

Review Article

Geotechnical Distinction of Landslides Induced by Near-Field Earthquakes in Niigata, Japan

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Landslides triggered by near-field earthquakes with epicentres directly beneath towns have attracted intense attention since the 2004 Mid-Niigata (Niigata-ken Chuetsu) Earthquake. Hilly and mountainous areas sustained heavy damage. Social problems developed when many towns became isolated because landslides cut off traffic and public service lifelines. Soil from landslides closed river channels and formed natural dams. The natural dams submerged some towns. Emergency measures were undertaken promptly to prevent debris flows caused by natural dam breaks. Subsequently, the 2007 Mid-Niigata Offshore (Niigata-ken Chuetsu-oki) Earthquake and the 2011 Northern Nagano Earthquake struck the Niigata region. Landslides triggered by those earthquakes differed in terms of their number, scale, and location. Therefore, characteristics of the landslide sites of the respective earthquakes were examined to ascertain their topographical and geological features. Furthermore, differences in groundwater level and damage related to compound disasters were explained for discussion of the stability progress of damaged slopes.

1. Introduction

Niigata prefecture is located in western and central Japan (Figure 1). In the midlands of Niigata, the Chuetsu region, various natural disasters have frequently struck in recent years. At 17:56 on 23 October, 2004, the Mid-Niigata (Niigata-ken Chuetsu) Earthquake, the main tremor of which had a magnitude of 6.8, struck central Niigata-ken (Chuetsu area) and severely damaged the infrastructure of hilly and mountainous areas including Kawaguchi town, Ojiya city, Nagaoka city, and their environs. Numerous landslides occurred especially in the “Yamakoshi area” (Figure 1). That village was isolated by the cutting of all roads and infrastructural lifelines. The epicentral thrust-fault earthquake had a hypocentre of about 13 km depth, with characteristic frequent strong aftershocks that engendered further damage. In addition, rainfall of more than 100 mm was recorded from typhoon number 23, which had passed through the Chuetsu region three days priorly. Data from the Japan Meteorological Agency (JMA) indicated that the daily rainfall of 21 October 2004 at Nagaoka city

reached 115 mm. Under those circumstances, more than 3,000 landslides occurred in the hilly area close to the seismic centre during the earthquake. The Japan Society of Civil Engineers [1] and Toyota et al. [2] reported specific damage caused by the disaster. Moreover, Tsukamoto et al. [3] and Rathje et al. [4] estimated the ground movement caused by landslides during the earthquake using investigation or remote sensing data. Geological and geomorphological features and special distributions of landslides in this area were reported by Chigira and Yagi [5] and Wang et al. [6]. Analyses of landslides including discontinuous dip layer were conducted by Onoue et al. [7] and Deng et al. [8]. They assumed that the landslides had been triggered by increase of pore water pressure in seam layers [9] and analysed the displacement using cyclic loading test results or Newmark’s method [10].

Heavy snow fell during the two winters following the Mid-Niigata Earthquake. Yearly snowfall is usually about 400 cm in Nagaoka, but it reached nearly 700 cm per year in each of the two years following the earthquake. The snow in one year was the heaviest in 19 years. The collapsed slopes

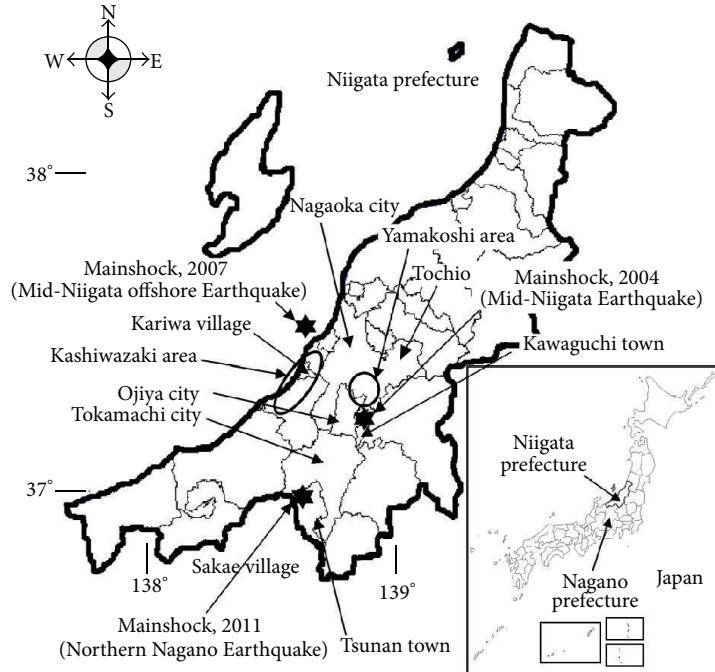


FIGURE 1: Map of Niigata prefecture.

exhibited interesting behaviour during snow and snow-melting seasons. Actually, this region has been notorious as a tertiary type landslide area. Landslides have frequently occurred in April and May: the snow-melting season.

Just three years after the Mid-Niigata Earthquake, at 10:30 on 16 July 2007, the Mid-Niigata Offshore (Niigata-ken Chuetsu-oki) Earthquake, the main tremor of which had a magnitude of 6.8, struck offshore about 30 km northwest of the epicentre of the Mid-Niigata Earthquake. The earthquake was caused by a thrust fault with a hypocentre of about 17 km depth. The JMA Seismic Intensity was recorded as “upper 6” in Kashiwazaki city, Nagaoka city, and Kariwa village. Major landslides were concentrated almost entirely along the “Kashiwazaki area” coastline (Figure 1). Earthquake damage was reported by the JGS [11], Onoue and Toyota [12], and Toyota and Onoue [13].

At 3:59 on 12 March 2011, immediately after the 2011 off the Pacific coast of Tohoku Earthquake (14:46 on 11 March 2011) [14], another earthquake (designated as the Northern Nagano Earthquake) occurred at the border of Nagano and Niigata prefectures [15]. Its main tremor had a magnitude of 6.7. The earthquake, caused by a thrust fault, had a hypocentre of about 8 km depth. The JMA Seismic Intensity was recorded as “upper 6” in Sakae village (Figure 1). Some landslides occurred in Sakae village, Tokamachi town, and Tsunan town under the remaining snow conditions.

For those successive earthquakes which occurred in close proximity, the landslide types are investigated for each earthquake and are compared considering the importance of groundwater levels on landslides. Moreover, the actual conditions of compound natural disasters were examined in

the Chuetsu area to assess the compounded damage of these successive natural disasters.

2. Geological and Geomorphological Features

In the Chuetsu region, thick alluvium covers plains; hilly areas are composed mainly of soft mudstone of quaternary and tertiary deposits (Figure 2). Quaternary deposits are new strata formed from 2 million years ago. Tertiary deposits are geological structures formed between 24 million and 2 million years ago. The geomorphology formed by folding presents a prominent landslide area in this region.

The Chuetsu region was originally notorious as a tertiary type landslide area [16]. This area has been struck by many natural disasters in recent years. In the Chuetsu area, including Nagaoka and Ojiya (Figure 1), thick alluvium covers the Niigata plain created by the Shinano River. Hilly areas are composed mainly of soft mudstone of quaternary and tertiary deposits. This region has been compressed along the northwest-southeast axis because of crustal movements. Its folded mountains present prominent landslide configurations such as the cuesta landform. Earth-related disasters are generally concentrated in the “West Hills” and “East Hills” (Figure 2). The latter region includes a catchment area dotted with many ponds and rice terraces.

Tertiary mudstone is distributed in the Tokamachi and Tsunan areas, which are near the Northern Nagano Earthquake epicentre. This geology resembles that of the East Hills and is also notorious as a tertiary type landslide area. Nevertheless, it is interesting that Andesitic rocks mainly compose mountainous areas in the northern part of Nagano

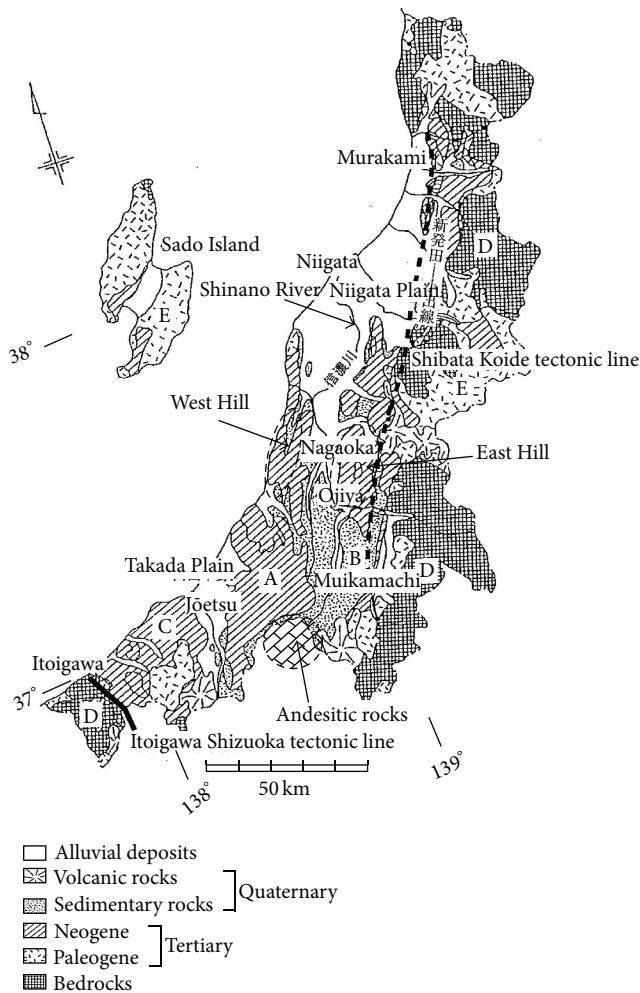


FIGURE 2: Geological map of Niigata [16].

when crossing the prefectoral border separating Niigata and Nagano (Figure 2).

3. Characteristics of Landslides

3.1. The Mid-Niigata Earthquake

3.1.1. Old Landslides. “Tanesuhara,” “Mushigame,” and “Asahikawa” in Yamakoshi area have been described as representative designated landslide areas. Figure 3 presents a landslide map of those areas during the Mid-Niigata Earthquake provided by the Geospatial Information Authority of Japan (GSI). River-clogging landslides along the Imo River during the earthquake are the “Terano,” “Nampei,” “Naranoki,” “Higashi-takezawa,” and “Junidaira” landslides from upstream (Figure 3). Among those landslides, Terano and Higashi-takezawa were large-scale landslides, which required urgent countermeasures against river clogging.

Table 1 presents the number of landslides occurring during 1949–2002 around Yamakoshi area [16]. Many landslides occurred in the Asahi River basin, extending from Mushigame, and in the Ohta River, which has Yomogihira

TABLE 1: Number of landslides during 1949–2002.

(a) Classified by basin	
	Number of landslides
Asahi River	29
Ohta River	19
Nanataki River	19
Imo River	17

(b) Classified by region	
	Number of landslides
Asahikawa	32
Tanesuhara	15
Mushigame	7

and Nigorisawa as designated landslide areas. Although 17 landslides occurred in the Imo River basin, almost all occurred in the Tanesuhara or Nakano landslide area located upstream. Landslides were reportedly only a few in Nampei, Higashi-takezawa, or Junidaira, where natural dams were created as a result of the earthquake. When classified by region (Table 1(b)) from most to least numerous, they are Asahikawa, Tanesuhara, and Mushigame.

The history of the former Yamakoshi village is well recorded [17]. Its history from 1700 indicates Tanesuhara as the site of the greatest recorded earth-flow disaster. Table 2 shows records of landslides in Tanesuhara. The landslides are only recorded in Tanesuhara because no such large villages existed in Yamakoshi area. Although landslides in prehistoric times are unknown, the first landslide recorded in Tanesuhara occurred in 1824. An exogenous factor causing landslides is snow-melt water in early spring. At that time, slopes were destroyed and two large clogging ponds were created in the Imo River. About a century after that event, a landslide occurred during the snow-melting season at almost the same place, thereby forming a natural dam. During the Mid-Niigata Earthquake, which occurred about 80 years after the previous event, the river-clogging landslide was broken at Terano near Nakano. The decisive difference is that the expected exogenous factor was not snow-melt runoff, but an earthquake. As described above, river clogging caused by landslides is a common phenomenon in the Imo River of Tanesuhara because large landslides that clog the river have occurred every century.

3.1.2. Geological Features. Related to unrecorded landslides of prehistoric times, the landslide history of Yamakoshi area was investigated using a topographical map that was compiled using information from an aerial photograph. Figure 4 portrays landslide locations during the Mid-Niigata Earthquake presented on the map of old landslide topography (provided by the National Research Institute for Earth Science and Disaster Prevention (NIED) and the Japan Science and Technology Agency (JST) [18]) in Yamakoshi area. Moreover, the figure was overlaid on a simplified geological map provided by Takeuchi et al. [19] and on landslide-designated areas obtained from a conservation map of Niigata prefecture [20].

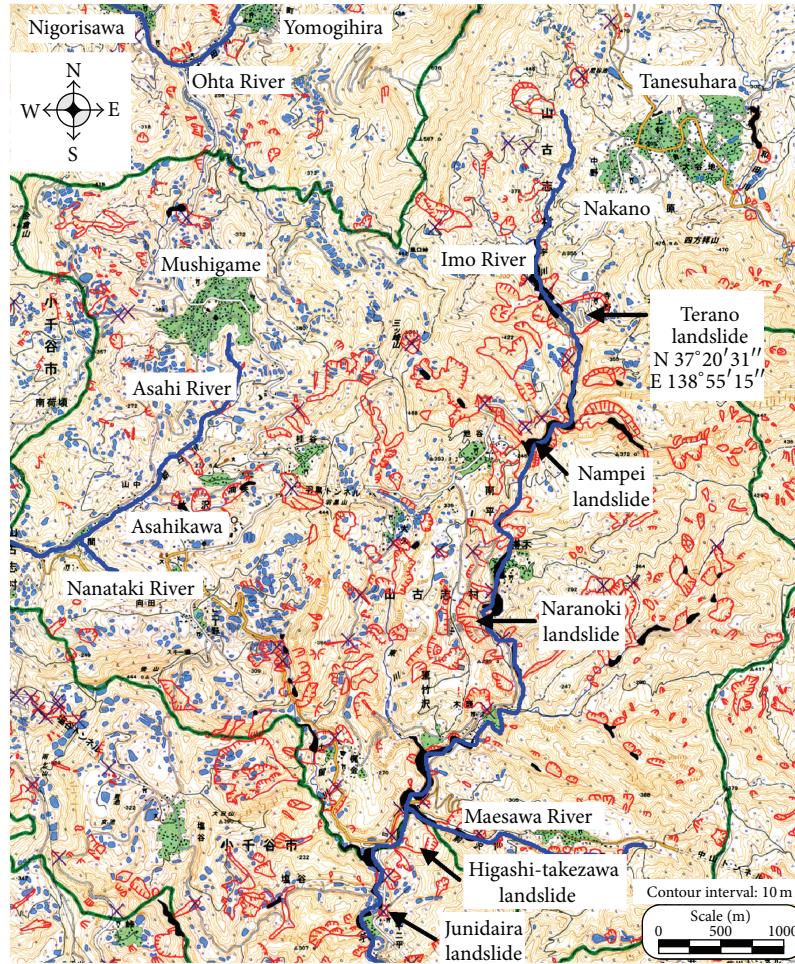


FIGURE 3: Disaster map around Yamakoshi area during Mid-Niigata Earthquake (provided by GSI).

TABLE 2: Old landslides in Yamakoshi area.

Number	Year	Disaster	Place	Conditions
1	1824 April: thawing season	Landslide length 1.4 km, width 700 m	Nakano	Disaster throughout the village. 50% of rice fields could not be cultivated. Flood induced by river clogging. Two ponds of 100 m length and 10 m depth were created.
2	1926 May	Landslide length 1.1 km, width 180 m	Nakano	Fields and mountains of more than 2 km ² were damaged. Floods induced by river clogging.
3	1929 April	Landslide width 50 m	Terano	Prefectural route (Tochio-Ojiya) was severed; bridge collapsed. River clogging is unclear.
4	1932	Landslide	Between Nakano and Terano	A large landslide occurred during construction of landslide measures. Details are unclear.

Many designated landslide areas are located in the East Hill area. Large-scale landslides that occurred during the earthquake such as those of Terano or Higashi-takezawa might be of a reactivated type of landslide because they coincide completely with the old landslide topography [18].

The west side of the map, which is classified in the Asahi River basin (Figure 4), is geologically an Araya deposit: massive dark grey mudstone. At the eastern side of the map, the Imo River basin (Figure 4), the deposit changes to

alternating sandstone and massive mudstone, designated as Kawaguchi and Wanatsu deposits. Alternation of sandstone and mudstone is distributed mainly along the Imo River, except in its upper course. As presented in Figure 4, more numerous landslides occurred during earthquakes in areas with alternated layers of sandstone and mudstone than in areas with massive mudstone deposits. This finding implies that sandy natural slopes are more fragile than clayey natural slopes during earthquakes. However, landslide-designated

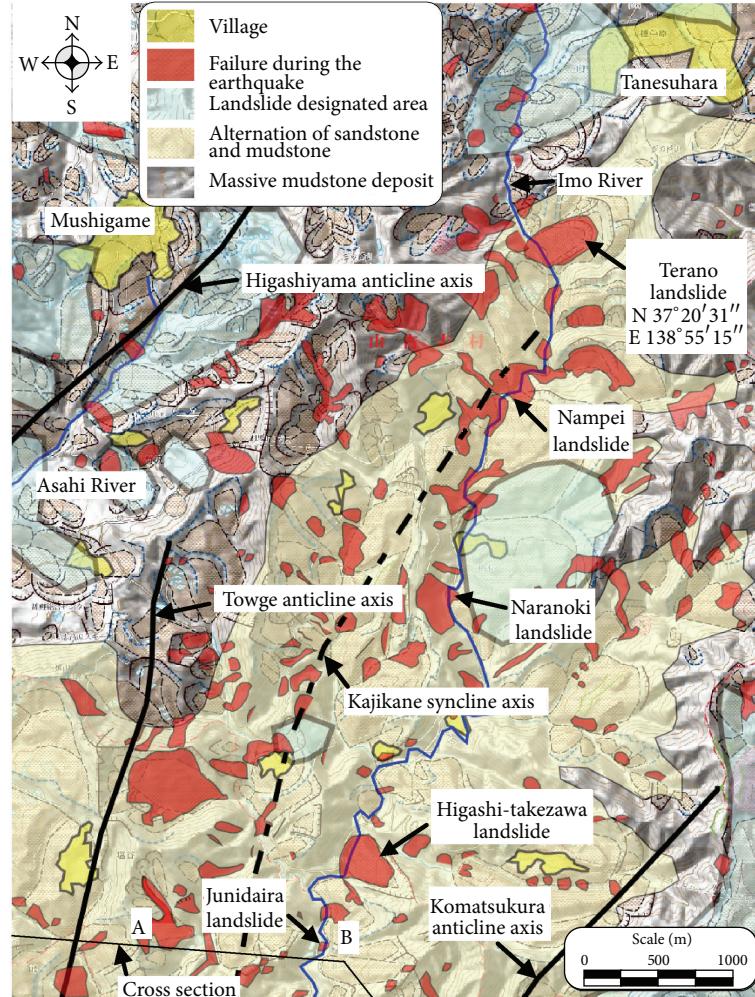


FIGURE 4: Landslide distribution and geological map around Yamakoshi area during Mid-Niigata Earthquake (provided by NIED and JST).

areas, in which landslides are induced by snowmelt waters, are distributed mainly in the massive mudstone deposits. Moreover, the notable geological features of this region are syncline and anticline structures. They form a complex topography in which synclinal axes and anticlinal axes are arranged with a short interval (Figure 4). For that reason, peculiarly cuesta topography is apparent in this region. Fragile and weak slopes are therefore formed easily. In addition, the river scours the riverbed and the slope toe. Thereby, the slope becomes unstable. For those reasons, it is considered that numerous landslides occurred during the earthquake.

Figure 5 depicts a geological cross section of the area south of Yamakoshi area (Junidaira) published by the National Institute of Advanced Industrial Science and Technology (AIST). The location of this sampled geological profile is presented in Figure 4. Sandstone (W) and sandy mudstone (S, Ku₂) are distributed widely around the Imo River. This representative folded mountain area is composed of syncline and anticline. Geological cross sections clarify that a dip slope is apparent on the left bank of the Imo River. A reverse-dip slope is apparent on the right bank of the river. Peculiar slope failures occurred at the right and left banks of the Imo

River. Surface failures occurred frequently at the right bank having reverse-dip slope strata, whereas problematical large landslides occurred occasionally at the left bank, which is a dip gentle slope.

3.2. Mid-Niigata Offshore Earthquake. According to a report of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) given on 6 August 2007, 108 slope failures occurred during the Mid-Niigata Offshore Earthquake. The main slope failure sites are concentrated in the steep slope of coastal terrace from Shiyya to Hijirigahana, which is about 25 km distant, as shown in Figure 6. Although almost all slides were surface collapses, large mass movements rarely occurred in inland areas as described in Toyota and Onoue [13] because the earthquake occurred not under a mountainous area but under an offshore area. The fault extended from the epicentre to the south. However, the landslides are much fewer than the more than 3,000 which occurred during the Mid-Niigata Earthquake, despite the similarity of the earthquakes.

3.3. Northern Nagano Earthquake. The earth-slide disasters during the earthquake were not perfectly clear because

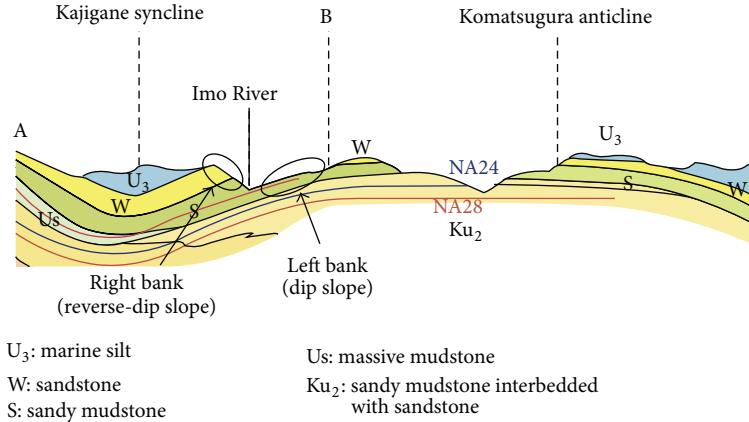


FIGURE 5: Geological cross section of the south of Yamakoshi area published by the National Institute of Advanced Industrial Science and Technology (AIST).

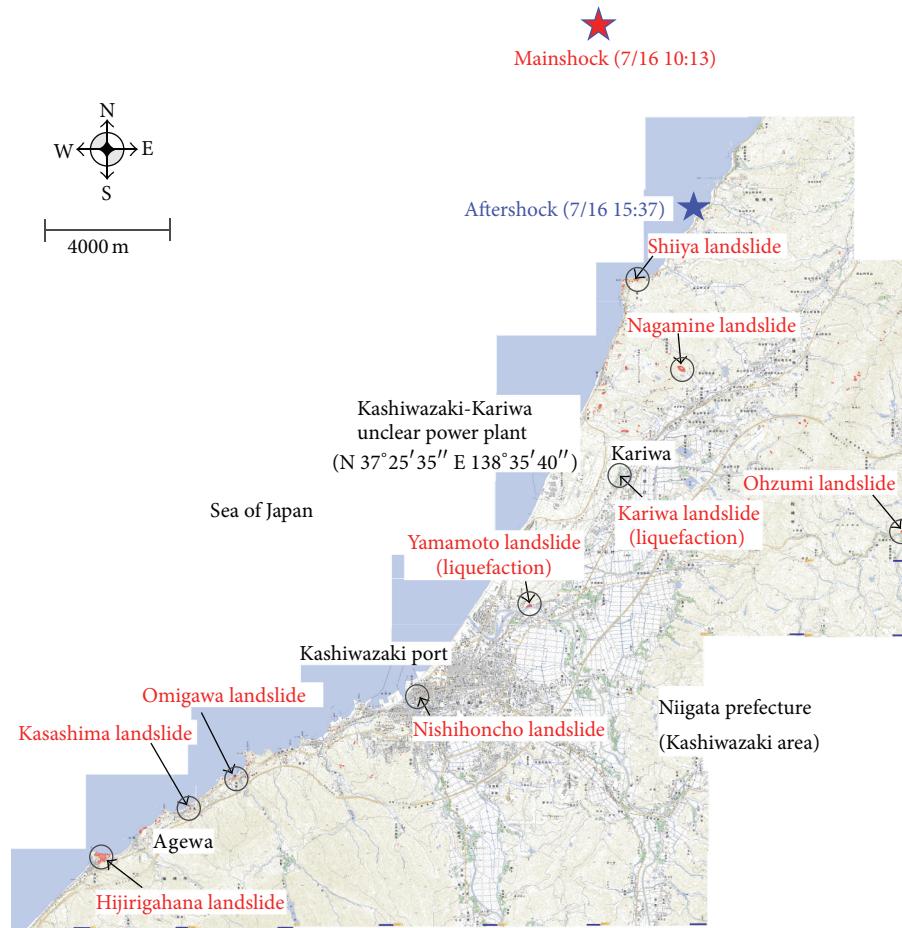


FIGURE 6: Landslide locations during the Mid-Niigata Offshore Earthquake (provided by GSI).

the snow remained deeper than 2 m in April in mountainous areas. According to the Niigata prefectural office, 19 slope failures threatening residential life were reported on 20 March 2011. The slope failures were concentrated in Tokamachi city and Tsunan town, which have tertiary mudstone as their

main geology (Figures 1 and 2). The Nagano prefectural office reported on 16 March 2011 that seven severe slope failures during the earthquake occurred in Sakae village, which has main geology of Andesitic rocks (Figures 1 and 2). Although the same type of earthquake occurred with

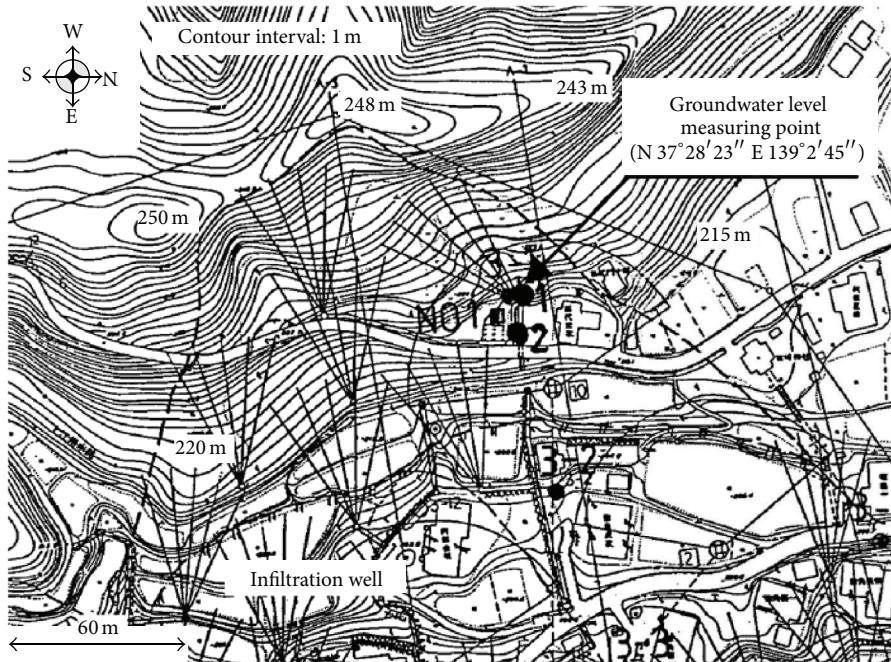


FIGURE 7: Topographical map (old landslide area at Tochio).

the Mid-Niigata Earthquake that occurred directly underneath the mountainous area, it remains unclear why so few earth disasters were generated by the earthquake.

4. Importance of Groundwater Level

Water level and pore water pressure have been measured at the author's laboratory since 1995 in the old landslide area at the former Tochio city (Figure 1). The data were acquired using a data logger every hour on the hour. A detailed topographical map of this area is presented in Figure 7. The observation point is inferred to be the upper part of the landslide. The gentle slope of a river terrace, which was formed by the meandering flow of river, spreads in the lower part of the landslide. Many infiltration wells have been made in this area as landslide countermeasures. After their installation, no remarkable mass movement has been reported to date. Figure 8 shows the depth of ground-installed water pressure sensors and their geologic column. A borehole with a strainer, which is 27 m deep, was made in the slope. Then a water pressure transducer was set at 12 m depth in the borehole for estimation of water level. For pore water pressure measurement, a water-pressure transducer in the borehole was buried in sand. Their upper and lower sides were sealed with bentonite. The ground consists of soft silty soil up to 10.3 m deep from the surface and a sandy gravel layer of about 70 cm. Soft underlying rock comprises sand and silt in sections deeper than 11 m.

Figure 9 presents records of groundwater level and hourly rainfall at Tochio during the Mid-Niigata Earthquake.

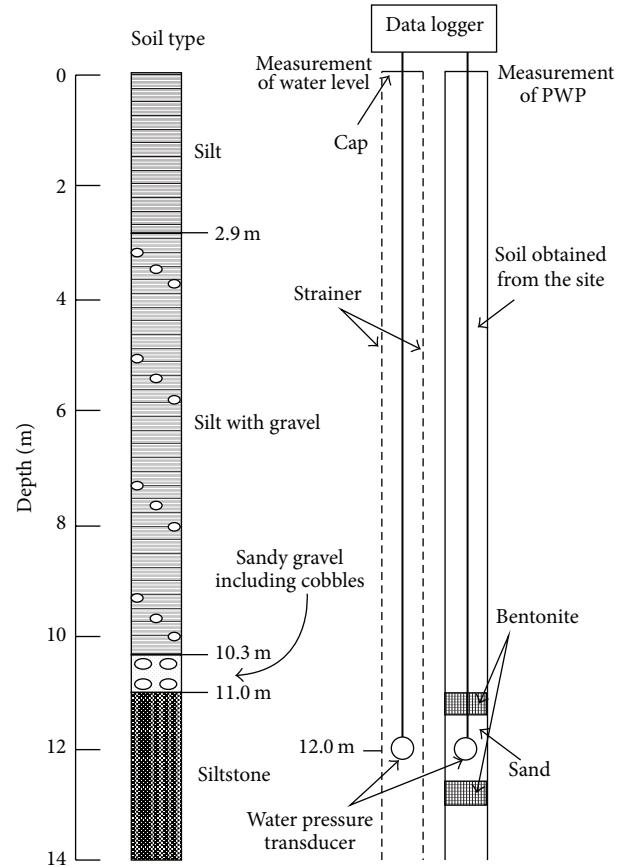


FIGURE 8: Depth of sensors and soil profiles.

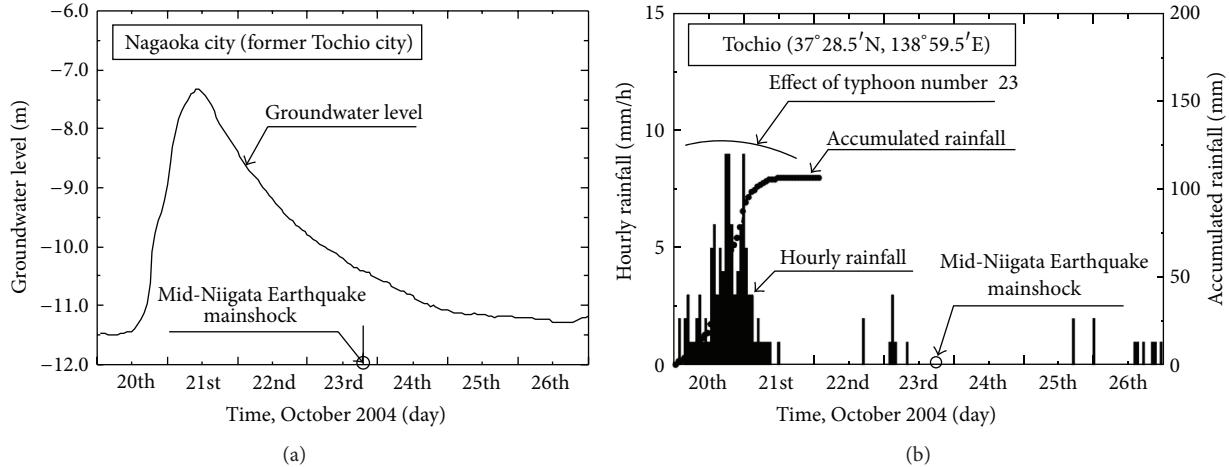


FIGURE 9: (a) Groundwater level and (b) rainfall during 20–26 October 2004.

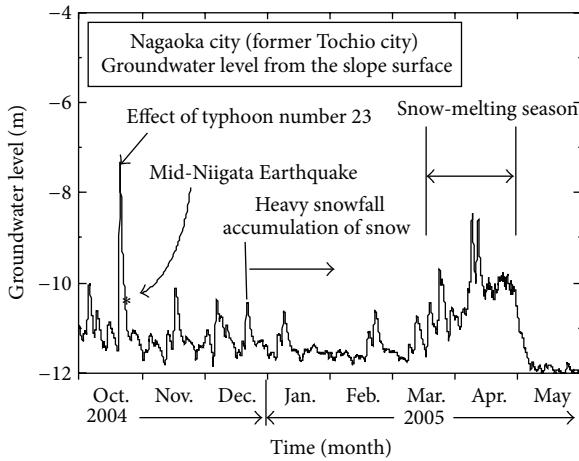


FIGURE 10: Groundwater level fluctuation.

Rainfall from typhoon number 23 occurred on 20 October 2004. The accumulated rainfall reached 100 mm in this area (Figure 9). The groundwater level rose quickly about 4 m with the rainfall. This area is inferred to include many catchment areas because the elevated groundwater levels descend gradually over a few days. The rise in the groundwater table induced by the typhoon had dropped by about 3 m in Tochio by the time of the Mid-Niigata Earthquake. It is apparent that this area still contained more water during the Mid-Niigata Earthquake than it did under ordinary conditions.

Groundwater level fluctuation (October 2004–May 2005) is shown in Figure 10. The groundwater level at three days before the Mid-Niigata Earthquake was the highest in the displayed period of time. The snow season starts from mid-December. The total amount of snowfall reached 699 cm at Nagaoka during that winter. Snow melting accelerates from March with the coming of spring. The groundwater level increases during the snow-melting season because of soaking of snow water and suddenly drops after snow melting (in May), as shown in Figure 10. For that reason, tertiary type landslides have occurred frequently in this area in April and

May: the snow-melting season. Therefore, it was feared that the slope damaged by the Mid-Niigata Earthquake starts moving again. Observations were continued during and after the snow season.

5. Follow-Up of Damaged Slope

The Chuetsu region is a heavy snow area. The risk of snow avalanche has been increasing because the Mid-Niigata Earthquake damaged snow-protection facilities and natural vegetation. According to Niigata prefecture, 228 avalanche mitigation fences and 8 snow sheds were damaged during the earthquake. Figure 11(a) shows an example of landslide in which soil mass slipped down with snow avalanche fences. Surface failures scoured the fence foundations. The fences were deformed because of falling soil. Soil accumulation behind fences and above snow sheds was also severe problem. As an emergency restoration, the accumulated soils were removed and large sandbags were emplaced to protect the infrastructure from the snow avalanche before the winter.

Snow avalanches occurred more frequently than year than in a normal winter. Some slopes were not covered with deep snow because a small snow slide occurred at all snowfalls. However, frequent patrols were conducted, preventing heavy damage. The risk of avalanche was reduced by the removal of unstable snow, construction of snow walls, and road closures during the winter. A new type of avalanche, where snow fell together with surface soil stripped from the damaged slope, was observed in Tokamachi City (Figure 1) as shown in Figure 11(b). An avalanche of this type, called a “snow-earth mixture avalanche,” is regarded as a compound natural disaster, causing extensive damage to residences and roads [21].

Landslides have occurred frequently during the snow-melting season in this area because of high groundwater levels (Figure 10). Therefore, it was feared that the slope damaged by the Mid-Niigata Earthquake starts moving again as a secondary disaster. Therefore, after snow melting, follow-up investigations were conducted to observe the slope failure sites. However, Toyota [22] reported that no large mass



FIGURE 11: (a) Damage to snow avalanche fence; (b) snow-earth avalanche [21].



FIGURE 12: Slope failures: upper row, before winter, and lower row, after snow-melting season.

movement occurred during the snow-melting season. These sliding masses induced by the Mid-Niigata Earthquake were therefore stable except for erosion from rain and snow melting. Situations of slope failures can be compared for those before winter and after the snow-melting season in Figure 12. There is no apparent difference between the photographs.

6. Earthquake Damage Comparisons

Comparisons between the Mid-Niigata Earthquake, the Mid-Niigata Offshore Earthquake, and the Northern Nagano Earthquake are presented in Table 3. All earthquakes are mutually similar except for the frequency of the aftershocks: they were frequent after the Mid-Niigata Earthquake, but not after other earthquakes. Many evacuees, to escape from the fear of repeated strong aftershocks, were compelled to reside for extended periods in inconvenient evacuation areas. Some

were afflicted with phlebothrombosis, often called “economy class syndrome.”

However, the types of damage related to the earth disaster were different among the earthquakes in spite of being only 60 km distant from the epicentre. Although the main landslide sites are hilly and mountainous areas and although more than 3,000 slope failures occurred during the Mid-Niigata Earthquake, 108 slope failures occurred mainly in the steep slope of the coastal terrace during the Mid-Niigata Offshore Earthquake according to a report of MLIT on 6 August 2007 because the earthquake occurred not under a mountainous area but under an offshore area. The Northern Nagano Earthquake occurred under mountainous areas between Nagano and Niigata. However, few landslides were reported, as described in Section 3.3. Two possible reasons can be considered. The first reason is that the main geology of Sakae Village in the northern part of Nagano is Andesitic rock,

TABLE 3: Comparisons of earthquakes.

	Mid-Niigata	Mid-Niigata Offshore	Northern Nagano
Date	23 Oct. 2004	16 July 2007	12 March 2011
Epicentre	Chuetsu area	Chuetsu offshore	Northern Nagano
Depth	13 km depth	17 km depth	8 km depth
Cause	Thrust fault	Thrust fault	Thrust fault
Magnitude	M6.8	M6.8	M6.7
JMA intensity	7 (at Kawaguchi)	6 upper (at Kashiwazaki)	6 upper (Sakae)
Max. acceleration	1750.2 gal (at Tokamachi)	812.7 gal (at Kashiwazaki)	803.5 gal (at Tsunan)
Aftershock	Frequent	Rare	Rare
Landslides	Thousands	Medium	Medium

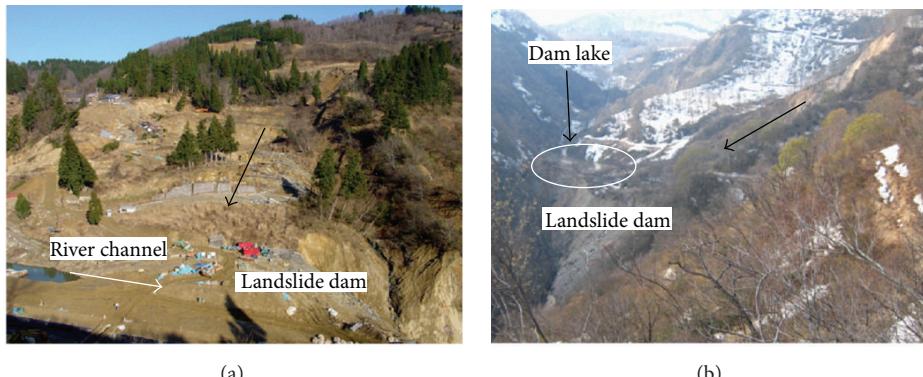


FIGURE 13: Typical river-clogging landslides that occurred (a) during the Mid-Niigata Earthquake and (b) during the Northern Nagano Earthquake.

which is different from the tertiary mudstone of the Chuetsu area (Figure 2). Examples of slope failures are exhibited in Figure 13. Figure 13(a) shows a river-clogging landslide at Yamakoshi area during the Mid-Niigata Earthquake. The weak soft deposit moved down and closed the Imo River channel. Figure 13(b) presents river-clogging landslides at Sakae Village during the Northern Nagano Earthquake. Apparently, the weathered part of a steep cliff fell and clogged a narrow valley. Then the dammed lake was created by the moving mass. However, the tertiary mudstone is distributed in Tokamachi and Tsunan areas (Figures 1 and 2) where strong seismic motion was recorded during the earthquake. Therefore, the second considered reason is that groundwater level might not be high during the Northern Nagano Earthquake compared with that of the Mid-Niigata Earthquake, as shown in Figure 9(a). From Figure 10, it is inferred that the ground water level remained low immediately before snow melting during the Northern Nagano Earthquake. Although snow remained deeper than 2 m in mountainous areas, few snow avalanches were triggered by the earthquake. Accumulated snow is apparently quite stable against earthquakes during this season (March). Consequently, the relations between the epicentre, the geography including geology, and groundwater level are extremely important factors to discuss to assess the risk of landslide damage.

7. Conclusions

Several earthquakes struck the Chuetsu area of Niigata successively in recent years. Damage investigations have been reported individually and have been mutually compared. Information about damage related to geotechnical engineering has been assembled and discussed from the viewpoint of compound natural disasters. Although no severe damage has been certified as a secondary disaster, these disasters underscore the possibility of compound natural disasters or slight damage such as erosion occurring in the damaged slopes. A summary of the main findings from the study is presented below.

- (1) The importance of groundwater level during landslide disasters was assessed using field measurement results. Results show that groundwater during the Mid-Niigata Earthquake was higher than that under normal conditions.
 - (2) Large-scale landslides during the Mid-Niigata Earthquake were regarded as reactivated type landslides because they occurred on old landslide traces.
 - (3) Most landslides during the Mid-Niigata Earthquake occurred at alternating sandstone and mudstone strata, but landslides that moved gradually during

- the snow-melting season usually involved mudstone in large quantities from tertiary deposits.
- (4) Landslides during the Mid-Niigata Offshore Earthquake were fewer than those which occurred during the Mid-Niigata Earthquake, perhaps because the main tremor occurred not under a mountainous area but under an offshore area during the Mid-Niigata Offshore Earthquake.
- (5) Landslides that occurred during the Northern Nagano Earthquake were also fewer than those that occurred during the Mid-Niigata Earthquake. The reasons considered are that the main geology of the mountainous area in northern Nagano is not tertiary mudstone but Andesitic rock. Moreover, the groundwater level might not be high compared to that prevailing during the Mid-Niigata Earthquake. Only a few snow avalanches triggered by the earthquake were reported in spite of snow that remained on the ground.
- (6) The risk of snow avalanche increased after the earthquakes because snow-protection facilities and natural vegetation were damaged.
- (7) Some additional damage occurred such as surface erosion and surface slides during rainfall and snow-melting season in the slopes damaged and loosened by the earthquakes. Carefully conducted daily observations are important to prevent a secondary disaster because some indications (slight damage) will precede severe damage. Timely countermeasures taken for cases of slight damage must be taken to reduce the risk of severe damage.
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Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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