Geological characteristics of landslides triggered by the 2004 Mid-Niigata Prefecture (Chuetsu) earthquake in Japan

MASAHIRO CHIGIRA[1]

[1] *Disaster Prevention Research Institute, Kyoto Univ. (e-mail: chigira@slope.dpri.kyoto-u.ac.jp)*

Abstract: The 2004 Chuetsu earthquake (M 6.8) triggered thousands of landslides in the Miocene to Quaternary sedimentary rocks in Japan. The most common landslides were shallow disrupted landslides on steep slopes without geologic preference, but deep, coherent landslides also occurred in many locations. We studied about 100 deep, coherent landslides by field investigation and by interpretation of aerial photographs and found that many of them had occurred due to the reactivation of previous landslides. These had planar sliding surfaces along bedding planes or along oxidation fronts. Planar, bedding-parallel sliding surfaces were exposed or inferred from the geometry of the deformed ground surface, such as "horsts and grabens" and "roll-over antiform". The bedding-parallel sliding surfaces were made at the boundary between the overlying sandstone and underlying siltstone or along the bedding planes of the alternated beds of sandstone and siltstone. Sliding surfaces along the oxidation front were made in the area of black mudstone. New landslides (rockslide-avalanches) occurred within the sliding surfaces in tuff bands of a few-cm thickness that were interbedded in the siltstone. Most of the deep landslides occurred on slopes undercut by erosion or artificial excavation, whether they were reactivated or new ones. One rockslide-avalanche occurred on a slope where buckling deformation preceded the earthquake. Valley bottom sediments were mobilized on low-angle slopes in many locations, probably because they were saturated and partial liquefaction occurred by the earthquake.

Résumé: Le tremblement de terre 2004 de Chuetsu (M 6.8) a déclenché des milliers d'éboulements dans le miocène aux roches sédimentaires quaternaires au Japon. Les éboulements les plus communs étaient des éboulements abrupts peu profonds sur les pentes raides sans préférence géologique, mais profondément, les éboulements logiques se sont également produits dans beaucoup d'endroits. Nous avons étudié environ 100 profonds, éboulements logiques par recherche de champ et par l'interprétation des photographies aériennes et avons constaté que bon nombre d'entre elles ont eu en raison produit de la réactivation des éboulements précédents. Ceux-ci ont eu les surfaces de glissement planaires le long des avions de literie ou le long des avants d'oxydation. Des surfaces de glissement planaires et literie-parallèles ont été exposées ou impliquées de la géométrie de la surface au sol déformée, telle que des "horsts et des grabens" et "antiform de renversement". Les surfaces de glissement literie-parallèles ont été faites à la frontière entre le grès sus-jacent et le caillou de ruissellement fondamental ou le long des plans de literie des lits alternés du grès et du caillou de ruissellement. Des surfaces de glissement le long de l'avant d'oxydation ont été faites dans le secteur du schiste noir. Les nouveaux éboulements (rockslide-avalanches) se sont produits dans les surfaces de glissement dans les bandes de tuff d'une épaisseur peu de-centimètre qui étaient intercalées dans le caillou de ruissellement. La plupart des éboulements profonds se sont produites sur des pentes dégagées par érosion ou excavation artificielle, si elles ont été réactivées ou des neufs. Une rockslide-avalanche s'est produite sur une pente où la déformation de boucle a précédé le tremblement de terre. Des sédiments inférieurs de vallée ont été mobilisés sur des pentes d'bas-angle dans beaucoup d'endroits, probablement parce qu'ils ont été saturés et la liquéfaction partielle s'est produite par le tremblement de terre.

Keywords: Earthquakes, landslides, mapping

INTRODUCTION

The 2004 Mid-Niigta prefecture earthquake (Japan Meteorological Agency; JMA), which occurred on October 23rd, 2004 in Niigata Prefecture, central Japan, induced a large number of landslides, causing severe damage and isolating villages in the epicentral mountainous areas. Thirteen people were killed in the earthquake, six by landslides. Thirty-three more people died later because of diseases induced by the earthquake or by the aftershocks that occurred up to March 22nd, 2005. This earthquake occurred in an area with many previous landslides, and thus the area still has unstable or metastable landslide mass. This earthquake was one of the major earthquakes to give various scientific data of earthquake-induced landslides in such an area; earthquakes that induced distributed landslides in the past decade or so include the 1999 Chi-Chi earthquake in Taiwan, the 1995 Hygoken-nanbu earthquake in Japan, and the 1994 Northridge and the 1989 Loma Prieta earthquakes in the USA.

This paper reports and discusses the basic causes and mechanisms of the deep landslides triggered by the 2004 Mid Niigta prefecture earthquake. A detailed distribution of the landslides was plotted by the Japan Geographical Survey Institute (2004) immediately after the earthquake, and was published as a 1:30,000 scale map, which counted 1353 landslides and greatly contributed to the recovery strategy from the disaster. Yagi et al. (2004) interpreted the aerial photographs taken by the Aero Asahi Corporation on October 28th, 2004 at a scale of 1:10,000, and plotted landslides and cracks on a detailed map that was made using an airborne laser scanner. We interpreted aerial photographs taken before and just after the earthquakes and conducted a field investigation: aerial photographs at a scale of 1:10,000 taken October 24th, 2004 by the Kokusai Kogyo Company and aerial photographs at a scale of 1:10,000 taken in 1975 and 1976 by the Japan Geographical Survey Institute. Our geological field investigation was conducted for two weeks, and clarified the geologic structures of major landslides. We obtained numerical data on the scale of the landslides from the digital elevation model with a 1-m grid made by an airborne laser scanner (Yagi et al., 2004).

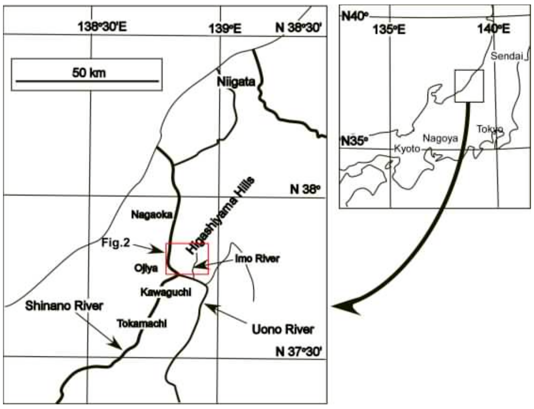

Figure 1. Index map of the study site. The area of Figure 2 is shown as a square.

GEOLOGICAL SETTING AND EARTHQUAKE CHARACTERISTICS

The epicentral area is located in the Higashiyama Hills and its neighboring alluvial plain, where the Shinano River flows from SW to NE then turns to NW to N after merging with the Uono River (Fig. 1). The Higashiyama Hills is northeast of the rivers. The elevation of the river near the Hills is 50-80 m, and the summit levels of the Higashiyama Hills range from 400 to 700 m. The central part of the Hills is cut by the Imo River flowing from north to south.

The geological outline is summarized as follows from Yanagisawa et al. (1986) and Kobayashi et al. (1991) (Fig. 2). The Higashiyama Hills are underlain by Miocene to Pleistocene strata, which trend NNE-SSW with several anticlines and synclines. Where the fold axes plunge, the trend of the strata changes to E-W locally. The axes are named the Higashiyama anticline, Konpira syncline, Toge anticline, Kajikane syncline, and Komatsugura anticline from the west to the east with a half wavelength of about 1 km (Fig. 2). The strata consist mainly of mudstone, alternating beds of siltstone and sandstone, and sandstone with subordinate dacitic or andesitic volcanic rocks. The formations shown in Fig. 2 are these volcanic rocks, thick mudstones - the Araya and the Ushigakubi Formations-, and a thick sandstone - the Wanatsu Formation; other areas in white in Fig. 2 mostly consist of the alternating beds of sandstone and siltstone. The volcanic rocks and the Araya Formation are Miocene in age, and the strata above it up through the Wanatsu Formation are of Pliocene age. The strata above the Wanatsu Formation are Quaternary. The Araya and the Ushigakubi Formations consist mainly of mudstone, but contain sandstone beds near the boundaries with other formations that consist of alternating beds of sandstone and siltstone.

The mainshock of the 2004 Mid Niigta prefecture earthquake (M6.8) occurred at 5:56 PM (Japan Standard Time) on October 23rd, 2004, with a local body wave magnitude (JMA) of 6.8 and with many aftershocks; three of the aftershocks exceeded magnitude 6. The hypocenter of the main shock was 13 km below Kawaguchi town (Fig. 2). An aftershock occurring at 6:34 PM on 23rd was 14 km deep to the east of Komatsugura.

DISTRIBUTION AND TYPE OF LANDSLIDES

Many landslides occurred in a wide area on the Higashiyama Hills, and were particularly dense along the Imo River and the Kajikane syncline (Fig. 2). This dense area seems to have experienced the most intense earthquake tremors, because almost all of the houses within this area collapsed or sustained severe damage. Material from relatively small landslides dammed rivers and created lakes in over 30 locations; two landslide dams were much bigger than the others, and the lakes that formed were drained immediately to prevent flooding upstream and downstream.

We mapped major landslides wider than 20 m or longer than about 100 m and deeper than about 5 m from the interpretation of the aerial photographs; the total number of these landslides was about 100. The landslides, except for shallow disrupted landslides, are classified as follows:

- Coherent landslide
- Rockslide avalanche
- Mobilization of valley fill.

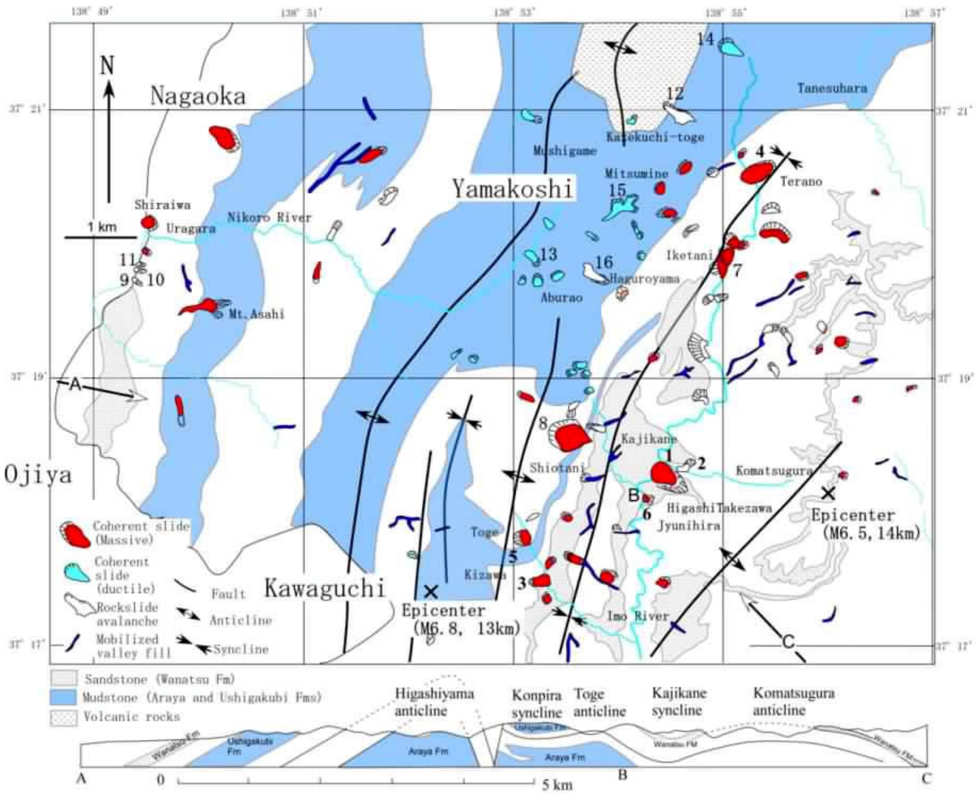

Figure 2. Geologic outline and the distribution of major landslides in the Higashiyama Hills. Geologic outline is modified from Yanagisawa et al. (1986) and Kobayashi et al. (1991).

This was a simple classification scheme that was based on those by Sato et al. (2004) and Yagi et al. (2004), although their classifications are more detailed. A coherent landslide corresponds to the Category II slide (Jisuberi in Japanese), and the shallow disrupted landslide or the rockslide avalanche (Houkai in Japanese) probably correspond to the Category I slide of Keefer (1984a, 2000). Besides these, flash floods from the breach of ponds used for fish farming also occurred, washing out surface sediments and causing debris flows.

The schematic sketches of landslides are shown in Fig. 3. Numbers 1 to 5 correspond to coherent landslides, numbers 6 and 7 to rockslide avalanches, and number 8 to mobilization of valley fill. Their characteristics will be described in the following sections. Coherent landslides will be described first according to geology: landslide of sandstone on siltstone, landslide of alternating beds of sandstone and siltstone, and landslide of weathered mudstone.

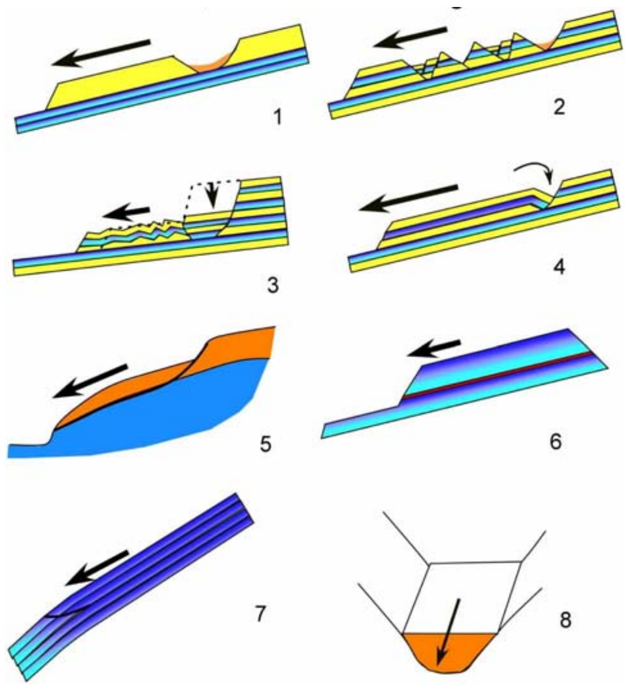

Figure 3. Internal structures of landslides. Corresponding numbers are shown in the text.

Landslide of sandstone on siltstone

Many landslides occurred along the base of a thick sandstone bed, which belongs to the Pliocene Wanatsu Formation described by Yanagisawa et al. (1986) (Fig. 2); it is underlain by siltstone or the alternating beds of siltstone and sandstone of the Pliocene Shiraiwa Formation. A typical landslide of this type was the Higashi-Takezawa slide (Type 1 in Fig. 3, Loc. 1 in Fig. 2, Photo 1 in Fig. 4), which blocked the Imo River, making a pond and flooding a small village upstream. This landslide was a partial reactivation of an existing old landslide. This old landslide was 350 m long and had a maximum width of 300 m. Although the foot of the slide mass was cut by the Imo River, forming a steep slope before the earthquake, a mound on the opposite side of the river indicates that the landslide once dammed the river and then was later eroded by the river.

Upslope from the head of the slid mass a sliding surface was exposed along the top of the siltstone bed below the sandstone that slid. The thickness sandstone that slid was estimated to be about 20 m, and its volume was estimated to be about 2 million m^3. The bedding plane was very planar and dipped northwestward at 20°. From the morphology of the new slide, the mass slid translationally without rotation first, and then climbed up the opposite slope, being rotated backward at its toe. The apparent friction angle, which is an inclination of a line connecting the top and the distal end of a landslide, was as small as 8°.

From the geologic structure and the existence of springs along the top of the siltstone bed, the overlying sandstone was assumed to be saturated with water before the earthquake. In addition, two to three days before the earthquake, there was precipitation of about 100 mm, which was observed at Tochio, 20 km to the north of this site, and this probably elevated the groundwater table within the slide mass. The pore pressure exerted by the groundwater and the earthquake tremor were significant factors in triggering the landslide. The reason why the uppermost and left part of the old slide mass did not slide may be due to the drainage along the periphery.

Landslide of alternating beds of sandstone and siltstone

Landslide with ridges and grabens (Type 2 in Fig. 3)

Ridges and grabens were made by the Terano slide (Loc. 4 in Fig. 2, Photo 3 in Fig. 4) , which was a reactivated landslide, that dammed the Imo River. The surface of the pre-earthquake slide gently inclined to the SW with an 8 m high landslide scarp and a steep toe, which was made by the erosion by the Imo River. This previous landslide mass was 140 m wide and 300 m long with a relatively smooth surface. This landslide used to dam the Imo River, and later was eroded by the river at the foot, being destabilized before the Mid Niigta prefecture earthquake, which triggered the landslide and dammed the river again.

The landslide triggered by the earthquake extended the existing main scarp, formed a subsidiary scarp in the middle, and made small ridges and grabens, a few meters to 10 m wide, although essentially no rotation was observed. The right and left flank scarps had different heights; the right (NW) scarp decreased in height downslope and disappeared at the middle, while the left scarp was as high as 8 m from the headscarp to near the toe. This may be due to the fact that the strike of the bedding plane was slightly oblique to the strike of the slope and outcropped at the NW side of the landslide. These morphological features and the geologic structure mentioned before indicate that the slide occurred translationally along planar bedding planes. The depth of the slide is estimated to be about 10 m, based on preliminary information from drilling performed in the middle of the landslide.

The toe of the landslide was immediately excavated to drain the dammed river, and the base of the landslide debris was exposed on the solid bedrock; groundwater was being discharged from this boundary. This fact and the fact that the landslide mass consisted of siltstone blocks floating in loose fine sand indicate that pore pressure reduced the effective stress and possibly some liquefaction occurred.

Landslide with lateral spreading at lower part of a slope and settlement of upper part (Type 3 in Fig. 3)

Several landslides with an extraordinarily high landslide scarp occurred, which the Iketani slide exemplifies (Loc.7 in Fig. 2, Photo 3 in Fig. 4). This slide is located near the axis of the Kajikane Syncline, and the beds had trends from E to W and dips of 10° southward. The bedding plane is apparently horizontal in E-W cross section, which was the movement direction of the slide. Comparison between the aerial photographs before and after the earthquake indicated that the upper part of the slide mass settled about 30 m with very small backward rotation (less than 10°) and the lower part moved laterally with pressure ridges. The slide mass consisted of alternating beds of siltstone and sandstone. This slide is inferred to have occurred by the lateral spreading of the lower part of the slope along the bedding plane due to intense earthquake shaking and by the subsequent settlement of the upslope part, leaving a large scarp. The aerial photographs before the earthquake indicated that this slide was a reactivation of the distal part of a previous landslide, which came from the east to block the Imo River once and later dissected by erosion.

Landslide with a "roll-over" antiform on the rear side. (Type 4 in Fig. 3)

A "roll-over antiform" was observed for the Shiotani landslide (Loc. 8 in Fig. 2, Photo 4 in Fig. 4), which was the largest slide triggered by the Mid Niigta prefecture Earthquake: 470 m wide and 740 m long with a 30-m high landslide scarp. This slide was also due to reactivation of a previously existing slide. This slide occurred on the southeastern slope of a 400-m high mountain. This slope was between an east-trending ridge and a south-trending ridge; an arcuate landslide scarp had been made upslope before the earthquake.

Figure 4. Photographs of landslide types. Photo numbers correspond to the numbers in Figure 3. Right and left are reversed from those in Figure 3 for the landslides of 2, 3, 5,.6, and 7.

The strata observed to the west of the slide trend NNW and dip 14˚ eastward, but they are inferred to have a northeastern trend under the slide area because the anticlinal axis plunges southward.

The aerial photographs taken before and after the earthquake showed that the uppermost part of the previous landslide was not reactivated. Based upon observations of the deviation in the angle between tree trunks and the ground surface it was considered that the ground surface in the reactivated area rotated backward 30^{o} at its head, but did not rotate in the middle. The toe of the slide overrode the opposite slope and rotated 25^{o} backward. These ground surface angles indicate that the slip surface in the middle and lower part of the slope was planar and parallel to the bedding plane, and became listric upslope. The strata above the listric slip surface rotated backward, forming a “roll-over” antiform in a manner similar to that shown by Ramsay and Huber (1987). The bedding plane exposed at the landslide back scar dipped 20˚ to the west, which was the result of the backward rotation of the previous landslide.

Landslide of weathered mudstone (Type 5 in Fig. 3)

Reactivation of weathered mudstone slides occurred in about 20 locations in the mudstone area of the Pliocene Araya Formation (Fig. 2); many of them were oxidized mudstone slides, exposing unoxidized black mudstone on their landslide back scars. The black mudstone exposed in the back scars was just beneath the oxidation front, and was probably the dissolved and deteriorated zone reported by Chigira (1990). This indicates that the sliding surfaces were made along or beneath the oxidation front, which is common for landslides induced by artificial excavation (Chigira, 1990). Most of the landslides of this type seem to have been undercut by erosion before the earthquake, based on the examination of aerial photographs. The sliding surfaces of this type of landslide may not be planar, but are inferred to be nearly parallel to the slope surface because the oxidation front is made by the downward migration of oxidizing water Chigira (1990).

Rockslide-avalanche

Primary rockslide with a sliding surface in a thin tuff bed (Type 6 in Fig. 3, Locs. 10 and 11 in Fig. 2)

This type of rockslide occurred in more than two locations along the western margin of the Higashiyama Hills (Photo 6 in Fig. 4). The strata here, the Shiraiwa Formation, mainly consists of siltstone, which intercalates white tuff beds of about 5 cm thickness. The sliding surface was within these tuff beds. The tuff consists of alternating laminae of medium to coarse sand-size grains and laminae of fine tuff. The sand-size tuff originates from pumice fragments and is highly porous, as observed under a microscope. The tuff consists mainly of smectite, quartz, and plagioclase, which were identified by using X-ay diffraction analysis.

The rockslides were 40 to 50 m wide, 120 to 160 m long, and about 5 to 8 m deep. The rockslides transformed to an avalanche and deposited material at the foot of the source area. Almost no debris remained in the source area, and a very planar sliding surface was exposed there. The slipped strata were cut at their foot along a road before the earthquake occurred. An excavated slope, a few meters high, cut into the siltstone below the tuff remained along the lower margin of the source areas after the earthquake. The bedding plane, which dipped 22˚, was sub-parallel to the cut slope, and intersected the cut slope at an acute angle. Consequently, the tuff bed in which the sliding surface was formed outcropped at the downslope, right margin, and upslope, on the opposite side of the ridge. The tuff consisted of porous material, was easily broken by hand and also absorbed a great amount of water. The southern or left margins of the two slides were both bounded by E-W trending high-angle joints.

Landslide evolved from buckling (Type 7 in Fig. 3, Loc. 12 in Fig. 2)

This type of landslide occurred in the northern part of the study area, on the southeastern slope of a NNE-SSW trending ridge (Photo 7 in Fig. 4). Along the southeastern foot of the ridge, a very clear knickline was observed; the upper slope inclined about 45˚ and the lower slope 25º. Aerial photographs taken before the earthquake showed that this slide occurred in a previous landslide scar. The underlying strata consist mainly of siltstone and probably lapilli tuff which was found in the debris. The stratification trends N45 to 55˚ E and dips to the east, crossing the trend of the slope (N40º E). The dip was 30º in the upper slope and 42º in the lower, forming a convex profile. Joints with a strike of N65º-70ºE to S245º-250ºW developed with intervals of between 5 to 30 cm. At the northeastern part of the back scar, we observed rock plates, which were separated by bedding planes and high angle joints, overthrust on the downslope plates with a separation of 3 cm; beneath these overthrusting plates were grass roots. These findings indicate that creep movement with buckling preceded the earthquake-induced landslide and the earthquake broke the buckled part of the beds.

Mobilization of valley fill (Type 8 in Fig. 3)

Sediments, which filled gentle valleys, were mobilized in about 30 locations (Fig. 2, Photo 8 in Fig. 4), damaging roads or paddy fields that crossed or were located on valley bottoms. This mobilization seemed to be due to the groundwater in sediments, which probably partially liquefied when shaken by the earthquake motions. Evidence of liquefaction was supported by muddy sand blows sometimes observed on mobilized sediments. Most mobilization of valley fill occurred in the areas of sandstone and alternating beds of sandstone and mudstone; very few valley fill mobilizations occurred in the area of mudstone, even though many landslides of weathered mudstone occurred in Yamakoshi Village, as stated before. They occurred in gentle valleys inclining 5 to 18˚, and many of them exceeded 100 m, with two being nearly 1000 m in length. The actual movement distances are not yet known. The widths of the mobilized sediments were from 10 to 30 m. The valleys where mobilization occurred were preferentially oriented: many mobilizations occurred in the valleys descending SW or W. This could be related to the earthquake shaking. However, four earthquakes with magnitudes of 6, or larger occurred within 30 minutes in the dark, so it was difficult to determine which earthquake triggered mobilizations.

DISCUSSION

The findings of the Mid Niigta prefecture earthquake indicate that undercutting of slopes was an important factor leading to earthquakes triggering catastrophic existing or new landslides. All of the investigated major landslides except for one, which was proceeded by buckling, were undercut by erosion or artificial cutting. Exactly the same undercutting condition was also found for the catastrophic landslides at the 1978 Izu-Oshima-Kinkai earthquake in central Japan. That earthquake triggered at least seven long run-out landslides in pyroclastic deposits with sliding surfaces in a paleozol. Six of them were new landslides and were undercut by erosion or artificial cutting, and the seventh was preceded by creep movement and buckling (Chigira, 1982). Therefore, although the infinite slope analysis has been used for shallow, slope-parallel beds, the undercutting condition needs to be incorporated into stability analyses. The importance of undercutting was pointed out by Keefer (1984a, b) from the literature on landslides triggered by earthquakes. Buckling could be dealt with in a similar way as undercutting. Landslides preceded by buckling occurred during the 1999 Chi-Chi earthquake on a much larger scale (Wang et al., 2003). The Higashiyama hills seem to have been experiencing many landslides caused by earthquakes and rainfall. In consideration of the iteration of the landslide and undercutting erosion, a long-term analysis which includes the global-sea level change and tectonic uplift must be conducted.

Most of the catastrophic landslides triggered by the Mid Niigta prefecture earthquake, which we investigated, had sliding surfaces along the planar bedding planes or near the oxidation front which, in general, is nearly slope-parallel

(Chigira, 1990). This earthquake also induced landslides that probably have curved sliding surfaces, but most of them had rather small displacements, forming only small cracks or scarplets. This difference might be related to the earthquake shaking, which includes cyclic loading in addition to static loading. Many of the catastrophic landslides triggered by other earthquakes also had planar sliding surfaces, including the Tsaoling and Chiu-fen-erh-shan landslides (Chigira et al., 2003; Wang et al., 2003) and other relatively small slides triggered by the 1999 Chi-Chi earthquake, the Bairaman slide (King et al., 1989), the Ontake slide (Endo et al., 1989; Voight and Sousa, 1994), landslides by the 1978 Izu-Oshima-Kinkai earthquake (Chigira, 1982), and landslides in Anchorage by the 1964 Alaska earthquake (Hansen, 1965; Seed and Wilson, 1967). Although there have been reports of landslides with curved sliding surfaces being triggered by earthquakes, the author asserts that landslides with planar sliding surfaces tend to be transformed to catastrophic or highly mobile landslides by earthquakes.

Planar sliding surfaces make characteristic surface morphologies, like ridges and grabens and "roll-over antiforms," as was seen in the Mid Niigta prefecture earthquake. Additional study is necessary to understand what factors determine the type of deformation and surface morphology of translational landslides with a planar sliding surface.

Acknowledgements: I am very grateful to the following researchers for their discussions with us in the field and in the laboratory. Yagi, H. of Yamagata University; Yamagishi, H. and Watanabe, N. of Niigata University; Nakasuji, A., Ohzu, K., Sudou, H., Fukui, K., and Tanase, T. of the Japan Society of Engineering Geology; Sekiguchi, T. and Sato, P. H. of the Geographical Survey Institute; Sassa, K. and Fukuoka, H. of Kyoto University; Ochiai, H. and Okada, Y. of the Forestry and Forest Products Research Institute; and Yamasaki, T. of the Japan Conservation Engineers Co. We are also grateful to Nagashima, T., the former mayor of Yamakoshi Village, who allowed us to enter the evacuated village. This research was supported by a Special Coordinating Fund for Promoting Science and Technology of the Ministry of Education, Culture, Sports, Science and Technology of Japan.

Corresponding author: Prof Masahiro Chigira, Disaster Prevention Research Institute, Kyoto Univ, Gokasho, Uji, Kyoto, 611-0011, Japan. Tel: +81 774 38 4100. Email: chigira@slope.dpri.kyoto-u.ac.jp.

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*, **4**, 1-32.

CHIGIRA, M., 1990. A mechanism of chemical weathering of mudstone in a mountainous area. *Engineering Geology,* **29**, 119-138.

CHIGIRA, M., WANG, W.-N., FURUYA, T. & KAMAI, T., 2003. Geological causes and geomorphological precursors of theTsaoling landslide triggered by the 1999 Chi-Chi Earthquake, Taiwan. *Engineering Geology*, **68**, 259-273.

ENDO, K., SUMITA, M., MACHIDA, M. & FURUICHI, M., 1989. The 1984 collapse and debris avalanche deposits of Ontake Volcano, central Japan. *In:* J.H. LATTER (ed), IAVCEI *Proceedings in Volcanology. Springer*, 210-229.

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

KEEFER, D., 1984a. Landslides caused by earthquakes. *Geological Society of America Bulletin*, **95**, 406-421.

KEEFER, D., 1984b. Rock avalanches caused by earthquakes: Source characteristics. *Science*, **223**, 1288-1290.

KEEFER, D.V., 2000. Statistical analysis of an earthquake-induced landslide distribution – the 1989 Loma Prieta, California event. *Engineering Geology,* **58**, 231-249.

KING, J., LOVEDAY, I. & SCHUSTER, R.L., 1989. The 1985 Bairaman landslide dam and resulting debris flow, Papua New Guinea. *Quarterly Journal of Engineering Geology*, **105**, 257-270.

KOBAYASHI, I., TATEISHI, M., YOSHIDA, T., & SHIMIZU, M., 1991. *Geology of the Nagaoka District. Geological Survey of Japan,* Quadrangle Series (Scale 1:50,000) Niigata (7) No. 38.

RAMSAY, J.G. & HUBER, M.I., 1987. *Folds and fractures. The techniques of modern structural geology*, 2. Academic press, London.

SATO, H., SEKIGUCHI, T. & KOJIRAI, R., 2004. Relationship between landslide distribution and geology, geomorphology, and epicenters. *In*: K. Sassa (Editor), *Symposium on landslide hazards by the 2004 Mid Niigta prefecture Earthquake*. Special Coordinating Fund for Promoting Science and Technology of the Ministry of Education, Culture, Sports, Science and Technology of Japan, Tokyo, 7-15.

SEED, H.B. & WILSON, S.D., 1967. The Turnagain Heights landslide, Anchorage, Alaska. *Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers*, 325-353.

THE JAPAN GEOGRAPHICAL SURVEY INSTITUTE, 2004. *A map of the disasters caused by the Mid Niigta prefecture Earthquake*. The Geographical Survey Institute, Japan. 1 sheet with a scale of 1:30,000.

VOIGHT, B. & SOUSA, J., 1994. Lessons from Ontake-san: a comparative analysis of debris avalanche dynamics. *Engineering Geology*, **38**, 261-297.

WANG, W.-N., FURUYA, T. & CHIGIRA, M., 2003a. Geomorphological Precursors of the Chiu-fen-erh-shan Landslide Triggered by the Chi-chi Earthquake in Central Taiwan. *Engineering Geology*, **69**, 1-13.

YAGI, H., YAMAZAKI, T. & MORIYAMA, T., 2004. Distribution map of landslides triggered by the 2004 Chuetsu earthquake, Japan Conservation Engineers, Tokyo.

YANAGISAWA, Y., KOBAYASHI, I., TAKEUCHI, K. TATEISHI, M. CHIHARA, K. & KATO, H., 1986. *Geology of the Ojiya District. Geological Survey of Japan,* Quadrangle Series (Scale 1:50,000) Niigata (7) No. 50.