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Recent Advances of Methods for Prediction of Disasters Triggered by Deep Catastrophic Landslide

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ABSTRACT Deep catastrophic landslides often caused serious damage. However, there is no widely used method for estimating spatial patterns of deep catastrophic landslide susceptibility. In the last several years, we studied about deep catastrophic landslides. First, we examined roles of bedrock geology and rock uplift rate on regional frequency of deep catastrophic landslides. Next, we proposed a new method to estimate landslide susceptibilities for many small catchments (ca. 1 km^2) over relatively large areas (ca. hundreds of km^2). Finally, we presented a new implantation method for large-scale debris flow triggered by deep catastrophic landslide. We combined several approaches, including historical data analysis, aerial photograph interpretation, geomorphological and geological surveys, statistical approach, numerical simulation etc. to provide these new methods. Here we synthesized these recent advances about methods for assessing the susceptibility of disasters induced by deep catastrophic landslide.

Key Words: Deep catastrophic landslide, susceptibility assessment, debris flow, landform, bedrock geology.

1. Introduction

In steep mountainous regions, landslides may include not only soils but also underlying weathered bedrock (e.g., Chigira and Kiho, 1994; Crosta and Agliardi, 2003). 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. In previous studies, "deep-seated landslide" was commonly used to describe landslides, which consist of both soils and weathered bedrock. However, deep-seated chronic landslides were often included in deep-seated landslide. Since we focused on only rapid (catastrophic) landslide, but excluded chronic landslides, we used "deep catastrophic landslides" in this study.

Deep catastrophic landslides may cause serious damage. For example, a deep catastrophic landslide killed more than 400 people at 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 trigger large-scale debris flow and have serious impacts on human lives and infrastructures (e.g., Taniguchi, 2008). Reducing these hazards requires the development of objective methods for assessing and mapping potential sources of deep catastrophic landslides (Uchida *et al.,* 2009).

Since 1960s, several studies have argued

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the deep catastrophic landslide susceptibility (e.g., Machida, 1967; Hatano, 1974; Chigira and Kiho, 1994; Crosta and Agliardi, 2003; Jitosono *et al.* 2008). Especially, field geological and geomorphological investigations on areas close to deep catastrophic landslides have yielded much information (e.g., Machida, 1967; Hatano, 1974). These studies clarified several geological structures, including active fault, caprocks etc. and landforms, including uphill-facing scarp etc., were often found in the area close to deep catastrophic landslides. Moreover, process-based studies argued that long-lasting, small-scale mass movements called gravitational mass rock creeps sometimes lead to deep catastrophic sliding (Chigira and Kiho, 1994; Crosta and Agliardi, 2003, Chigira, 2009), suggesting that the signature of long-lasting, small-scale mass movements should be an index of deep catastrophic landslide susceptibility. Further, recent studies 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 (e.g., Jitousono *et al.,* 2008). However, there is no widely used method for estimating spatial patterns of deep catastrophic landslide susceptibility.

In the last several years, we studied about deep catastrophic landslides. First, Uchida *et al.* (2007) examined roles of bedrock geology and rock uplift rate on regional frequency of deep catastrophic landslides. Also, Suzuki *et al.* (2007) and Yokoyama *et al.* (2011) examined positional relationships between deep catastrophic landslide, landforms and geological structures. Based on these results, Tamura *et al.* (2008) and Uchida *et al.* (2011) proposed a new method to estimate landslide susceptibilities for many small catchments (ca. 1 km^2) over relatively large areas (ca. hundreds of km^2). Then, Takezawa *et al.* (2010) and Uchida *et al.* (2011) confirmed applicability of our proposed method to assess deep catastrophic landslide susceptibility using recent landslide maps. Finally, we argued prediction of run-out processes of large scale debris flow triggered by deep catastrophic landslide. Takezawa *et al.* (2009) and Nishiguchi *et al.* (2011a) surveyed characteristics of large scale debris flow triggered by deep catastrophic landslide. Then, Nishiguchi *et al.* (2010; 2011b) proposed a new method for clarifying potential area damaged by deep catastrophic landslide. Here we introduce recent advances about methods for prevention of deep catastrophic landslide. since several papers published by only Japanese. Moreover, we will synthesize these advances, since a combination of several methods is very important to conduct countermeasures for prevention of deep catastrophic landslide,

2. Deep catastrophic landslide frequency map of Japan

It has been considered that rock uplift rate, climate and bedrock geology affect occurrence of deep catastrophic landslide (e.g., Montgomery, 2001; Korup *et al.,* 2007). However, the information about rock uplift rate and bedrock geology has not been used for assessing deep catastrophic landslide susceptibility. While, Uchida *et al.* (2007) examined the role of rock uplift rate and bedrock geology on deep catastrophic frequency using historical landslide inventories.

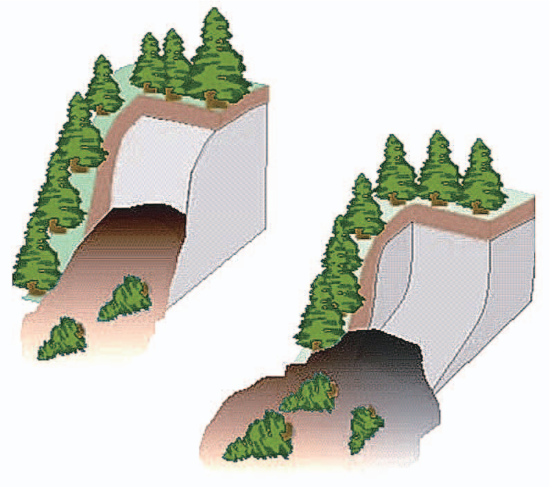


Fig.1 Schematic illustration of shallow land slide and deep catastrophic landslide

At first, we compiled an inventory of deep catastrophic landslide ($V>10^6 m^3$) in Japan since 1868 (Uchida *et al.,* 2007). We excluded from this dataset slow failures of a more chronic nature, such as deep-seated chronic landslides and deep-seated gravitational creep and rock flows. We only focused on the rainfall or snowmelt triggered landslide, but had excluded seismic landslide from this dataset. We only compiled landslides which had reliable information about location and occurrence date. Then, our dataset includes about 120 landslides (Uchida *et al.,* 2007).

Using this dataset, Uchida *et al.* (2007) examined the relationship between landslide frequency and rock uplift rate and bedrock geology. 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 Quaternary Research Group in 1968. This map shows total rock uplift amount from the beginning of the Quaternary. Quaternary Research Group estimated rock uplift rate based on topographic and geological field survey.

Uchida *et al.* (2007) clarified following points;

(1) Landslide frequency increased as the rock uplift rate increased.
(2) Rock type gave small impacts on landslide frequency
(3) Landslide frequency at areas underlain by Quaternary rocks was smaller than that of Tertiary and Paleo-Mesozoic rocks.
(4) Landslide frequency on accetionary 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. 2).

3. Assessing the deep catastrophic landslide susceptibility at catchment scale

1. Backgrounds

It has been argued that landforms, geological structures and topography may be useful indicators of deep catastrophic landslide susceptibility (e.g., Jitosono *et al.,* 2008). However, the information about relationship between landforms, geological structures and deep catastrophic landslides are limited to date. Consequently, there is no widely used method for estimating spatial patterns of deep catastrophic landslide susceptibility using the information about landforms, geological structures and topography.

So, at first, we investigated recent 18 deep catastrophic landslides in Japan and showed t that ancient deep catastrophic landslides were commonly observed at the area close to new deep catastrophic landslides (Suzuki *et al.,* 2007). Also, Suzuki *et al.* (2007) reported that the faults were often found in areas close to deep catastrophic landslides.

Next, we conducted detailed analysis about positional relationships between deep catastrophic landslide, landforms and geological structures by using dataset of Mt. Wanitsuka, Miyazaki Prefecture of Japan (Yokoyama *et al.,* 2011). Yokoyama *et al.* (2011) indicated that the density of deep catastrophic landslide decreased systematically away from the ancient deep catastrophic landslide, active faults and landforms affected by long-lasting gravitational mass movement (e.g., down-hill facing scarp, rock creep slope etc. please see Fig. 3). According to both previous studies and our recent studies, we summarized landforms which often observed at the area close to deep catastrophic landslides, as shown in Fig. 3 (Uchida *et al.,* 2011).

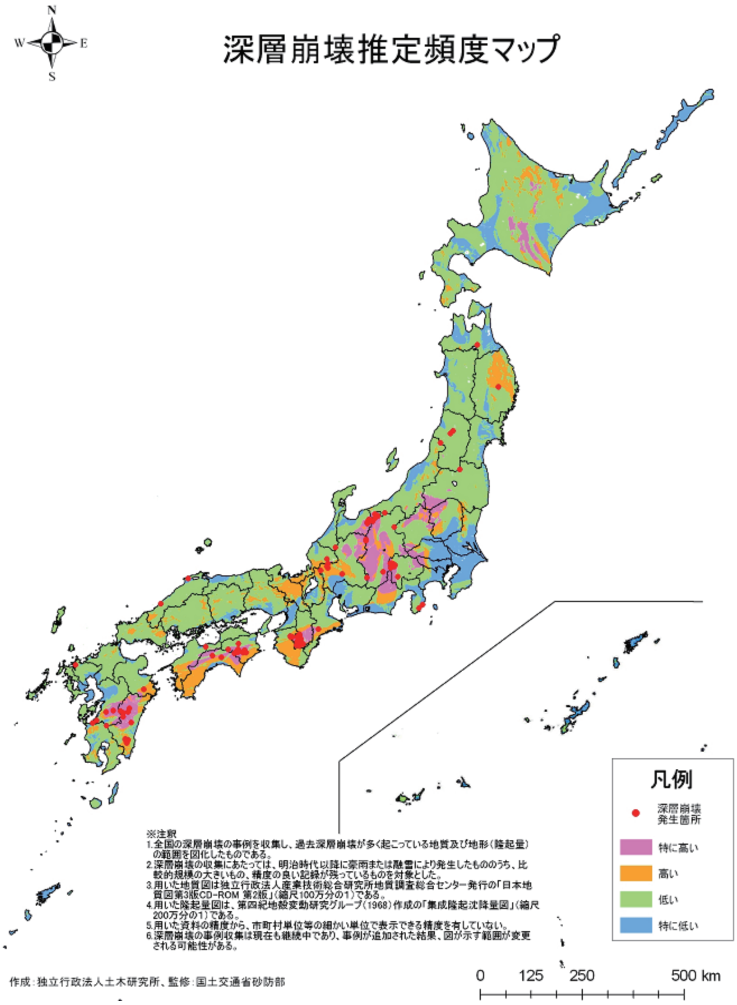
2. Proposed method

Tamura *et al.* (2008) and Uchida *et al.* (2011) propose a new method to estimate landslide susceptibilities for many small catchments (ca.

1 km^2) over relatively large areas (ca. hundreds of km^2). Our method identifies catchments prone to deep catastrophic landslides according to three criteria (Fig. 4):

(1) catchments with ancient deep catastrophic landslide scars,
(2) catchments with faults and landforms due to long-lasting mass movements (see Fig. 3),
(3) catchments with many steep slopes that have large upslope contributing areas.

Moreover, we proposed that the susceptibility of a given catchment increases with the number of these criteria that are satisfied (Fig. 4). To determine detailed criteria about faults, landforms and topography (ca. What kinds of landforms are useful indicators for a given site? What is the relationship between landslide occurrence and topography, such as slope gradient and upslope contributing area?), we conducted preliminary analyses. Because landslide processes are strongly affected by bedrock geology and climate, we limited our preliminary



※注釈
1.全国の深層崩壊の事例を収集し、過去深層崩壊が多く起こっている地質及び地形（隆起量）の範囲を図化したものである。
2.深層崩壊の収集にあたっては、明治時代以降に豪雨または融雪により発生したもののうち、比較的規模の大きいもの、精度の良い記録が残っているものを対象とした。
3.用いた地質図は独立行政法人産業技術総合研究所地質調査総合センター発行の「日本地質図第3版CD-ROM 第2版」（縮尺100万分の1）である。
4.用いた隆起量図は、第四紀地殻変動研究グループ（1968）作成の「集成隆起沈降量図」（縮尺200万分の1）である。
5.用いた資料の精度から、市町村単位等の細かい単位で表示できる精度を有していない。
6.深層崩壊の事例収集は現在も継続中であり、事例が追加された結果、図が示す範囲が変更される可能性がある。

作成：独立行政法人土木研究所、監修：国土交通省砂防部

Fig.2 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. Areas of pink. orange, green and blue mean "very high frequency region", "high frequency region", "low frequency region" and "very low frequency region", respectively. Red circles in the figure represent locations of historic deep catastrophic landslide. (http://www.mlit.go.jp/common/000121614.pdf)

analyses to a study area with homogeneous bedrock geology and climatic conditions (Fig. 5). Based on the detailed criteria determined by the preliminary analyses, we assessed the susceptibility of deep catastrophic landslide for each small catchment in the study area. We used geological map and aerial photograph to map ancient deep catastrophic landslide, landforms and geological structures.

We applied our proposed method to study areas surrounding Mt. Wanitsuka, in Miyazaki Prefecture, western Japan and Mt. Kurikoma, in Iwate and Miyagi Prefectures, northern Japan (Takezawa *et al.,* 2010; Uchida *et al.,* 2011). Twelve deep catastrophic landslides occurred in the study area of Mt. Wanitsuka by a large typhoon in 2005, and 78 deep catastrophic landslides occurred in the study area of Mt. Kurikoma by a large earthquake in 2008. In both areas, the ratio of catchments with new deep catastrophic landslides to all catchments increased as the number of satisfied criteria increased. So, we successfully demonstrated the applicability of this method for deep catastrophic landslides triggered by both typhoons and earthquakes (Takezawa *et al.,* 2010; Uchida *et al.,* 2011). This means that our proposed method is effective for assessing deep catastrophic landslide susceptibility at catchment scale. However, we are thinking that assessing deep catastrophic landslide susceptibility at hillslope scale is necessary for conducing effective countermeasures.

4. Simulation of run-out process for a debris flow triggered by deep catastrophic landslide

1. Background

Most models are used to describe stony debris flows assume that they consist of solid and fluid phases (e.g., Takahashi, 1977). In models of this type, if the river bed or hill slope is stable, both sediments and interstitial water are assumed to be stationary (Fig. 6a). When sediments move in a debris flow, their motion under these models is considered to be laminar, while that of the interstitial water is turbulent (e.g., Hotta *et al.,* 1998) (Fig. 6b), so these models comprise a “solid phase” of sediments exhibiting laminar flow and a “fluid phase” of interstitial water exhibiting turbulent flow. While, several researchers hypothesized that the motion of fine sediments in a large-scale debris flow triggered by deep catastrophic landslides could be rep-

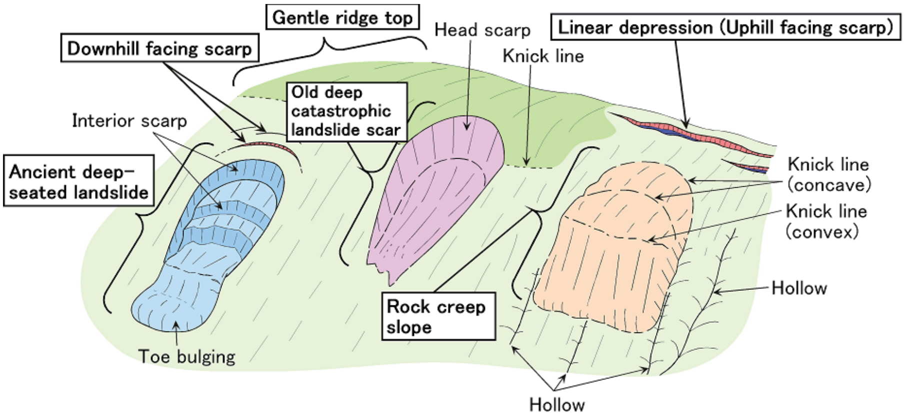


Fig.3 Conceptual diagram of landforms related to deep catastrophic landsliding (after Uchida *et al.,* 2011). “Old deep catatstrophic landslide” is often bounded by well-defined arcuate headscarp. “Rock creep slope” can be characterized by (1) poorly developed hollows, and (2) several concave and convex knicklines. Moreover, sides of rock creep slope are often bounded by hollows. “Ancient deep-seated landslide” often includes (1) well-defined arcuate headscarp, (2) several interior scarp and (3) bulging toe. “Gentle ridge top” is relatively flat-lying pan at ridge tops surrounded by convex knicklines

resented by a fluid phase, whereas the motion of the coarse sediment was that of a solid phase (e.g., Nakagawa *et al.,* 1998; Egashira *et al.,* 1998). However, there is no widely used method for predicating potential hazard area of large-scale debris flow triggered by deep catastrophic landslide.

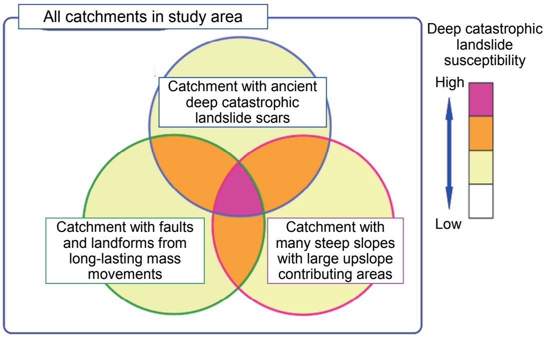
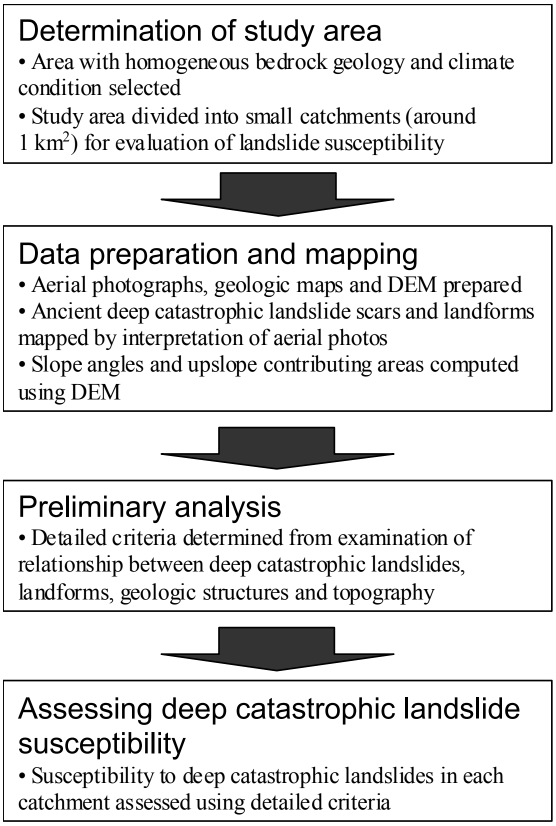


Fig.4 Schematic diagram of proposed method for assessing deep catastrophic landslide susceptibility (after Tamura *et al.*, 2008)



Determination of study area

- Area with homogeneous bedrock geology and climate condition selected
- Study area divided into small catchments (around 1 km^2) for evaluation of landslide susceptibility

Data preparation and mapping

- Aerial photographs, geologic maps and DEM prepared
- Ancient deep catastrophic landslide scars and landforms mapped by interpretation of aerial photos
- Slope angles and upslope contributing areas computed using DEM

Preliminary analysis

- Detailed criteria determined from examination of relationship between deep catastrophic landslides, landforms, geologic structures and topography

Assessing deep catastrophic landslide susceptibility

- Susceptibility to deep catastrophic landslides in each catchment assessed using detailed criteria

Fig.5 Flowchart of proposed method for assessing deep catastrophic landslide susceptibility (after Uchida *et al.*, 2011)

To clarify the characteristics of large-scale debris flow triggered by deep catastrophic landslides, we conducted field survey and compiled previous data for large scale debris flow (Takezawa *et al.,* 2009; Nishiguchi *et al.,* 2011a). Peak discharge of debris flows induced by deep catastrophic landslides were about from 10 to 100 times as large as that of peak discharge of debris flow induced by removal of unstable sediment on stream bed (Takezawa *et al.* 2009). This suggested that turbulence intensity of debris flows induced by deep catastrophic landslides was much larger than that of small scale debris flow. Moreover, Nishiguchi *et al.* (2011a) found that grain sizes of sediment in large-scale debris flow were widely distributed, compared to small-scale debris flow. So, we assumed that as similar to previous hypothesis proposed by Nakagawa *et al.* (1998) and Egashira *et al.* (1998), the motion of sediment in large-scale debris flow cannot described single type motion of sediments, since grain sizes of sediment were widely distributed and turbulence intensity was large.

2. Proposed method

To describe run-out processes of large-scale debris flows triggered by deep catastrophic landslides, we developed a technique for simulation of large-scale stony debris flows (Nishiguchi *et al.,* 2010). Based on field survey and previous studies, we assumed that the sediments in large-scale debris flows comprise two types of sediments, coarse sediments and fine sediments, and that the motion of the fine sediment in a debris flow is similar to that of the interstitial water (Fig. 6c). Then, we defined a maximum diameter for sediments that behave like a fluid (hereafter refer to “D_c”). On the basis of the concept, we characterized the key parameters for our numerical simulation, such as sediment concentration at the upper boundary of the numerical simulation (C_d), fluid density of the debris flow averaged in time and space (ρ), and representative particle diameter of sediment behave as solid phase in the debris flow (D), as follow; where $P(D_c)$ is the ratio of sediment smaller than D_c to all sediment, ρ_w is the water

$$C_d = (1-w)(1-P(D_c)) \quad (1)$$

$$\rho = \frac{w_d\rho_w + (1-w_d)\rho_s P(D_c)}{w + (1-w)P(D_c)} \quad (2)$$

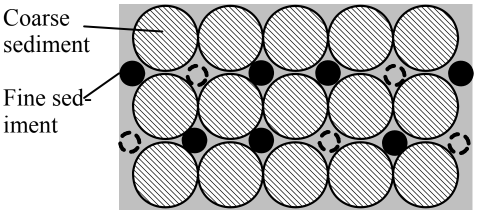
$$D = d(D_c) \quad (3)$$

density, ρ_s is the solid density of sediment, $d(D_c)$ is the weighted average particle diameter greater than D_c, w is the water content of landslide soil and bedrock, and w_d is water content of the debris flow averaged in time and space. We also modified the continuity equation for sediment in our simulation based on the definition of D_c (Nishiguchi *et al.,* 2011b).

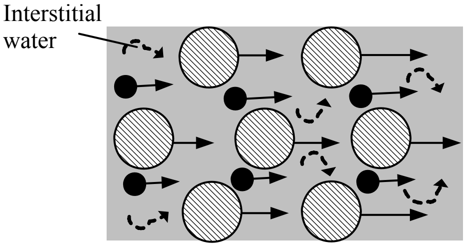
We conducted detailed field surveys of a past debris flow in Japan and used topographic data from LiDAR imagery (1 m resolutions), porosity measurements of soil and weathered bedrock, and the grain size distribution of the debris flow sediments to test our model. We also proposed a new process-based method for determination of hydrographs at the lower end of the landslide scar.

Using these new data and methods, we conducted numerical simulations of the past debris flow. We used the "Kanako2D" debris flow simulator, which can simulate 1D debris flows in gullies and 2D debris flows in alluvial fans (Nakatani *et al.,* 2008). This simulator can be applied to transport of sediments ranging from bed load to stony debris flow. Detailed governing equations were shown in elsewhere (e.g., Nakatani *et al.,* 2008; Nishiguchi *et al.,* 2011b). If we assumed $D_c = 0$, the calculated run-out distance was dramatically shorter than that of observed. However, if when the concept of fine sediment behaving like fluids was included in the numerical simulation, our simulation reproduced well the observed erosional and depositional pattern (Nishiguchi *et al.,* 2010) (Fig. 7).

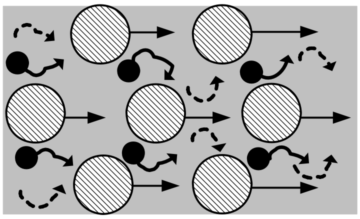
Further, we examined reality of values of D_c that we used in our numerical simulation. We assumed that if the turbulence intensity of interstitial water was large enough to suspend fine sediments, these sediments can act as part of



(*a*) *Static condition*



(*b*) *Small-scale debris flow*



(*c*) *Large-scale debris flow*

Fig.6 Conceptual diagram of static condition, small-scale debris flow and large-scale debris flow triggered by deep catastrophic landslide (after Nishiguchi *et al.,* 2011b)

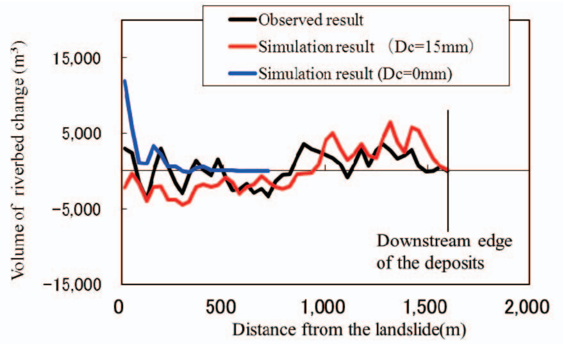


Fig.7 Observed and simulated results of river bed change due to large-scale debric flow triggered by deep-catastrophic landslide in Atsumarigawa, Minamata City, Kyushu Japan. This debris flow occurred in July, 2003. Volume of river bed change was calculated as the total volume of river bed change at each section. Distances of sections were 35 m. (after Nishiguchi *et al.,* 2011b)

the fluid. To evaluate the turbulence intensity of interstitial water, we calculated turbulence velocity proposed by Hotta *et al.* (1998) and compared with the settling velocity of the fine sediment. We confirmed that the turbulence velocity of interstitial water were around much larger than the settling velocity of the fine sediment (Nishiguchi *et al.,* 2011b), supporting the reality of our numerical simulations.

5. A way forward

Here we introduced about (1) a new method to estimate deep catastrophic landslide frequency for regional scale, (2) a new method to estimate deep catastrophic landslide susceptibilities for many small catchments (ca. 1 km^2) over relatively large areas (ca. hundreds of km^2) and (3) a new method to estimate potential hazard area of large-scale debris flow triggered by deep catastrophic landslide. We combined several approaches, including historical data analysis, aerial photograph interpretation, geomorphological and geological surveys, statistical approach, numerical simulation etc. to provide new methods. However, to mitigate disasters by deep catastrophic landslide, we considered several efforts are still necessary. We proposed several key issues for future efforts, as follow:

(1) Method to estimate deep catastrophic landslide susceptibilities for hillslope scale (ca. 0.01 km^2)
(2) Method to estimate the volume of future deep catastrophic landslide
(3) Method to detect signature of deep catastrophic landslide, such as small-scale displacement
(4) Method design countermeasures for disasters induced by deep catastrophic landslide.

We believe several new techniques, such as airborne laser altimetry (e.g., Uchida *et al.,* 2010), differential interferometric synthetic aperture radar (e.g., Roering *et al.,* 2009), and helicopter-borne electromagnetic surveys (Suzuki *et al.,* 2009) etc., have to combine for providing new methods.

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