

# Evaluating Landslide Damage During the 2004 Chuetsu Earthquake, Niigata, Japan

A series of earthquakes, the strongest with a magnitude of 6.6 on the Richter scale (6.8 on the Japan Meteorological Agency (JMA) scale), jolted Niigata Prefecture, Japan, late in the afternoon of 23 October 2004, killing about 40 people and injuring about 3000, largely as the result of building collapse. More than 100,000 residents were forced to evacuate their homes, and 2200 residents of Yamakoshi village and other areas have not yet returned.

The three strongest earthquakes ( $M > 6.2$  on the JMA scale) occurred within less than 40 min with epicenters spread across Ojiya city and Hirokami and Yamakoshi villages in Niigata Prefecture. These earthquakes were characterized by shallow focal depths (9–14 km) that generated strong levels of ground motion, resulting in extensive damage throughout the region.

Despite the moderate size of the earthquakes, thousands of landslides occurred with much associated damage to roads, farmland, residential areas, and water bodies. The unusual level of landslide damage was related to the combined effects of the short time span for the three major earthquakes (so-called “triple punch”); soft regolith materials (unconsolidated sand and silt) in tectonically active steep terrain; proximity of epicenters; high antecedent rainfall; shallow focal depth; and land use activities. This investigation in the most affected areas a few days after the earthquake provides an overview of the extent, different characteristics, and complicating causes of landslides encountered on natural and constructed slopes.

## *Characteristics and Distribution of Landslides*

Most of the earthquake-induced landslides on natural slopes were located in the area throughout Ojiya city and Yamakoshi village, and occurred in the regional geological structure consisting of sandy siltstone and

thin-bedded alternations of sandstone and siltstone [Yanagisawa *et al.*, 1986]. Many types of hillslope failures, ranging from large, deep-seated coherent (Figure 1a) and disrupted landslides (Figure 1b) to smaller, shallow landslides in highly weathered material (Figure 1c), were found. Although about 100 mm of rain fell in the region three days prior to

the earthquake (Figure 2a), field reconnaissance indicated that most soils and regoliths (especially in shallower failures) were quite dry near the ground surface.

One of the more conspicuous and highest-impact landslides triggered by the Chuetsu earthquake was a large block glide

that occurred along the road into Yamakoshi village (Figure 1a). The sliding mass traveled relatively undisrupted across the Imokawa River, where it created a dam blocking the confluence of the Imokawa and Maesawa rivers. During the impact of the block glide with the river, the landslide displaced alluvial sediments onto the opposite bank, as evidenced by freshwater fish and alluvial cobbles found in the landslide deposits. The initiation of this large failure may have been exacerbated by the heavy antecedent rainfall (Figure 2a); water inputs to the deep failure plane at this site (~25 m) likely destabilized this landmass, although during the actual failure, the block glide moved intact.

Many earthquake-induced landslides were observed along the Shinano River; such valley hillslopes oversteepened by fluvial incision are naturally susceptible to landslides. A landslide was investigated along the Shinano River which destroyed National Road 17 (Figure 1b). The high level of disruption observed within the failed mass may be related to the interaction between local site conditions and ground motion. The failure occurred at the corner of a mountain ridge where unusually high peak accelerations may develop due to the dynamic response of the ridge itself. Furthermore, most of the shallow landslides in

**The unusual landslide damage was linked to the combined effects of the three earthquakes (“triple punch”) and other environmental factors.**

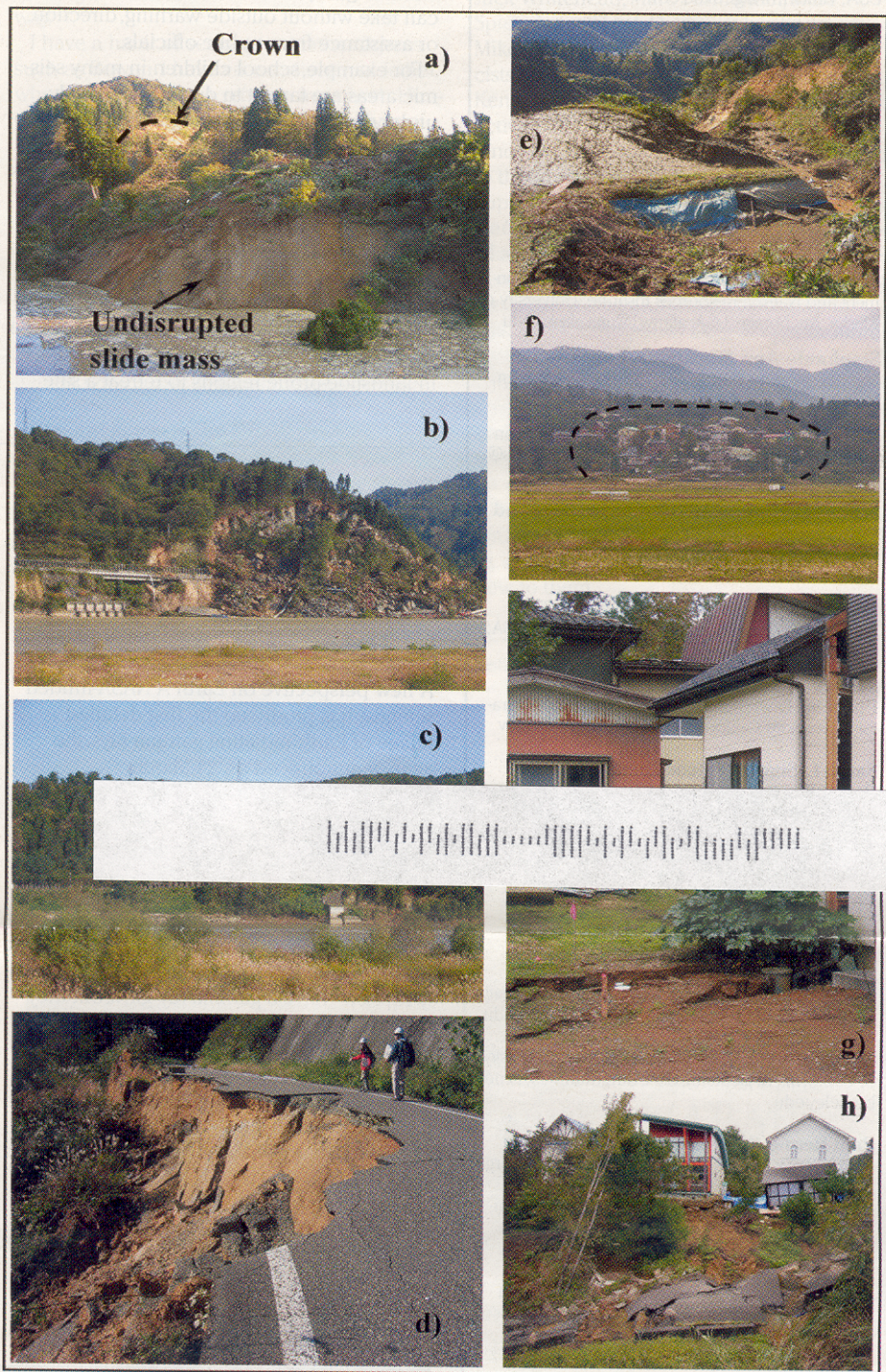


Fig. 1. Earthquake-triggered landslides. (a) Deep-seated block glide in Yamakoshi village. (b) Highly disrupted landslide along Shinano River; (c) Numerous shallow landslides on natural slopes. (d) Road fill-slope failure (Yamakoshi village). (e) Landslide in a paddy field. Otoyoshi residential area: (f) Location on old earthflow (dashed line); (g) Tension cracks indicating reactivation of the earthflow during the earthquake; and (h) Damage to residences and roads.

## Landslide Damage

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this area (e.g., Figure 1c) were located close to the crest of the mountain ridge, emphasizing the importance of topography in the amplification of seismic waves.

The spatial distribution of landslides within radii of 2.9 km around the three major epicenters (magnitudes  $> 6.2$ ) was examined to assess the geographic distribution of slope failures during the 23 October event (Figure 3). The tremors occurred in the following sequence: First, a  $M6.8$  earthquake occurred at 1756 local time (LT), followed by a  $M6.3$  earthquake at 1803 LT, and finally a  $M6.5$  earthquake at 1834 LT (Figure 2b). Between the  $M6.3$  and  $M6.5$  tremors, a smaller ( $M6.0$ ) earthquake occurred.

The spatial distribution of landslides was extracted from the earthquake-induced landslide map developed by the *Geographical Survey Institute of Japan* [2004]. This mapping was based on information acquired from two aerial photographs (resolutions of 1/10,000 and 1/12,500, Geographical Survey Institute and PASCO Consulting Company, 24 October 2004) combined with the results of field investigations conducted from 24 to 26 October 2004. Given this spatial resolution, the landslides shown in Figure 3 are generally larger than  $\sim 100 \text{ m}^2$  (surface area); landslides that occurred during rains and aftershocks more than a few days after the major earthquakes are not included.

The area around the  $M6.5$  epicenter, close to central Yamakoshi village, experienced the highest density of landslides (12 landslides per  $\text{km}^2$ ; Figure 3). This high density may have resulted from the cumulative shaking effects associated with the two earlier earthquakes of  $M6.8$  and  $M6.3$  (Figure 2b), in addition to the topographic and geologic factors controlling the stability of the region. Similar landslide densities (2.7–3.0 landslides per  $\text{km}^2$ ) were observed proximate to these earlier two earthquakes. For the  $M6.3$  earthquake epicenter, only landslides within the shaded area (Figure 3) were mapped, and the resulting density reflects this smaller area. The number of landslides around the initial and largest ( $M6.8$ ) earthquake epicenter was 79, about 4 times less than the number of landslides around the  $M6.5$  earthquake epicenter.

Although many landslides occurred on valley slopes adjacent to the Shinano River (see the  $M6.8$  epicenter in Figure 3), the landslide density in this area is lower, due partly to the flatter valley bottom in the southern and western parts of the inscribed circle. Additionally, the terrain around the  $M6.5$  epicenter is not only steep, but also highly dissected. A higher percentage of landslides in this area ( $\sim 65\%$ ) occurred on slopes  $> 30^\circ$  compared with the area around the  $M6.8$  epicenter ( $\sim 36\%$  of the landslides occurred on slopes  $> 30^\circ$ ). The smaller landslide density around the  $M6.3$  earthquake epicenter may be related to the greater spatial separation of this epicenter from the other two.

## *Influences of Land Use*

Anthropogenic factors such as roads, forest conversion to agriculture, and residential development are known to decrease slope stability [*Sidle et al.*, 1985]. Earthquakes exacerbate such potential instabilities by the

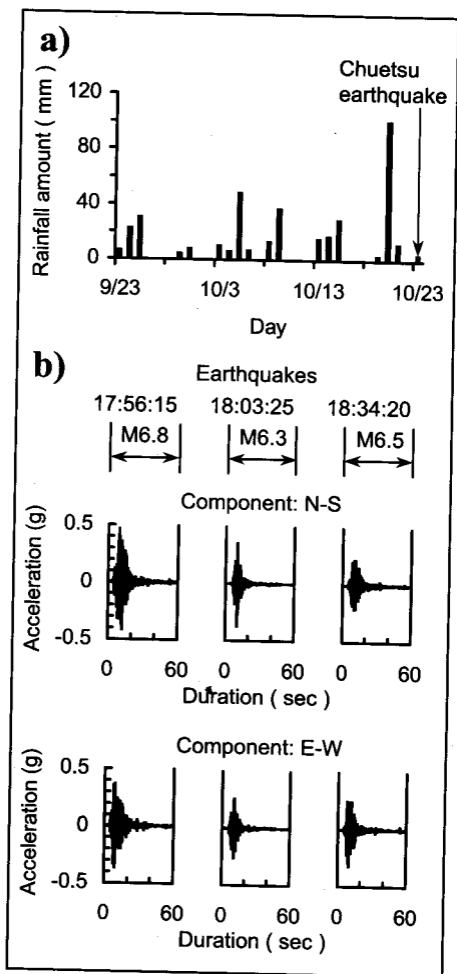


Fig. 2. (a) Rainfall in Nagaoka city during the one-month period prior to the earthquake. (b) Horizontal ground accelerations during the three largest earthquakes recorded at the K-NET station in central Nagaoka city (data supplied by the National Research Institute for Earth Science and Disaster Prevention, Japan).

ground motion induced and the enhancement of pore water pressure in wet regoliths. Near the major epicenters, as well as in neighboring villages and towns, earthquake-triggered landslides were observed that were highly affected by road cuts, road fills, paddy fields on hillslopes, and residential fills.

Road cuts remove support along the uphill side of road corridors [Sidle *et al.*, 1985]; thus ground motion arising during an earthquake often triggers numerous landslides at such sites. Road fill materials on hillslopes naturally destabilize road embankments by adding weight to the hillslope, oversteepening the outside portion of the embankment, and sometimes incorporating poor materials or insufficiently compacting materials within the embankment.

In the regions around the three major epi-

In the regions around the three major epicenters, hundreds of new road cut and fill-slope failures were observed. Additionally, much cut and fill-slope material remained tenuously unstable awaiting failure during forthcoming rainstorms or periods of snowmelt. A fill-slope failure along the local road leading into Yamakoshi village was deposited directly into the Maesawa River, contributing to the dam formation (Figure 1d). Such moderate-to-large fill-slope failures cause severe environmental problems, especially when the debris reaches streams. Repairing fill-slope failures along roads can also be very costly, especially in remote and steep terrain. Cut-slope failures along roads in the area caused chronic maintenance problems, which will continue for some time; typically these failures are smaller than road fill failures.

Many earthquake-induced failures occurred in terraces and adjacent hillslopes around rice paddy fields. Oftentimes, the berm around paddy fields ruptured due to the ground

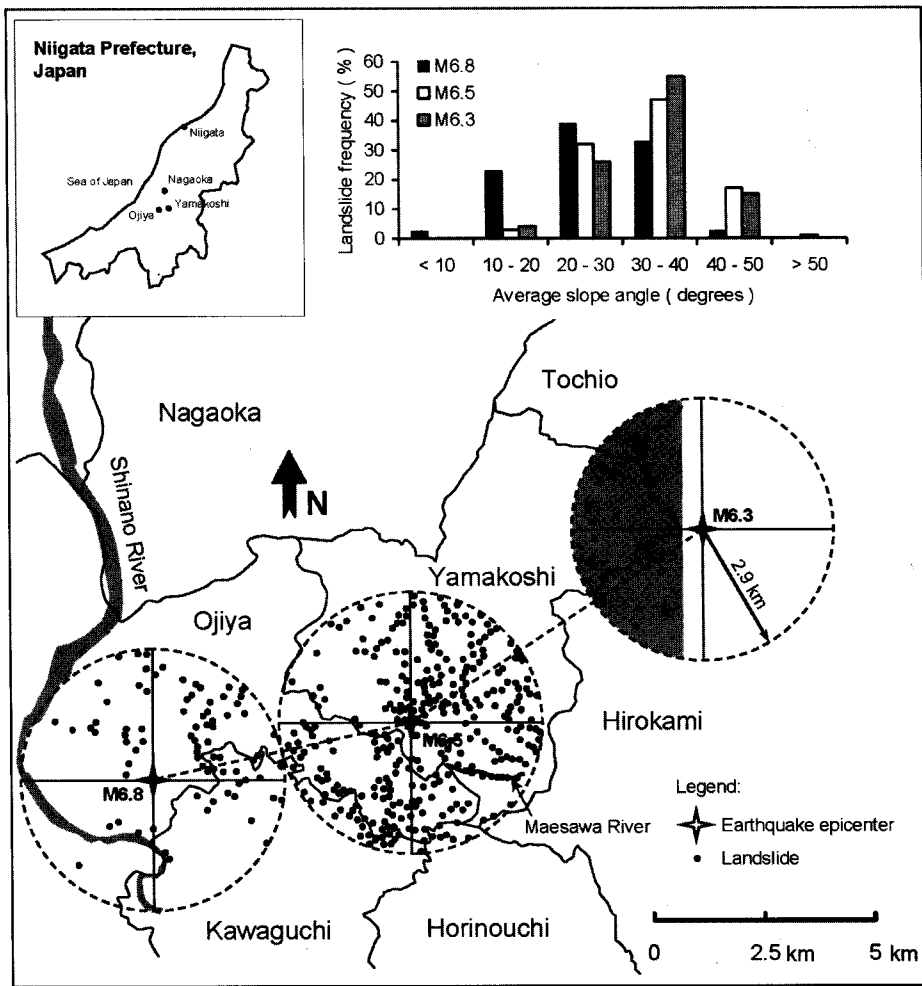


Fig. 3. Distribution of landslides and landslide frequency for different slope gradient classes around the three major epicenters of the Chuetsu earthquake. The radius shown for each epicenter is 2.9 km.

shaking and high moisture content. In spite of their small magnitude, these failures may affect the occurrence of future landslides and debris flows, as shown in Figure 1e. Water draining from damaged rice paddy fields can infiltrate into cracks and saturate hillslope soils, thereby increasing the landslide hazard. Ground failures within paddy fields and small debris flows emanating from paddy fields were common in Yamakoshi village.

Numerous landslides also occurred in residential fill slopes constructed on reclaimed land in Nagaoka city. Damage to houses and roads due to earthquake-induced landslides in the Otoyoshi development of Nagaoka city was significant. This development was actually built on an old earthflow (Figure 1f) that was reactivated during the Chuetsu earthquake. Tension cracks in fill were evidence of the earthquake-induced reactivation of the earthflow (Figure 1g), whereas the damaged homes and roads were consequences of the earthquake-induced failures in fill (Figure 1h).

Another residential area (Takamachi danchi) of Nagaoka city incurred substantial damage to houses and roads due to seismically induced failures of artificial fill slopes. The road encircling this development was constructed on fill material and was partly destroyed during the earthquake. Takamachi danchi covers about 4.1 ha and lies on Pliocene to Middle Pleistocene sediments composed of sand, silt, and gravel. About 70 of the 522 homes in the development were damaged due to deformations and failures of artificial fill slopes.

The fill material in both the Otoyoshi and Takamachi regions was partly saturated due to the series of typhoons that struck Japan before the earthquake (Figure 2a). Poor drainage systems within the retaining structures supporting the fill contributed to the accumulation of water in the fill slopes and exacerbated the instability.

### *Lessons Learned*

Even though the Chuetsu earthquake was of moderate magnitude, the consequent landslide damage was huge. This damage is attributed to the shallow focal depth of the major earthquakes and the consequent strong ground acceleration, as well as geologic and topographic conditions. The highest density of landslides was found in an area near the second-highest earthquake magnitude ( $M6.5$ ), possibly due to the "triple punch" effect that included the two earlier earthquakes ( $M6.8$  and  $6.3$ ). Several of the approximately 40 deaths related to the earthquakes were direct consequences of landslides.

Major transportation routes, along with many smaller roads, were closed due to landslides, and a landslide dam formed at the confluence



of the Imokawa and Maesawa rivers. Large landslides into streams and rivers added heavy sediment loads and caused much environmental damage. Water, power, gas, and communication lines were severely damaged during the earthquake, partly by landslides.

At this early stage following the earthquake, it is impossible to quantify the total direct and indirect costs due to the earthquake-induced landslides. Many additional landslides will undoubtedly occur during spring 2005 snowmelt, due to the large snow accumulation in the area. One significant indirect cost is the lost productivity of the many displaced residents in the area.

Clearly, land use activities in rural and urban areas exacerbated the extent of earthquake-triggered landslides. Even though rice paddy fields were not impounded at the time of the earthquake, soils were wetter than in surrounding areas, thus contributing to more extensive ground failures. Rural mountain roads increased landsliding by undercutting and overloading hillslopes. Even roads with retaining walls suffered extensive landslide damage.

Furthermore, landslide damage in more gently sloping terrain was widespread where artificial fills were placed on natural or reclaimed land. Such sites are problematic for landowners in Japan, because the government will not compensate residents for property damage due to failures in fill material as the government does for hillslope landslides affecting residences. This preliminary survey after the Chuetsu earthquake emphasizes that better guidelines for rural road location and residential development (particularly related to artificial fills) will drastically reduce future damage in such earthquake-prone regions.

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## More on the Challenges of Natural Hazards

In the 11 January 2005 issue of *Eos*, Sorooshian offered cogent suggestions about how we, as professional scientists, might do more to make the world safer from natural hazards. Not explicitly mentioned was an additional important contribution we can make that requires no additional research. It is simply to more effectively apply what is already known by increasing public awareness of both the hazards themselves and the simple, life-saving responses to hazards that people can take without outside warning, direction, or assistance from public officials.

For example, school children in many seismic areas are taught to duck immediately under desks or tables during earthquakes ("drop, cover, and hold on"). Similarly, people living in coastal areas along subduction zones can be taught that earthquakes may cause tsunamis and to respond to a felt earthquake by moving as quickly as possible to high ground or to inland areas and remaining there for a few hours.

Other examples include (1) educating people living on or immediately below steep slopes in landslide-prone regions to retreat a safe

distance away from slopes during and following relatively intense or prolonged rainfall (e.g., La Conchita, California), and (2) teaching people who live in confined valleys in arid areas or downstream of volcanoes to run for high ground as soon as they hear the growing, low-frequency rumble or roar of an approaching flash flood or lahar.

As Earth scientists, we are commonly sought out by the media whenever natural hazards are making news, and our comments on TV and radio can be broadcast to millions. We are also a trusted source of information for public officials at all levels of government.

Yet at the same time, sociologic research has shown that a message coming from multiple sources must be consistent for it to be considered trustworthy by the public.

This presents an opportunity for scientific organizations such as AGU to advance public safety by working with emergency managers, educators, and disaster-response organizations such as the Red Cross to devise and promote simple, immediate responses to various hazards, and then disseminating these hazard messages to their membership. Each of us

scientists would thus be enabled to discuss key hazard messages whenever appropriate opportunities arise with the media, public officials, or the general public. In addition, AGU members could assist school districts in developing hazards education curricula, as the U.S. Geological Survey is doing for communities in the shadow of Mount Rainier in Washington State.

Dissemination of simple messages about hazards does not negate the need for more research or for technological approaches to hazards mitigation (such as tsunami warning systems). It simply empowers people to help themselves and their neighbors when no officials are available to tell them what to do when confronted at the last minute by unexpected danger.

With tsunamis, it may seem only common sense to Earth scientists to run away from (and not toward) the water when the sea is drawn rapidly down and away from the beach as a tsunami approaches. But that response is counterintuitive for most people. Everyone must be able to recognize what is happening and then know how to react. Such information can save lives, and Earth scientists can help get it to the people who need to know. Had this information been available to the people in Sumatra and Thailand who felt the 26 December 2004 M9 earthquake but thought nothing of it, tens of thousands of lives could have been saved.

—THOMAS C. PIERSON, U.S. Geological Survey, Cascades Volcano Observatory, Vancouver, Wash.

# FORUM

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