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Geological and Geomorphological Characteristics of Deep-Seated Catastrophic Landslides Induced by Rain and Earthquakes

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ABSTRACT Deep-seated catastrophic landslides are large, rapid mass movements that are usually accompanied by rock avalanches and can devastate wide areas; therefore, prediction of the potential sites of such landslides is essential to mitigate these hazards. Geological and geomorphological data from recent landslides may contribute to identifying potential landslide sites. Rain-induced landslides may have a characteristic hydrogeological structure, in which a permeable layer overlies an impermeable layer. Many rain-induced and earthquake-induced landslides are preceded by gravitational slope deformation; the topographic consequences of this, such as linear depressions or scarplets, may be useful for prediction. Existing landslide bodies are very unstable and easily reactivated by earthquakes, and can move catastrophically, which may occur if the material has collided with the opposing slope and has stabilized, and is subsequently undercut by erosion. Earthquakes induce first-time landslides in pyroclastics, carbonate rocks, water-saturated valley fillings, and other geological bodies under certain conditions.

Key Words: Deep-seated landslide, gravitational slope deformation, catastrophic landslide, rain, earthquake.

1. Introduction

A catastrophic landslide is a rapid, large mass movement that usually accompanies rock avalanches or sturzstroms (Heim, 1932), devastating wide areas. When landslides yield a large volume of debris, landslide dams frequently occur and can form lakes, leading to flooding upstream and downstream if dams are breached. If a landslide is induced during a heavy rainstorm, the landslide dam would be at risk of breaching because of a rapid rise in water level (Chigira, 2009; Tsou *et al.,* 2011). Many catastrophic landslides have been induced by earthquakes (Voight, 1978; Evans and DeGraff, 2002; Hewitt, 2006) and less numbers by rainstorms (Sidle and Chigira, 2004; Catane *et al.,* 2007, 2008; Evans *et al.,* 2007; Guthrie *et al.,* 2009; Tsou *et al.,* 2011). The largest recorded earthquake-induced examples are the Usoi landslide, with a volume of 2 billion m^3 (Schuster and Alford, 2004), and the Daguanbao landslide, with a volume of 0.837 billion m^3 (Huang *et al.,* 2008; Chigira *et al.,* 2010); the latter was induced by the 2008 Wenchuan earthquake in Sichuan, China. Keefer (1984) and Rodriguez *et al.* (1999) summarized earthquake-induced landslides and discussed the relationship between their distribution and earthquake magnitude. The largest recorded catastrophic rain-induced landslides are the Shiaoling landslide in Taiwan, with a volume of 25 million m^3 (Tsou *et al.,* 2010), and a landslide in Leyte in 2006, with a volume of 15 million m^3 (Catane *et al.,* 2007; Evans *et al.,* 2007).

Several mechanisms have been proposed for the fast, long runout movement of debris: grain collision (Heim, 1932), air-layer lubrication

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(Shreve, 1966), sliding surface liquefaction (Sassa *et al.,* 1996), pressure from vaporized pore water (Goguel, 1978), acoustic fluidization (Melosh, 1979), and rock fragmentation (Davies and McSaveney, 2009). Multiple mechanisms may operate during a given failure event, depending on the geological, geomorphic, and hydrological conditions.

To mitigate the effects of catastrophic landslides, site prediction is required. Potential landslide sites should be selected from wide areas and selection must be based on topographic and geological features because deterministic approaches, such as sophisticated slope stability analysis, require detailed information on geological structure, groundwater conditions, and geotechnical properties. Many catastrophic landslides have been preceded by gravitational deformation (Chigira and Kiho, 1994; Kilburn and Petley, 2003; Crosta *et al.,* 2006; Geertsema *et al.,* 2006), which could provide clues to help predict potential landslide sites. However, not all catastrophic landslides are preceded by gravitational deformation, particularly when they are induced by earthquakes.

This study provides a review of case studies of recent catastrophic landslides induced by rainfall and earthquakes, in order to clarify the topographic and geological features of potential landslide sites and thereby contribute to the establishment of a methodology for predicting potential sites. Most of the landslides considered in this study occurred in humid, temperate, or subtropical Asian countries.

2. Deep-seated catastrophic landslides induced by rain

1. Recent deep-seated landslides induced by rainstorms

The characteristics of rainfall-induced landslides are controlled by rainfall pattern as well as geological and geomorphic conditions. Shallow landslides are typically induced by intense rainfall, while deep-seated landslides require large volumes of water. Table 1 lists recent rainstorm disasters in Japan. The rainfall data for these disasters are not discussed in this paper, but they indicate that deep-seated landslides and shallow landslides have occurred during rainstorms with different characteristics in most cases. In addition, large landslides commonly occur after the maximum rainfall intensity or even after the cessation of rainfall (Chigira, 2009; Tsou *et al.,* 2011), possibly because the initiation of such landslides requires a longer period of increasing groundwater pressure.

2. Geology of rain-induced deep-seated landslides

Large landslides induced by rainstorms are initiated by the build-up of groundwater pressure, and are therefore affected by groundwater behavior below slopes. Groundwater permeates more easily in permeable materials, such as fractured rocks or young volcanic rocks. Areas of volcanic rock may therefore be susceptible to rainstorm-induced landslides. On 20 July 2003, a large rockslide (26,000 m^3) was induced by a rainstorm at Minamata in the west of Kyushu Island, Japan (Fig. 1), producing a debris avalanche that rushed downslope, hitting houses and resulting in 15 fatalities (Chigira and Sidle, 2004; Sidle and Chigira, 2004). This landslide had a typical hydrogeological structure, in which jointed andesitic lava was underlain by massive autobrecciated lava and heavily weathered, clayey, tuff breccias without fractures. The autobrecciated lava was well cemented with no open spaces and was therefore assumed to be essentially impermeable. The andesitic lava slid on the tuff breccias. This landslide could have been caused by a build-up of pore-water pressure within the fractured andesitic lava on top of the impermeable material.

Landslides of a similar type occurred during the 1998 Fukushima rainstorm (Chigira, 2002). This type of landslide is commonly accompanied by water gushing and is highly mobile. Based on the results of finite element analysis, Reid (1997) reported that slope stability at the base of a horizontal permeable layer, overlying an impermeable layer, is decreased during a rainstorm event.

3. Rain-induced catastrophic landslides preceded by long-term gravitational deformation

Large landslides induced by rainfall are commonly preceded by gravitational slope deformation, which could be used as a clue to predict potential landslide sites (Chigira, 2009). Gravitational slope deformation that involves volumes greater than around 100,000 m^3 may be detected using aerial photographs. This is based on the experience of rainstorm disasters in 2004 in Miyagawa and in 2005 in Mimikawa, both in Japan (Tables 1, 2).

Landslides that occurred during the 2004 Miyagawa disaster were of several types. The Satonaka landslide, which killed 5 people, had a wedge-shaped sliding surface consisting of two faults. Aerial photographs taken before the landslide clearly show that steps had formed on a slope surface along the two faults, suggesting displacement along the faults (Fig. 2). The Kasugadani landslide, which was the largest during this disaster, was also preceded by small displacements, resulting in a scarplet along a ridge top. These displacements have not been quantified, but appear to be on the scale of meters or tens of meters.

A 2005 rainstorm in Kyushu induced five large, catastrophic landslides along the Mimi River. A comparison of aerial photographs taken before and after the disaster reveals that all five landslides were preceded by gravitational deformation, which formed scarplets along their tops (Chigira, 2009). Displacement along the scarplets was less than 16% of the total slope length. The scarplets, which are likely to have been the surface extensions underground slip surfaces (shear surfaces), were therefore small and presumably did not extend further downslope. Moriwaki (2001) performed a statistical analysis of various field and experimental data on landslides and found that failure is triggered at a critical strain, defined as the ratio between displacement of a slope in its upper part and the slope length just before landsliding. This measure is consistent with the ratio between the length of a scarplet and the slope length, as discussed above. The critical strain obtained by Moriwaki (2001) varied from 0.006 to 0.02, smaller than the values obtained in this study, but this may support the idea that the landslides considered in the current study were in a critical condition just before failure (Chigira, 2009). These landslides were caused by geological and structural factors (Table 2).

The Shiaolin landslide, which was induced in 2009 by Typhoon Morakot in Taiwan and killed over 400 people, was one of the largest recorded rain-induced landslides. Satellite images taken before the landslide clearly show irregularly shaped bulges and depressions within the future source area, indicating that gravitational slope deformation had already occurred (Tsou *et al.,* 2011). This type of deformation has been observed since the landslide in many outcrops in the source area. Deformation was of the buckling type, which may be the most likely to induce failure because when

Fig.1 Rockslide-avalanche induced by a rainstorm at Minamata, Kyushu, in 2003. Photograph taken by the Asia Air Survey Corporation

Table 1 A list of recent rainstorm disasters in Japan. Typhoon Morakot in Taiwan is included for reference

Date	Trigger	Place (Prefecture)	Geology	Large landslide	Many Shallow landslides
29 June 1999	Rain (Baiu front)	Hiroshima	Granite	—	○
28-29 July 2000	Rain (Front)	Rumoi (Hokkaido)	Soft sedimentary rocks	—	○
11-12 Sept. 2000	Rain (Front+T14)	Tokai	Granite	—	○
20 July 2003	Rain (Front)	Minamata (Kumamoto) Hishikari (Kagoshima)	Andesite lava and pyroclastics	○	○
9-10 Aug. 2003	Rain (T10)	Hidaka (Hokkaido)	Soft sandstone and conglomerate	—	○
Ditto	Ditto	Ditto	Melange	—	○
13 July 2004	Rain (Baiu front)	Nagaoka (Niigata)	Mudstone	—	○
Ditto	Ditto	Fukui	Volcanic rocks	—	○
28-29 Sept. 2004	Rain (T21)	Miyagawa (Mie)	Hard sedimentary rocks	○	—
1 Aug. 2004	Rain (T10)	Kisawa (Tokushima)	Greeenstone and hard sedimentary rocks	○	—
29 Sept. 2004	Rain (T21)	Ehime-Kagawa	Hard sandstone and mudstone	—	○
29 Sept. 2004	Rain (T21)	Saijo (Ehime)	Schist	○	○
6 Sept. 2005	Rain (T14)	Mimikawa (Miyazaki)	Hard sedimentary rocks	○	—
19 July 2006	Rain (Baiu front)	Okaya (Nagano)	Ash	—	○
21 July 2009	Rain (Baiu front)	Hofu (Yamaguchi)	Granite	—	○
16 July 2010	Rain (Front)	Shobara (Hiroshima)	Soil	—	○
9 Aug. 2009	Typhoon Morakot	Shiaolin (Kaoshiung)	Sedimentary rock	○	○

Table 2 A list of recent rain-induced landslides in Japan and two major landslides in Taiwan and Phillipine

Disaster	Landslide	Slope length (m) of source area	Slope inclination (°)	Volume (m^3)	Geology	Cause	Precursory topography	"Strain" (d/L) (%)	Casualty	Referebces
Mimigawa catchment by 2005 Typhoon 14, 2005	Koba	225	28	250,000	Ms (Shimanto G)	Shear zone	Scarplet and convex slope	7	0	Chigira (2009)
	Koba-N	300	35	1,130,000	Ss (Shimanto G)	High-angle minor fault	Scarplet and convex slope	5	0	
	Matsuo-shinbashi	450	30	1,280,000	Ms and Ss (Shimanto G)	Bedding and low-angle minor fault	Scarplet and convex slope	3	0	
	Shimato	200	34	360,000	Ss (Shimanto G)	Shear zone	Scarplet and convex slope	10	0	
	Nonoo	505	34	3,300,000	Ms and Ss (Shimanto G)	Bedding?	Scarplet and convex slope (undercut)	4	0	
Miyagawa cathment by the Typhoon 21, 2004	Kasugadani	220	40	500,000	Chert, Ms, Ss (Sambagawa belt)	Minor fault, Dip slope	Scarplet	-	0	Chigira (2007)
	Takidani	90	30	19,000	Greenstone (Sambagawa belt)	Wedge-pair of faults	Scarplet	-	5	
	Kotaki	45	33	5,000	Ms (Sambagawa belt)	Dip slope along a fold axis	No	-	1	
	Ooi	80	40	50,000	Ms (Sambagawa belt)	Buckling	No	-	0	
Saijo by the Typhoon 14, 2004	Arakawa	240	32	170,000	Pelitic schist (Sambagawa belt)	Minor fault	Scarplet and convex slope	-	0	
Southern Leyte, 2006	Guinsaugon	600	48	15,000,000	Volcanic, sedimentary and volcaniclastic rocks	Philippine fault	Tension crack?	-	Over 1100 people killed	Evans *et al.* (2007)
Typhoon Morakot, 2009	Shiaolin	1200	24	25,000,000	Ms, Ss, Sils	Dip slope, buckling, and wedge-shaped detachment	Irregularly shaped convex and concave slopes	-	ver 400 people killed	Tsou *et al.* (2010)

the lower limb of a buckle fold is removed, the whole upslope limb fails (Fig. 3). The beds that slid in the Shiaolin landslide were Miocene–Pliocene sandstone, mudstone, and siltstone. The sliding surface was wedge-shaped, defined by faults, joints, and bedding planes.

3. Deep-seated catastrophic landslides induced by earthquakes

Severe earthquakes have induced numerous mass movements of various sizes. Smaller landslides are usually concentrated on steep slopes and ridge tops because of the amplification of seismic shaking (Pederson *et al.,* 1994). Large, deep-seated landslides are controlled largely by local geological structure.

Keefer (1984) compiled data from earthquake-induced landslides and produced diagrams to illustrate how landslide distribution is controlled by distance from the epicenter of an earthquake or a fault. However, several earthquakes as large as magnitude 7 occurred recently in an area in Japan without a known active fault, which suggests that evaluating landslide potential on the basis of active fault distribution is difficult at present. Maps of landslide-susceptible could be made using the Newmark method (Newmark, 1965; Wilson and Keefer, 1983; Jibson *et al.,* 2000), which calculates the displacement of a surface layer by seismic shaking over limit equilibrium values, but requires assumptions regarding subsurface structure and mechanical properties, which are generally difficult to obtain over wide areas. Even if seismic shaking is predicted, variations in subsurface properties would be an obstacle to evaluating the stability of slopes using the New Mark method. The occurrence of earthquake-induced landslides is also affected by antecedent rainfall, which makes it difficult to predict such events. Table 3 shows recent major earthquakes that induced severe landslides, along with older earthquakes for comparison.

The following section summarizes the case histories of large, catastrophic landslides induced by earthquakes, focusing on their site characteristics. The landslides are classified as first-time slides, reactivation of existing landslides after collision with the opposite slope and undercutting by erosion, and landslides preceded by gravitational slope deformation. Subsequently, the effect of antecedent rainfall on earthquake-induced landslides is considered.

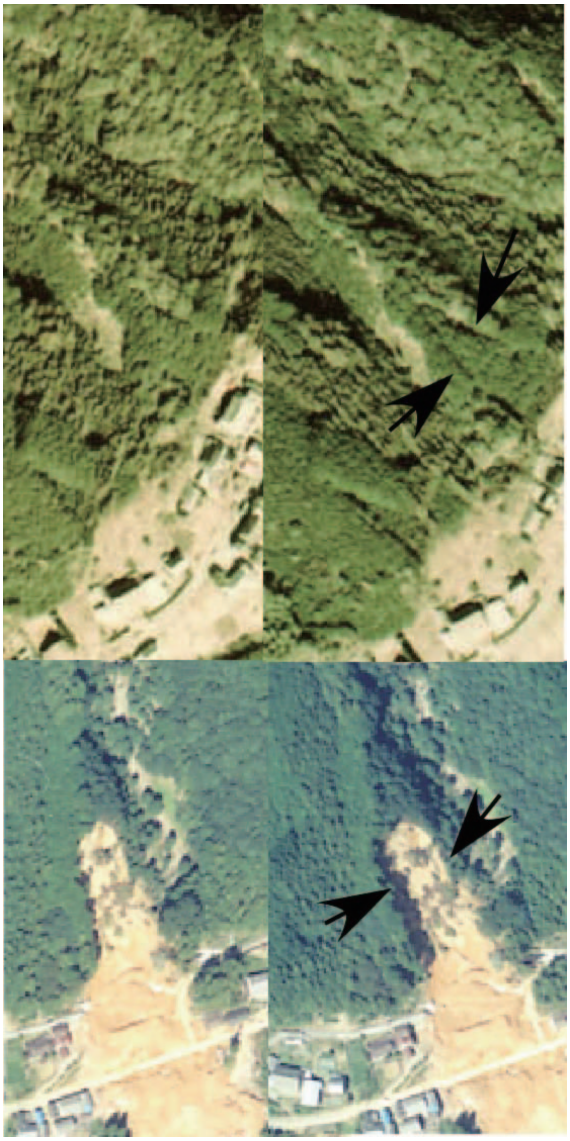

Fig.2 The rainstorm-induced Satonaka landslide. The upper two photographs are stereopairs taken before the landslide (Geospatial Information Authority of Japan). The lower two photographs are stereopairs taken after the landslide (Asia Air Survey Corporation)

1. First-time slides

(1) Landslides in pyroclastics

Pyroclastic fall deposits have featured in many highly mobile landslides induced by earthquakes, including the 1923 Kanto earthquake (Kamai, 1990), the 1949 Imaichi earthquake (Morimoto, 1950, 1951), the 1968 Off Tokachi earthquake (Inoue *et al.,* 1970), the 1978 Izu-Oshima Kinkai earthquake (Chigira, 1982), the 1984 West Nagano Prefecture earthquake (Fig. 4; Tanaka, 1985; Kobayashi, 1987), the 2001 Elsal Vador earthquake (Evans and Degraff, 2002), the 2009 Sumatra earthquake, and the 2011 Tohoku earthquake. The depth of sliding surfaces, which formed in weathered pumice, scoria, or ash, varied from 2–3 to 100 m. A clay mineral, halloysite, is a major component of layers in which sliding surfaces formed and is considered to have properties that are fragile during seismic shaking (Chigira, 1982). The Ontake landslide, induced by the 1984 West Nagano Prefecture earthquake, is the largest landslide of this type. It occurred on a slope that had been undercut by erosion. Pumice and scoria beds, in which the sliding surface formed, had been exposed at the bottom of the undercut slope. Many other landslides of this type have occurred on undercut slopes (Chigira, 1982).

The catastrophic landslides of pyroclastics induced by the 1968 Off Tokachi, 1978 Izu-Oshima Kinaki, and 2011 Tohoku earthquakes occurred on slopes as gentle as 8°, and the apparent friction angles ranged from 7° to 17° (Fig. 5), indicating the high mobility of landslides.

Table 3 A list of recent earthquakes, which induced many landslides. Three older earthquakes are shown for reference

Earthquake	Date	M	Fault type	Surface fault rupture	Geology	Geologic age	Reference
1949 Imaichin EQ	26 Dec. 8:17 8:25	6.4 6.7	?	yes	Sedimentary rocks Plutonic rock, Pyroclastics	Paleozoic-Quaternary	Morimoto (1951)
Off Tokachi EQ in 1968	16 May	7.9	Trench	—	Pyroclastics	Pleistocene	Inoue *et al.* (1970)
Izu-Oshima-Kinkai EQ in 1978	14 Jan.	7.0	Dextral	yes	Volcanics	Miocene-Pleistocene	Chigira (1982)
Chi-Chi EQ in 1999	21 Sept.	7.3	Reverse	yes	Sedimentary rocks	Paleogene to Quaternary	Wang *et al.* (2003)
Kozushima-Oki EQ in 2000	1 July	6.4	Trench	no	Volcanics	Quaternary	Miyazaki *et al.* (2005)
Elsalvador EQ in 2001	29 March	7.7	Trench	—	Pyroclastics Volcanics	Quaternary?	Evans and DeGraff (2002)
Mid Niigata Prefecture EQ in 2004	23 Oct.	6.8	Reverse	yes (obscure)	Sedimentary rocks	Neogene and younger	Chigira and Yagi (2006)
Northern Pakistan EQ in 2005	8 Oct.	7.6	Reverse and Dextral	yes	Sedimentary rocks Metamorphic rocks	Precambrian to Neogene	Petley *et al.* (2006)
Noto Peninsula EQ in 2007	25 March	6.9	Reverse	no	Sedimentary rocks Volcanic rocks	Neogene and younger	
Off Mid Niigata Prefecture EQ in 2007	16 July	6.8	Reverse	no	Sedimentary rocks	Neogene and younger	
Iwate and Miyagi Inland EQ in 2008	14 June	7.2	Reverse	yes (obscure)	Volcanic rocks and pyroclastics	Neogene and younger	
Wenchuan EQ in 2008	12 May	7.9	Reverse	yes	Sedimentary rocks Metamorphic rocks, Granite	Precambrian to Neogene	Chigira *et al.* (2010)
2011 Tohoku EQ	11 March	9	Trench	—	Sedimentary rocks Metamorphic rocks, Granite Pyroclastics	Paleozoic-Quaternary	

(2) Landslides in carbonate rocks

The 2008 Wenchuan earthquake induced thousands of landslides in carbonate rocks such as dolomite and limestone (Huang and Li, 2008). Sliding surfaces of many landslides in carbonate rocks are rough, with depressions and protrusions that formed by the dissolution of carbonate rocks by groundwater. Carbonate rocks are easily dissolved by groundwater, which flows through discontinuities such as bedding, joints, and faults, and decreases the area of rock surfaces in contact along the discontinuities, thereby reducing shear resistance and making a slope more susceptible to earthquake shaking (Chigira *et al.,* 2010). The voids created by dissolution make the rock mass highly permeable, meaning that rainfall generally does not cause pore-water pressure to build up sufficiently to cause a landslide.

The huge Bairaman landslide (0.2 km^3) was induced by a Mw 7.1 earthquake in 1985 (King *et al.,* 1989). The second and third largest non-volcanic landslides on earth, the Saidmarreh landslide in Iran, with a volume of 25 km^3 (Harrison and Falcon, 1937), and the Flims landslide in Switzerland with a volume of 12 km^3 (Heim, 1932), respectively, also occurred in limestone in prehistoric time. These two were presumably triggered by earthquakes. The largest landslide induced by the 2008 Wenchuan earthquake, the Daguanbao landslide, also occurred on a carbonate slope (see below for details).

(3) Landslides with unique geological structures

Weak rocks supported downslope by a buttress of competent rocks are susceptible to strong earthquakes, and if the support fails, catastrophic failure is likely to occur. The 1959 Hebgenlake earthquake (M7.1) induced the Madison landslide in Montana, with a volume of 21 million m^3, located 27 km from the epi-

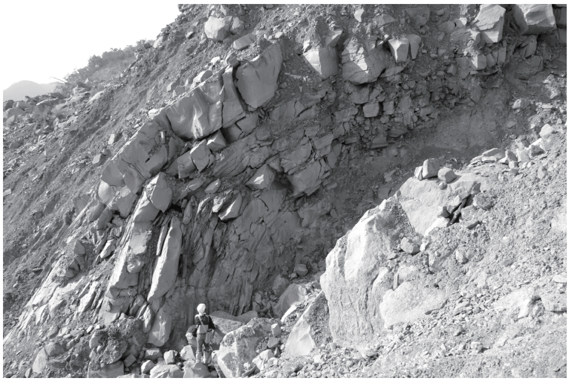

Fig.3 **Gravitational buckle fold developed in sandstone and mudstone in the source area of the 2009 Shiaolin landslide, Taiwan**

Fig.4 **The Ontake landslide induced by the 1984 West Nagano Prefecture earthquake (source: Shinano Mainichi Shimbun)**

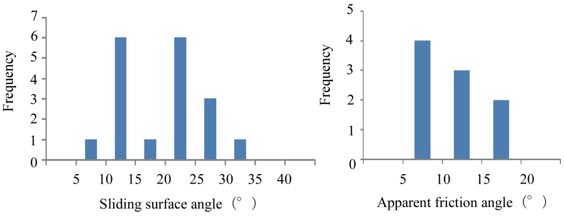

Fig.5 **Sliding surface angles and apparent friction angles of catastrophic landslides induced by four earthquakes: the 1923 Kanto earthquake, the 1968 Off Tokachi earthquake, the 1978 Izu-Oshima-Kinkai earthquake, and the 2011 Tohoku earthquake**

center (Hadley, 1964). The rocks that failed consisted of dolomite, schist, and gneiss, with foliation dipping downslope at 40° to 55°. Dolomite had occupied the foot of the slope and supported the weathered schist and gneiss at higher elevations before the landslide event. Once the dolomite buttress was destroyed by the earthquake, the whole slope slid down.

(4) Landslides due to excess pore-water pressure

Excess pore-water pressure generated by earthquake shaking can reduce the effective stress and induce catastrophic landslides of valley fill, artificial embankments, and unconsolidated sediments. Such landslides may be accompanied by liquefaction.

ALOS satellite images acquired after the 2008 Wenchuan earthquake reveal that some landslides have long lobate forms, suggesting they were accompanied by flow. A notable example is the Xiejiadian landslide, which occurred across the probable fault rupture. This landslide is 1.5 km long and up to 250 m wide, with an apparent friction angle of 22° (Chigira *et al.,* 2010). The headscarp is a steep cliff of Precambrian granite located above a small valley that channeled the flow. The volume of the failed rock mass is much less than the volume of the deposit. Bedrock in the valley below the cliff is overlain by bluish grey, water-saturated, clayey debris that formed before the landslide and was covered by the landslide deposit, which consists of water-saturated brownish debris with rubble. The surfaces of the landslide deposits are characterized by wrinkles, streaks of rock fragments of consistent color, and streaks of soil clods, as commonly observed in rock avalanches. A cross-section through the landslide debris near its distal end revealed reverse grading, in which larger blocks up to 5 m across are concentrated at the surface. These characteristics strongly suggest that valley fill sediments were mobilized by pore-water pressure build-up or liquefaction and flowed down the valley. Loading by landslide debris from above may have played a role in initiating the movement of the valley fill.

Similarly long, lobate landslides in valley bottoms were induced in more than 34 locations by the 2004 Mid Niigata Prefecture earthquake in Japan, which occurred after about 100 mm precipitation fell during the preceding 3 days (Chigira and Yagi, 2005). These events were also attributed to pore-water pressure build-up or liquefaction in valley fill material. The occurrence of liquefaction is indicated by muddy sand blows observed on landslide deposits (Chigira and Yagi, 2005). Sand blows were not observed on the deposits of the Xiejiadian landslide, but water-saturated clayey material was observed at its base and the movement mechanism was flow. These observations indicate that pore-water pressure build-up and possibly liquefaction caused the long runout. Long lobate landslides similar to the Xiejiadian landslide were recorded at 35 other locations in the affected area of the Wenchuan earthquake on 10-m-resolution ALOS AVNIR-2 images. The landslides ranged in length from 600 to 2830 m and had an average length of 1160 m.

On flat coastal areas in North America and Scandinavia, earthquakes have triggered landslides in quick clay, including the 1964 Alaska earthquake, which induced the Turnagain Heights landslides (Hansen, 1965; Seed and Wilson, 1967).

Some earthquakes are accompanied by abnormal water upwelling, triggering landslides in epicentral areas. This occurred during the 1965 Matsushiro earthquake in central Japan (Morimoto *et al.,* 1967; Tsuneishi and Nakamura, 1970), which was accompanied by surface ruptures aligned along a zone 2 km wide, in which 10 million m^3 of water was ejected over 2 months. The water upwelling induced three landslides, the largest of which had a volume of 100,000 m^3.

2. Reactivation of a landslide after collision with the opposite slope and subsequent undercutting

Landslides that have collided with the opposite slope, stabilized and then been undercut by erosion, are generally very unstable, because the downslope support has been removed. Many such landslides were induced by the 2004 Mid Niigata Prefecture earthquake, which hit an area containing many existing landslides (Chigira and Yagi, 2005). An earthquake in northern Pakistan during 2005 induced two large landslides of this type: Dandbeh (Hattian) and Pir Bandiwala. The former landslide was the largest during this earthquake and had a volume of 27 million m^3 (Chigira *et al.,* in preparation). Other reported volumes for the Dandbeh slide are 65 million m^3 (Schneider, 2008) and 68 million m^3 (Dunning *et al.,* 2007).

3. Landslides after gravitational slope deformation

Landslides induced by earthquakes, except for the first-time slides discussed above and the reactivation of existing landslides, are generally preceded by gravitational deformation. Gravitational slope deformation occurs in various forms, which can be classified (Fig. 6) for foliated rocks according to the geometric relationship between foliation and the slope (Chigira, 2000a). The different types include buckling, bending, sliding, and dragging, the first three of which are known to have preceded earthquake-induced, large, catastrophic landslides (Chigira *et al.,* 2003; Wang *et al.,* 2003; Chigira and Kiho, 1994).

Buckling deformation occurred before the Chiu-fen-erh-shan landslide in Taiwan (50 million m^3), which occurred on a dip slope of sedimentary rocks and was induced by the Chi-Chi earthquake (Ms 7.7) (Wang *et al.,* 2003). The sliding surface was along bedding-parallel faults, which developed during flexural slip folding. The buckling deformation appeared as a linear depression and a step on the slope. The earthquake fractured a thick sandstone bed at the foot of the slope that supported the beds at higher elevations, resulting in failure of the entire slope. The largest landslide induced by the 2008 Wenchuan earthquake may also have been preceded by this type of gravitational slope deformation (Chigira *et al.,* 2010), which appeared as a linear ridge-top depression.

Bending (or toppling) gravitational slope deformation is known to have preceded two gigantic landslides in Japan: the Kanagi landslide (>8.5 million m^3; Chigira, 2000b) induced by the 1707 Hoei earthquake, and the Shiratoriyama landslide (5 million m^3) induced by the 1707 Hoei earthquake (Anma, 1987; Tsuchiya, 2000). This type of gravitational deformation commonly appears as an array of linear depressions (Fig. 7). Some gravitationally deformed slopes of this type show evidence of continuous deformation, yielding sediment (Chigira and Kiho, 1994; Chigira, 2000a).

The sliding type of gravitational slope deformation may involve displacement along distributed sliding zones within a slope, although it would be concentrated along a limited number of sliding zones with relatively large amounts of displacement. The Tsaoling landslide (125 mil-

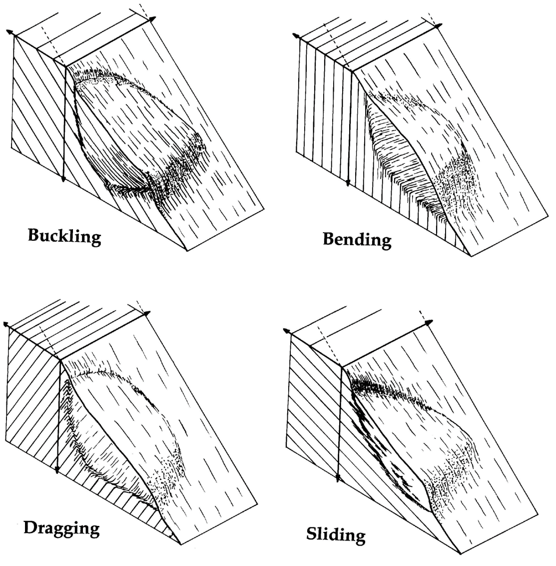

Fig.6 Schematic sketch showing the relationship between foliation and slope attitude (Chigira, 2000a)

lion m^3) was preceded by gravitational sliding along bedding planes. This deformation appeared as linear depressions aligned with and located near to the upper boundary of the future landslide.

4. Earthquake-induced landslides and antecedent rainfall

When focusing on earthquake-induced landslides, it is possible to neglect the effects of rainfall on landslide occurrence, but recent studies of earthquake-induced landslides suggest that antecedent rainfall has a strong influence on such events (Dellow and Hancox, 2006; Chigira, 2007). Antecedent rainfall, therefore, should be examined carefully when analyzing the frequency, distribution, and type of earthquake-induced landslides. This is particularly important when making a statistical model or validating deterministic models on the basis of case histories.

Here, landslide occurrence is examined for two cases in Japan. One case includes three earthquakes in weak sedimentary rock, and the other includes five earthquakes that induced landslides in pyroclastic fall deposits.

Three earthquakes (the 2004 Mid Niigata Prefecture earthquake (Mj6.8), the 2007 Noto Peninsula earthquake (Mj6.9), and the 2007 Off Mid Niigata Prefecture earthquake (Mj6.8)) hit areas of weak sedimentary rock on the northwestern side of Honshu Island, Japan. The affected areas had approximately the same geological and geomorphological settings, but the Mid Niigata Prefecture earthquake induced over 100 deep-seated large landslides, whereas the other two earthquakes induced a small number (<10) of large landslides. Comparing the antecedent rainfall for these three earthquakes (Fig. 8), it becomes obvious that the Mid Niigata Prefecture earthquake had been preceded by much more rainfall than the other events (170 mm in 10 days compared with <50 mm, re-

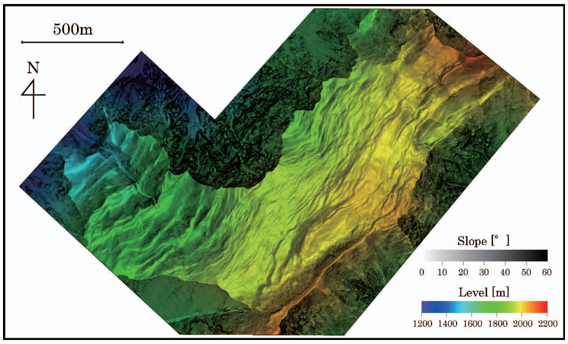

Fig.7 Topographic feature image, consisting of an elevation image superimposed on a slope image, around Aka-kuzure, showing many linear depressions or furrows associated with flexural toppling (Chigira and Kiho, 1994; Chigira, 2000a)

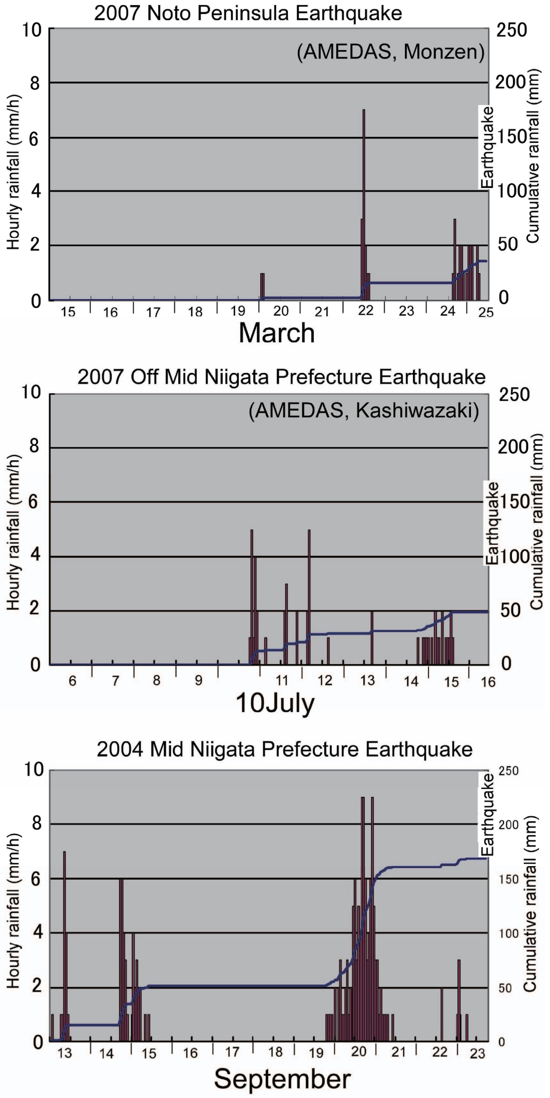

Fig.8 Antecedent rainfall during the 10 days before the 2004 Mid Niigata Prefecture earthquake, the 2007 Noto Peninsula earthquake, and the 2007 Off Mid Niigata Prefecture earthquake

spectively). In particular, 110 mm of rainfall fell on the 3 days preceding the Mid Niigata Prefecture earthquake, resulting in a special type of landslide that involved the mobilization of valley-fill material due to an increase in pore-water pressure and/or liquefaction, which was induced in many valleys in addition to on slopes.

Four examples of earthquakes that induced highly mobile landslides of pyroclastic fall deposits are the 1949 Imaichi earthquake (which induced >50 such landslides), the 1968 Off Tokachi earthquake (>150 landslides), the 1978 Izu-Oshima-Kinkai earthquake (7 landslides), and the 2011 Tohoku earthquake (10 landslides). The landslides induced by the Izu-Oshima-Kinkai earthquake were limited in number due to the limited distribution of the pyroclastic fall deposits; all seven landslides occurred within a small area of 1 km^2. The seismic intensities in the areas of the above landslides were 5 to 6 in the scale of the Japan Meteorological Agency (Table 4), and the intensities were highest in the landslide areas of the Tohoku earthquake. That the Tohoku earthquake induced much fewer landslides of this type could be attributed to the much smaller amount of antecedent rainfall in comparison with the other earthquakes, particularly within the 60 days before the earthquake. The sliding surfaces of the landslides by the four earthquakes stated above consisted of weathered ash, pumice, or palaeosol, which retain water for a long time in the ground and become much stiffer when dry.

4. Conclusions

Large, catastrophic landslides are generally induced by rainfall and earthquakes, and their site characteristics are closely related to the mechanism of their formation. A characteristic hydrogeological structure, in which a permeable layer overlies an impermeable layer, may be a fundamental cause of large rain-induced landslides. Their occurrence can be attributable to increasing pore-water pressure along the upper surface of the impermeable layer. Gravitational slope deformation is an important basic cause of rain-induced and earthquake-induced landslides. The buckling type of gravitational slope deformation, in particular, may be most susceptible to catastrophic movement. Gravitational deformation usually appears as topographic features (e.g., scarplets and linear depressions) that are indicative of a potential landslide site. Earthquakes induce catastrophic first-time landslides on slopes developed in pyroclastic fall deposits and in carbonate rocks, and on slopes with specific features, such as weak rocks supported by a competent buttress and the build-up of excess pore-water pressure by earthquake shaking. Previous landslides that collided with the opposite slope and were subsequently undercut by erosion are highly susceptible to earthquake shaking.

Table 4 A list of earthquakes, which induced landslides of pyroclastics in Japan. The rainfall data are from the AMEDAS of the Japan Meteorological Agency. The landslide data of the Imaichi earthquake and the Off Tokachi earthquake are based on Morimoto (1951) and Inoue *et al.* (1972), respectively

Earthquake	Date	Seismic intensity at the landslide sites (JMA-scale)	Antecedent rainfall			Landslides of pyroclastics
			10 days	30 days	60 days	
1949 Imaichi earthquake	26 Dec	5〜6	22.5	80.8	255	>50
1968 Tokachi-oki earthqua	16 May	5	181	292	307	>150
1978 Izu-Oshima kinkai earthquake	14 Jan	5〜6	12	172	334	7 (due to the limited distribution of the pyroclastics)
2008 Iwate-Miyagi Inland earthquake	14 June	5+〜6+	89	284.5	388	>100
2011 Tohoku earthquake	11 March	6+〜6−	12.5	83.5	93.5	~10

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