ASSESSMENT FOR DEEP CATASTROPHIC LANDSLIDE SUSCEPTIBILITY IN JAPAN

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ABSTRACT

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. First, we examined roles of bedrock geology and rock uplift rate on regional frequency of deep catastrophic landslides. According to these results, we had roughly classified Japan into four categories in terms of past deep catastrophic landslides frequency and published "Deep catastrophic landslide frequency map of Japan" Then, we propose a new method to estimate landslide susceptibilities for many small catchments (~1 km^2) over relatively large areas (hundreds of square kilometres). 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 started the survey for clarification of potential sources of deep catastrophic landslide in high frequency region using this method.

Keywords: Deep-catastrophic landslide: Rock uplift rate: Bedrock geology; Landform; Topography

INTRODUCTION

In steep mountainous regions, not only soils but also weathered bedrocks were sometimes sliding simultaneously. Velocities and volumes of these landslides were often very large. In this study, these landslides are referred to "deep catastrophic landslide" (Fig. 1). This study excludes slow failures of a more chronic nature, such as deep-seated chronic landslide, deep-seated gravitational creep or rock flow, from the deep catastrophic landslide.

Deep catastrophic landslide occurred and triggered serious damages (e.g., Taniguchi, 2008; Shieh et al., 2009). However, there is currently no widely used method for estimating spatial patterns of deep catastrophic landslide susceptibility of catchment or hillslope scale (Montgomery, 2001). It can be considered that where the rate of valley floor lowering is greater than soil production, weathering-limited shallow landslide cannot keep pace with the local base level lowering, and slope angle and height of valley side become large. So, in these regions, landscapes respond to rock uplift rate through landslide involving not only soil and soils but also bedrocks on hillslopes (e.g., Schmidt and Montgomery, 1995; Burbank et al., 1996; Montgomery, 2001; Chigira, 2009). While, it has been widely recognized that rock mass strength played an important role of slope stability and instability. Recently, Clarke and Burbank (2010) argued that patterns of bedrock fractures might largely control depth and frequency of deep landslide. So, it can be thought that although the erosion rate by landslide was controlled by rock uplift rate, if the depth of landslide were controlled by bedrock geology, the frequency of landslide should be controlled by rock uplift rate and bedrock geology. So, first, here we tested this concept to estimate regional-scale frequency of deep catastrophic landslide occurrence.

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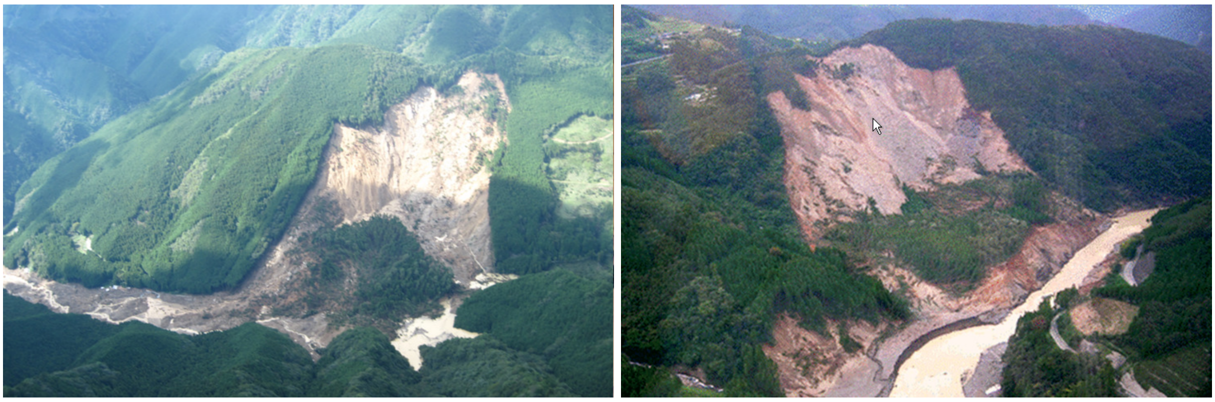

Fig. 1 Recent deep catastrophic landslide in Japan (left photo; Iya, Wakayama, 2011, right photo; Mimikawa, Miyazaki, 2005)

Since the 1960s, many researchers investigated landforms and geological structures on the slope where deep catastrophic landslide occurred (e.g., Machida, 1967; Jitousono et al., 2008; Yokoyama et al., 2009). Based on these detailed field investigations, much information has been stored. However, these information has not been successfully used for assessing spatial patterns of deep catastrophic landslide susceptibility. So, at first, we review previous studies about landforms and geological structures on the slope where deep catastrophic landslide occurred. According to the review, we proposed a new method for estimating spatial patterns of deep catastrophic landslide susceptibility for large area. Then, we test applicability of our new method using a data in Wanitsuka Mountains, Miyazaki, Japan.

HISTORICAL DATA OF DEEP CATASTROPHIC LANDSLIDE IN JAPAN

A database of deep catastrophic landslide was compiled through a literature search, comprising journals, conference proceedings, and event and technical reports. Most of used literatures were written by Japanese. We confirmed the area of landslide using current topographic map, aerial photograph or field survey. Then, we did not include the landslide which cannot be confirmed.

We included only rainfall and snowmelt triggered landslide and landslide occurred after 1868 (the beginning of Meiji era). We included landslides in the database, if the volume of landslide was larger than 10^6 m^3 or the area of landslide was larger than 10^5 m^2. Then, number of deep catastrophic landslide in the database is 149. For each landslide, the information included: (i) the geographical location, (ii) the landslide geometrical properties, including length, width, depth, area, and volume, (iii) date of occurrence and (iv) triggered phenomena.

ROLE OF BEDROCK GEOLOGY AND ROCK UPLIFT RATE ON DEEP CATASTROPHIC LANDSLIDE OCCURRENCE

Using Seamless Digital Geological Map of Japan (1:1,000,000) published by Geological Survey of Japan, bedrock geology was classified into 12 groups in terms of rock type, geological age and accretionary prism or not.

To evaluate rock uplift rate, we used Quaternary Tectonic Map of Japan published by the Research Group for Quaternary Tectonic Map, Tokyo in 1968 [see the Research Group for Quaternary Tectonic Map, 1968]. This map shows total rock uplift amount from the beginning of the Quaternary. They estimated rock uplift amount based on topographic and geological field survey. They assumed that the erosion flat surfaces were formed not far from the sea level and the relative height between sea level and erosion flat surface might equal to rock uplift amount during Quaternary age. Also, they surveyed altitudes of boundary horizons between the marine Pliocene and Pleistocene formations and assumed that the altitude approximate1y represent the rock uplift amounts during the Quaternary age. Using this map, we classified into five categories (0-250 m, 250-500 m, 500-750 m, 750-1000 m and >1000 m) in terms of rock uplift amount during Quaternary. We calculated deep catastrophic landslide density using these data GIS.

The density of deep catastrophic landslide clearly increased with increase of rock uplift amount during Quaternary age (Fig. 2). Only 12 landslides occurred in regions where rock uplift amount were smaller than 500 m. Density of deep catastrophic landslide at regions where uplift amount was larger than 500 m were larger by one order of magnitude than that where rock uplift amount was smaller than 500 m.

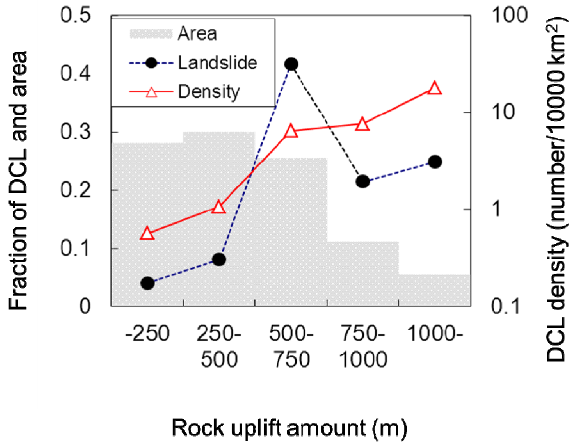

Fig. 2 Density and fraction of deep catastrophic landslide versus rock uplift amount during Quaternary. Shade bars represent rock uplift rate amount distribution for all of Japan.

The deep catastrophic landslide density in Paleo/Mesozoic rock was higher than that of Quaternary and Tertiary rocks (Fig. 3a). The density in sedimentary rocks slightly higher than that of volcanic rock and metamorphic and plutonic rocks (Fig. 3b). The deep catastrophic landslide density in accretionary prism was about 7 times larger than that of outside accretionary prism (Fig. 3c). The difference of deep catastrophic landslide density in terms of geological age and rock types were smaller than the effect of accretionary prism and rock uplift amount (Figs 2 and 3).

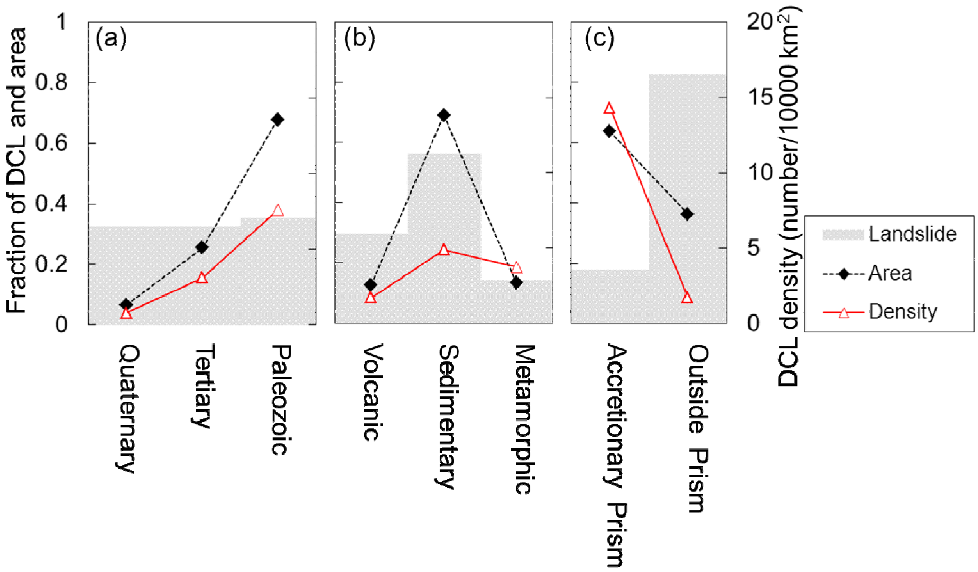

Fig. 3 Density and faction of deep catastrophic landslide versus (a).geological age, (b) rock type and (c) accretionary prism. Shade bars represent geological age, rock type and accretionary prism.

The deep catastrophic landslide density generally increased with increase of rock uplift amount, regardless of geological age, rock type and accretionary prism (Fig. 4). The deep catastrophic landslide density in Quaternary rock was smaller than that of Tertiary and Paleo/Mesozoic rock, except for the case that rock uplift amount ranged from 250 to 500 m (Fig. 4a), suggesting that the frequency of deep catastrophic landslide occurrence in Quaternary rocks was smaller than that of Tertiary and Paleo/Mesozoic rocks. The deep catastrophic landslide density in accretionary prism was commonly larger than that outside accretionary prism, regardless of rock uplift amount (Fig, 4c). However, the role of rock types was not clear (Fig. 4b), indicating that effects of rock type on frequency of deep catastrophic landslide occurrence was small, compared to effects of geological age and accretionary prism.

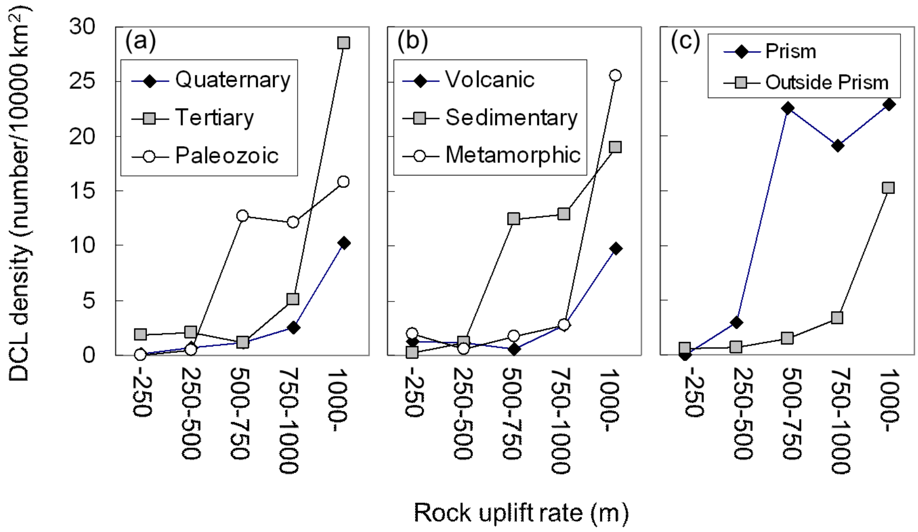

Fig. 4 Density of deep catastrophic landslide versus rock uplift amount during Quaternary sorted by (a) geological age, (b) rock type and (c) accretionary prism

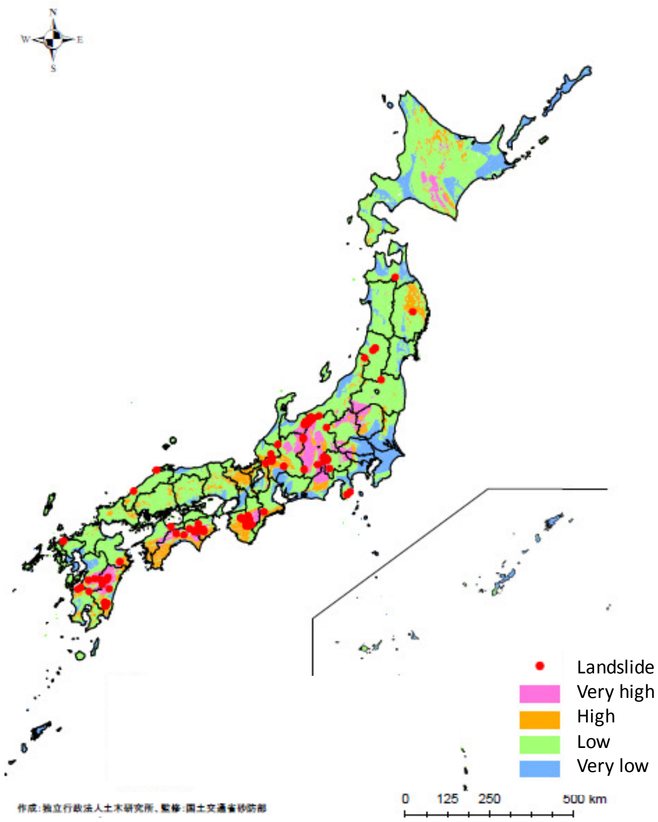

Fig. 5 Deep catastrophic landslide frequency map of Japan published by Ministry of Land, Infrastructures, Transport and Tourism of Japan and Public Works Research Institute on August, 2010

Based on these analyses, we can conclude that (1) Landslide frequency increased with increase of rock uplift rate, (2) Rock type gave small impacts on landslide frequency, (3) Landslide frequency at areas underlain by Quaternary rocks were smaller than that of Tertiary and Paleo-Mesozoic rocks, and (4) Landslide frequency on accretionary prism was higher than that of outside prism. Based on these results, Ministry of Land, Infrastructures, Transport and Tourism of Japan and Public Works Research Institute have roughly classified Japan into four categories in terms of past deep catastrophic landslides frequency and published "Deep catastrophic landslide frequency map of Japan" (Fig. 5).

METHODS FOR ASSESSING POTENTIAL DEEP CATASTROPHIC LANDSLIDE SOURCES

We developed a method for assessing the susceptibility of small catchments (~1 km^2) to deep catastrophic landslides over relatively large areas (hundreds of square kilometres). We proposed three criteria for determining a susceptible catchment (Fig. 6): (1) Presence of ancient deep catastrophic landslide scars, (2) Presence of faults or landforms caused by long-lasting mass movements, and (3) Presence of many steep slopes with large upslope contributing areas (Tamura et al., 2008; Uchida et al., 2011). 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.

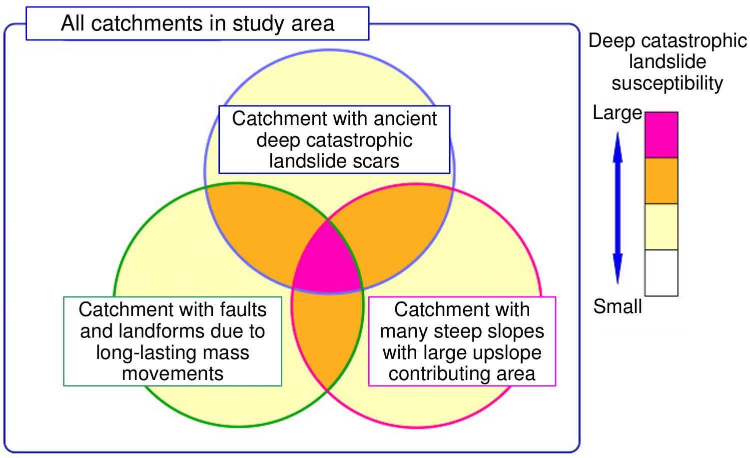

Fig. 6 Conceptual diagram of proposed method for assessing deep catastrophic landslide susceptibility

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. 7). 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, see equations 1 and 2) proposed by Yokoyama et al. (2011). 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. 7).

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. 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. 8). Finally, we used geologic maps to compile active and inactive faults that might control deep catastrophic landslides.

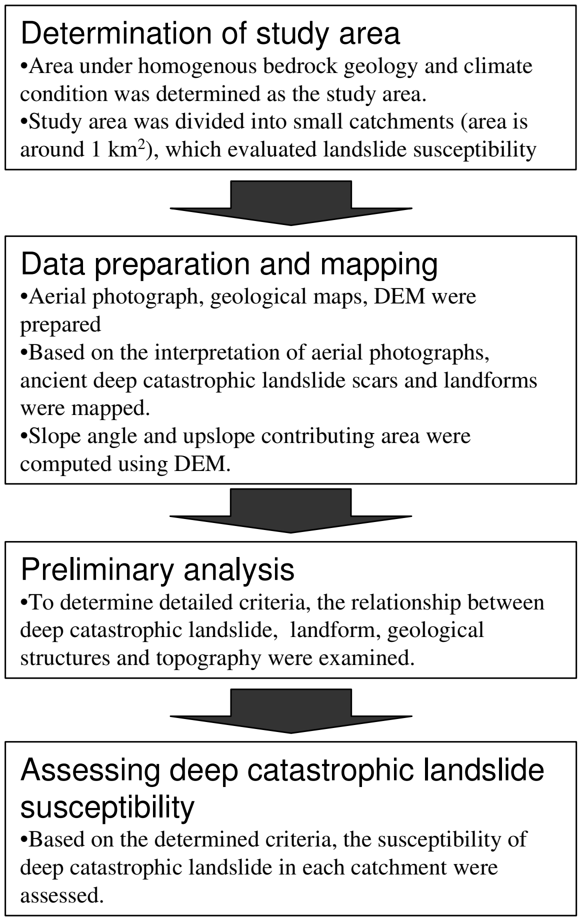

Fig. 7 Flowchart of proposed method for assessing deep catastrophic landslide susceptibility

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 km^2. 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.

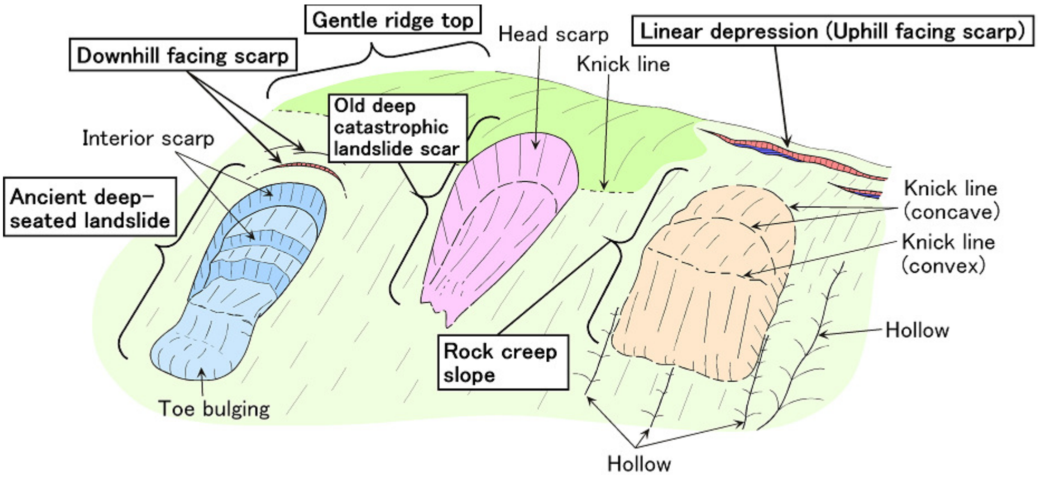

Fig. 8 Conceptual diagram of landforms related to landsliding

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.

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. If the centre 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. 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

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

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

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.

APPLICABILITY TEST OF PROPOSED METHOD

We applied our proposed method to a study area surrounding Mount Wanitsuka in Miyazaki Prefecture, western Japan. 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 km^2, with altitudes ranging from 150 to 1118 m. The site is deeply incised and dominated by hillslopes, with no riparian area. Streams are very steep with longitudinal gradients ranging from 5° to 20°. Slope angles range from 15° to 30°, 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.

On the basis of the results of the preliminary analyses, 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 and (3) Catchments with >200 highly susceptible grid cells. 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). This result demonstrates that our proposed method can be used to assess the relative susceptibility of 1-km^2 catchments to deep catastrophic landslides over relatively large areas (130 km^2).

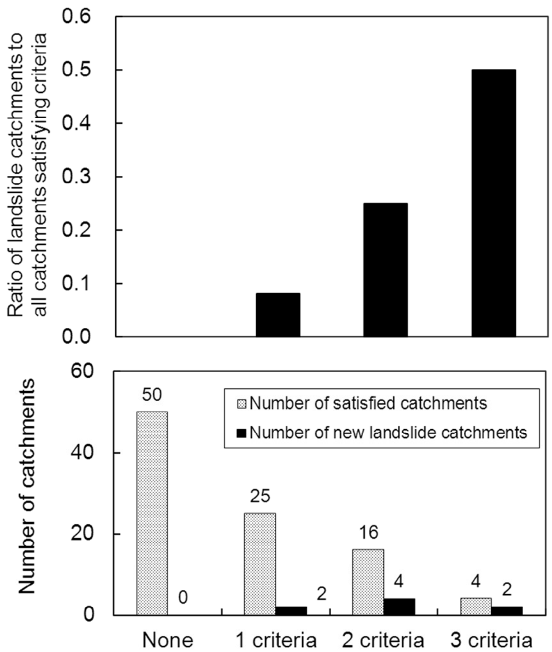

Fig. 9 Total catchments and new landslide catchments satisfying different numbers of susceptibility criteria (lower panel) and their ratios

We also applied our proposed method to study areas surrounding Mt. Kurikoma, in Iwate and Miyagi Prefectures, northern Japan [Takezawa et al., 2010]. Seventy-eight deep catastrophic landslides occurred in the study area of Mt. Kurikoma by large earthquake. We confirmed applicability of our proposed method for assessing deep catastrophic landslide susceptibility triggered by earthquakes.

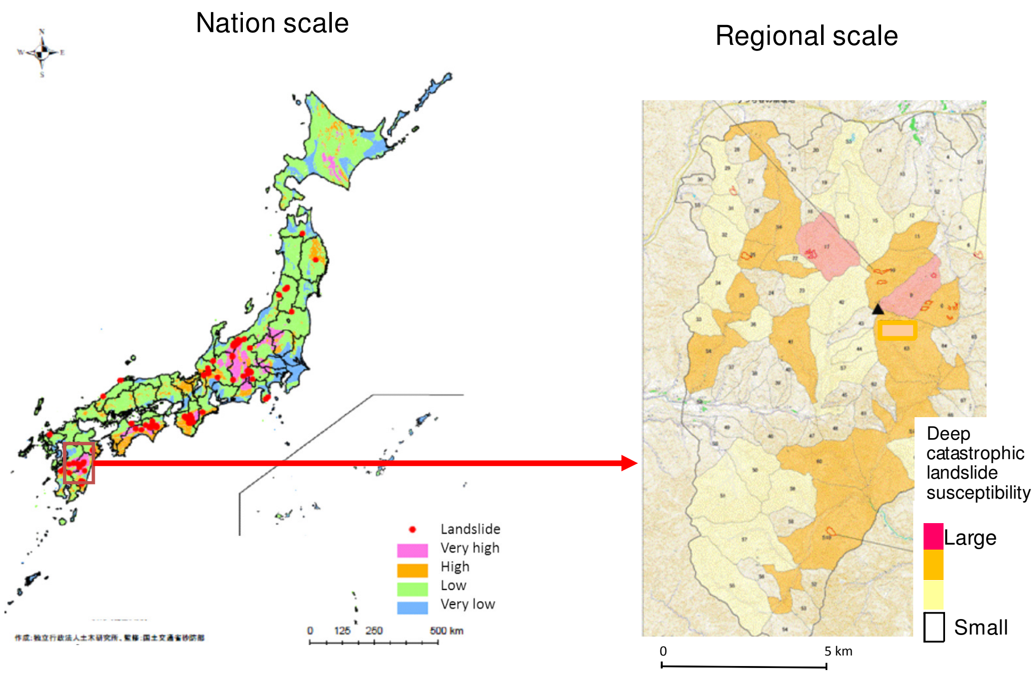

Fig. 10 Recent advances in assessing for deep catastrophic landslide susceptibility in Japan

Ministry of Land, Infrastructures, Transport and Tourism of Japan and Public Works Research Institute started the survey for clarification of potential sources of deep catastrophic landslide using this method since 2009. Ministry of Land, Infrastructures, Transport and Tourism of Japan is trying to complete the survey for very high frequency region in next few years (see Fig. 10).

Although the project for regional scale assessment are still continuing, several problems have been arised. Main problems are as follow. First, results of the interpretation of aerial photographs for mapping of landforms are sometimes dependent on skills of engineers and resolution of aerial photograph. So, basically, we used the same resolution aerial photograph for each region. Moreover, we are trying to develop new method for identifying landforms [e.g., Uchida et al., 2010]. Second, it was sometimes difficult to apply the proposed method to the region where many deep catastrophic landslides have been occurred, since the value of N_L/N was high. In this case, the values of P_i and $P(n)$ might be relatively small, thus, we had to focus small differences of P_i and $P(n)$ to determine detailed criteria in terms of landforms and geological structures, and topography.

CONCLUSIONS

Here we showed two recent advances in assessing for deep catastrophic landslide susceptibility in Japan (Fig. 10). First, we examined roles of bedrock geology and rock uplift rate for occurrence of deep catastrophic landslide. Based on these analyse, we proposed "Deep catastrophic landslide frequency map of Japan" for clarifying nation-scale deep catastrophic landslide susceptibility. Then, we proposed a new method to estimate regional-scale landslide susceptibilities for many small catchments (~1 km^2) over relatively large areas (hundreds of square kilometres).

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