4–3.7 | 3.7–3.88 | 3.88–4.1 | 4.1–4.44 | 4.44–4.72 | 4.72–5.11 | 5.11–5.4 | 5.4–5.7 | 5.7 < |
|--------|---------|----------|----------|----------|----------|----------|----------|----------|-------|
| 0°–10° | 6281    | 3516     | 3768     | 4510     | 2896     | 3297     | 2202     | 2166     | 7169  |
| 10°–15°| 6623    | 3472     | 3459     | 3497     | 1906     | 1890     | 1191     | 1116     | 1940  |
| 15°–20°| 7214    | 3482     | 3069     | 2956     | 1399     | 1249     | 712      | 563      | 948   |
| 20°–25°| 6380    | 3117     | 2509     | 2258     | 1028     | 885      | 410      | 309      | 446   |
| 25°–30°| 5287    | 2643     | 2211     | 1926     | 747      | 540      | 246      | 132      | 226   |
| 30°–35°| 4568    | 2347     | 1858     | 1396     | 536      | 363      | 133      | 83       | 114   |
| 35°–40°| 3332    | 1709     | 1366     | 1026     | 299      | 208      | 84       | 38       | 52    |
| 40° <  | 4096    | 2397     | 2100     | 1609     | 511      | 310      | 97       | 28       | 63    |

Total number of points 144514

Table 2 Calculation of the number of topographical factor points that intersect with the past landslide area.

| Slope  | 3.4–3.7 | 3.7–3.88 | 3.88–4.1 | 4.1–4.44 | 4.44–4.72 | 4.72–5.11 | 5.11–5.4 | 5.4–5.7 | 5.7 < |
|--------|---------|----------|----------|----------|----------|----------|----------|----------|-------|
| 0°–10° | 2       | 1        | 0        | 0        | 0        | 3        | 1        | 0        | 9     |
| 10°–15°| 1       | 3        | 2        | 3        | 6        | 4        | 3        | 1        | 4     |
| 15°–20°| 9       | 4        | 11       | 11       | 10       | 6        | 3        | 0        | 5     |
| 20°–25°| 10      | 12       | 11       | 19       | 5        | 3        | 0        | 1        | 3     |
| 25°–30°| 12      | 18       | 14       | 19       | 5        | 3        | 0        | 0        | 3     |
| 30°–35°| 31      | 13       | 10       | 13       | 3        | 3        | 2        | 0        | 0     |
| 35°–40°| 19      | 16       | 9        | 6        | 3        | 2        | 0        | 0        | 0     |
| 40° <  | 77      | 51       | 38       | 43       | 25       | 4        | 1        | 0        | 1     |

Total number of points 610

Fig. 8 Landslide potential map of the northern area of Jember District based on geologic structures and microtopographical elements.
### Table 3 Landslide event ratios.

| Slope | 3.4–3.7 | 3.7–3.88 | 3.88–4.1 | 4.1–4.44 | 4.44–4.72 | 4.72–5.11 | 5.11–5.4 | 5.4–5.7 | 5.7 < |
|-------|---------|----------|----------|----------|----------|----------|----------|----------|---------|
| 0°–10°| 0.0003  | 0.0003   | 0.0000   | 0.0000   | 0.0009   | 0.0005   | 0.0000   | 0.0013   |
| 10°–15°| 0.0002  | 0.0009   | 0.0006   | 0.0009   | 0.0031   | 0.0021   | 0.0025   | 0.0009   | 0.0021   |
| 15°–20°| 0.0012  | 0.0011   | 0.0036   | 0.0037   | 0.0071   | 0.0048   | 0.0042   | 0.0000   | 0.0053   |
| 20°–25°| 0.0016  | 0.0038   | 0.0044   | 0.0084   | 0.0049   | 0.0034   | 0.0000   | 0.0032   | 0.0067   |
| 25°–30°| 0.0023  | 0.0068   | 0.0063   | 0.0099   | 0.0067   | 0.0056   | 0.0000   | 0.0000   | 0.0133   |
| 30°–35°| 0.0068  | 0.0055   | 0.0054   | 0.0093   | 0.0056   | 0.0083   | 0.0150   | 0.0000   | 0.0000   |
| 35°–40°| 0.0057  | 0.0094   | 0.0066   | 0.0058   | 0.0100   | 0.0096   | 0.0000   | 0.0000   | 0.0000   |
| 40° <  | 0.0188  | 0.0213   | 0.0181   | 0.0267   | 0.0489   | 0.0129   | 0.0103   | 0.0000   | 0.0159   |
|        |         |          |          |          |          |          |          |          | 0.0042   |

### Table 4 The range (red shading) of highly susceptible grids in terms of topography.

| Slope | 3.4–3.7 | 3.7–3.88 | 3.88–4.1 | 4.1–4.44 | 4.44–4.72 | 4.72–5.11 | 5.11–5.4 | 5.4–5.7 | 5.7 < |
|-------|---------|----------|----------|----------|----------|----------|----------|----------|---------|
| 0°–10°| 0.075   | 0.067    | 0.000    | 0.000    | 0.000    | 0.216    | 0.108    | 0.000    | 0.297   |
| 10°–15°| 0.036   | 0.205    | 0.137    | 0.203    | 0.746    | 0.501    | 0.597    | 0.212    | 0.488   |
| 15°–20°| 0.296   | 0.272    | 0.849    | 0.882    | 1.693    | 1.138    | 0.998    | 0.000    | 1.250   |
| 20°–25°| 0.371   | 0.912    | 1.039    | 1.993    | 1.152    | 0.803    | 0.000    | 0.767    | 1.594   |
| 25°–30°| 0.538   | 1.613    | 1.500    | 2.387    | 1.586    | 1.316    | 0.000    | 0.000    | 3.145   |
| 30°–35°| 1.608   | 1.312    | 1.275    | 2.206    | 1.326    | 1.958    | 3.563    | 0.000    | 0.000   |
| 35°–40°| 1.351   | 2.218    | 1.561    | 1.385    | 2.377    | 2.278    | 0.000    | 0.000    | 0.000   |
| 40° <  | 4.454   | 5.041    | 4.287    | 6.331    | 11.590   | 3.057    | 2.442    | 0.000    | 3.760   |

**Fig. 9** Selection of the threshold number of topographical factor points most correlated with landslide events.
Fig. 10 Landslide potential map of the northern area of Jember District based on topographical factors.

Fig. 11 Deep-seated rapid landslide potential map of the northern area of Jember District based on combined factors.
highly susceptible grids meeting the conditions shown in Table 4; these are highly susceptible to deep catastrophic landslides in terms of topography, because both the hit ratio and cover ratio were relatively large. Figure shows the spatial pattern of highly susceptible grids in terms of topography.

6. DISCUSSION AND CONCLUSIONS

Finally, we proposed a susceptibility map for deep-seated rapid landslides in Jember District (Fig. 11). We were unable to test the accuracy of this result, but several points agreed well with previous studies by Uchida et al. [2011] and Takezawa et al. [2012]:

1) Old deep-seated rapid landslide scars were often located in grids where the located landforms might be affected by long-term gravitational deformation, i.e., old deep-seated chronic landslides and circular arc cracks.

2) The ratio of the number of landslide grids to all grids increased with increasing local slope gradient and upslope contribution area (Table 4). These findings support the applicability of the proposed method in Jember District, although there were several limitations pertaining to data availability.

We believe that there are several possible ways that the map can be used to mitigate disaster due to deep-seated rapid landslide (Fig. 11). For example:

1) Local government can identify deep-seated rapid landslide hazard areas by conducting a field survey of the highly susceptible grids.

2) Local government can survey the condition of infrastructure such as houses and public facilities in the highly susceptible grids and determine a safe zone for evacuation.

3) Local government can install monitoring equipment for detecting deep-seated rapid landslide and flash floods and build an upstream observation center for river flow.

4) Local government and local people can establish a good communication system between the river flow observation center and downstream residential areas to provide warning that a flash flood will occur.

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