Characteristics of Slope Failures During Natural Disasters Considering Geographical Features and Groundwater Level: Case Study of the Chuetsu Region of Niigata, Japan

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ABSTRACT: Several natural disasters—earthquakes, heavy rainfall, and snow—struck the Chuetsu region of Niigata during the short period of 2004-2011. Recently it has been pointed out that damage by a certain natural disaster is exacerbated by other natural disasters occurring before and after the natural disaster. This phenomenon, designated as a compound disaster, is of widely acknowledged importance. Records of such uncommon disaster circumstances and effects are presumed to be valuable from the viewpoint of disaster prevention. Therefore, actual conditions of damaged areas were investigated in the Chuetsu area to assess the degree of damage, with consideration of geographical features including geology and groundwater level. Moreover, the results of follow-up monitoring related to the damaged slopes during the unprecedented Chuetsu Earthquake are briefly introduced in this paper.

Keywords: ground water level, model test, monitoring on site, site investigation, slope stability

1. INTRODUCTION

Niigata prefecture is located in western and central Japan. The midlands of Niigata are called the Chuetsu region (Fig. 1). Various natural disasters have frequently struck this region in recent years. First, this section presents outlines of those disasters.

An unprecedented local downpour occurred in the Chuetsu region on 13 July 2004. It was designated as the “7.13 Niigata flood disaster”. The total amount of rainfall reached 250 mm in an area that was 20 km north–south and 100 km east–west, including Nagaoka and neighbouring cities (Fig. 1). The total amount of rainfall exceeded 400 mm in Tochio city (now the eastern part of Nagaoka city). The Niigata Prefectural Government reported that the heavy rainfall broke 11 dikes and caused more than 300 landslides. Consequent damage included 15 deaths (2 of 15 were killed by landslides) and more than 26,000 flooded homes. The JSCE (2004) and Toyota et al. (2006a) reported details of the damage situation during the disaster.

At 17:56 on 23 October 2004, the Niigata-ken Chuetsu Earthquake (designated as the Chuetsu Earthquake), whose main tremor was of magnitude 6.8, struck the Chuetsu area and severely damaged infrastructure in hilly and mountainous areas including Ojiya city, Nagaoka city, and their environs. Numerous landslides occurred especially in the “Yamakoshi” area (Fig. 1). A village was isolated by the cutting of all roads and lifelines. The earthquake, an epicentral thrust-fault earthquake with a hypocentre at about 13 km depth, produced characteristic frequent strong aftershocks that engendered further damage. In addition, rainfall of more than 100 mm was recorded from typhoon No. 23, which passed through the Chuetsu region three days before the earthquake. Daily rainfall of 21 October 2004 at Nagaoka city, based on data from the Japan Meteorological Agency (JMA), 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 JSCE (2006) and Toyota et al. (2006b) reported specific damage induced by the disaster.

Heavy snowfall occurred in the Chuetsu region during the two winters succeeding the Chuetsu Earthquake. Yearly snowfall is usually about 400 cm in Nagaoka, but it reached nearly 700 cm for each of the two years following the earthquake. This level of snowfall was the heaviest in 19 years. It is interesting how damaged slopes behave during snow and snow-melting seasons. Actually, this region has been notorious as a tertiary type landslide area. Landslides have occurred frequently in April and May: the snow-melting season.

Only three years after the Chuetsu Earthquake, at 10:30 on 16 July 2007, the Niigata-ken Chuetsu-oki Earthquake (designated herein as the Chuetsu-oki Earthquake), with a main tremor of magnitude 6.8, occurred at an offshore area about 30 km northwest of the epicentre of the Chuetsu Earthquake (Fig. 1). The earthquake emanated from a thrust fault; its hypocentre was about 17 km deep. 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 coastline of the “Kashiwazaki” area (Fig. 1). Earthquake damage was reported by the various investigators (the JGS (2009), Onoue and Toyota (2008), and Toyota and Onoue (2008)).

At 3:59 on 12 March 2011, soon after the 2011 East Japan Great Earthquake (14:46 on 11 March 2011), an earthquake occurred at the boundary between Nagano and Niigata prefectures (designated herein as the Northern Nagano Earthquake), with a main tremor of magnitude 6.7 (Fig. 1). The earthquake emanated from a thrust fault; its hypocentre was about 8 km deep. The JMA Seismic Intensity was recorded as “upper 6” in Sakae village. Some landslides occurred in Sakae village, Tokamachi town, and Tsunan town under the accumulated snow conditions.

The importance of groundwater level on slope failure was demonstrated by the results of model tests and disaster investigation. The slope failure types are shown for each natural disaster and are compared. Furthermore, actual conditions of compound natural disasters were examined in the Chuetsu region to assess the cumulative damage of successive natural disasters.

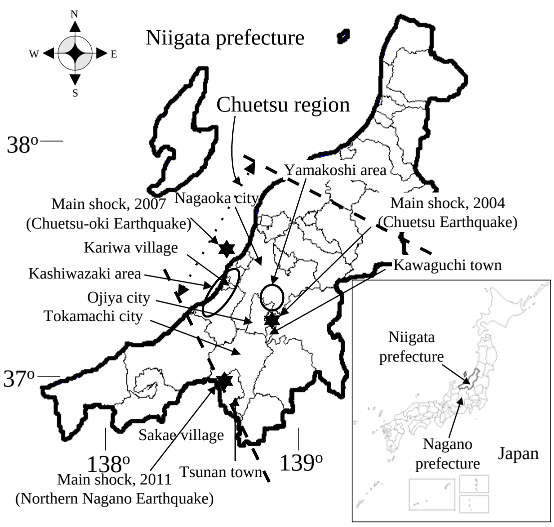

Figure 1 Locations of natural disasters in Niigata

2. GEOLOGICAL FEATURES AND EARTH DISASTERS

2.1 Geological Features

As described above, the Chuetsu region has been struck by many natural disasters in recent years. Even before these recent events, this region had been known as a tertiary type landslide area (Niigata Branch of the Japan Landslide Society (JLS), 2003). Figure 2 depicts a geological map of Niigata prefecture. In the Chuetsu area, thick alluvium covers the Niigata plain, which was created by the Shinano River; hilly areas mainly comprise soft mudstone of quaternary and tertiary deposits. This region has been compressed in a northwest–southeast direction by crustal movements. The folded mountains present a prominent landslide area resembling a cuesta landform. Earth disasters generally occur in the “West Hills” and “East Hills” (Fig. 2). The East Hill region includes a catchment area dotted with numerous ponds and rice terraces.

Tertiary mudstone is distributed in Tokamachi and Tsunan areas, which are near the epicentre of the Northern Nagano Earthquake. This geology resembles that of the East Hills, and is notable as a tertiary type landslide area. Mainly Andesitic rocks compose mountainous area in northern Nagano, which can be noted when crossing the prefectural boundary between Niigata and Nagano (Fig. 2). Typical landslides at the geologic boundary of tertiary mudstone and Andesitic rocks are explained in the following section.

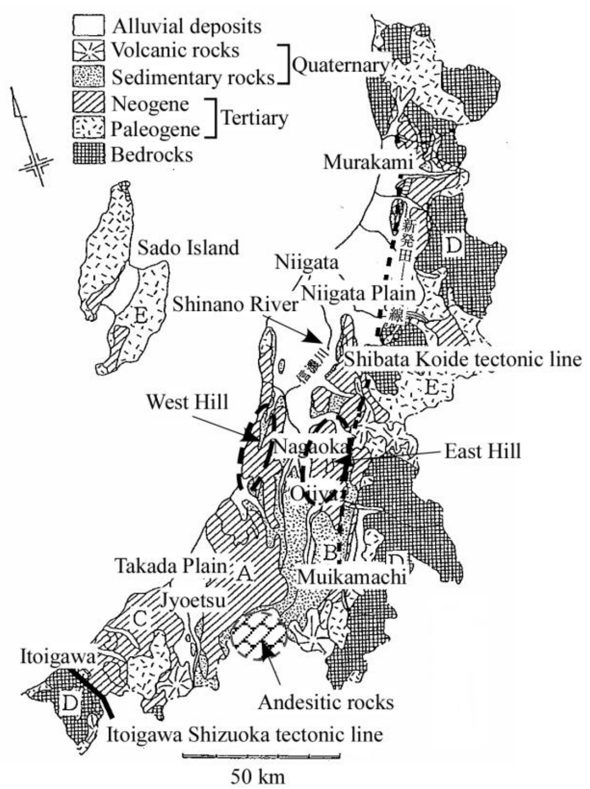

Figure 2 Geological map of Niigata (the JLS (2003))

2.2 The 7.13 Niigata Flood Disaster

In Fig. 3, based on data of the Niigata Prefectural Government, the numbers of landslides are shown on a map of Niigata with contour lines representing rain precipitation. A tendency exists for landslides to be numerous in heavy rain areas, except in Izumozaki town, which is at the west end of an area of rain concentration. The east end of the rain concentration is geologically composed of older and harder strata. The most damaged area is in the East Hill area (Fig. 2), which almost agrees with the centre of rain precipitation. Regarding landslides in Izumozaki, it can be pointed out that more landslides have taken place in the West Hill areas despite of the smaller amount of rain; those hill areas are folded mountains of the same geological age with the East Hill area. The main reason for this difference in landslide frequency is probably that many surface collapses occur on steep hills extending close to the coastline of Izumozaki town (Toyota et al., 2006a). Vegetation on that hill is mainly grass and shrubbery. A weathered soft rock layer is buried several tens of centimetres under the surface soil. Topography and geology are also important determinants of the degree of earth disasters because this type of slope is apparently vulnerable to heavy rainfall and earthquakes.

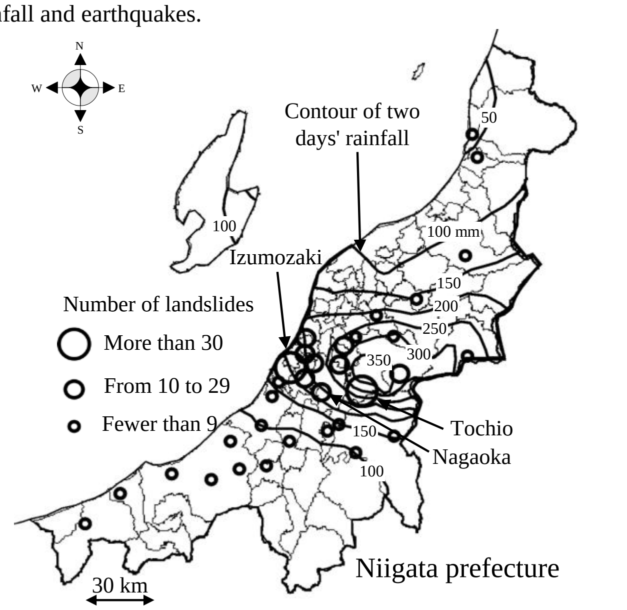

Figure 3 Number of landslides during the 7.13 Niigata flood disaster

2.3 The Chuetsu Earthquake

Figure 4 was prepared by overlaying a map of the locations of landslides occurring during the earthquake in the Yamakoshi area (Fig. 1) on a simplified geological map provided by Takeuchi et al. (2003). Landslide designated areas obtained from a conservation map of Niigata prefecture (1982) are also shown in the figure. Many designated landslide areas are located in the East Hill area. River-clogging landslides along the Imo River during earthquakes are known as the “Terano”, “Naranoki” and “Higashi-takezawa” landslides. Large-scale landslides such as those of Terano and Higashi-takezawa, which required urgent actions to alleviate river clogging, might be of a reactivated type because they coincide completely with the old landslide topography (Towhata and Toyota, 2010).

The west side (brown colour) of the map, which is classified as the Asahi River Basin (Fig. 4), is geologically an Araya deposit of massive dark grey mudstone. At the downward side (ochre colour) of the map, which is classified as the Imo River Basin (Fig. 4), the deposits are alternating sandstone and mudstone, named the Kawaguchi and Wanatsu deposits. This alternation of sandstone and mudstone is distributed mainly along the Imo River, except in its upper course. As presented in Fig. 4, numerous landslides occurred during earthquakes more frequently in areas with alternated layers of sandstone and mudstone than in areas with massive mudstone deposits. This finding implies that sandy natural slopes (alternating sandstone and mudstone) are more fragile than clayey natural slopes (massive mudstone) during earthquakes. However, landslide-designated areas, indicating that snowmelt waters have induced landslides, are distributed mainly in the massive mudstone deposits. Moreover, the notable geological features of this region are syncline and anticline structures. A peculiarly cuesta-like topography is apparent in this region because of its complex topography: synclinal axes and anticlinal axes are arranged with a short interval (Fig. 4). Fragile and weak slopes are therefore easily formed. In addition, the river scours the riverbed and the slope toe. Then the slope becomes u unstable. For those reasons, it is considered that numerous landslides occurred during the earthquake.

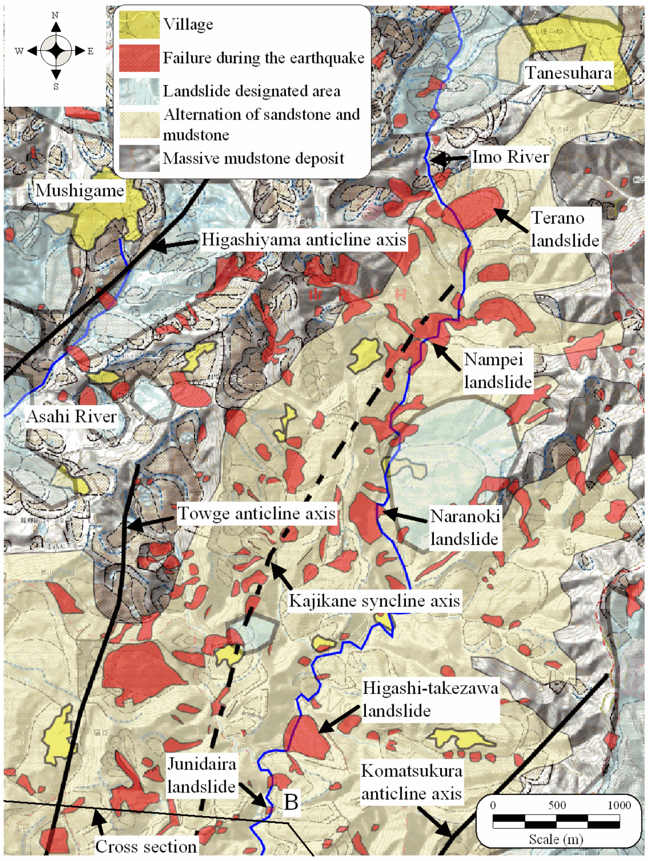

Figure 4 Landslide distribution during the Chuetsu Earthquake and geological map of Yamakoshi (Based on Takeuchi et al. (2004))

2.4 The Chuetsu-oki Earthquake

According to a report of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) issued on 6 Aug. 2007, 108 slope failures occurred during the Chuetsu-oki Earthquake. Figure 5 depicts the main slope failure sites including those caused by liquefaction during the earthquake. The main slope failures are concentrated in the steep slope of coastal terrace from Shiiya to Hijirigahana, which is about 25 km distant, because the earthquake occurred not under a mountainous area but under an offshore area and the fault moved from the epicentre to the south. Large mass movements rarely occurred in inland areas except for the case described by Ohzumi (Toyota and Onoue, 2008). Although the epicentre location is important to ascertain potential damage to an area, results show that the slopes of coastal terrace are weak during the earthquake, just as in the case of the 7.13 Niigata flood disaster.

2.5 The Northern Nagano Earthquake

Earth disasters during the earthquake have not been clarified because the snow-pack remains 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 Tunan town, whose main geology is tertiary mudstone. The Nagano prefectural office reported on 16 March 2011 that during the earthquake, seven severe slope failures occurred in Sakae village, whose main geology is Andesitic rock. In spite of the same type earthquake with the Chuetsu Earthquake that occurred directly underneath the mountainous area, it is interesting that only a limited number of earth disasters were generated during the earthquake. Comparison with other earthquakes, considering geology and groundwater level, is conducted in the following section.

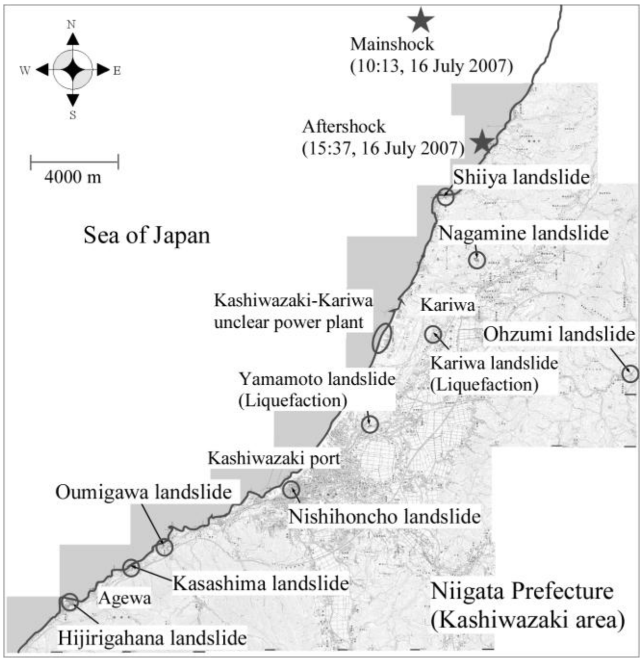

Figure 5 Main landslide distribution during the Chuetsu-oki Earthquake

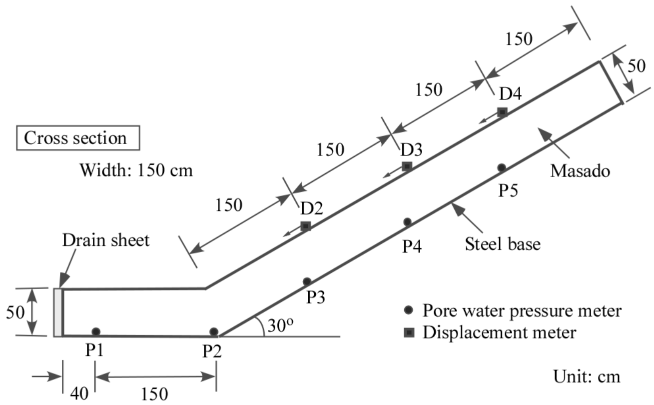

Figure 6 Model slope and sensor location

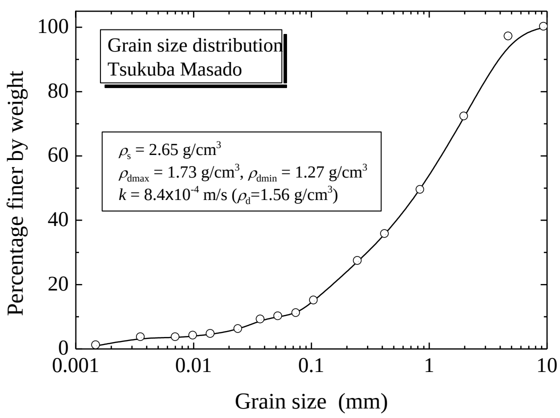

Figure 7 Grain size distribution of Masado

Photo 1 Progressive failure during rainfall (drained condition)

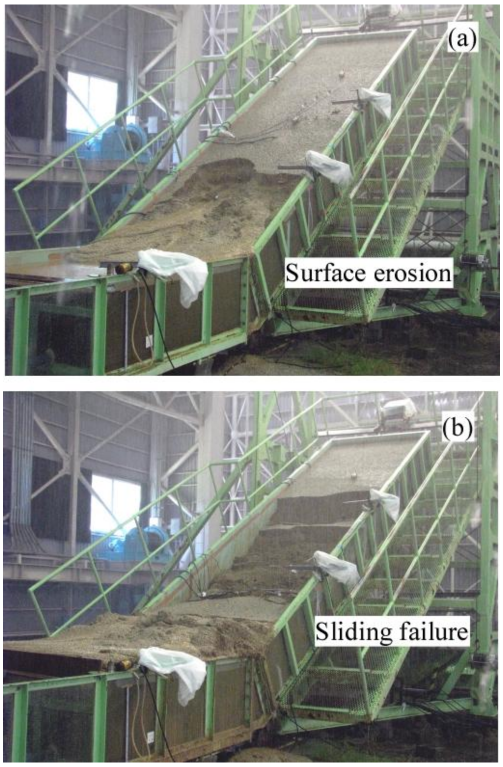

Photo 2 Progressive failure during rainfall (undrained condition)

3. IMPORTANCE OF GROUNDWATER LEVEL

3.1 Model Tests

Model slope tests were conducted using a rainfall simulator to examine the effect of groundwater level on slope failure at the National Research Institute for Earth Science and Disaster Prevention (NIED). Figure 6 shows the positions of sensors in the model slope. The model slope size is 600 cm long and 150 cm wide, with a slope of 30°. The soil is 50 cm deep perpendicular to the slope surface. The container base is made of steel with projections of 1 cm height at every 60 cm in slope direction to increase friction between the soil and steel. Sensors of various kinds including pore water pressure meters (Flush diaphragm type), soil moisture sensors, tensiometers, displacement meters (Potentiometer type), and clinometers are emplaced in the model slope. However, only the results of pore water pressure and the surface displacement are reported (Fig. 6). Masado (decomposed granite) obtained from Tsukuba mountain in Ibaraki prefecture was used for the model slope material. Figure 7 shows the grain size distribution of Tsukuba Masado: the soil particle density, ρ_s, is 2.65 g/cm^3; the permeability coefficient, k, is 8.4×10^{-5} m/s at dry density of ρ_d=1.56 g/cm^3. Masado with 9% water content was compacted horizontally at each 20 cm layer, as the dry density of the slope, ρ_d, became 1.6 g/cm^3. Rainfall of 15 mm/h was provided initially to the model slope for four hours (Initial rainfall) to achieve a stable condition as a gravitational static condition because of rainfall. After 24 hours had passed after the initial rainfall, rainfall of 50 mm/h was provided to the model slope until failure (Main rainfall).

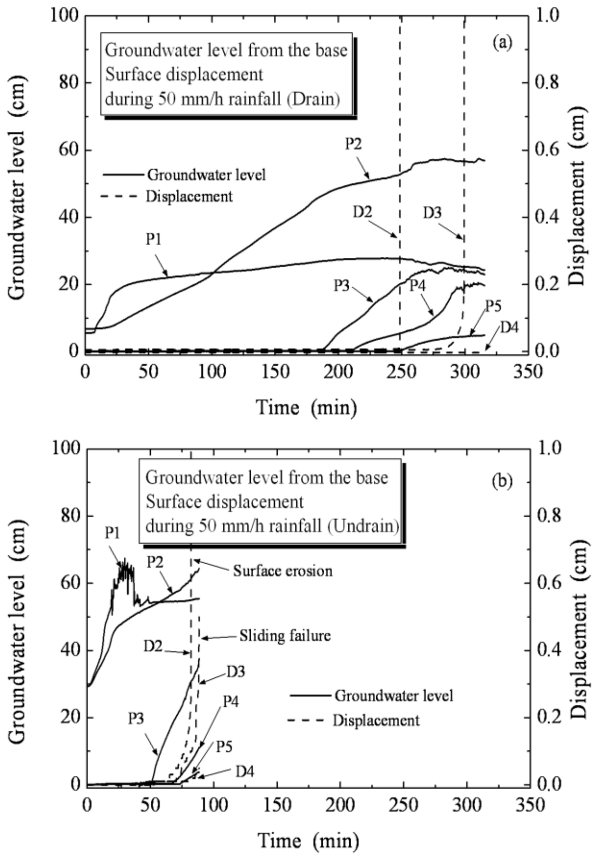

Figure 8 Groundwater level and surface displacement during rainfall: (a) Drained condition, (b) Undrained condition

Two test cases were conducted to compare the relation between the increase of groundwater level and the failure time. The first case is designated as the drained condition (Case 1), in which groundwater accumulated by rainfall is drained from the front vertical surface using the drain sheet as shown in Fig. 6. The second case is designated as the undrained condition (Case 2), in which groundwater is accumulated in the container without draining. It overflows from the container during rainfall, as shown in Photo 1 and 2. Figure 8 shows the groundwater level from the base estimated using pore water pressure meters and surface displacement during the main rainfall. The groundwater levels of about 6 cm and 30 cm, which are induced by the initial rainfall, respectively remain in the flat parts of the model slopes in Case 1 and Case 2. Groundwater level measured by P1 and P2 sometimes exceeds 50cm, which is depth of model ground. The reasons are that depth of the container is 60cm and that surface soil partly flows down by surface erosion. When the groundwater level of P5 increased, large deformation occurred near the toe of the slope (D2) in both cases. Especially in Case 2, the deformation behaviour showed a sign of failure that gradually developed to about 10 cm before P5 increased. The deformation of D2 was triggered by surface erosion, as shown in Photos 1(a) and 2(a). In Case 1 (Fig. 8(a)), the surface erosion gradually extended to D3, as presented in Photo 1(b). However, the displacement of D3 in Case 2 (Fig. 8(b)) was generated by the sliding failure, as depicted in Photo 2(b). The difference of groundwater level is that the increase of P3 is limited in Case 1, whereas P3 is increasing in Case 2 until sliding failure is generated. A large difference is also apparent in the failure time between Case 1 and Case 2. It is inferred that the rise of groundwater level in a slope is a key factor for slope stability because of the relation between the groundwater level and failure time. The failure type and triggering time are closely related with the groundwater level of the slope. Therefore, it is useful to monitor groundwater levels to discuss slope stability problems.

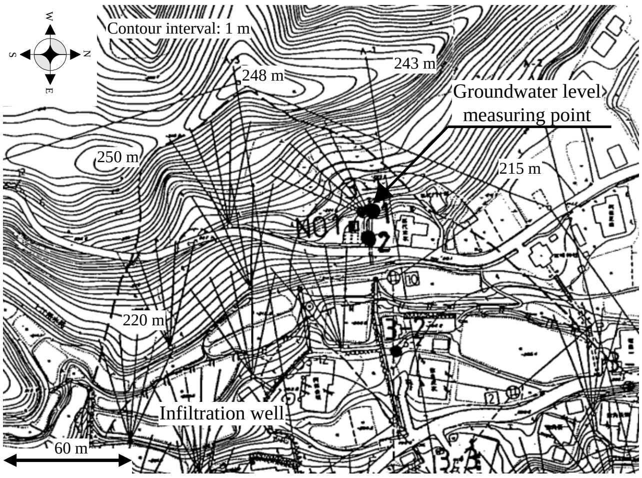

Figure 9 Topographical map (old landslide area at Irishiogawa)

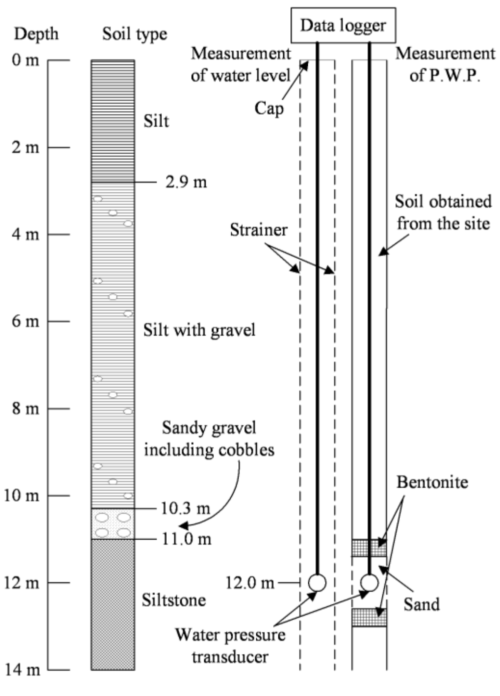

Figure 10 Depths of sensors and soil profiles

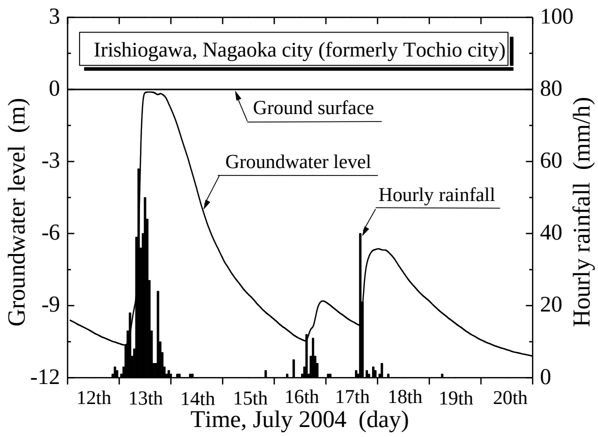

Figure 11 Groundwater level during the 7.13 Niigata flood disaster

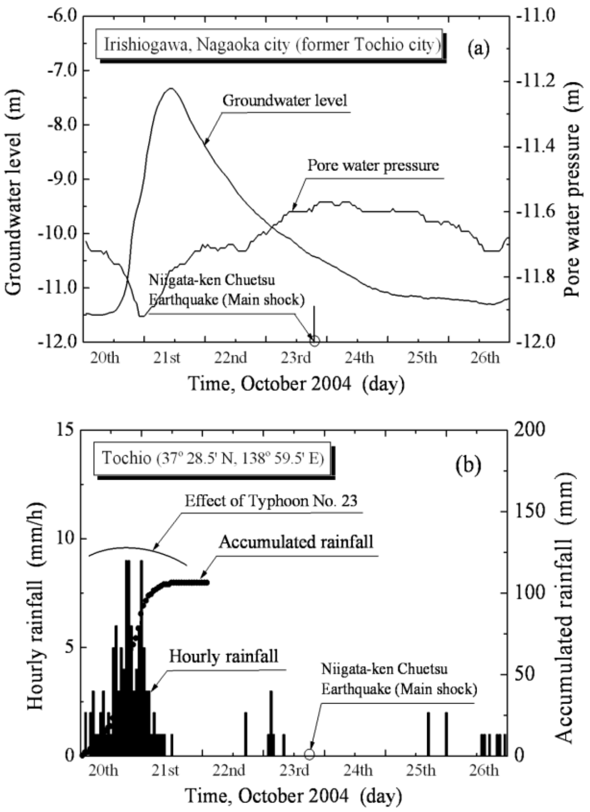

Figure 12 Groundwater level during the Chuetsu Earthquake

3.2 Groundwater Level during the Disasters

Groundwater level and pore water pressure have been measured at the author's laboratory since 1995 in the old landslide area, which is Irishiogawa of Nagaoka city (former Tochio city). Data were acquired every hour on the hour using a data logger. A topographical map of this area is presented by Toyota et al. (2006a). A detailed topographical map of this area is shown in Fig. 9. The observation point is inferred to be the upper part of the landslide. The gentle slope of a river terrace, formed by the meandering flow of the river, spreads in the lower part of the landslide. Many infiltration wells have been made in this area as landslide countermeasures. Since their installation, no remarkable mass movement has been reported to date, even during the Chuetsu Earthquake. Figure 10 shows the depth of ground-installed water pressure sensors and their geologic column of Irishiogawa. Two boreholes of 27 m deep were made in the slope and casings with strainers at different depth are equipped in the boreholes (Fig. 10). Then a water pressure transducer was set at 12 m depth in the borehole to estimate the water level. For pore water pressure measurements, a water pressure transducer in the borehole was buried using sand. Then, its upper and lower sides were sealed with bentonite as shown in Fig. 10. The borehole remained was buried completely using soil obtained from the site. The ground consists of soft silty soil up to 10.3 m depth 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.

First, fluctuation of the groundwater level during the 7.13 Niigata flood disaster is demonstrated with hourly rainfall data in Fig. 11. The rainfall data of the nearest areas from the measuring point were selected from among data provided by the JMA. The measuring point of Irishiogawa is about 4 km distant from the rainfall-recorded points. The groundwater level rises immediately by about 11 m with rainfall. From this quick rise, a permeable layer might exist in the slope. However, the groundwater level descends gradually over a few days, meaning that groundwater flowed into this catchment area after the rainfall. Although the mass movement induced by this rainfall is not obvious because the slope deformation has not been measured, deformation was not confirmed by visual observation. It is clear that an unstable state having a high groundwater level was generated in the slope during heavy rainfall.

Figure 12 presents records of the groundwater level and hourly rainfall at Irishiogawa during the Chuetsu Earthquake. The pore water pressure was also measured in this term. Rainfall of typhoon No. 23 was precipitated on 20 Oct. 2004. The rainfall accumulation reached 100 mm in this area (Fig. 12). The groundwater level rose quickly, about 4 m, with the rainfall and descended gradually over a few days. The rise in the groundwater table induced by the typhoon had dropped by about 3 m in Irishiogawa by the time of the Chuetsu Earthquake. It is apparent that this area contained more water during the Chuetsu Earthquake than it does under ordinary conditions.

The pore water pressure dropped on 20 Oct. 2004 with low atmospheric pressure; it then increased gradually. Although the pore water pressure reached a peak at the time of the Chuetsu Earthquake, its increase of about 20 cm in the water head is too small to affect slope stability. The pore water pressure sensors might not have been installed near the unstable slip surface where pore water pressure will change highly during disaster events.

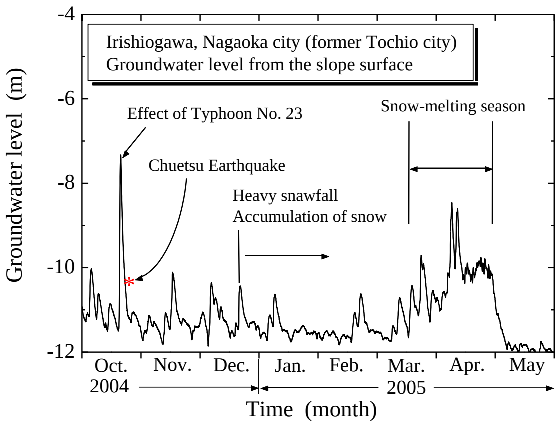

Figure 13 Groundwater level fluctuation: Oct. 2004 – May 2005

Fluctuation of the groundwater level during October 2004 – May 2005 is presented in Fig. 13. It is understood that groundwater level at three days before the Chuetsu Earthquake was the highest during 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. Then it drops suddenly after snow melting (in May) as presented in Fig. 13. It is noteworthy that tertiary type landslides in this area have frequently occurred in April and May, which are months of the snow-melting season. Therefore, the slope damaged by the Chuetsu Earthquake was feared to begin moving again, but no large mass movement occurred during the snow-melting season. The Northern Nagano Earthquake occurred in a mountainous area on 12 March 2011. Only limited slope failures were observed during the earthquake. From estimation using Fig. 13, although the year differs, there is a possibility that the groundwater level had not increased at the time of the earthquake.

4. CHARACTERISTICS OF SLOPE FAILURES DURING NATURAL DISASTERS

4.1 Comparison of Earthquake damage

Data for the Chuetsu Earthquake, Chuetsu-oki Earthquake, and the Northern Nagano Earthquake are presented for comparison in Table 1. For comparison, data of the 7.13 Niigata flood disaster are also included in the table. All earthquakes are mutually similar except in terms of the frequency of the aftershocks, which were very frequent after the Chuetsu Earthquake, although they were inactive after other earthquakes. Many evacuees, to escape from the fear of repeated strong aftershocks, were compelled to live for extended periods in inconvenient evacuation areas. Some of them suffered from phlebothrombosis; often designated as "economy class syndrome".

However, the damage related to the disasters was vastly different despite the separation of only 60 km among epicentres of the respective earthquakes. Although the main slope failure sites are hilly and mountainous areas and although more than 3,000 slope failures occurred during the Chuetsu Earthquake, 108 slope failures occurred mainly in the steep slope of coastal terrace during the Chuetsu-oki Earthquake according to the MLIT report of 6 Aug. 2007 because the earthquake occurred not under a mountainous area but under an offshore area. The Northern Nagano Earthquake occurred under a mountainous area between Nagano and Niigata prefectures. However, few landslides were reported, as described in section 2.5, although earth disasters occurring during the earthquake had not been perfectly clear because of remaining snow. Two possible reasons can be considered. The first reason is that the main geology of Sakae village in northern Nagano is Andesitic rock, which is different from the tertiary mudstone of the Chuetsu region (Fig. 2). Examples of slope failure are presented in Photo 3. Photo 3(a) shows the river-clogging landslide at Terano in the Yamakoshi area (Fig. 4) during the Chuetsu Earthquake. The weak soft deposit moved down and halted the current of the Imo River. Several river-clogging landslides of this type occurred along the Imo River (e.g. at Higashi-Takezawa in Fig. 4). Photo 3(b) shows the river-clogging slope failure at Sakae village during the Northern Nagano Earthquake. Apparently, the weathered part of the steep cliff collapsed and clogged the narrow valley. Then, a dammed lake was created by the moving mass. However, tertiary mudstone, which is the same material as that of the area damaged during the Chuetsu Earthquake, is distributed in the Tokamachi and Tunan areas, where strong seismic motion was recorded during the earthquake (Figs. 1 and 2). Less damage occurred from the Northern Nagano Earthquake than from the Chuetsu Earthquake because the groundwater level might not have been high during the earthquake in spite of high groundwater level during the Chuetsu Earthquake, as presented in Fig. 12. As presumed from Fig. 13, it is inferred that the groundwater level remained low immediately before the snow thawing. Although snow remained deeper than 2 m in mountainous areas during the Northern Nagano Earthquake, the earthquake triggered few snow avalanches. It is also interesting that the accumulated snow is expected to be quite stable against earthquakes during this season (March). Consequently, information about the

Table 1 Earthquake data for comparison

	7.13 flood disaster	Chuetsu Eq.	Chuetsu-oki Eq.	Northern Nagano Eq.
Date	13 July 2004	23 Oct. 2004	16 July 2007	12 March 2011
Epicentre	--------	Chuetsu region (Mountanious)	Chuetsu region (Offshore)	Northern Nagano (Mountanious)
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 etc.)	6 upper (at Sakae)
Max. acc.	--------	1750.2 gal (at Tokamachi)	812.7 gal (at Kashiwazaki)	803.5 gal (at Tsunan)
Aftershock	--------	Frequent	Rare	Rare
Landslides	Hundreds of	Thousands of	Medium	Medium
Main geology	Tertiary mudstone	Tertiary sandstone Tertiary mudstone	Tertiary mudstone	Tertiary mudstone Andesitic rock
Groundwater	Very high	High	Low	Low

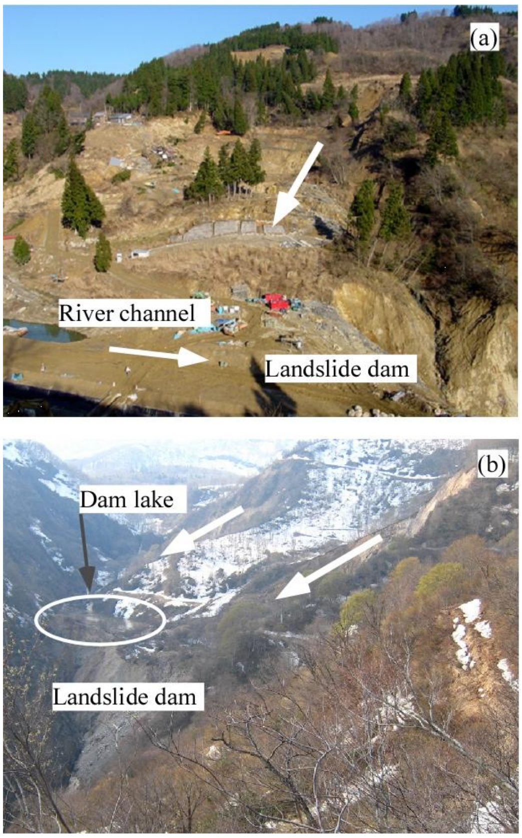

Photo 3 Typical river-clogging slope failures that occurred (a) during the Chuetsu Earthquake and (b) during the Northern Nagano Earthquake

epicentre, the geography including geology, and groundwater level are important factors when discussing the severity of earth disasters.

Figures 14(a) and 14(b) show grain size distributions of soil samples taken from slope failure sites of the Chuetsu and the Chuetsu-oki Earthquakes. All samples portrayed in Fig. 14(a) were obtained from the main scarps of the slope failures along the Imo River (except Shiodani) during the Chuetsu Earthquake. They are sands including less than 10% fines. Therefore, sandy natural slopes collapsed mainly during the earthquake, not clayey natural slopes. The mudstone that lay exposed after the slope failures at Higashi-takezawa is composed mainly of silt: siltstone. These results agree with information shown in the geological map: alternating sandstone and mudstone strata. Figure 14(b) portrays the grain size distribution of colluvial deposits and mudstones exposed after the slope failures during the Chuetsu-oki Earthquake. Mudstone contains much more fines than colluvial deposits do. Furthermore, the colluvial deposits have higher fines contents than those shown Fig. 14(a). Therefore, silty and clayey deposits were more predominant in natural slope failure sites during the Chuetsu-oki Earthquake than in the Chuetsu Earthquake in spite of their roughly equivalent geological age in East Hill, West Hill, and coastal areas of Kashiwazaki (Fig. 2). This aspect might explain the lower number of failure sites associated with the Chuetsu-oki Earthquake than with the Chuetsu Earthquake.

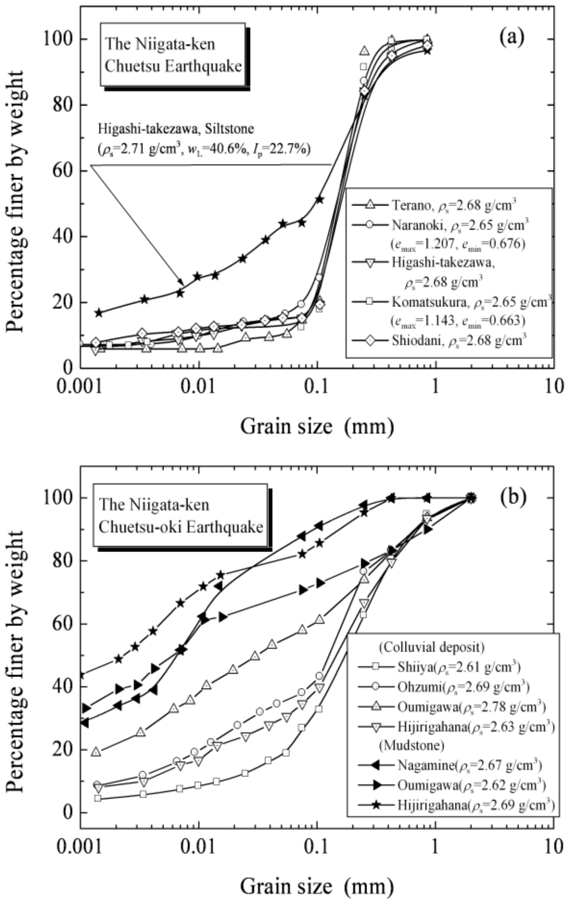

Figure 14 Grain size distributions obtained from failure sites that were (a) damaged by the Chuetsu Earthquake and (b) damaged by the Chuetsu-oki Earthquake

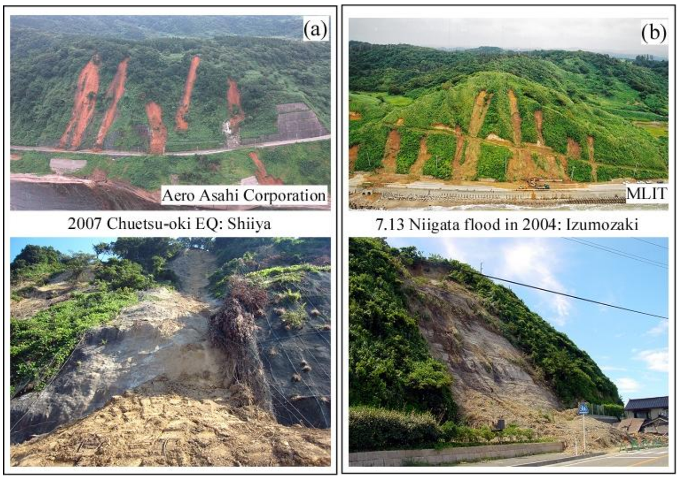

Photo 4 Surface failures that occurred (a) during the earthquake and (b) during the heavy rainfall

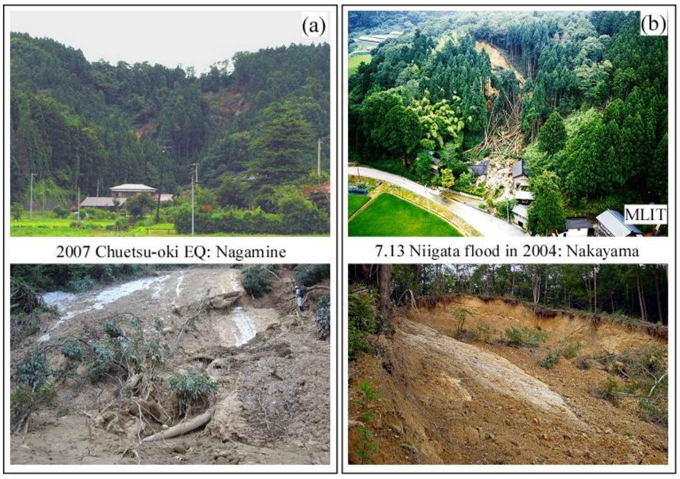

Photo 5 Dip slope failures that occurred (a) during the earthquake and (b) during the heavy rainfall

4.2 Comparisons of Slope Failures Induced by Rainfall and Earthquakes

Three months after the 7.13 Niigata flood disaster, the Chuetsu Earthquake occurred. The centres of the rain and the earthquake were near each other, but there was low agreement in areas and slopes damaged by the rain and the earthquake. The slopes damaged during rainfall are always vulnerable to earthquakes. Moreover, slope failures of similar types occurred during both rainfalls and earthquakes. Photo 4(a) shows the surface failure in Shiiya (Toyota and Onoue, 2008) that occurred during the Chuetsu-oki Earthquake. Photo 4(b) also shows a surface failure that happened during the 7.13 Niigata flood disaster in 2004 in Izumozaki (Fig. 3), which is about 10 km north of Shiiya. The weathered surface, which lies in a steep coastal terrace with reverse-dip slope, fell in both earthquake and rainfall events.

Smooth mudstone appeared after the slope failure in both Photos 5(a) and 5(b). They are, respectively, Nagamine during the Chuetsu-oki Earthquake (Toyota and Onoue, 2008) and Nakayama of Izumozaki during the 7.13 Niigata flood disaster. Colluvial mass movement often occurs on a discontinuous smooth layer having low permeability in both earthquake and rainfall events. Toyota et al. (2006a) stated that the strength of three types, which are colluvial deposits, mudstone, and friction between colluvial deposits and mudstone, should be estimated as determine the location of the slip surface in this type of slope failure. The results of triaxial compression and ring shear tests demonstrated that slope failure in Nakayama was triggered at the slip surface between colluvial deposits and mudstone. Another case also exists in which a low-cemented thin sandy layer is sandwiched by mudstones. In that case, pore water pressure increases with cyclic loading induced by an earthquake. The strength decrease, exacerbated by increase of pore water pressure, causes landslides along the weak layer. As a case study of the Chuetsu Earthquake, Deng et al. (2007) conducted plane–strain compression tests using undisturbed siltstone including thin tuffaceous sandstone layer. They reported that the failure mechanism was controlled by the tuffaceous sandstone because it was much weaker than pure siltstone. Although it is difficult to identify the existence of a weak layer before failure, its detection is crucial to specify hazard zones.

Photo 6 (a) Damage of snow avalanche fence and (b) a snow-earth avalanche (Kamiishi and Machida, 2008)

5. FOLLOW-UP OF DAMAGED SLOPE

The Chuetsu region is a heavy snow area. The risk of snow avalanche has been increasing because the Chuetsu Earthquake damaged snow-protection facilities and natural vegetation. According to Niigata Prefecture government reports, 228 snow avalanche prevention fences and 8 snow sheds were damaged during the earthquake. Moreover, slope failures involved fences (Photo 6(a)), although the sliding masses were not huge in many cases. Surface failures scoured the fence foundations and the fences were deformed by of the weight of the falling soil. Soil accumulation behind fences and above snow sheds was also a severe problem preventing the proper function of those facilities. As an emergency restoration activity, the accumulated soil was removed and large sandbags were emplaced to protect the infrastructure from a snow avalanche in case of the coming winter. Snow avalanches occurred frequently than during a normal winter. Some slopes were not covered with deep snow because small snow slides had occurred with each snowfall. Nevertheless, heavy damage did not occur because patrols were conducted frequently, and the risk of avalanche was reduced through removal of unstable snow, construction of snow walls, and road closures during the winter. A new type of avalanche, in which snow fell together with surface soil of the damaged slope, was observed in Tokamachi city (Fig. 1) as portrayed in Photo 6(b). This type of avalanche, called a "snow-earth mixture avalanche", is regarded as a compound natural disaster causing extensive damage to homes and roads (Kamiishi and Machida, 2008).

Landslides have occurred frequently during the snow-melting season in this area because of high groundwater levels (Fig. 13). Therefore, a slope damaged by the Chuetsu Earthquake was feared to begin moving again, causing a secondary disaster. After the snow had melted, follow-up investigations were conducted to observe the damaged slope sites. However, it is reported by Toyota (2010) that no large mass movement occurred during the snow-melting season, although surface erosion and small surface failures were observed during snow-melting and rainy seasons. These sliding masses induced by the Chuetsu Earthquake were therefore stable except for erosion from rain and snow-melt.

6. CONCLUSIONS

Earthquakes, heavy rainfall, and snowfall have successively struck the Chuetsu region of Niigata in recent years. Damage investigations have been reported individually and have been mutually compared. Information about damage related to geotechnical engineering sites was assembled and assessed from the viewpoint of compound natural disasters. No severe damage has been certified as a secondary disaster, although the possibility of compound natural disasters or slight damage has been revealed. The main findings obtained from this study are presented below.

1. The importance of groundwater level during natural disaster on slope stability was demonstrated by model test results. Results show that groundwater was higher than under normal conditions during the Chuetsu Earthquake.
2. The greater part of slope failures during the Chuetsu Earthquake occurred at alternating sandstone and mudstone strata. In contrast, landslides, which move gradually during the snow melting season, usually involved masses of mudstone of tertiary deposits.
3. Slope failures that occurred during the Chuetsu-oki Earthquake were fewer than those that occurred during the Chuetsu Earthquake. The reason might be that the main tremor occurred not under a mountainous area but under an offshore area during the Chuetsu-oki Earthquake. Another reason is that silty and clayey deposits were predominant at natural slope failure sites during the Chuetsu-oki Earthquake, whereas sandy deposits were predominant at failure sites during the Chuetsu Earthquake.
4. Slope failures during the Northern Nagano Earthquake were fewer than those that occurred during the Chuetsu Earthquake. The reasons include the fact that the main geology of mountainous areas is not tertiary mudstone but Andesitic rocks in the Northern Nagano area. Moreover, the groundwater level might not be high compared with that during the Chuetsu Earthquake. It is also interesting that only a few snow avalanches were triggered by the earthquake, although about 2 m of snow had accumulated at that time.
5. Rainfall and earthquakes have produced similar types of slope failures such as surface failure and failures on discontinuous layers, which indicates that the risk of slope failures is exacerbated by compound disasters.
6. The snow avalanche risk increased after 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. However, severe additional damage has not occurred in the Chuetsu region. Careful daily observations are important to prevent a secondary disaster because some indications, such as slight damage, will precede severe damage. Timely countermeasures for slight damage are necessary to reduce the risk of severe damage.

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