Characteristics of Deep Catastrophic Landslides around the World: Occurrences and Distribution

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We summarize published information on approximately 500 cases of deep catastrophic landslides (DCL) with volumes greater than 10^5 m^3. We then analyzed the characteristics of DCL around the world. The numbers of reported DCL increased from the 1990s in both Japan and around the world. This may be related to the development of monitoring and disaster prevention of DCL. Most DCL occurred within tectonically active regions such as Japan, Southeast Asia, New Zealand, the western part of the American continents, the European Alps, and the Himalaya. DCL in Japan tended to be smaller than those around the world. Rainfall-induced DCL were dominated by volumes of 10^4–10^6 m^3, whereas earthquake and volcanic-activity triggered DCL had volumes of 10^6–10^8 m^3 and greater than 10^9 m^3, respectively. Our worldwide database and shared information will aid the development of a platform for international cooperation on sediment management related to disaster and mitigation practices.

Key words: deep catastrophic landslides, distribution, characteristics, Pacific Rim, sediment-related disasters, mitigation

1. INTRODUCTION

Deep catastrophic landslides (DCL), also referred to as “sturzstroms” in early literature [*Hsü*, 1975], have induced various disasters such as debris flows, natural dam formation, and damage to downstream regions [*Kilburn and Pasuto*, 2003]. With failure depths that generally exceed 10 m into bedrock, DCL have occurred in many regions of the world [*Korup et al*., 2007; *Adikari and Noro*, 2010]. Since the 1980s, the word “catastrophic” has been applied to refer to rapid large-mass slope movements [e.g., *Schuster and Crandell*, 1984]. The frequencies of DCL within a given landscape are generally low compared with those of shallow rapid landslides (depth of failure less than 1 m). However, DCL and their resultant sediment production contribute to the characteristics of landscape features and long-term patterns in sediment delivery from headwater regions to coastal areas [*Dadson et al*., 2004; *Korup and Tweed*, 2007]. Therefore, examining the magnitude and frequency characteristics of deep catastrophic landslides is one of the key requirements for understanding the geomorphic evolution of a given landscape and for developing regional countermeasure plans for sediment disasters.

Deep catastrophic landslides are triggered by various factors including rainfall, earthquakes, and volcanic activities [*Schuster et al*., 2002; *Sidle and Ochiai*, 2006; *Cecinato*, 2011]. DCL features can also develop from an aggregate of small landslides. In contrast, failure planes related to DCL induce subsequent small-scale failures and soil erosion. Therefore, interactions between small and large landslides are important for understanding the mechanisms of landsliding. Moreover, topographic deformation, which may appear as fissures and cracks, may result in localized instability [*Uchida et al*., 2011]. Fractured and weathered bedrock combined with heavy rainfall induces changes in groundwater flow regimes that may contribute to the triggering of DCL during and after storm events

[*Tsu et al*., 2011]. Consequently, the magnitudes and frequencies of specific types of DCL may differ depending on geological and climactic conditions.

Based on the wide range of occurrences of DCL, the characteristics of DCL can be analyzed comprehensively to understand patterns of their magnitudes [*Uchida and Nishiguchi*, 2011]. The resultant damage associated with DCL may also differ depending on geological, tectonic, and climatic setting. Although some previous studies have cataloged the occurrences of large landslides [e.g., *Korup et al*., 2007], the potential occurrence and damage associated with such large landslides have not been examined fully with respect to magnitude. Moreover, Japanese datasets have not typically been incorporated into the data because information was not available in English. Therefore, the objectives of this study are to (1) gather information on the DCL that have occurred in Japan and around the world and (2) examine the distribution and occurrences of these DCL. In general, DCL are defined by their volume and failure depth; this study focused primarily on landslides with volumes greater than 10^5 m^3 because information on failure depth was limited.

2. METHODOLOGY

We collected data from previously published literature and then developed a database in ArcGIS. Primary literature for the dataset included *Korup et al*. [2007], *Larsen et al*., [2010], *Cecinato* [2011], and *Uchida and Nishiguchi* [2011]. Both worldwide and regional inventories were also included. In this database, we included various technical terms such as "giant landslide," "deep-seated landslide," "rockslide," and "rock avalanche." We defined all of these large-scale mass movements as DCL with area and volume more than 10^4 m^2 and 10^5 m^3, respectively. We distinguished slow deep-seated landslides in which most of the failure mass remained on the sliding plane as the failure mass was transported downstream. We summarized latitude, longitude, altitude, country, year of occurrence (or period of years), area and volume, depth of mass movement, and triggering factors (i.e., rainfall, earthquake, or volcanic activities). A map showing location, altitude, and local relief was calculated based on the Shuttle Radar Topography Mission (SRTM-30) [*Farr et al*., 2007]. Because local relief is one of the controlling factors for the occurrence of DCL, local relief was considered by the vertical difference in elevation between the highest and lowest points within a 5-km diameter from a given DCL occurrence [*Montgomery and Brandon*, 2002; *Korup et al*., 2007; *Takezawa et al*., 2013]. Local relief was also considered an indicator for topography development with respect to uplift and downward erosion [*Hirano*, 1971].

3. REGIONAL CHARACTERISTICS

We here highlight and summarize some representative DCL in various regions of the world.

3.1 Japan

The Japanese Archipelago with local relief ranging from 500 to 1500 m is one of the regions of the world having very frequent occurrences of DCL. Many DCL in this region occurred because of heavy rainfall. During typhoon Talas in September 2011, 72 DCL (area >1 ha) occurred in the Kii Peninsula of Japan [*Chigira et al.*, 2013]. The volumes of the

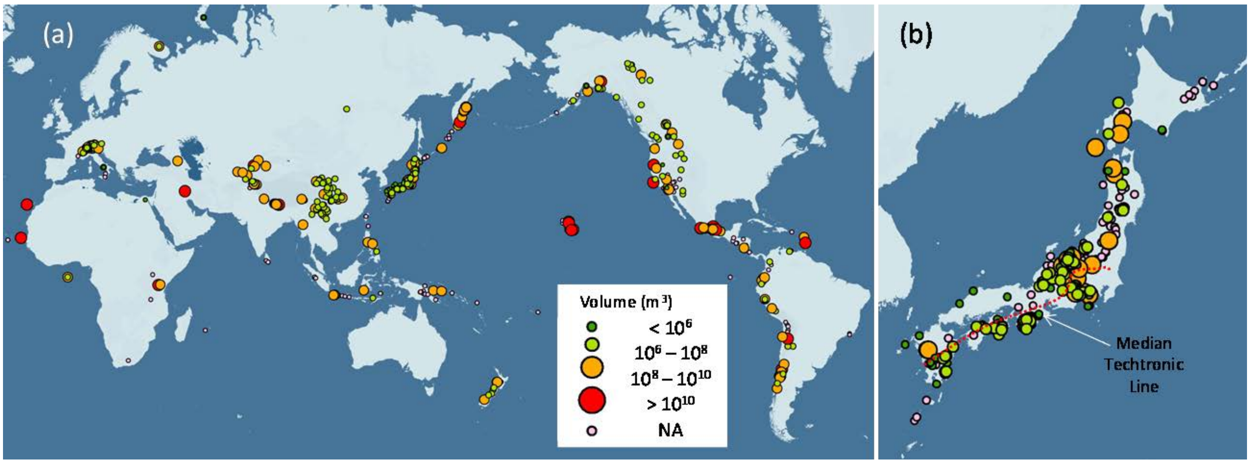

Fig. 1 Occurrences of deep catastrophic landslides (a) around the world and (b) in Japan. Sizes of circles indicate the volume of the landslides.

DCL ranged from 10^5 to 10^7 m^3. Historically, many DCL also occurred in this same area in 1891. Most of these DCL were concentrated in Jurassic to Paleogene sedimentary rocks. A linear depression and/or topographic knick line associated with long-term gravitational deformation of a hillslope is one indicator for susceptibility to DCL [*Uchida et al*., 2011].

DCL associated with high and intense precipitation have also occurred in the southern Kyushu area. In 2005, heavy rainfall accumulating to 600 mm in two days induced landslides with volumes of 10^5 to 10^6 m^3 on Wanizuka Mountain in Miyazaki Prefecture. *Shimizu* [2009] reported that this area was highly susceptible to various DCL that occurred in the 1930s. *Akther et al*. [2011] provided evidence of historical DCL based on radiocarbon dating of buried pieces of wood. This information for Japan suggested that areas that had experienced DCL have high potential for occurrence of additional DCL [*Uchida et al*., 2011].

3.2. East Asia

Many DCL and related disasters have also occurred in Taiwan [*Hung et al*., 2002] and China [*Chigira et al*., 2010] (**Table 1**). The famous Shaolin landslide in August 2009 produced a mass volume of 25×10^6 m^3 due to rock failures [*Tsou et al*., 2011]. These DCL were triggered by heavy precipitation of nearly 1600 mm over 3 days. In Taiwan, recent and past Tsao-Ling landslides have been well recorded as DCL [*Hung et al*., 2002]. Six DCL triggered by either heavy rainfall or earthquake occurred from 1862 to 1979. These landslides produced from 10^7 to 10^8 m^3 of sediment and formed natural dams in rivers.

3.3 Southeast Asia and New Zealand

Regions of Southeast Asia have also experienced various mass movements and disasters triggered by heavy rainfall. Catastrophic landslides with volumes of 10^6 m^3 occurred in Papua New Guinea in 2012 [*Robbins et al*., 2013]. In 2006, a large mudslide occurred in the Philippine province of Southern Leyte [*Catane et al*., 2007]. This DCL event produced a mass of 20×10^6 m^3 covering a total area of 3 km^2 and transport distance of 4 km. Some studies have described occurrences of DCL in Vietnam. For instance, landslides occurred in Bac Kan when continuous rainfall exceeded 180 mm [*Duc*, 2013]. Landslides in Binh Dinh province in December 2005 occurred in mountainous areas with slope gradients from 28 to 31 degrees. DCL with volumes of 10^5 m^3 occurred during storm events in Lang Chom.

Various researches have been conducted on both historical and recent DCL in New Zealand. Mount Cook in the Southern Alps collapsed in 1991 and produced 10^7 m^3 of sediment. The rock avalanche travelled 7 km downstream. Various dam formations related to DCL have been summarized by *Korup* [2005].

3.4 Himalaya and related regions

The local relief in these areas is the greatest in the world, and a large number of DCL have occurred. DCL and resultant debris flows have occurred in headwater regions of the Himalaya and produced severe damage downstream due to the debris flows and related flash flooding [*Waltham*, 1996]. DCL in this region can be triggered by rock avalanches

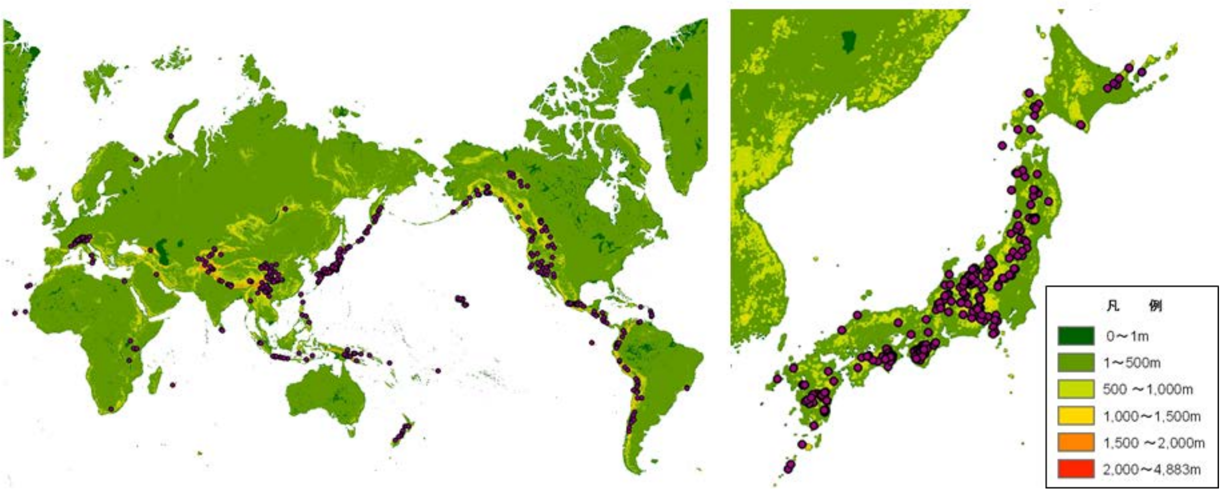

Fig 2. Local relief and occurrences of deep catastrophic landslides.

Table 1. Summary of DCL records after 1800 around the world.

Area	Number	Note
Japan	281	
East Asia and Central Eurasian continent	84	DCL in Russia and China, Taiwan were included.
Central Asia	14	DCL in Nepal and India were included.
Southeast Asia and Oceania	15	
Europe	24	
Africa	3	
North America	31	
Central and South America	30	
Total	482	

and/or earthquakes. For instance, large landslides triggered by rock-slope failure with 2000 m of relief occurred along the Seti River in May 2012 [*Ekstrom and Stark*, 2013]. These DCL also triggered flash floods downstream carrying rock, snow, ice, and glacially deposited fine fragments.

3.5. North and South America

Catastrophic landslides have occurred in Pacific coastal areas from Alaska to Patagonia. A large number of catastrophic landslides with volumes greater than 10^6 m^3 occurred in northern British Columbia from the 1970s to 2000s [*Geertsema et al*., 2006]. *Geertsema et al*. [2006] also concluded that the frequency of DCL has tended to increase, potentially because of climate change.

Schuster et al. [2002] summarized DCL that occurred in the Andes Mountains from Venezuela to Chile and in Argentina. For instance, DCL with estimated volumes of 10^9 m^3 occurred in Peru in 1974. The DCL originated from rockslides from underlying sandstone and a natural dam formed by transported mass. The triggering mechanism of this event is unknown, but many DCLs around the Andes region have occurred due to earthquakes.

3.6. Europe

The European Alps have been a subject of research on DCL for several decades. The Tessina landslides in the northeastern Italian Alps produced masses of more than 10^6 m^3 with sequences of events occurring from the 1960s. A catastrophic mass movement with a volume of 10^8 m^3 occurred in Vienna, Italian Alps, in October 1963. Overflowing and damage to the reservoir dam caused massive impacts downstream [*Van Westen and Lulie Getahum*, 2003] .

DCL have also occurred frequently in Iceland. Heavy rainfall triggered massive debris flows with volumes of 6–9 × 10^5 m^3 in the Solvadalur area [*Saemundsson et al*., 2003]. Because of its geology and frequent earthquake activity, Iceland's landscape is favorable for DCL.

4. OCCURRENCES

We identified 482 DCL that have occurred worldwide since 1800 (**Table 1**). DCL with large volumes and areas have occurred within tectonically active regions such as western Japan, Southeast Asia, New Zealand, the western part of the American continents, the European Alps, and the Himalaya (**Fig. 1a**). In Japan, DCL have occurred along the median tectonic line and in those parts of the Hokkaido area where the uplift rates range from 1 to 5 mm yr^{-1} (**Fig. 1b**). The spatial extent of occurrences of DCL is related to local relief **(Fig. 2)**,

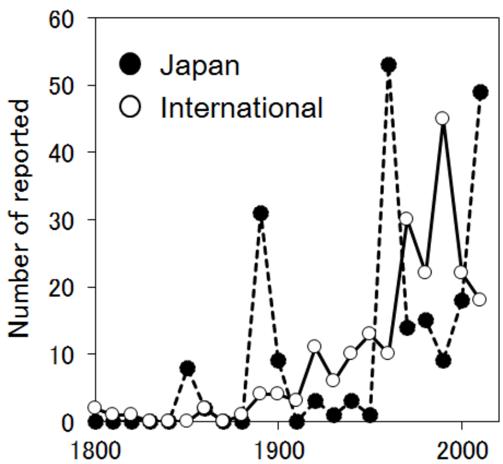

Fig 3. Number of reported landslides in the Japanese and international datasets.

and the frequencies of such DCL can be potentially high in these high-relief areas [*Aoto et al*., 2014]. DCL are also important factors in long-term erosion processes [*Hirano et al*., 1971; *Korup et al*., 2007], as well as in uplift and downward erosion rates [*Komatsubara et al*., 2014].

The number of DCL occurring after 1800 is shown in **Fig. 3**. Since 1900, the numbers of reported DCL have been increasing. Historically, DCL have occurred on a geological time scale and have established a "template" for regional topographic conditions (*Korup et al*., 2007). The patterns of the dataset indicate that large DCL have become much better known since intensive and detailed investigations started being conducted after the disasters. The greatest numbers of DCL in the global dataset were reported in late 1990s to 2000s (**Fig. 2**). This result may also relate to social awareness and the increasing impact of DCL around the world. Other associated factors may include rapid population growth and land-use changes around mountainous regions, especially in developing areas.

The Japanese dataset showed similar patterns because modern scientific observations for DCL have been developed and conducted since the early 20th century. Shallow rapid landslides occurred commonly in the 1960s to 1970s because of rapid land development and forest degradation. However, occurrences of DCL were more pronounced and had greater impacts on local communities in the 1990s and afterward (**Fig. 3**). Occurrences of DCL also showed some periodic patterns in the Japanese dataset. For instance, higher numbers of occurrences appeared in the 1890s, 1960s, and 2010s [*Uchida and Nishiguchi*, 2011]. These researchers, however, stated that these patterns may be somehow adventitious. Hence, studies of patterns and triggering factors (e.g., earthquakes and heavy rainfall) are important for investigating regional characteristics of DCL frequency.

5. SIZE AND TRIGGERING FACTORS

In Japan, most of the DCL volumes appear to range from 10^5 to 10^7 m^3. On the other hand, DCL volumes in the global dataset show a peak at 10^8 m^3 (**Fig. 4a**). This pattern may be associated with a bias in the dataset such that worldwide data are more skewed toward larger DCL sizes compared with Japanese data. Moreover, because the mean local relief worldwide tended to be higher than that in Japan, it is also possible that DCL volumes could potentially be greater at mountain slopes with higher relief.

Differences in triggering factors of DCL may also affect DCL volume. Rainfall-induced DCL are dominated by volumes ranging from 10^5 to 10^6 m^3, whereas DCL triggered by earthquakes and volcanic activities have volumes ranging from 10^6 to 10^8 m^3 and $>10^9$ m^3, respectively (**Fig. 4b**). For instance,

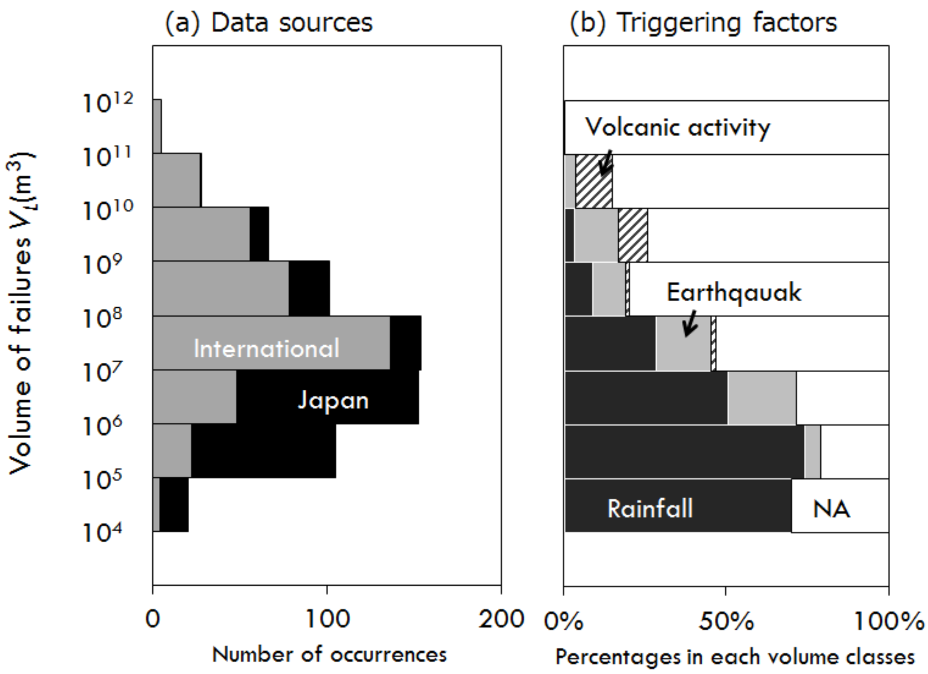

Fig. 4 Occurrences (a) and triggering factors (b) of deep catastrophic landslides.

DCL induced by heavy rainfall in locations such as Japan and Papua New Guinea had volumes ranging from 10^5 to 10^6 m^3 [*Robbins et al*., 2013]. Landslides on Mt. St. Helens, USA, in 1980 produced a mass of 10^9 m^3 [*Voight et al*., 1981], and landslides on Mt. Barakawaeng, Indonesia, in 2004 had a volume of 10^8 m^3 [*Shimizu et al*., 2008].

6. SUMMARY AND CONCLUSIONS

Our database revealed global patterns and characteristics of DCL occurrences. Based on global records of sediment damage, *Adikari and Noro* [2010] demonstrated that approximately 60% of 21,000 fatalities associated with sediment disasters occurred in Asian countries, followed by 25% on the American continents. This pattern suggests that areas with rapid population growth and migration of local populations to mountainous areas are most vulnerable to landslide damage to local settlements [*Petley et al*., 2005]. Although DCL have occurred in developed areas, such as Japan and Europe, observation and evacuation practices have been applied rather effectively compared with developing countries. Therefore, the numbers of fatalities in Japan and Europe may have been lower.

Despite such mass movement and disaster characteristics, patterns and occurrences of DCL remain relatively unknown for the purposes of prediction and mitigation. Therefore, comprehensive perspectives and analyses of landslides from small to DCL are important for determining their characteristics [*Klar et al*., 2012]. With frequency information for DCL [e.g., *Aoto et al*., 2013], spatial and temporal patterns of sediment movement can be characterized, and it may be possible to predict the resultant disasters and damage. These worldwide databases and shared information will aid the development of a platform for international cooperation in sediment management related to disasters and mitigation.

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