Behavior and Mechanism of Earthquake-Induced Landslides within Pre-Existing Landslide Topography: the Case of the 2004 Mid-Niigata Prefecture Earthquake, Japan

Hasbaator,1) Masaaki Hanaoka,1) Einosuke Nozawa,2) Atsushi Momose3) and Kenji Sasaki3)  
1) Snow Avalanche & Landslide Research Center, Erosion and Sediment Control Research Group, Public Works Research Institute, Japan (has@sanwa-boring.co.jp)  
2) Erosion Control Division, Public Works Department, Niigata Prefecture, Japan  
3) Mitsubishi Materials Natural Resources Development Corp., Japan

Abstract

The Mid-Niigata Prefecture earthquake known as the Chuetsu earthquake triggered numerous slope failures, including landslides, in the Chuetsu region. Among those landslides, about 40% occurred in the pre-existing landslide topography areas. We studied several representative landslides in this area, and discuss two of them in this paper; the Shiotani-kamisawagawa and the Amayachi landslides. These are located in the Imo-gawa river basin, the most heavily damaged area during this earthquake and strong aftershocks. The comprehensive studies, include drillings, revealed that these two landslides occurred in pre-existed landslide areas. They also reveal that the Shiotani-kamisawagawa landslide occurred deeper than older one, whereas the Amayachi landslide occurred almost along the older landslide. The main triggering factor of those landslides is obviously the Chuetsu earthquake, but the heavy rainfall, the geological composition and structure are considered to be additional factors that contributed to the occurrence of the landslides.

Keywords: landslide, rupture surface, the Mid-Niigata Prefecture Earthquake, earthquake-induced landslide

Introduction

On October 24, 2004 at 17:56, a strong earthquake (M_{JMA}6.8) shook the Chuetsu region, Niigata Prefecture, causing serious damages and destructions. This earthquake (Here after called the Chuetsu earthquake) measured a seismic intensity of 7, the largest ever recorded in the seismological observation history of Japan. A series of strong aftershocks shook the same area, and about 3,800 slope failures with an amount of about $1 \times 10^8$ m$^3$ of sediments occurred. It is usually known that earthquake-induced slope failures rarely occur within the pre-existing landslide topographic areas. It was considered that slope failures mainly occur along ridge lines of steep slopes and/or on convex slopes, but rarely occur on gentle slopes. It was found that among the landslides triggered by the Chuetsu earthquake, a large number were reactivated landslides. For example, about 40% of the 53 investigated places were reactivated landslides (Ishii et al., 2005). Numerous studies have been carried out on the Chuetsu earthquake-induced landslides. These studies focused on the classification of landslides (Oyagi et al., 2005), the geological and geomorphological characteristics (Chigira, 2005), the movement characteristics (Moriwaki et al., 2005) and the sliding mechanism (Sassa et al., 2005). However, there is no detailed and comprehensive investigation on the reactivated landslides induced by this earthquake. To clarify the occurrence mechanism of reactivated landslides induced by this earthquake, we selected several representative landslides (table 1) in the Imo-gawa, the Asahi-kawa and the Aikawa-gawa catchment areas. This study describes the activity and geological structure of these landslides by using comprehensive and detailed investigation methods, such as geomorphological and geological analysis and cyclic ring shearing test. In this paper, we report our findings on two selected landslides that occurred in the Imo-gawa river basin; one is the Shiotani-kamisawagawa landslide representing slopes composed of alternation of sandstones and mudstones, the other is the Amayachi landslide representing a massive mudstone area.

Location and regional setting

The topography of Chuetsu region is characterized by the significant difference between the two sides of the Uono River and its tributary, the Aburuma River (Fig.1). On the eastern side lie the steep ridges of the Echigo Mountains trending NNE-SSW direction with an elevation of 1,500–2,000m. On the western side lie the lower hilly terrains of the Uonuma, the Higashiyama and the Higashi-kubiki hilly terrains and the basins distributed between these terrains, showing a NNE-SSW direction. These terrains have very clear NNE directed
Table 1. Representative landslides caused by the Chuetsu Earthquake

<table>
<thead>
<tr>
<th>Location</th>
<th>Geological component</th>
<th>Geological structure</th>
<th>Slope angle (°)</th>
<th>Length (m)</th>
<th>Width (m)</th>
<th>Depth (m)</th>
<th>Displacement (m)</th>
<th>Volume ($\times 10^4$ m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amayachi</td>
<td>Ms</td>
<td>dip slope</td>
<td>15～20</td>
<td>250</td>
<td>150</td>
<td>18</td>
<td>40</td>
<td>350</td>
</tr>
<tr>
<td>Terame</td>
<td>Asm</td>
<td>dip slope</td>
<td>18～22</td>
<td>360</td>
<td>170</td>
<td>25</td>
<td>50</td>
<td>1,000</td>
</tr>
<tr>
<td>Koguriyama</td>
<td>Asm</td>
<td>dip slope</td>
<td>15～25</td>
<td>460</td>
<td>170</td>
<td>22</td>
<td>30</td>
<td>1,500</td>
</tr>
<tr>
<td>Shiotani-Kamisawagawa</td>
<td>Asm</td>
<td>dip slope</td>
<td>15～20</td>
<td>650</td>
<td>450</td>
<td>80</td>
<td>100</td>
<td>7,500</td>
</tr>
<tr>
<td>Higashi-Takezawa</td>
<td>Ms &amp; Asm</td>
<td>dip slope</td>
<td>18～22</td>
<td>350</td>
<td>250</td>
<td>30</td>
<td>60</td>
<td>1,300</td>
</tr>
<tr>
<td>Toge-Shiotani-gawa</td>
<td>sMs</td>
<td>reverse dip</td>
<td>25～30</td>
<td>250</td>
<td>150</td>
<td>18</td>
<td>30</td>
<td>900</td>
</tr>
<tr>
<td>Shiotani-minami</td>
<td>SLSG</td>
<td>dip slope</td>
<td>15～20</td>
<td>150</td>
<td>100</td>
<td>15</td>
<td>30</td>
<td>230</td>
</tr>
<tr>
<td>Tamugi-ga-yama-Kodaka</td>
<td>sMs</td>
<td>dip slope</td>
<td>15～20</td>
<td>350</td>
<td>270</td>
<td>20</td>
<td>50</td>
<td>1,800</td>
</tr>
</tbody>
</table>

Asm: Alternation of sandstone and mudstone; Ms: Mudstone; sMs: Sandy Mudstone; SLSG: Silt, sand and gravel

Fig. 1. Topographical map of the Chuetsu region, Niigata Prefecture, Japan. Drawn from 50m mesh digital map of GSI, Japan. 1: Shiotani-kamisawagawa; 2: Amayachi; * epicenter of the main-shock.

straight ridges, reflecting the result of geological structures and tectonics of this region. The elevation in the Uonuma hilly terrain picks at 700m decreasing towards north, and the ridge lines are biased east, forming an asymmetrical topography. However, in the Higashiyama hilly terrain the elevation varies between 300–500m. The Imo-gawa River flowing from north joins to the Uono River. The mainshock of the Chuetsu earthquake was located in southern side of the Higashiyama hilly terrain, and its focal area covers the southern and middle
part of Higashiyama hilly terrain and the northern part of the Uonuma hilly terrain.

The Chuetsu region is the most famous active fold area in Japan. In the Higashiyama hilly terrain, folded sedimentary rocks are distributed widely from the Miocene to the Pleistocene (Fig. 2), mainly striking NNE-SSW direction. Several folding axes, distributed about 1 km interval from west to east, pass through this region. They are the Higashiyama anticline, the Konpirayama syncline, the Toge anticline, the Kajigane syncline and the Komatsugura anticline. The rocks are mainly composed of mudstones, alternation of sandstones and mudstones, Tertiary sandstones, and sand, silt and gravel of the Uonuma Quaternary formation.

According to NIED (2004), many landslides existed in and around the Imo-gawa river basin before the earthquake. Slope failures induced by the Chuetsu earthquake seem to have concentrated along the right bank of the Imo-gawa River and its tributaries. Geologically, these failures occurred in the areas where deposited the Nishiyama Formation (similar to Kawaguchi formation) (Nozaki, 2005).

**Shiotani-kamisawagawa landslide**

**Outline of the landslide**

This landslide is located in the Shotani region, Ojiya City, 10km east of the central Ojiya City, and 4km northeast from the epicenter of the earthquake (see Fig.1). The landslide occurred in a 200–400m elevated southeast-facing slope on the right bank of the Dodome-gawa River, a tributary of the Imo-gawa River (Fig.3). There is an east-west directed ridge line on the head of the landslide slope and a cliff on the opposite site. In
the lower part of the landslide slope, a small channel flowing southwest-northeast forms a narrow area near the junction point with the Dodome-gawa River. On the right bank of this channel, there is a cliff with ridge line, including Mt. Dainichi-yama (390m), bending southeast-northeast. As described above, the topography of the landslide slope before the earthquake is characterized by the surrounding ridge lines of the slope. The slopes angles vary between 15 and 20 degree before the occurrence of the landslide, and were mostly used as carp breeding areas. The length of the landslides is about 650m, its width is about 450m, and the height of the main scarp is about 50m. The analysis of topographical map and aerial photographs taken before the occurrence of the landslide reveal that landslides occurred in these areas previously.

The regional geological map shows that the study area is composed of the Araya, the Kawaguchi and the Ushikubi formations of upper Miocene to Pliocene (Fig.2). The bedrock is composed of alternation of sandstones and mudstones of the Kawaguchi formation. And, the landslide area is characterized by dip slope structure due to the axis of the Toge anticline passing in the upper part of the landslide slope.

Landslide behavior

Induced by the Chuetsu earthquake, a very clear scarp and wide depression was formed between the scarp and moved masses in the upper part of the landslide slope (Photo.1). The width of the large depression is about 100m. Back-tilted surface near the main scarp, and a smaller depression (30m wide and 3m high) perpendicular to the large one was observable in the upper part of the landslide. These might be formed by
primary deformation of the landslide. In the middle part of the landslide slope, cracks, tilted rice fields and surface failures are observable. In the toe area, pressure ridge caused by the collision of the landslide masses with the opposite slope, spring waters and ponds are also visible.

According to the deformation mechanism of the landslide, the area was able to be divided into two units: I and II. Furthermore, unit I was able to be subdivided into sub-blocks I-1, I-2 and I-3, and unit II was able to be divided into II-1 and II-2 (Fig.4). Here, the II-1 was estimated be to moving together with the unit I, whereas II-2 unit might be triggered by I unit.

According to measurement of direction and displacement using aerial photographs and topographical map taken before and after the landslide, the displacement is larger in the upper part (100m maximum), smaller in the middle and the toe areas (about 40–60m), and the movement direction was estimated to be about S40E.

Geological component and rupture surface

Around the landslide area, the bedrock outcrops consists of an alternation of sandstones and mudstones. The layers of sandstone are thin and composed of fine to medium sized grain. The weathered rocks are light brown colored and very weak while the fresh rocks are hard and blackish in color. In the outcrop area near the main scarp, a mudstone domain with alternation of sandstones and mudstones are observable. The sandstone layers are very thin varying from several cm to several ten cm (Photo.2). These sedimentary rocks distributed along a NE-SW direction and dipping 10 to 30 degree south indicates a dip slope structure of the landslide area. However, in the upper part of the main scarp, the sediments are dipping 12 degree north suggesting the existence of the axis of anticline. The overlaying deposits are mainly composed of fragments of mudstone and sandstone mixed with silt and clay.

On the main scarp, the rupture surface cuts the bedding surface made of alternation of sandstones and mudstones (N75W, 12S), and clear slickenlines were observed on it (Photo.2). Such slickenlines, observable on the rupture surfaces near the main scarp, are trending S30–45E (Fig.5). This direction coincides with the movement direction estimated from the displacement of carp ponds on the landslide slope.

A total of 7 drillings were conducted in the landslide area; 5 along the main survey line and 2 in the toe area (Fig.4). These drillings revealed that the landslide slope is composed of silt mixed with fragments of mudstones and sandstones, weathered rocks (including heavily weathered), fractured mudstones (intercalating thin sandstone layers) and fresher rocks of alternation of mudstones and sandstones, from top to bottom (Fig.6). Generally, the composition of the slope is thin in the middle part, but become thicker in the upper part and the toe area, varying from 12 to 14m. The weathered mudstones and sandstones are 3m thick in the upper
An outcrop of rupture surface near the main scarp of the Shiotani-kamisawagawa landslide. Slickenlines are observable on the surface.

The deformation of the surface and the drilling results indicate a shallow rupture surface and a deeper rupture surface are considered in the landslide. The shallower surface may be related to secondary causes, while the earthquake causes the deeper surface.

In BV-1, silt mixed with fragments of mudstone is distributed up to a depth of 49.1m. Below this layer are found the fractured mudstone, and humus materials are observed in the boundary of these layers, considered as disrupted by the slip. In BV-2, slickenlines are observed at a depth of 37.9m although this drilling could not reach the deeper slip surface. In BV-3, at a depth of 62.85m, heavily fractured mudstones are distributed above the fresh mudstones, and there are weak clay and slickenside near the boundary. In BV-4, at a depth of 79.05m, slickenside was observed near the boundary of the mudstones and the fractured mudstones. In BV-5, at a depth of 62.6m, near the boundary of the mudstones and fractured mudstones, the formation is heavily fractured and very weak, and some slickenlines were observed.

Considering the observations from the drilling cores, we estimated that the deep-seated slip surface could be inferred as shown in Fig.6.

**Mechanism of the landslide**

The instability of the surrounding topography, the weak geological formations of the slope, and the dip-slope structure due to the active folding are important factors in the landslide occurrence. However and undoubtedly the main and direct trigger of the landslide is the strong ground motion caused by the earthquake. The landslide area located only 4km from the mainshock epicenter, and all of the surrounding areas belong to the strong motion focal area. The 100mm rainfall that fell on the region on October 20, 2004 might have
caused an increase of the pore water pressure increasing the risk of sliding. In addition, land use practices on the slopes might have caused the infiltration of water through the cracks after earthquake. All of these might have contributed to the occurrence of the landslide.

The scarp of the landslide formed almost along the ridge line of the landslide slope coinciding with the increase of acceleration response along the ridge lines by the strong motion of the earthquake (Asano et al., 2006). The landslide slopes were convex in shape before the earthquake and the landslide moved without changes in its shape. Drillings revealed that the slip occurred in a very deep layer. We could estimate that the slip occurred after the fracture of rocks due to the strong motion and then the sliding occurred along boundary of the fractured rocks and fresh mudstones. According to the back-tilting deformation near the main scarp, we estimated that the slip in the middle part of the slope is deep-seated translational, whereas in the upper part it might be rotational. Based on the outcrops near the main scarp and around the area, the slip was estimated to have occurred along the bedding layer in the deep zone, and then the rotational slip occurred in the upper part.

The overview of the landslide reveals that the displacement in the upper part is large and formed a large depression, whereas it is small in the middle and the toe area. The smaller displacement of the toe area is due to the collision with the opposite slope. Furthermore, the intensive aftershocks might have caused many secondary deformations on the landslide slope, such as cracks, small depression and tilting of the field.

The slickenlines found on the rupture surface indicate that the landslide moved southeast, coinciding with the direction of displacement of field and roads. From the drilling cores, we observed some slickensides and slickenlines, mainly along the boundary of the fractured mudstones and fresh mudstones, thus we estimated that the rupture surface lie along the bedding surface at deeper zone.

**Amayachi landslide**

**Outline of the landslide**

The Amayachi landslide is located in the Tanesuhara area, 4.5 km northeast of the former Yamakoshi Village Office and 9 km northeast of the epicenter of the earthquake (Fig.1). This area is the source of the Imo-gawa River. Along the banks of this river distribute gentle slopes that vary from 300–500m in elevation. These slopes are used as rice fields and carp breeding ponds. In this area, numerous landslide topographies exist among them are the landslides focus of the prevention works carried out by the Niigata Prefecture, such as the Tanesuhara and the Amayachi areas. The Amayachi landslide occurred on the left bank of one the tributary of the Imo-gawa River on a SSE facing slope (Fig.7). The slope angle was about 15–20 degree before the landslide occurs and convex in shape. The landslide is 250m long, 150m wide and the height of the scarp is about 20m.


The geology of this area is mainly composed of the Sarukuradake, the Toyagamine, the Araya and...
the Kawaguchi formations of Tertiary. The landslide slope mainly consists of the massive mudstones of the Araya formation. We observed the heavily weathered mudstone near the main scarp of studied slopes and confirmed through drillings that the slope is mainly composed of the colluvium, weathered mudstones and fresh mudstones.

The geological structures of the area show a NE-SW domain structure coinciding with the ridge line of the Sarukuradake-Nokogiri-yama and the axis of the Higashiyama anticline. The sedimentary rocks of the studied slopes are laying NNE-SSW and dipping southward with a 25–45 degree angle, so the landslide occurred in a dip-slope structure.

**Landslide behavior**

Photo.3 and Photo.4 show the whole view of the landslide area before and after the landslide occurrence, respectively. The slope before the landslide occurrence was estimated to be the landslide affected gentle slope, although that was changed by artificially, such as used as rice field. After the earthquake, a clear main scarp formed on the slope, and there were very dynamic and complex deformations in the middle part of the slope (Photo.5) and a pressured deformation was observed in the toe area. The height of the main scrap is about 20m, and the heavily weathered mudstones outcropped near the scarp, and pouring groundwater is visible. In the middle part of the slope, the rice fields were complicatedly deformed forming clear cracks, steps, depressions, and tilted and undulated terrains. The road that passes through the landslide slope was destroyed over 160m long by the sliding. The horizontal displacement was about 30–40m. The toe of the landslide was pressured and the moving mass blocked the channel forming a dam.

The analysis of the displacement of the road and rice fields using aerial photographs taken before and after the landslide occurrence reveals that the direction of the sliding is S20–30E. On the left side of the landslide, slickenlines, about S17E in direction, were observed coinciding with above direction.

The landslide could be divided into five units according to the deformation and movement of soil masses (Fig.8). Block I is the main unit of this landslide. Blocks II and III are considered as separated units based on the collapsed soil. Block IV is located on the left side of block I and block V is on the right side, and is almost similar to the pre-existing one. Unit V unit is located on the older landslide slope. The piles and concrete blocks constructed on the upper part of this unit were destroyed by the earthquake.

**Geological component and rupture surface**

Around the study slopes, there are several outcrops in which the bedrock made of massive mudstone outcropped. The weathered mudstone observed near the main scarp seemed very weak. The overlapping
Photo. 3. A panorama view of the landslide slope of the Amayachi, taken before the slide occurring.

Photo. 4. A panorama view of the Amayachi landslide, numbers indicate block partition and arrows indicate moving direction.

Photo. 5. Dynamic deformation of the middle part of the Amayachi landslide. Taken from main scarp.

Material is colluvium composed of clay mixed with mudstone pieces formed by older landslides. A total of 5 drillings were constructed on the landslide slopes by the Niigata Prefectural government (Fig.8). Fig.9 shows a geological cross section along the survey line indicated in Fig.8. Following is the description of the drilling cores of BV-1-BV-3 drill holes along the survey line. Drillings revealed that the slope consist of; colluvium, weathered mudstone (including heavily weathered) and fresh mudstone, from top to bottom. The heavily weathered mudstone layer consist of clay mixed with fractured rocks indicating that this layer belong to the moved masses. However, below this layer is found a lightly weathered mudstone, mudstones, but also hard and fresh formation estimated to belong to the bedrock.

The observation of the drilling cores reveals that the rupture surface location is estimated as follows: In BV16-1 drilling core, at the depth of 11.5-11.8m, the core shows a clay formation including the layer of clay mixed with fractured rocks. Since the upper part of this layer is very weak and disturbed, and the lower part is very hard and fresh, we estimated that the rupture surface is located near this boundary. In BV16-2, at a depth of 18.0–18.1m, the upper part of the layer is weak whereas the lower part is fresh. In addition, there is a thin layer of clay near the boundary. In BV16-3, at a depth of 14.6m, the formation found above this depth is weak and loose. Between 14.0m and 14.6m a very disturbed formation exists. Thus, this location is estimated as the rupture surface and is shown in Fig.9.
Mechanism of the landslide

As described above, this landslide occurred on a slope where previously landslides occurred. In 1980 and 1981, landslides occurred on the same slope, but only partially overlapped. The weak geological composition of the slope and the dip-slope structure of the slope are important factors in the landslide occurrence. This landslide triggered by the Chuetsu earthquake lies along the weathered rocks and the mudstones. The very complex deformation of the slope indicated that this landslide initiated in shallower depth in the mudstone formations, it then continued to be deformed by the strong aftershocks and the movement of the landslide itself. The deformation indicates a shallower slip and a soft composition of the covering materials.

The direction of the landslide movement is SE. The slope situation and the movement direction point out that this landslide may have acted along the older one. Considering the rapid movement of the landslide, we could confirm that the direct trigger of this landslide is the strong ground motion during the earthquake and the strong aftershocks. In addition, the 81mm rainfall that fell on the region days earlier may have induced an increase of pore water pressure increasing the susceptibility to sliding.

The massive mudstone composition of the landslide area indicates the low possibility of liquefaction. Thus, the strong motion is considered to be the main and direct trigger of this landslide. Furthermore, there is a high possibility that this landslide occurred along the older one, because of the geological situation and the location of the rupture surface.
Summary

The Shiotani-kamisawagawa landslide is the biggest among the landslides triggered by the Chuetsu earthquake, and occurred in the older landslide topography. The rupture surface is cutting the bedding layer in the main scarp, but lies along the layer in the deeper zone. It is estimated that the rupture surface newly formed in the deeper zone.

The Amayachi landslide on the other hand occurred on a gentle slope along the older landslide. The direct cause of these two landslides is obviously the strong ground motion during the Chuetsu earthquake. However, these two landslides differ in the depth of the rupture surface, the geological composition and the displacement.

Acknowledgement

We are grateful to the Niigata Prefecture for providing the drilling data. Thanks are also due to Dr. Ould Elemine Cheibany and Dr. Naoki Watanabe of Niigata University for critical reading of our manuscript.

References

Geographical Survey Institute of Japan (2001) 50m mesh digital map, CD-ROM “Japan II”
Hasbaator and Hanaoka M. (2006) Sliding Mechanism of the Landslide Induced by the Chuetsu Earthquake, a case of the Tamugiyama-kotaka Landslide, Abs. of the 2006 Japan Sabo Society of Japan, 2006, Wakayama, Japan
National Research Institute of Earth Science and Disaster Prevention (2004): Map of landslides topography around Yamakoshi Village
Earthquake, Abs. of the 44th Landslide Society of Japan, P.5–8