Geohazards in Asian countries

Masahiro CHIGIRA[(1)]

(1) Disaster Prevention Research Institute, Kyoto University, Japan
E-mail:chigira@slope.dpri.kyoto-u.ac.jp

Abstract

Geohazards, 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 sequence of deposits, in which halloysite-rich soil and pumice may accommodate a sliding surface.

Keywords: geohazards, deep-seated landslide, rock avalanche, Asia

1. 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 summarizes 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. For more detailed descriptions, see Chigira (2014). 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.

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; Chigira, 2009; Crosta et al., 2006; Dramis and Sorrisovalvo, 1994; Kilburn and Petley,

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)
Phillipine	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)

2003), 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.

2. Earthquake-induced landslides

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

2.1 Landslides prepared by chemical weathering processes

(1) 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, which was originally formed by chemical weathering and then buried by subsequent pyroclastics. Similar landslides involving a sliding surface in a paleosol have occurred during many other earthquakes (Table 2) The distribution of halloysite-rich soil could be predicted by the study of both volcano-stratigraphic characteristics and

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

Earthquake		1949 Imaichi	1968 Tokachi-Oki	1978 Izu-Oshima-Kinkai	1984 Naganoken-Seibu	2011 Tohoku	2001 El Salvador	2009 Padang
Date		26 Dec.	16 May	14 Jan.	14 Sept	11 March	13 Jan.	30 Sept.
Magnitude		Mjma 6.4	Mjma7.9 (Mw8.2)	Mjma 7.0	Mjma6.8	Mw 9.0	Mw7.7	Mw 7.5
Seismic Intensity at landslide sites (JMA)		5～6	5	5～6	6	6-~6+	MM 6, 7 4~5-	MM 8 (USGS) 5+(JMA)
Antecedent rain (mm)	Rain gage	Utsunomiya	Hachinohe	Inatori	Ontakesan	Shirakawa	—	—
	10 days	22.5	181	12	183	12.5	no data (Nov.-Apr.: dry season)[h]	Unknown (occurred during a rainstorm)
	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[j]	<10[e]	>1000[g]	160[i]
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[i]
Slid material		Shichihonzakura pumice and Imaichi pumice[l]	Towada-Hachinohe tephra[b,c]	East Izu monogenic volcanic tephra[d]	Scoria, lava, agglutinate, terrace deposits,	Tephra from Nasu volcano[e]	Pumice etc.	Pumice (Qhpt)
Source of the slid materials		Nantai volcano	Towada Volcano	Higashi-Izu monogenetic volcanoes	Ontake Volcano	Nasu Volcano	?	Tandikat Volcano[i]
Sliding surface depth (m)		3~5 m[a]	<3 m[b], 1~2.5 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		○	○	○	○	○	○	○
Undercut		Unknown	Unknown	○	○	○	○	Mostly
Fatality		8	33	7	29	13	844[g]	600?
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)						

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°; these landslides are commonly very mobile with low equivalent coefficients of friction. Equivalent coefficients of friction are known to decrease with increasing landslide volume (Hsu, 1975; Scheidegger, 1973), but landslides of this type have exceptionally low values even for small-volume landslides.

(2) Carbonate rocks and mudstone

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

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).

2.2 Mechanical preparation

The mechanical preparation for large earthquake-induced landslides is deep-seated gravitational slope deformation, which has preceded many landslides (Chigira et al., 2003; Wang et al., 2003; Chigira et al., 2012b). 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. The Qingping landslide induced by the Wenchuan earthquake occurred on an underdip cataclinal slope and formed a landslide dam. This landslide left clearly observed buckle folding on the landslide scar.

A special type of underdip cataclinal 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

Table 3 A list of earthquake-induced landslides with special reference to geological

Earthquake	Country	Magnitude	Seismic intensity at the landslide site	Landslide	Volume (10^6 m^3)	Rock type	dip (°)	Structure*		Precursory landform	Reference
715 earthquake	Japan	M 6.5–7.5**	Unknown	Ikeguchi	93	Sandstone, mixed rocks, green stone	50–60	UC	Bt	Head scarp	Chigira (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+~7 (JMA)	Higashitakezawa	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)
				Yinxinggou	100?	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 million	Sandstone, siltstone, tuff, welded tuff	0–2	OC	CU	Linear depression	Ohno et al. (2010)

*: OC: overdip cataclinal; UC: underdip cataclinal; A: anaclinal: Bt: buttress; B: buckling; FT: flexural toppling; U: undercut; CU: collided the opposite slope then undercut

**: Usami (2003)

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).

An overdip 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 Tsaoling landslide induced by the 1999 Chi–Chi earthquake had an overdip cataclinal slop structure, and linear depressions had developed along the position of its future crown before the earthquake. 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).

2.3 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.

2.4 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. The occurrence of landslides in pyroclastic fall deposits is also strongly influenced by antecedent rainfall. The effects of antecedent rainfall on earthquake-induced landslides have also been reported from New Zealand (Dellow and Hancox, 2006). 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.

3. 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 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 accretionary 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 indicated that the catastrophic failures had been 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 and 26 of the total of 39 deep-seated catastrophic landslides had small scarps marking the positions of the heads of the subsequent landslides (Chigira, 2013). 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. Chigira et al. (2013a) analyzed the internal structures of a gravitationally deformed slope with irregularly shaped depressions and protrusions, and proposed that gravitational shear zones are first nucleated and then 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.

3. 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.

Acknowledgements

T. Kamai, Y. Matsushi, and C.-Y. Tsou of the Disaster Prevention Research Institute are thanked for helpful discussions, and some of the research results used in this paper was derived from collaborative research studies with these authors. C. Lim of the University of Kebangsaan, Malaysia and C. Tang of Chengdu University of Technology, China provided the statistics of landslide hazards in their respective countries. This research was supported by the Research Collaboration with Disaster Prevention Research Institute, Kyoto Unviersity, and JSPS KAKENHI Grant Number 26282102.

References

Chigira, M. (1982): Dry debris flow of pyroclastic fall deposits triggered by the 1978 Izu-Oshima-Kinkai earthquake: the "collapsing" landslide at Nanamawari, Mitaka-Iriya, southern Izu Peninsula. Journal of Natural Disaster Science, Vol. 4, pp. 1-32.

Chigira, M., 1990, A mechanism of chemical weathering of mudstone in a mountainous area. Engineering Geology, v. 29; pp. 119-138.

Chigira, M., 1992, Long-term gravitational deformation of rocks by mass rock creep. Engineering Geology, v. 32; pp. 157-184.

Chigira, M., 2007, Site characteristics of gigantic landslides. Kinmiraisha, Nagoya, 256 pp.

Chigira, M., 2009, September 2005 rain-induced catastrophic rockslides on slopes affected by deep-seated gravitational deformations, Kyushu, southern Japan. . Engineering Geology, v. 108; pp. 1-15.

Chigira, M., 2013, Deep-seated catastrophic landslides - where are potential sites? Kinmiraisha, Nagoya, 231 pp.

Chigira, M., 2014. Geological and geomorphological features of deep-seated catastrophic landslides in tectonically active regions of Asia and implications for hazard mapping. Episodes, 37, 284-294.

Chigira, M., Hariyama, T., Yamasaki, S., 2013a, Development of deep-seated gravitational slope deformation on a shale dip-slope: observations from high-quality drillcores. Tectonophysics, v. 605; 104-113.

Chigira, M., Nakasuji, A., Fujiwara, S., Sakagami, M., 2012. Soil slide-avalanches of pyroclastic fall deposits induced by the 2011 off the Pacific Coast of Tohoku Earthquake. Jour. Japan Soc. Eng. Geol., 52, 222-230.

Chigira, M., Nakasuji, A., Fujiwara, S., Sakagami, M., 2014, Soil-Slide Avalanches of Pyroclastic Fall Deposits Induced by the 2011 Off the Pacific Coast of Tohoku Earthquake. In: H. Kawase (Ed.), Studies on the Off the Pacific Coast of Tohoku Earthquake.

Springer, Tokyo, pp. 65-86.

Chigira, M., Tsou, C.-Y., Matsushi, Y., Hiraishi, N., Matsuzawa, M., 2013b, Topographic precursors and geological structures of deep-seated catastrophic landslides caused by Typhoon Talas. Geomorphology, v. 201; pp. 479-493.

Chigira, M., Wang, G., Wu, S., 2012a, Landslides induced by the Wenchuan earthquake. In: J.J. Clague, D. Stead (Eds.), Landslides Types, Mechanisms and Modeling. Cambridge University Press, Cambridge, pp. 383-392.

Chigira, M., Wang, G., Wu, X., 2012b, Landslides induced by the Wenchuan earthquake. In: J.J. Clague, D. Stead (Eds.), Landslides: Types, mechanisms and modeling. Cambridge University Press, Cambridge, pp. 383-392.

Chigira, M., Wang, W.-N., Furuya, T., Kamai, T., 2003, Geological causes and geomorphological precursors of the Tsaoling landslide triggered by the 1999 Chi-Chi Earthquake, Taiwan. Engineering Geology, v. 68; pp. 259-273.

Chigira, M., Wu, X., Inokuchi, T., Wang, G., 2010, Landslides induced by the 2008 Wenchuan earthquake, Sichuan, China. Geomorphology, v. 118; pp. 225-238.

Chigira, M., Yagi, H., 2005, Geological and geomorphological characteristics of landslides triggered by the 2004 Mid Niigata prefecture Earthquake in Japan. Engineering Geology, v. 82; pp. 202-221.

Crosta, G.B., Chen, H., Frattini, P., 2006, Forecasting hazard scenarios and implications for the evaluation of countermeasure efficiency for large debris avalanches. Engineering Geology, v. 83; pp. 236-253.

Crosta, G.B., Imposimato, S., Roddeman, D., Chiesa, S., Moia, F., 2005, Small fast-moving f low-like landslides in volcanic deposits: The 2001 Las Colinas Landslide (El Salvador). Engineering Geology, v. 79; pp. 185-214.

Cruden, D.M., 1989, Limits to common toppling. Canadian Geotechnical Journal, v. 26; pp. 737-742.

Dellow, G.D., Hancox, G.T., 2006, The influence of rainfall on earthquake-induced landslides in New Zealand, New Zealand Geotechnical Society 2006 Symposium. Institution of Professional Engineers. Proceedings of technical groups / Institution of Professional Engineers New Zealand Nelson, New Zealand, pp. 355-368.

Dramis, F., Sorrisovalvo, M., 1994, Deep-seated gravitational slope deformations, related landslides and tectonics. Engineering Geology, v. 38(3-4); pp. 231-243.

Evans, S.G., Bent, A.L., 2004, The Las Colinas landslide, Santa Tecla: A highly destructive flowslide triggered by the January 13, 2001, El Salvador earthquake. In: W.I. Rose, J.J. Bommer, D.L. Lopez, M.J. Carr, J.J. Major (Eds.), Natural hazards in El Salvador. Geological Society of America Special Paper, Boulder, Colorado, pp. 25-37.

Evans, S.G., Guthrie, R.H., Roberts, N.J., Bishop, N.F., 2007, The disastrous 17 February 2006 rockslide-debris avalanche on Leyte Island, Philippines: a catastrophic landslide in tropical mountain terrain. Nat. Hazards Earth Syst. Sci., v. 7; pp. 89-101.

Hadley, J.B., 1964, Landslides and related phenomena accompanying the Hebgen Lake earthquake of August 17, 1959. U. S. Geol. Surv. Prof. Paper, v. 435; pp. 107-138.

Hansen, W.R., 1965, Effects of the earthquake of March 27, 1964 at Ancourage, Alaska. U. S. Geol. Surv. Prof. Paper, 542A, 68.

Hirano, M., Ishii, T., Fujita, T., Okuda, S., 1985, Geomorphological and geological characteristics of 1984 landslide hazard in Ohtaki village, Nagano Prefecture, Japan. Annuals of Disaster Preventin Research Institute, Kyoto Uiversity, v. 28; pp. 519-532.

Hsu, K.J., 1975, Catastrophic debris streams (sturzstroms) generated by rockfalls. Geological Society of America Bulletin, v. 86; pp. 129-140.

Inoue, Y., Honsho, S., Matsushima, M., Esashi, Y., 1970, Geological and soil mechanical studies on the slides occurred during the 1968 Toakachioki earthquake in southeastern area of Aomori Prefecture. Central Research Institute of Electric Power Industry, Report, pp. 1-27.

Jibson, R.W., Crone, A.J., Harp, E.L., Baum, R.L., Major, J.J., Pullinger, C.R., Escobar, C.D., Martinez, M., Smith, M.E., 2004, Landslides triggered by the 13 January and 13 February 2001 earthquakes in El Salvador. In: W.I. Rose, J.J. Bommer, D.L. Lopez, M.J. Carr, J.J. Major (Eds.), Natural hazards in El Salvador. Geological Society of America, Boulder, pp. 69-88.

Kilburn, C.R.J., Petley, D.N., 2003, Forecasting giant, catastrophic slope collapse: lessons from Vajont, Northern Italy. Geomorphology, v. 54; pp. 21-32.

King, J., Loveday, I., Schuster, R.L., 1989, The 1985 Bairaman landslide dam and resulting debris flow, Papua New Guinea. Quarterly Journal of Engineering Eeology, v. 105; pp. 257-270.

Matsuura, S., Asano, S., Okamoto, T., 2008, Relationship between rain and/or meltwater, pore-water pressure and displacement of a reactivated landslide. Engineering Geology, v. 101; pp. 49-49.

Montgomery, D.R., Dietrich, W.E., 1994, A physically based model for the topographic control on shallow landsliding. Water Resources research, v. 30-4; pp. 1153-1171.

Montgomery, D.R., Schmidt, K.M., GreenbergH.M., DietrichW.E.. 2000, Forest clearing and regional landsliding. Geology, v. 28-4; pp. 311-314.

Morimoto, R., 1951. Geology of Imaichi District with special reference to the earthquakes of Dec. 26th., 1949. (II). Bulletin of the Earthquake Research Institute, 29, 349-358.

Morimoto, R., Nakamura, K., Tsuneishi, Y., Ossaka, J., Tsunoda, N., 1967, Landslides in the epicentral area of the Matsushiro earthquake swarm -Their relation to the earthquake fault. Bull. Earthq. Res. Inst, v. 45; pp. 241-263.

Nakano, M., Chigira, M., Lim, C.-S., 2013. Landslides of pumice fall deposits induced by the 2009 Padang earthquake and the formation of halloysite, Japan Geoscience Union Meeting 2013, Makuhari, HDS06-02.

Ohno, R., Yamashita, S., Yamasaki, T., Koyama, T., Esaka, F., Kasai, S., 2010. Mechanisms of a large-scale landslide triggered by the Earthquake in 2008 - A study on Arato-sawa Landslide -. Journal of Japan Landslide Society, 47, 8-14.

Petley, D., 2012, Global patterns of loss of life from landslides. Geology, v. 40; pp. 927-930.

Petley, D., Dunning, S., Rosser, N., Kausar, A.B., 2006, Incipient landslides in the Jhelum Valley, Pakistan following the 8th October 2005 earthquake. Disaster Mitigation of Debris Flows,Slope Failures and Landslides, pp. 47-55.

Sato, H.P., Hasegawa, H., Fujiwara, S., Tobita, M., Koarai, M., Une, H., Iwahashi, J., 2007, Interpretation of landslide distribution triggered by the 2005 Northern Pakistan earthquake using SPOT 5 imagery. Landslides, v. 4(2); pp. 113-122.

Scheidegger, A.E., 1973, On the prediction of the reach and velocity of catastrophic landslides. Rock Mechanics, v. 5; pp. 231-236.

Schneider, J.F., 2008, Seismically reactivated Hattian slide in Kashmir, Northern Pakistan. J. Seismol., v. 13(3); pp. 387-398.

Seed, H.B., Wilson, S.D., 1967, The Turnagain Heights landslide, Anchorage, Alaska. Journal of theSoil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers, pp. 325-353.

Sibson, R.H., 1996, Structural permeability of fluid-driven fault-fracture meshes. Journal of Structural Geology, v. 18; pp. 1031-1042.

Suzuki, T., 1993, Stratigraphy of Middle Pleistocene tephra layers around Nasuno Plain, in north Kanto, central Japan. Journal of Geography, v. 102(1); pp. 73-90.

Tanaka, K., 1985, Features of slope failures induced by the Naganoken-Seibu Earthquake, 1984. Tsuchi-to-Kiso, v. 33(11); pp. 5-10.

Toda, S., Tanaka, K., Chigira, M., Miyakawa, K., Hasegawa, T., 1995, Coseismic behavior of groundwater by the 1995 Hyogo-ken nanbu earthquake. Jishin, v. 48; pp. 547-553.

Tsou, C.-Y., Feng, Z.-Y., Chigira, M., 2011, Catastrophic landslide induced by Typhoon Morakot, Shiaolin, Taiwan. Geomorphology, v. 127; pp. 166-178.

Voight, B., Janda, R.J., Glicken, H., Douglass, P.M., 1983, Nature and mechanics of the Mount St Helens rockslide-avalanche of 18 May 1970. Geotechnique, v. 33; pp. 243-273.

Waitt, J., R.B., Pierson, T.C., Macleod, N.S., Janda, R.J., Voight, B., Holcomb, R.T., 1983, Eruption-Triggered avalanvche, flood, and lahar at Mount St.Helens-Effects of winter snowpack. Science, v. 221; pp.1394-1397.

Wang, W.-N., Furuya, T., Chigira, M., 2003, Geomorphological Precursors of the Chiu-fen-erh-shan Landslide Triggered by the Chi-chi Earthquake in Central Taiwan. Engineering Geology, v. 69; pp. 1-13.

Yoshida, M., Chigira, M., 2012, The relation between weathering of pyroclastic fall deposits and the collapses caused by the 1968 Tokachi-Oki earthquake. Jour. Japan Soc. Eng. Geol., v. 52; pp. 213-221.