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Geological and geomorphological features of deep-seated catastrophic landslides in tectonically active regions of Asia and implications for hazard mapping

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Deep-seated catastrophic landslides, particularly rock or debris avalanches, travel extremely rapidly for long distances, causing severe damage over wide areas. This paper summarizes the geological and geomorphological features of such events, which were induced by earthquakes and rainstorms in Asia, and then uses these features to predict future potential sites of failures. Most of the rock avalanches are preceded by gravitational slope deformation with topographic features, in which small scarps along future head of landslide are the most representative; the scarps can be identified in topographic images made by high-resolution airborne LiDAR DEMs and may suggest the instability just before catastrophic failure. Earthquake-induced debris avalanches of pyroclastic fall deposits are not preceded by gravitational slope deformation but are of specific type and sequence of deposits, in which resiliicified paleosol with halloysite may be the most important to accommodate a sliding surface.

Introduction

The numbers of lives lost in landslides in tectonically active regions is generally constantly large in comparison with those resulting from episodic earthquakes or volcanic eruptions (Petley, 2012), although the latter have received more attention as fatal natural hazards. In recognition of the fatal nature of landslides in such regions, the Japanese government changed its policies regarding earthquake prediction research after the 2011 Tohoku earthquake, to also include earthquake-induced hazards such as landslides, since research only on earthquakes cannot mitigate the associated hazards that contribute to the scale of such disasters. Most Asian countries are located in tectonically active, high-rainfall areas, and devastating landslides triggered by rainstorms, earthquakes, and snowmelt are frequent in many locations. Recent notable triggers include the 2011 typhoon Talas (Chigira et al., 2013b), 2011 Tohoku earthquake in Japan, 2009 typhoon Molakot in Taiwan (Tsou et al., 2011), 2009 Padang earthquake in Indonesia (Nakano et al., 2013), and 2008 Wenchuan

earthquake and subsequent rainstorms in China (Chigira et al., 2010; Chigira et al., 2012a) (Table 1).

To mitigate landslide-induced disasters, it is necessary to know where and when landslides are likely to occur, and how and when to evacuate threatened areas prior to an event. Rock or debris slide avalanches are especially hazardous, and such events must be anticipated and prepared for, as they generally occur suddenly and travel quickly over long distances, affecting large areas. This paper focuses on the geological and geomorphological features of potential sites of rock or debris slide avalanches with respect to predicting the locations of these types of landslides.

Several approaches have been developed to predict potential sites of landslides, including those of physical modeling, stochastic modeling, and the indexing of geological and geomorphological features (Guzzetti et al., 1999). Physical modeling, such as slope stability analysis under conditions of heavy rainfall or an earthquake, requires information related for example to hydrological or geotechnical factors and subsurface structures, which are unavailable in many areas (Jibson et al., 1998; Montgomery et al., 2000). Stochastic modeling can be effective for investigating rather shallow landslides, which usually occur repeatedly in areas with particular geological characteristics, such as particular types of weathering profiles. In contrast, the occurrence of deep-seated catastrophic landslides is highly dependent on local and specific geological and/or geomorphological conditions. Therefore, an understanding of the typology of these specific conditions may allow predictions regarding potential sites of rock and debris slides.

On the basis of our studies on the geological and geomorphological features of catastrophic rock and debris-slide avalanches in Asian countries, I have reached the conclusion that it is possible to predict at least the potential sites of such events. Most of the catastrophic rock-slide avalanches induced by either rainstorms or earthquakes are preceded by a particular type of gravitational slope deformation (Chigira, 1992; Dramis and Sorrisovalvo, 1994; Kilburn and Petley, 2003; Crosta et al., 2006; Chigira, 2009), whereas debris-slide avalanches caused by earthquake-induced failure of pyroclastic fall deposits are not (Chigira, 1982; Chigira et al., 2014). The latter, however, occur in areas of a particular type of pyroclastic succession characterized by heavily weathered pyroclastics or paleosol(s) at depth.

In this paper, I summarize the geological and geomorphological features of potential sites of deep-seated catastrophic landslides as a basis for establishing a methodology of landslide hazard mapping.

Table 1. Recent landslide hazards in Asia

Country	Trigger	Type of landslide	Fatality by landslides	References
China	2008 Wenchuan earthquake	Landslide on natural slopes	>20000	Huang and Fan (2013)
	Rainstorms after the 2008 Wenchuan earthquake	Debris flows	3029	Chuan Tang (oral communication)
Taiwan	1999 Chi-Chi earthquake	Landslide on natural and valley fills of residential houses	39/Chiu-fen-erh-shan 29/Tsaoling	Chigira et al. (2003) Wang et al. (2003)
	Typhoon Molakot, 2009	Landslide on natural slopes	More than 400 by the Shiaolin landslide	Tsou et al. (2011)
Malaysia	Typhoon Greg, 1996	Landslide on natural slope	302	Lim Chounsian (oral communication)
Indonesia	2009 Padang earthquake	Landslide on natural slopes	More than 400	Nakano et al. (2013)
Phillipines	2006 Rain	Landslide on natural slopes	1100 by Ginsaugon landslide	Guthrie et al. (2009) Evans et al. (2007)
Japan	2011 Tohoku earthquake	Landslide on natural and valley fills for residential houses	12 by landslides (mostly by tsunami)	Chigira et al. (2014)
	Typhoon Talas, 2011	Landslide of natural slopes	56 by landslides	Chigira et al. (2013)

Catastrophic earthquake-induced landslides, such as those that have occurred in North America as a result of quick clay produced by glaciers (Hansen, 1965; Seed and Wilson, 1967), do not occur along the coastal regions of east or Southeast Asia, and therefore this type of landslide is not discussed here. Similarly, landslides induced by the collapse of large volcanic edifices, such as occurred during the 1982 Mt. Saint Helens event (Voight et al., 1983; Waitt et al., 1983),

are related to volcanic activity, not rainfall or earthquakes, and therefore also lie outside the scope of this paper.

Earthquake-induced landslides

Recent earthquakes, such as the 2011 Tohoku earthquake in Japan, 2009 Padang earthquake in Indonesia, 2008 Wenchuan earthquake

Figure 1. A typical catastrophic landslide induced by an earthquake on a slope of pyroclastic fall deposits. *The Hanokidaira landslide induced by the 2011 Tohoku earthquake.* (Photo courtesy: National Institute for Land and Infrastructure Management and Public Works Research Institute).

in China, 2008 Iwate–Miyagi inland earthquake in Japan, 2005 northern Pakistan earthquake, and 2004 Mid-Niigata Prefecture earthquake in Japan, have proved of use in understanding where and why large catastrophic landslides are induced by earthquakes. These landslides have generally occurred where chemical weathering or gravitational deformation of rocks have preceded and reached near-threshold conditions just prior to the catastrophic failure induced by earthquakes.

Landslides prepared by chemical weathering processes

Pyroclastic fall deposits

The 2011 Tohoku earthquake induced long-run-out catastrophic landslides in pyroclastic fall deposits with sliding surfaces in a halloysite-rich paleosol (Figure 1), which was originally formed by chemical weathering and then buried by subsequent pyroclastics. The paleosol, which had been formed by the leaching out of silica, alkali, and alkaline earth elements, reacted with percolating rainwater that had obtained silica during its infiltration through the new deposits, then resiliified and formed halloysite. This process is understood to be the primary reason for the occurrence of halloysite in these buried

paleosols (Chigira, 1982; Kleber et al., 2007; Chigira et al., 2014). Similar landslides involving a sliding surface in a paleosol have occurred during many other earthquakes (Table 2), including the 2009 Padang earthquake. The largest landslide of pyroclastic fall deposits was the 1984 Ontake landslide induced by the Naganoken–Seibu earthquake in Japan with a volume of $36 \times 10^6 \text{ m}^3$ (Okuda et al., 1985). It had a sliding surface in halloysite-rich weathered pumice bed (Tanaka, 1985). The next largest was the Las Colinas landslide, which had a volume of $1.83 \times 10^5 \text{ m}^3$, and which was induced by the 2001 El Salvador earthquake (Evans and Bent, 2004; Crosta et al., 2005); this landslide had a sliding surface in a paleosol even though clay minerals were not actually identified in that case. The distribution of halloysite-rich soil could be predicted by the study of both volcano-stratigraphic characteristics and weathering mechanisms.

Landslides of this type do not occur on steep slopes because the pyroclastic fall deposits themselves do not form slopes steeper than the angle of repose, and such landslides may occur on gentle slopes even shallower than 20° (Figure 2); these landslides are commonly very mobile with low equivalent coefficients of friction (Figure 2). Equivalent coefficients of friction are known to decrease with increasing landslide volume (Scheidegger, 1973; Hsu, 1975), but landslides of this type have exceptionally low values even for small-volume landslides (Figure 3).

Table 2. A list of catastrophic landslides of pyroclastic fall deposits

Earthquake		1949 Imaichi	1968 Tokachi-Okii	1978 Izu- Oshima-Kinkai	1984 Naganoken- Seibu	2011 Tohoku	2001 El Salvador	2009 Padang	2008 Iwate Miyagi Inland
Date		26 Dec.	16 May	14 Jan.	14 Sept.	11 March	13 Jan.	30 Sept.	14 June
Magnitude		Mjma 6.4	Mjma7.9 (Mw8.2)	Mjma 7.0	Mjma 6.8	Mw 9.0	Mw 7.7	Mw 7.5	Mjma 7.2
Seismic Intensity at landslide sites (JMA)		5~6	5	5~6	6	6~6+	MM 6, 7 4, 5- (JMA)	MM 8 (USGS) 5+ (JMA)	5+~ 6+
Antecedent rain (mm)	Rain gauge	Utsunomiya	Hachinohe	Inatori	Ontakesan	Shirakawa			Komanoyu
	10 days	22.5	181	12	183	12.5	no data (Nov.-Apr.: dry season) ^{h)}	Unknown (occurred during heavy rain)	89 284.5 388
	30 days	80.8	292	172	555	83.5			
	60 days	255	307	334	839	93.5			
Number of collapsing landslide		88 ^{a)}	152 ^{b)}	7 ^{d)} (controlled by the material distribution)	5 ⁱ⁾	<10 ^{e)}	>1000 ^{g)}	160 ⁱ⁾	>100
Sliding surface		Weathered pumice Halloysite ^{a)} Paleosol ^{m)}	Paleosol (Sandy ash) Halloysite ^{c)}	Paleosol Halloysite ^{d)}	Weathered pumice and scoria Halloysite ^{k)}	Paleosol Halloysite ^{e)}	Paleosol ^{f)} No report of clay minerals	Mixed layer of paleosol and pumice Halloysite ^{j)}	Various Many in weathered pumice
Slid material		Shichihonzakura pumice and Imaichi pumice ^{l)}	Towada- Hachinohe tephra ^{b,c)}	East Izu monogenic volcanic tephra ^{d)}	Scoria, lava, agglutinate, atterrace deposits,	Tephra from Nasu Volcano ^{e)}	Pumice etc.	Pumice (Qhpt)	Various
Source of the slid materials		Nantai volcano	Towada Volcano volcanoes	Higashi-Izu monogenetic	Ontake Volcano	Nasu Volcano ^{l)}	?	Tandikat Volcano ⁱ⁾	Various
Sliding surface depth (m)		3~5 m ^{a)}	<3 m ^{b)} , 01~2.5 m ^{c)}	2~6 m ^{d)}	5 m~200 m (Ontake) ^{j)}	3~9 m ^{e)}	50~70 m (Las Colinas) ^{f)}	3.5~5.5 m ⁱ⁾	-
Slope-parallel bedding		O	O	O	O	O	O	O	No
Undercut		Unknown	Unknown	O	O	O	O	Mostly	Various
Fatality		8	33	7	29	13	844 ^{g)}	600?	O

Reference: a: Morimoto (1951); b: Inoue et al. (1970); c: Yoshida and Chigira (2012); d: Chigira (1982); e: Chigira et al. (2012); f: Crosta et al. (2005); g: Jibson et al. (2004); h: Evans and Bent (2004); i: Nakano et al. (2013); j: Hirano et al. (1985); k: Tanaka (1985); l: Suzuki (1993); m: Chigira (unpublished data)

Figure 2. Slope angles and apparent friction angles of soilslide-avalanches of pyroclastic fall deposits. Data: 1923 Kanto earthquake (Kamai, 1990), 1968 Off Tokachi earthquake (Inoue et al., 1970), 1978 Izu-Oshima Kinkai earthquake (Chigira, 1982), 1984 Naganoken-Seibu earthquake (Tanaka, 1985; Hirano et al., 1985), and 2011 off the Pacific coast of Tohoku earthquake.

Carbonate rocks

Carbonate rocks are easily dissolved by carbonic acid in groundwater, thereby leading to the formation of karstic landscapes with features such as caverns and dolines. The 2008 Wenchuan earthquake induced numerous landslides of carbonate rocks (Table 3; Huang, 2011; Huang and Fan, 2013). Many of these landslides occurred on the dip slopes of well-stratified carbonate rocks with sliding surfaces developed along bedding planes. The sliding surfaces commonly have rough surfaces with dimple-like depressions and fractured protrusions, with the depressions being formed by the dissolution of carbonates (Chigira et al., 2010) and fractured protrusions being formed at the contact between the overlying slide rock and the rock beneath. Groundwater flow along a bedding plane dissolves carbonates and decreases the areas of contact between rock masses above and below the surface; these contacts are finally broken by seismic shaking. The enlargement of pore spaces, in contrast, drains groundwater, and hence pore-water pressure build up is unlikely to

occur during rainfall events. Catastrophic landslides of carbonate rocks were also induced in many places during the 2005 Kashmir earthquake (Sato et al., 2007).

Mudstone

Many slow-moving landslides in weak mudstone have been recorded in Japan, Malaysia, and Indonesia. These landslides are generally induced by melting snow or rainfall (Matsuura et al., 2008). Although rapid and catastrophic landslides of mudstone are generally not reactivated or newly induced by earthquakes, the 2004 mid-Niigata Prefecture earthquake triggered many such landslides in Neogene marine mudstone areas as well as in sandstone areas (Chigira and Yagi, 2005). Landslides in these areas may be related to the weathering of marine mudstone, whose weathering is dominated by the oxidation of pyrite (Chigira, 1990). Pyrite oxidation forms sulfuric acid, which in turn dissolves microfossils as well as other acid-labile minerals, and acts to deteriorate mudstone and to form micropores.

Thus, weakened mudstone with many micropores might be sheared during an earthquake, generating abnormally high pore pressures, in turn leading to liquefaction of the sliding surface (Sassa et al., 1996). This may be a reasonable cause of a catastrophic landslide in mudstone.

Mechanical preparation

The mechanical preparation for large earthquake-induced landslides is deep-seated gravitational slope deformation, which has preceded many landslides. Such landslides include the Daguangbao landslide, which was triggered by the Wenchuan earthquake and is one of the largest historic landslides (Chigira et al., 2012b), and the Chiu-fen-erh-shan and Tsaoling landslides, which occurred during

Figure 3. Equivalent coefficients of friction and landslide volumes. Landslides of pyroclastic fall deposits are plotted far below the trend of the other landslides.

Table 3. List of earthquake-induced landslides of various rocks with special references to geologic structures and precursory landforms.

Earthquake	Country	Magnitude	Seismic intensity at the landslide site	Landslide	Volume (10 ⁶ m ³)	Rock type	dip (°)	Structure*	Precursory landform	Reference Chigira
715 earthquake	Japan	M 6.5-7.5**	Unknown	Ikeguchi	93	Sandstone, mixed rocks, green stone	50-60	UC Bt	Head scarp	(2013)
1707 Hoei	Japan	M 8.4	5-6(JMA)**	Kanagi	8.5	Sandstone, mudstone	60-90	A FT	Furrows	Chigira (2000)
1985 Papua New Guinea	Papua New Guinea	M 7.1	MM 8? (14 km from the epicenter)	Bairaman	200	Limestone	8	OC U	Linear depression	King et al. (1989)
1999 Chi-Chi	Taiwan	Mw 7.6	465.3 gal EW 370.5 gal NS, and 274.7 gal UD 6 km north of the site	Chiu-fen-erh-shan	50	Sandstone, mudstone, shale	20-36	UC B	Linear depression, steps	Wang et al. (2003)
				Tsaoling	125	ditto	14	OC U	V-shaped linear depression	Chigira et al. (2003)
2004 Mid Niigata Prefecture	Japan	Mw 6.6 (Mj 6.8)	6+, 6-, 7 (JMA)	Higashitake-zawa	2	Sandstone, mudstone	20	OC CU	Head scarp	Chigira and Yagi (2005)
				Shiono	5	ditto	14	OC CU	Head scarp	
				Terano	0.5	ditto	14	OC CU	Head scarp	
				Kazefukitoge	0.09	ditto	30-42	UC B	Unknown	
2005 Northern Pakistan	Pakistan	Mw 7.6	MM 8	Dandbeh	65	Sandstone, mudstone	20 (plunge of a syncline)	OC CU	Small scarps	Chigira (2007), Schneider (2008)
				Pir Bandiwala	1	Sandstone, mudstone	Unknown	Unknown CU	Head scarp	
2008 Wenchuan	China	Mw 7.9	824.1 gal EW, 802.7 gal NS and 622.9 gal UD	Daguanbao	837	Carbonate rocks	35-38 (oblique)	UC B	Linear depression	Chigira (2010)
				Yinninggou	Unknown	Carbonate rocks	25?	OC U	Unknown	
2008 Iwate Miyagi Inland	Japan	Mw 6.9 (Mj 7.2)	328 gal EW, 413 gal NS	Aratozawa	67	Sandstone, siltstone, tuff, welded tuff	0-2	OC CU	Linear depression	Ohno et al. (2010)

*: OC: overthrust; UC: underthrust; A: anastomosing; Bt: buttress; B: buckling; FT: flexural toppling; U: undercut; CU: collided the opposite slope then undercut

** : Usami (2003)

the 1999 Chi-Chi earthquake (Chigira et al., 2003; Wang et al., 2003). Deep-seated gravitational slope deformation reduces the strength of rocks forming the slope, which would then become more susceptible to mass movement triggered by earthquake tremors.

Gravitational slope deformations that precede and prepare a site for earthquake-induced catastrophic landslide failure include several particular types (Table 3). The Chiu-fen-erh-shan landslide was preceded by buckle folding on a convex dip slope (Wang et al., 2003, B in Table 3); deformation on this slope was expressed topographically as linear depressions and steps. Buckle folding occurs on underthrust slopes (Cruden, 1989), in which the slope dips in the same direction as the dip of the foliation but with a gentler angle. Buckle folding can significantly destabilize a slope when it proceeds with the overturning of the lower limb of the fold, because when the lower limb is broken the whole slope loses its support at the foot. Landslides of this type, such as the Kazefukitoge landslide, also occurred during the 2004 Mid-Niigata Prefecture earthquake (Chigira and Yagi, 2005), and are also reported to have preceded the Daguanbao landslide, the largest landslide induced by the 2008 Wenchuan earthquake (Chigira et al., 2010). The Qingping

landslide induced by the Wenchuan earthquake occurred on an underthrust slope and formed a landslide dam. This landslide left clearly observed buckle folding on the landslide scar (Figure 4).

A special type of underthrust slope that may become the site of an earthquake-induced landslide is a buttress-type structure, in which resistant beds at the foot of the slope support the upper part of the slope (Bt in Table 3). A well-known case is the Madison landslide, which was triggered by the 1959 Hebgen Lake earthquake in the USA (Hadley, 1964). In that case, heavily weathered gneiss and schist were supported by dolomite in the lower part of the slope, but the shaking of the earthquake broke the support and the whole slope failed. Whether gravitational slope deformation occurred before the event is not known. An earthquake-induced landslide with a similar buttress structure was the Ikeguchi landslide induced by the AD 715 earthquake in central Japan (Chigira, 2013). On the slope that hosted the landslide, beds of mixed rock and greenstone were supported by a thick, massive sandstone bed at the foot, which eventually failed because of seismic motion. The topography prior to the landslide is inferred from an adjacent slope, where the mixed rocks and greenstone

Figure 4. A buckle fold on the landslide scar of the Qingping landslide, which was induced by the 2008 Wenchuan earthquake and formed a landslide dam.

beds have been displaced downslope but remain supported by a thick sandstone bed, leaving a small scarp along the ridge. Gravitational slope deformation almost certainly preceded the catastrophic failure in AD 715.

An over dip cataclinal slope, in which a slope dips in the same direction as the bedding but more steeply (OC in Table 3), may be subject to gradual sliding, forming a linear depression or a scarp upslope. The Tsaoiling landslide induced by the 1999 Chi–Chi earthquake had an over dip cataclinal slope structure, and linear depressions had developed along the position of its future crown before the earthquake. The Bairaman landslide induced by the 1985 earthquake in Papua New Guinea had a structure and linear depression upslope similar to that of the Tsaoiling landslide (King et al., 1989).

Another type of landslide frequently triggered by earthquakes is the reactivation of a previous landslide that ran out across a river from one side of the valley and collided with the opposing slope, and which was subsequently undercut by erosion (CU in Table 3). The reactivation occurs because the support of the upslope material is removed, and therefore the landslide body becomes unstable. This type of landslide occurred in many locations during the 2004 Mid-Niigata Prefecture earthquake in Japan (Chigira and Yagi, 2005). The Hattian landslide, which was triggered by the 2005 northern Pakistan earthquake, had similar characteristics (Chigira, 2007; Dunning et al., 2007; Schneider, 2008).

Landslides induced by water blow-out during earthquakes

A distinctive type of landslide was induced by the 1966 Matsushiro earthquake, which caused groundwater to gush out along seismogenic faults, with the rise in water pressure inducing rotational landslides (Morimoto et al., 1967). Faults may locally cause groundwater pressure to build up by the accumulation of tectonic strain on them (Sibson, 1996), and the affected areas are in some situations more than 100 km away from the source fault (Toda et al., 1995). The locations of induced landslides are, however, limited to those areas close to surface fault ruptures.

Preceding rainfall

Rainfall that precedes an earthquake (antecedent rainfall) is known to be a significant influence on the occurrence of landslides, because the groundwater level can rise and decrease the suction forces within soil through the development of positive pore water pressure. The 2004 mid-Niigata Prefecture earthquake, Japan, triggered about 100 landslides with volumes exceeding 10^5 m^3 (Chigira and Yagi, 2005), but the 2007 Noto–hanto and the 2007 off-mid-Niigata Prefecture earthquakes induced very low numbers of landslides, even though these earthquakes had similar seismic intensities in the areas with similar geological and geomorphological settings to those of the 2004 mid-Niigata Prefecture earthquake (Table 4). The observed difference in landslide occurrence has been explained in terms of the rainfalls preceding these earthquakes (Chigira, 2007): the 2004 mid-Niigata Prefecture earthquake was preceded by more than 100 mm of rainfall within the three days prior to the earthquake, but the other two earthquakes were preceded by much smaller amounts of rainfall (Figure 5).

The occurrence of landslides in pyroclastic fall deposits is also strongly influenced by antecedent rainfall. The 2011 Tohoku earthquake caused shaking with intensities of >6 on the Japan Meteorological Agency scale over wide areas, but triggered fewer than 10 landslides on slopes formed from pyroclastic fall deposits. Comparing the rainfall amounts for 10, 30, and 60 days before the earthquakes that induced landslides in pyroclastic fall deposits (Table 2, Figure 6), the 2011 Tohoku earthquake was characterized by having the smallest amounts in all three intervals. The 1949 Imaichi earthquake had similar rainfall amounts during the 10- and 30-day intervals to those of the 2011 Tohoku earthquake, but induced 88 landslides in pyroclastic fall deposits. The materials of landslides induced by both of these earthquakes are widely distributed (Suzuki, 1993), so more landslides would have been triggered if factors other than seismic shaking had been close to their critical values for slope instability. These factors include antecedent rainfall, slope direction, undercutting conditions, and seismic behavior (Chigira, 1982); of these factors, antecedent rainfall is likely to be the most influential when a large area is considered. The 1978 Izu–Oshima–Kinkai earthquake induced only seven landslides, but these landslides were densely packed within an area of 1.5 km^2 , wherein materials sourced from nearby monogenic volcanoes were distributed (Chigira, 1982). The 1984 Naganoken–Seibu earthquake induced only five landslides, but these were huge and the largest landslide had a volume of 36 million m^3 (Okuda et al., 1985). Notably, the Naganoken–Seibu earthquake was preceded by a much greater amount of rainfall than those earthquakes listed in Table 2.

Table 4. A comparison among the earthquakes that affected the areas with similar geologic and topographic settings. Only 2004 the Mid Niigata Prefecture earthquake induced many large landslides.

Earthquake	Date	Magnitude (Mj)	Seismic intensity (JMA)	Fault type	Rock types	Age	Landslide numbers	Reference
Mid Niigata Prefecture EQ in 2004	23 Oct.	6.8	6--7	Reverse	Sedimentary rocks	Neogene and younger	More than 100 large landslides	Chigira and Yagi (2006)
Noto Peninsula EQ in 2007	25 March	6.9	6--6+	Reverse	Sedimentary rocks Volcanic rocks	Neogene and younger	A few large landslides	
Off Mid Niigata Prefecture EQ in 2007	16 July	6.8	6+	Reverse	Sedimentary rocks	Neogene and younger	A few large landslides	

The effects of antecedent rainfall on earthquake-induced landslides have also been reported from New Zealand (Dellow and Hancox, 2006). The 1929 Buller and the 1931 Hawke's Bay earthquakes were both of Ms 7.8 and induced landslides in areas of intensities of 9 and 10 on the Modified Mercalli Intensity scale, but the former earthquake induced much larger and greater numbers of landslides. The Buller earthquake was preceded by 183.9 mm of rainfall over 10 days but the Hawke's Bay earthquake by only 8.4 mm. The geological and physiographical settings differed between these two areas, but soil moisture conditions are likely to have accounted for at least some of the difference in landslide occurrence between these two events. In Pakistan, Petley et al. (2006) reported

that the 2005 northern Pakistan earthquake induced rather a low number of landslides because the amount of antecedent rainfall was small.

The effects of antecedent rainfall on landslide occurrence, as discussed above, must be considered when a landslide hazard map is constructed on the basis of historical records, because the pattern and number of landslides induced by previous earthquakes might have been very different if those earthquakes had been preceded by smaller or larger amounts of rainfall. The time intervals for the evaluation of antecedent rainfall that must be accounted for may depend on geological conditions. For example, weathered pyroclastic materials should retain water for much longer than sandy materials.

Table 5. A list of rainstorms that induced deep-seated catastrophic landslides or many shallow landslides in Japan.

Year	Date	Trigger(T: typhoon)	Place (Prefecture)	Geology	Deep-seated landslide	Many Shallow landslides
1998	26 to 31 August	Rain (Front)	Fukushima	Vapor-phase crystallized ignimbrite	–	O
1999	29 June	Rain (Baiu front)	Hiroshima	Granite	–	O
2000	28-29 July 11-12 Sept.	Rain (Front)	Rumoi (Hokkaido)	Soft sedimentary rocks	–	O
		Rain (Front+T14)	Tokai (Aichi)	Granite	–	O
2003	20 July	Rain (Baiu Front)	Minamata (Kumamoto) Hishikari (Kagoshima)	Andesite lava and pyroclastics	O	O
	9-10 August	Rain (T10)	Hidaka (Hokkaido)	Sandstone and conglomerate	–	O
	Ditto	Ditto	Ditto	Melange	–	O
2004	13 July	Rain (Baiu front)	Nagaoka (Niigata)	Weak mudstone	–	O
	Ditto	Ditto	Fukui	Volcanic rocks	–	O
	28-29 Sept.	Rain (T21)	Miyagawa (Mie)	Accretional complex (Hard sedimentary rocks)	O	–
	1 Aug.	Rain (T10)	Kisawa (Tokushima)	Accretional complex (Greenstone and hard sedimentary rocks)	O	–
	29 Sept.	Rain (T21)	Ehime-Kagawa	Heavily weathered hard sandstone and mudstone	–	O
	29 Sept.	Rain (T21)	Saijo (Ehime)	Schist	O	O
2005	6 Sept.	Rain (T14 (Nabi))	Mimikawa (Miyazaki)	Accretional complex (Hard sedimentary rocks)	O	–
2006	19 July	Rain (Baiu front)	Okaya (Nagano)	Loam	–	O
2009	21 July	Rain (Baiu front)	Hofu (Yamaguchi)	Granite	–	O
2010	16 July	Rain (Baiu front)	Shobara (Hiroshima)	Soil	–	O
2011	4 Sept.	Rain (T12 - Talas)	Kii Mountains (Nara Wakayama)	Accretional complex (Hard sedimentary rocks)	O	–
2012	12 July	Rain (Baiu front)	Aso (Kumamoto)	Volcanic ash	–	O
2013	16 Oct.	Rain (T26 - Wipha)	Izu-Oshima (Tokyo)	Volcanic ash	–	O

Figure 5. Antecedent rainfalls before the 2005 Mid Niigata Prefecture earthquake that induced many deep-seated landslides and other two earthquakes that induced much less numbers of landslides. See text for the details.

Thus, a longer time frame for considering the effects of antecedent rainfall may need to be considered when evaluating the effects of antecedent rainfall and earthquakes with respect to mapping landslide hazards.

Rainfall-induced landslides

In addition to the occurrence of earthquakes, most Asian countries are located in rainy areas, where large amounts of precipitation increase the probability of landslide occurrence. To predict the potential sites of shallow landslides, the effects of rainstorms have been studied deterministically using physical models (Montgomery and Dietrich, 1994; Montgomery et al., 2000). However, such

Figure 6. Antecedent rainfalls before the earthquakes that induced catastrophic landslides of pyroclastic fall deposits.

modeling needs data on both slope geometry and mechanical properties, which vary widely and are often not able to be estimated appropriately. Potential sites of shallow landslides may thus not be easily identified. In contrast, deep-seated landslides occur on slopes with very site-specific geological and geomorphological conditions; many such landslides are characterized by prior gravitational slope deformation (Chigira, 2009; Chigira et al., 2013b).

Deep-seated catastrophic landslides induced by typhoon Talas 2011 in Japan were significant, because ten were surveyed using 1-m high-resolution digital elevation models (DEMs) before the landslide events (Chigira et al., 2013b). These landslides occurred mainly in the Shimanto Belt, which is underlain by Cretaceous to Paleogene accretion complexes represented by mixed rocks and broken formations. In a recent study, Chigira et al. (2013b) analyzed the topography existing prior to the catastrophic failures triggered by typhoon Talas, and the results have shown that the catastrophic failures were preceded by gravitational slope deformation. Chigira (2013) analyzed the pre-typhoon Talas topography for an additional 29 catastrophic landslides using high-resolution DEMs and found that they were all preceded by gravitational deformation. Twentysix of the total of 39 deep-seated catastrophic landslides had small scarps marking the positions of the heads of the subsequent landslides (Figure 7, Chigira, 2013). These scarps were caused by gravitational slope deformation that preceded the catastrophic failure. Although the scarps may have been enlarged by degradation, their sizes relative to the whole slopes suggest that minimal amounts of slope deformation had occurred in the period immediately before the catastrophic failure. The scarp ratio, defined as the ratio of the length of a scarp to that of the whole slope, both measured along the slope line, ranged from 1% to 23%. Amongst landslides with small scarps, 38% had scarp ratios of <4% and 50% had scarp ratios of <8%. These data suggest that the gravitational slope deformations that preceded catastrophic failures were relatively small, and indicate that the slopes involved were likely to have been at critical condition just prior to catastrophic failure. Typical landslides featuring these small scarps occurred on slopes with wedge-shaped discontinuities dominated by thrust surfaces that were undulating and which discontinuously sandwiched competent rocks of sandstone, chert, or greenstone. The sliding surfaces that appeared just after catastrophic failure had undulating and stepped surfaces, which strongly suggests that the slopes before failure included materials that resisted whole-slope sliding. These stepped

Figure 7. Slope images and cross sections of the upper part of the Akatani landslide induced by the 2011 typhoon Talas. *a)* After the landslide. *b)* Before the landslide. *c)* Cross-section along Y–Y' in B before (solid line) and after (dashed line) the landslide. *d)* Cross section along X–X' in B before (solid line) and after (dashed line) the landslide. Numbers 1 and 2 correspond to the scarp numbers in (b). Numbers in parentheses are slope angles and horizontal lengths along the slope line. Slope images were made using high resolution DEMs by the Ministry of Land, Infrastructure, Transport and Tourism.

features are similar to the “rock bridges” described by Eberhardt et al. (2004). Chigira et al. (2013a) analyzed the internal structures of a gravitationally deformed slope with irregularly shaped depressions and protrusions, and proposed that following their nucleation gravitational shear zones develop and connect to each other to form a through-going shear zone, which appears as a small scarp on the slope surface along the head of the moving body of material. The small scarps before catastrophic failure may therefore indicate an incipient landslide.

Typhoon Talas also induced one landslide with a large headscarp on a dip slope of alternating beds of sandstone and mudstone. This landslide had been gravitationally deformed with a buckle fold downslope (Chigira et al., 2013b). Buckle folds commonly accommodate large headscarps because the support from the lower

slope at the lower limb remains even after a substantial amount of deformation. However, if the lower limb is exposed to intense erosion or failure, even a small amount of gravitational deformation may be sufficient to cause a catastrophic failure of the whole slope. The Shiaolin landslide, induced by typhoon Molakot in 2009 in Taiwan (Tsou et al., 2011), is an example of this type of landslide. The Shiaolin landslide had a volume of 25 million m³ and demolished one village, causing over 400 fatalities.

The Ginsaugon landslide in Leyte, the Philippines, occurred without a clear trigger but had been preceded by about 700 mm of rainfall within the 10-day period before the landslide event (Evans et al., 2007). There is no report of whether this landslide had distinctive precursory topography, but judging from the nearby slopes and the fact that the landslide had a sliding surface along a spray fault of the

creeping Philippine Fault (Evans et al., 2007), it is very likely that there was a small headscarp before the catastrophic event.

Conclusions

The geomorphological features of deep-seated catastrophic landslides are evaluated in this paper as a basis for hazard mapping. Potential sites of shallow landslides are generally difficult to identify because of the wide variations in both subsurface structures and properties. In contrast, deep-seated landslides are predictable in many cases on the basis of specific geological and geomorphological features. Recent studies of deep-seated landslides indicate that many such landslides were preceded by gravitational slope deformation, except in the cases of earthquake-induced landslides in pyroclastic fall deposits and some mudstones and carbonate rocks. Earthquake-induced landslides in pyroclastic fall deposits, however, would be predictable by also specifying the materials that would slide or accommodate a sliding surface based on investigations of both volcanostratigraphy and material weathering. The other types of catastrophic landslide are preceded by gravitational slope deformation, which can be predicted using topographic features.

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