A New Method for Assessing Deep Catastrophic Landslide Susceptibility

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In steep mountainous regions, deep catastrophic landslides that involve weathered bedrock as well as soils can cause serious damage. However, there is currently no widely used method for estimating spatial patterns of susceptibility to deep catastrophic landslides. We propose a new method to estimate landslide susceptibilities for many small catchments ($\sim 1 \text{ km}^2$) over relatively large areas (hundreds of square kilometers). Our method identifies catchments prone to deep catastrophic landslides according to three criteria: (1) catchments with ancient deep catastrophic landslide scars, (2) catchments with faults and landforms caused by long-lasting mass movements, and (3) catchments with many steep slopes that have large upslope contributing areas. We demonstrated the applicability of this method using data from Mount Wanitsuka, Miyazaki Prefecture, Japan, where deep catastrophic landslides occurred during a typhoon in 2005.

Key words: Deep catastrophic landslide, susceptibility assessment, landform, aerial photograph, topography

1. INTRODUCTION

In steep mountainous regions, landslides may include not only soils, but also underlying weathered bedrock. The velocities and volumes of these landslides are often very large. We refer to these landslides as “deep catastrophic landslides” (**Fig. 1**), but have excluded from this category slow failures of a more chronic nature such as deep-seated chronic landslides and deep-seated gravitational creep and rock flows.

Deep catastrophic landslides may cause serious damage. For example, a deep catastrophic landslide killed more than 400 people in Shaolin Village, Taiwan, in 2009 [Shieh *et al.*, 2009], and more than 1100 people were killed on Leyte Island, Philippines, in 2006 [Evans *et al.*, 2007]. Deep catastrophic landslides may also form landslide dams and have serious impacts on human lives and infrastructure [e.g., Costa and Schuster, 1988; Uchida *et al.*, 2009]. Reducing these hazards requires the development of objective methods to assess and map potential sources of deep catastrophic landslides. Uchida *et al.* [2007]

showed that the frequency of deep catastrophic landslides is strongly affected by bedrock geology and rock uplift rate. Considering this, we roughly classified Japan into four categories of past deep catastrophic landslides frequency [Uchida *et al.*, 2007]. However, there is no widely used method for estimating spatial patterns of deep catastrophic landslide susceptibility on the scale of individual

Fig. 1 Conceptual diagram of a shallow landslide (a) and a deep catastrophic landslide (b)

catchments or hillslopes [Montgomery, 2001].

Several recent studies have addressed the deep catastrophic landslide susceptibility of catchments or hillslopes. For example, *Jitousono et al.* [2008] presented data about hydrological conditions at slopes where deep catastrophic landslides have occurred and proposed a method for estimating susceptibility using water chemistry of streams and springs. Several technologies have been used to analyze long-lasting mass movements, which often progress to deep catastrophic sliding [e.g., *Chigira and Kiho*, 1994; *Crosta and Agliardi*, 2003; *Chigira*, 2009], including airborne laser altimetry [e.g., *Kasai et al.*, 2009; *Uchida et al.*, 2010], differential interferometric synthetic aperture radar [e.g., *Roering et al.*, 2009], and helicopter-borne electromagnetic surveys [*Suzuki et al.*, 2009]. However, these methods are not feasible for assessment of deep catastrophic landslide susceptibility for areas of several hundred square kilometers because of their budgetary and labor demands.

Since the 1960s, field investigations of landforms and geologic structures on slopes where deep catastrophic landslides have occurred have yielded much information [e.g., *Machida*, 1967; *Hatano*, 1974]. However, this information has not been successfully used to assess spatial patterns of deep catastrophic landslide susceptibility. Therefore, we reviewed previous studies of landforms and geologic structures on these slopes [e.g., *Suzuki et al.*, 2007; *Yokoyama et al.*, 2011]. We also conducted new analysis using data for recent deep catastrophic landslides [e.g., *Yokoyama et al.*, 2011]. On the basis of the review and new data analysis, we propose a new method for estimating spatial

patterns of deep catastrophic landslide susceptibility for many small catchments over relatively large areas. The method was published as a manual for assessing spatial patterns of potential deep catastrophic landslide sources [*Tamura et al.*, 2008].

Here, we briefly introduce our previous studies regarding the role of landforms and geologic structures in deep catastrophic landslide occurrence in section 2. We then introduce our proposed method for estimating spatial patterns of deep catastrophic landslide susceptibility in section 3. Finally, we tested this method in a 130-km² study area around Mount Wanitsuka, Miyazaki Prefecture, Japan using new dataset, as described in sections 4 and 5.

2. CHARACTERISTICS OF DEEP CATASTROPHIC LANDSLIDES

Several lines of evidence suggest possible indices for efficient determination of a site's susceptibility to deep catastrophic landslides. These include historical, geomorphic, geologic, and topographic data.

2.1 Ancient deep catastrophic landslide

Shimokawa and Iwamatsu [1986], *Takaya and Suzuki* [2007], and *Suzuki et al.* [2007] showed that scars of ancient deep catastrophic landslides are often found near new deep catastrophic landslides. *Jitousono et al.* [2008] also argued that new catastrophic landslides are likely to occur where ancient deep catastrophic landslide scars exist. *Yokoyama et al.* [2011] found that deep catastrophic landslides have a significantly higher probability of

Table 1 Characteristics of landforms related to deep catastrophic landslides

Landforms	Characteristics
Old deep catastrophic landslide scar	Areas bounded by well-defined arcuate headscarps
Rock creep slope	Poorly developed hollows or valleys
	Sides often bounded by small hollows
	Concave and convex knicklines
Ancient deep-seated chronic landslide	Areas bounded by well-defined arcuate headscarp
	Several interior scarps
	Bulging toe
Downhill-facing scarp	Scarps run generally above landslide headscarp
	Arcuate shape
Linear depression	Bounded by uphill- and downhill-facing scarps
	Include double-crested ridge
	Commonly running along ridge lines
Gentle ridge top	Relatively flat-lying part at ridge tops surrounded by convex knicklines
	Low relief

Fig. 2 Conceptual diagram of landforms related to landsliding (see Table 1)

occurrence near ancient deep catastrophic landslide scars than far from them. These studies suggest that ancient deep catastrophic landslide scars may be an index of susceptibility to deep catastrophic landslides.

2.2 Landforms from long-lasting mass movements

Long-lasting, small-scale mass movements called gravitational mass rock creeps sometimes lead to deep catastrophic sliding. The terms deep-seated gravitational creep, sacking (sagging), and rock flow have been used to denote similar phenomena [e.g., Brückl and Parotidis, 2005]. Indeed, evidence of gravitational mass rock creep is often observed at the scars of deep catastrophic landslides [e.g., Iwamatsu and Shimokawa, 1986; Wang *et al.*, 2003]. Slopes affected by gravitational mass rock creep (hereafter, “rock creep slopes”) have been mapped from aerial photographs, and their positional relationship with deep catastrophic landslides has been analyzed [e.g., Suzuki *et al.*, 2007; Yokoyama *et al.*, 2011]. These studies showed that rock creep slopes are common in areas near deep catastrophic landslides, suggesting that rock creep slopes might serve as an index for assessing deep catastrophic landslide susceptibility.

In addition, Terado [1986] reported ancient deep-seated chronic landslides in areas near recent deep catastrophic landslides. Both gravitational mass rock creep and deep-seated chronic landslides have been shown to be associated with double-crested ridges, linear depressions, uphill-facing scarps (counterscarps), small downhill-facing scarps, and cracks and trenches [e.g., Chigira, 1992; Agliardi *et al.*, 2009; Nishii and Matsuoka,

2010] (Fig. 2). These landforms have also been shown to be common around deep catastrophic landslides [Hatano, 1974; Mokudai and Chigira, 2004; Crosta *et al.*, 2006; Chigira, 2009; Yokoyama *et al.*, 2011]. These studies suggest that landforms associated with long-lasting mass movements may be useful for assessment of deep catastrophic landslide susceptibility.

2.3 Geologic structures

Geologic structures are also thought to contribute to deep catastrophic landslides because geologic structures often control long-lasting mass movements [e.g., Agliardi *et al.*, 2009]. Previous studies have reported the presence of faults in areas close to deep catastrophic landslides [e.g., Nakagawa and Okunishi, 1977; Teramoto *et al.*, 1987; Takaya and Suzuki, 2006; Chigira, 2009]. These findings suggest that the spatial distribution of faults can provide useful information about deep catastrophic landslide susceptibility.

2.4 Topography

Generally, mass movements on hillslopes are strongly controlled by local slope angle [e.g., Hatano, 1974; Montgomery, 2001]. Deep catastrophic landslides are no exception. Korup *et al.* [2007] and Korup and Schlunegger [2007] have shown that local relief controls deep catastrophic landslides.

Moreover, an area’s susceptibility to shallow landslides is known to be controlled not only by local slope angle, but also by the upslope contributing area through its effect on increasing soil pore water pressure [e.g., Hatano, 1974; Montgomery and Dietrich, 1994]. For deep

Fig. 3 Schematic diagram of proposed method for assessing deep catastrophic landslide susceptibility

catastrophic landslides, the role of the upslope contributing area is not fully understood because groundwater flow cannot be fully described by surface topography [e.g., *Uchida et al.*, 2008; *Jitousono et al.*, 2008]. However, it is plausible that the upslope contributing area of steep slopes with large local relief should be large. Many researchers have noted that upper slopes above the head of deep catastrophic landslides are often gentle compared with the slopes where deep catastrophic landslides occurred [e.g., *Machida*, 1967; *Terado*, 1986; *Teramoto et al.*, 1987; *Chigira*, 2009; *Mokudai and Chigira*, 2004]. This suggests that deep catastrophic landslides tend to initiate along convex slope breaks (**Fig. 2**). If the edges of relatively gentle ridge tops are more susceptible to deep catastrophic landslides, then the hypothesis that steep slopes with large upslope contributing areas have greater deep catastrophic landslide susceptibility is supported.

3. ASSESSING POTENTIAL DEEP CATASTROPHIC LANDSLIDE SOURCES

3.1 Outline of the method

We developed a method for assessing the susceptibility of small catchments ($\sim 1 \text{ km}^2$) to deep catastrophic landslides over relatively large areas (hundreds of square kilometers). Considering the review in section 2, we proposed three criteria for determining a susceptible catchment (**Fig. 3**):

1. Presence of ancient deep catastrophic landslide scars.
2. Presence of faults or landforms caused by long-lasting mass movements.
3. Presence of many steep slopes with large upslope contributing areas.

Moreover, we hypothesized that the susceptibility of a given catchment increases with the number of

these criteria that are satisfied. Because deep catastrophic landslide frequency was not high, it was difficult to conduct statistical analysis to weight these criteria. Therefore, we simply used the number of these criteria that were satisfied as the susceptibility.

To determine detailed criteria about faults, landforms, and topography, we conducted preliminary analyses. Because landslide processes are strongly affected by bedrock geology and climate, we limited our preliminary analyses to a study area with homogeneous bedrock geology and climatic conditions (**Fig. 4**). Many previous empirical models for assessing shallow landslides have been developed using regression analysis between parameters, such as slope angle and slope curvature, and landslide susceptibility [e.g., *Guzzetti et al.*, 2005]. However, because the numbers of historical deep catastrophic landslides were not high, regression analyses would not have been suitable. To clarify the roles of landforms and topography, we used two indices (normalized hit ratio and cover ratio) proposed by *Yokoyama et al.* [2011] (see 3.3). *Yokoyama et al.* [2011] successfully quantified relationships between deep catastrophic landslides, landforms, and geological structures.

Using the detailed criteria determined by the preliminary analyses, we assessed the susceptibility to deep catastrophic landslides for each small catchment in the study area (**Fig. 4**).

3.2 Mapping deep catastrophic landslides, landforms, and geologic structures

We created an inventory map of deep catastrophic landslides by stereoscopic examination of aerial photographs. We also included all deep catastrophic landslides shown on the geologic map.

Fig. 4 Flowchart of the proposed method for assessing deep catastrophic landslide susceptibility

The mapped landslides included the entire landslide scar, excluding the runout zone, limited to the locations where the landslides initiated.

We also mapped four landform types related to long-lasting mass movements by interpretation of aerial photographs: rock creep slopes, ancient deep-seated chronic landslides, downhill-facing scarps, and linear depressions (**Fig. 2**). In addition, we mapped gentle ridge tops. We defined the characteristics of these landforms (**Fig. 2** and **Table 1**) on the basis of previous studies [e.g., *Hatano*, 1974; *Chigira*, 1992; *Chigira and Kiho*, 1994; *McKean and Roering*, 2004; *Roering et al.*, 2005; *Nishii and Matsuoka*, 2010] for our interpretation of aerial photographs. Finally, we used geologic maps to compile active and inactive faults that might control deep catastrophic landslides.

3.3 Preliminary analyses for choosing susceptibility criteria

3.3.1 Landforms and geologic structures

Our preliminary analysis focused on the relationships between landforms, geologic

structures, and previous deep catastrophic landslides. First, we divided the study area into catchments with areas of approximately 1 km². If the polygon of a given catchment overlapped an ancient deep catastrophic landslide polygon, we defined the catchment as an “old landslide catchment.”

To examine the relationships between landforms, geologic structures, and old landslides, we calculated the normalized hit ratio P_i and cover ratio C_i for each landform or geologic structure using the equations

$$P_i = \frac{N_{L,i} / N_i}{N_L / N} \quad (1)$$

$$C_i = \frac{N_{L,i}}{N_L} \quad (2)$$

where $N_{L,i}$ is the number of old landslide catchments with landform or geologic structure i , N_i is the number of catchments with landform or geologic structure i , N_L is the number of all old landslide catchments in the study area, and N is the number of all catchments in the study area.

As the first step, two or three landforms or geologic structures with high P and C were chosen as candidates that might be strongly related to deep catastrophic landslides. We then combined these candidates into a single index and calculated P and C values for the index to assess its relationship to deep catastrophic landslide occurrence. The method for combination was as follows: for example, given “rock creep slope” and “active fault” as candidates, we calculated the P and C values for catchments with (1) “rock creep slope” AND “active fault” and (2) “rock creep slope” AND/OR “active fault.” Finally, we assessed catchments with geological structures and/or landforms that have high P and C values as high-susceptibility catchments for deep catastrophic landslides in terms of their landform and geologic structure.

3.3.2 Topography

In our topographic analysis, we examined the relationship between three quantities: old landslide ratio, local slope angle, and upslope contributing area. The old landslide ratio was calculated as follows. We divided grid cells into 72 topographic categories in terms of local slope angle and upslope contributing area (**Table 2**). If the center of a given cell was inside an ancient deep catastrophic landslide polygon, we defined it as a “landslide cell.” We calculated the old landslide ratio as the ratio of landslide cells to the total number of cells in

each topographic category. We calculated the local slope angle and upslope contributing area using the D8 single-flow-direction procedure [O'Callaghan and Mark, 1984]. If the old landslide ratio of a topographic category was more than twice the mean landslide ratio in the study area (the ratio of all landslide cells to all cells in the study area), cells in that category were considered "highly susceptible cells."

Next, to examine the relationship between highly susceptible cells in a catchment and ancient deep catastrophic landslides, the normalized hit ratio $P(n)$ and cover ratio $C(n)$ at different threshold numbers n of highly susceptible cells were calculated as

$$P(n) = \frac{N_L(n)/N(n)}{N_L/N} \quad (3)$$

$$C(n) = \frac{N_L(n)}{N_L} \quad (4)$$

where $N(n)$ is the number of catchments exceeding n highly susceptible cells and $N_L(n)$ is the number of old landslide catchments exceeding n highly susceptible cells. Finally, we assessed catchments exceeding the threshold number of high-susceptibility cells as high-susceptibility catchments for deep catastrophic landslides in terms of topography.

4. APPLICABILITY TEST OF PROPOSED METHOD

4.1 Study site

We applied our proposed method to a study area surrounding Mount Wanitsuka in Miyazaki Prefecture, western Japan (Fig. 5). The region is humid and temperate: the mean annual precipitation in this region is around 2600 mm, and the mean temperature is around 18°C. The studied area covered approximately 130 km², with altitudes ranging from 150 to 1118 m. The site is deeply incised and dominated by hillslopes, with small riparian area. Streams are very steep with longitudinal gradients ranging from 5° to 20°. Slope angles range from 15° to 40°, and slope lengths range from 100 to 1500 m. The area is underlain by sedimentary rocks (sandstone and mudstone) of the Cretaceous Shimanto Group. The area is covered by forest.

Twelve deep catastrophic landslides occurred in the study area during 5–9 September 2005, and these landslides triggered many debris flows [Taniguchi, 2008]. Total rainfall of 1013 mm and

maximum rainfall intensity of 43 mm/h were measured at the summit of Mount Wanitsuka during the triggering event.

4.2 Data and preparation

The study area was divided into 95 catchments with areas ranging from 0.3 to 5.8 km² (Fig. 5). Thus, the value of N in equations 1 and 3 was 95.

We mapped the deep catastrophic landslides triggered in September 2005 ("new landslides") using 1:8000 aerial photographs taken just after the heavy rainfall. In two catchments, multiple new deep landslides occurred. Six catchments were found to have one new landslide. We also mapped ancient deep catastrophic landslide scars ("old landslides") using 1:16,000 aerial photographs taken in 2003, and included deep catastrophic landslides mapped on the Engineering Geological Map of Kyushu Region, as old landslides. In addition, we mapped landforms including rock creep slopes, ancient deep-seated chronic landslides, downhill-facing scarps, linear depressions, and gentle ridge tops from the 2003 aerial photographs using the definitions in Table 1.

The distribution of active faults was based on the Digital Active Fault Map of Japan. Inactive faults were taken from mapped faults shown on the Seamless Digital Geological Map of Japan (1:200,000) published by Geological Survey of Japan that did not match those on the Digital Active Fault Map. We created polygon data for old landslides, new landslides, rock creep slopes, ancient deep-seated chronic landslides, and gentle ridge tops and used line data for downhill-facing scarps, linear depressions, and active and inactive faults. We used a 50-m digital elevation model (DEM) supplied by the Geographical Survey Institute of Japan to calculate local slope angles and upslope contributing areas.

5. RESULTS AND DISCUSSION

5.1 Relationship between old landslides and landforms or geologic structures

Normalized hit ratios P of catchments with active faults, rock creep slopes, and downhill-facing scarps were >1.8. P -values of catchments with inactive faults, ancient deep-seated chronic landslides, and gentle ridge tops were approximately 1.0, meaning that the possibility of old landslides existing in these catchments was almost the same as the average possibility in the whole study area (Fig. 6). We did not find any linear depression in the study area.

Fig. 5 Map of study area showing outlines of 95 catchments and landslide-related features. The inset map shows the study area location on Kyushu Island, western Japan

Cover ratios C of catchments with inactive faults and rock creep slopes were >0.5 ; C values of catchments with downhill-facing scarps, ancient deep-seated chronic landslides, and gentle ridge tops were approximately 0.4; and C values of catchments with active faults were approximately 0.13 (**Fig. 7**). That is, catchments with rock creep slopes and downhill-facing scarps had high P and C values. We chose rock creep slopes and downhill-facing scarps as landforms related to deep catastrophic landslide occurrence.

Next, we calculated P and C for catchments with (1) rock creep slopes AND downhill-facing scarps and (2) rock creep slopes AND/OR downhill-facing scarps (**Figs. 6 and 7**). Our results

indicated that catchments with rock creep slopes, downhill-facing scarps, or both have the highest values of P (2.1) and C (0.61). Subsequently, we defined catchments with rock creep slopes and/or downhill-facing scarps as highly susceptible to deep catastrophic landslides in terms of landforms and geologic structures.

5.2 Relationship between topography and old landslides

Table 2 shows the relationship of the landslide ratio to different combinations of local slope angle and upslope contributing area. We confirmed that the landslide ratio increased with both local slope angle and upslope contributing area. Landslide

Fig. 6 Normalized hit ratios of features related to deep catastrophic landslide susceptibility

Fig. 7 Cover ratios of features related to deep catastrophic landslide susceptibility

Table 2 Landslide ratios resulting from combinations of local slope angle and upslope contributing area. Shaded categories represent less than 1% of all grid cells in the study area. The red line encloses highly susceptible topographic categories

Local slope angle (deg.)	Upslope contributing area ($\log(m^2)$)								
	3.4	3.7	3.9 ~ 4.0	4.1 ~ 4.4	4.4 ~ 4.7	4.7 ~ 5.1	5.1 ~ 5.4	5.4 ~ 5.7	5.7 ~
~ 10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10 ~ 15	0.0	0.0	0.0	0.5	0.6	0.0	0.0	0.0	0.0
15 ~ 20	0.3	0.8	0.6	1.3	1.7	0.0	0.0	1.7	0.0
20 ~ 25	0.3	0.4	0.9	1.8	1.6	3.4	3.6	0.0	0.0
25 ~ 30	0.5	1.3	1.6	1.1	3.2	1.1	4.3	0.0	0.0
30 ~ 35	2.6	1.3	4.1	6.8	3.4	0.0	0.0	0.0	0.0
35 ~ 40	0.0	3.0	2.5	3.5	0.0	0.0	0.0	0.0	0.0
40 ~	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

ratios of categories outlined in red in **Table 2** were more than twice the mean value for the study area. We chose cells matching the categories outlined in red in **Table 2** as highly susceptible cells.

Figure 8 shows P and C values at different values of susceptibility threshold n in equations 3 and 4. Cover ratio decreased with increasing n , whereas the normalized hit ratio was the highest at $n = 200$. We subsequently defined catchments with >200 highly susceptible grid cells meeting the conditions shown in **Table 2** as highly susceptible to deep catastrophic landslides in terms of topography.

5.3 Assessing deep catastrophic landslide susceptibility

On the basis of the results of the preliminary analyses described in sections 5.1 and 5.2, we used the following three criteria to assess deep catastrophic landslide susceptibility for each catchment:

1. Catchments with ancient deep catastrophic

landslide scars

2. Catchments with rock creep slopes and/or downhill-facing scarps

3. Catchments with >200 highly susceptible grid cells (**Table 2**)

Of our 95 catchments, 50 did not satisfy any of these criteria (**Fig. 9**). We confirmed that no deep catastrophic landslides occurred in these catchments during the storms of September 2005. In the remaining catchments, 25, 16, and 4 satisfied 1, 2, and 3 criteria, respectively. The ratio of catchments with new deep catastrophic landslides to all catchments increased as the number of satisfied criteria increased (**Fig. 9**). **Figure 10** shows the numbers of catchments with new landslides and the number of catchments satisfying the given criteria. We confirmed that our three proposed criteria were effective for assessing landslide susceptibility. These results demonstrate that our proposed method can be used to assess the relative susceptibility of 1-km² catchments to deep catastrophic landslides over relatively large areas

(130 km²).

6. CONCLUSIONS

Our review of previous studies suggests that

1. Susceptibility to deep catastrophic landslides may be high where many deep catastrophic landslides occurred in the past.
2. The spatial distribution of landforms related to long-lasting mass movements, such as rock creep slopes, ancient deep-seated chronic landslides, linear depressions, and downhill-facing scarps, may provide an index for deep catastrophic landslide susceptibility.
3. The spatial distribution of geologic structures that control long-lasting mass movements, such as active faults, may provide an index for deep catastrophic landslide susceptibility.
4. Deep catastrophic landslide susceptibility may be high on steep slopes with large upslope contributing

Fig. 8 Plot showing variation of normalized hit ratio and cover ratio with threshold number of high-susceptibility grid cells

areas.

5. Deep catastrophic landslide susceptibility may be high at the edge of gentle ridge tops.

From these considerations, we proposed a new method for estimating spatial patterns of deep catastrophic landslide susceptibility for many small catchments over large areas. Our method identifies catchments prone to deep catastrophic landslides according to three criteria: (1) catchments with ancient deep catastrophic landslide scars, (2) catchments with faults and landforms caused by long-lasting mass movements, and (3) catchments

Fig. 9 Total catchments and new landslide catchments satisfying different numbers of susceptibility criteria (lower panel) and their ratios (upper panel)

Fig. 10 Numbers of catchments with new landslides and catchments satisfying the given criteria

with many steep slopes with large upslope contributing areas. We confirmed the applicability of this method in a study area around Mount Wanitsuka, Japan.

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