Characteristics of Slope Failure Induced by the Mid Niigata Prefecture Earthquake and the Snow Melting after the Snow Term

Kazuya Akiyama,[1)] Jun-ichi Kurihara[2)] and Kiichiro Ogawa[3)]

1) Volcano and Debris Flow Team, Erosion and Sediment Control Research Group, Public Works Research Institute [Present affiliation: Erosion and Sediment Control Division, Research Center for Disaster Risk Management, National Institute for Land and Infrastructure Management, Ministry of Land, Infrastructure and Transport, 1 Asahi, Tsukuba, Ibaraki 305-0804, Japan (akiyama-k92ta@nilim.go.jp)]

2) Volcano and Debris Flow Team, Erosion and Sediment Control Research Group, Public Works Research Institute , 1-6, Minamihara, Tsukuba, Ibaraki 305-8516, Japan (j-kuriha@pwri.go.jp)

3) Asia Air Survey Co., Ltd., 1-2-2, Manpukuji, Aso-ku, Kawasaki-shi, Kanagawa 215-0004, Japan (ki.ogawa@ajiko.co.jp)

Abstract

The Mid Niigata Prefecture Earthquake (Chuetsu Earthquake) on October 23, 2004 caused multiple landslides and slope failures in the Chuetsu region of Niigata Prefecture, particularly in the vicinity of the Imo River and its tributaries. The Chuetsu region is located in a heavy snowfall area, and shortly after the earthquake there were heavy snowfalls, which raised concerns of landslides and slope failures when the snow subsequently melted. The aim of this study was to investigate sediment yield by slope failures (excluding landslides and minor surface exfoliation) associated with the Chuetsu Earthquake and subsequent rainfall and snow melt in the Imo River basin region. The characteristics of slope failure by the earthquake and melting of snow were subject to quantitative analysis by comparing aerial photographs with laser profiler data in each unit basin area. There was little slope failure before the earthquake. However, the statistics show 1,419 slope failures (covering a total area of nearly 1,480,000 m^2) caused by the earthquake in the Imo River basin, and another 1,448 slope failures (nearly 440,000 m^2) by subsequent melting of snow. The majority of slope failures caused by the earthquake occurred at the top of ridge-type and parallel-type slopes. In the snow-thawing season, however, collapses also occurred in valley-shaped slopes as well as ridge-type and parallel-type slopes. There were a significant number of spreading collapses in the head or side part of slope failures caused by the earthquake. Slope failures caused by the earthquake accounted for 3.9% of the total land area of the Imo River basin, while slope failures caused by snow accounted for 1.2%. Unit basins with a high area of slope failures caused by earthquake tended to be a high area of slope failures caused by snow melting, and typically had a geological composition of sand or sand alternating with mud.

Keywords: slope failure, earthquake, snow

Introduction

The Chuetsu Earthquake in Niigata prefecture on October 23, 2004, caused a number of landslides and slope failures, primarily in the river basin area of the Imo River, a tributary of the Uono River, which is itself a part of the Shinano River system. The Chuetsu region is located in a heavy snowfall area, and snowfalls after the earthquake raised concerns of further sediment disasters caused by the subsequent melting of snow. Table 1 contrasts the topographical characteristics of slope failure attributable to earthquake and rainfall. It is known that earthquakes loosen the ground on a mountain, making it more vulnerable to secondary disasters, usually caused by subsequent rainfall. However, there have been few quantitative studies to date on the effect of post-earthquake rainfall and snow melt, and little is known about the effect of that for the long term. In river basin regions prone to slope failure due to earthquake, sediment disaster prevention strategies should consider not only the danger of immediate slope failure due to earthquake but also the potential for secondary slope failures caused by subsequent rainfall or snow melt, and how to be variation of this potential over time.

In this study, a quantitative analysis of slope failures caused by the Chuetsu Earthquake and those caused during subsequent snow season was conducted, looking in particular at the impact of rainfall and snow melt. This paper describes the findings of an analysis of slope failure characteristics at the time of the earthquake and during the winter of 2004–2005.

pp. 749–758

Table 1. Characteristics of slope failure due by earthquake and rainfall

	earthquake	rainfall
Vertical location of slope failure	Many slope failures are located on the top of slope	Many slope failures are located on hillside
Slope inclination	Many slope failures occurred in the range 35∽ 55∞	Many slope failures occurred in the range 30∽ 40∞
Slope form	Many slope failures are apt to occure under the following conditions 1)around the break of slope 2)on ridge-type or parallel-type slopes 3)remarkable unevenness of slope surface	Many slope failures are apt to occure under the following conditions 1)along the valley line 2)except the ridge of mountain 3)concave geographical features

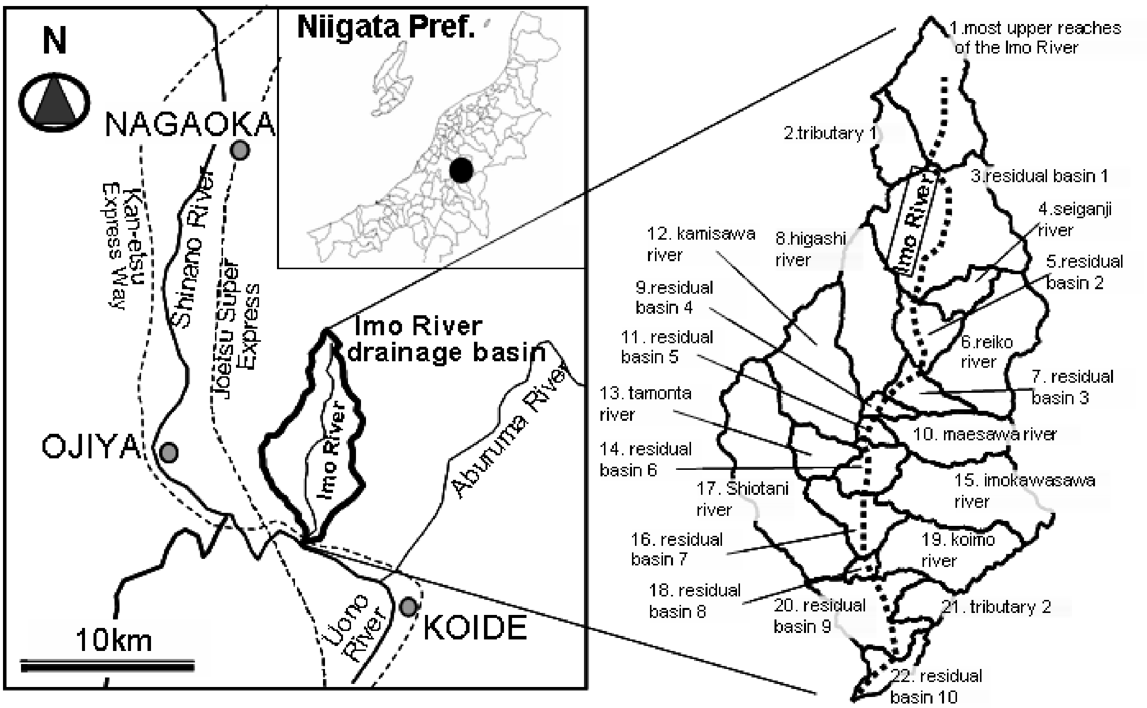

Fig. 1. Study area

Analysis

Investigation area and methodology

The analysis covered a total area of 38 km^2 in the Imo River basin, which suffered a number of slope failures by the Chuetsu Earthquake. For the purposes of our research, the study area was divided into 22 small basins (or "unit basins") as shown in Figure 1.

Since separate slope failures were caused by the Chuetsu Earthquake and the subsequent melting of accumulated snow, this study analyses each phenomena separately (denoted "earthquake slope failure" and "post-melt slope failure" respectively). Landslides and minor surface exfoliation phenomena were excluded from the scope of the study.

Post-melt slope failures were further divided into three categories according to the relationship to the initial earthquake slope failure, as shown in Figure 2.

1. New: slope failures occurred on the outside of earthquake slope collapses

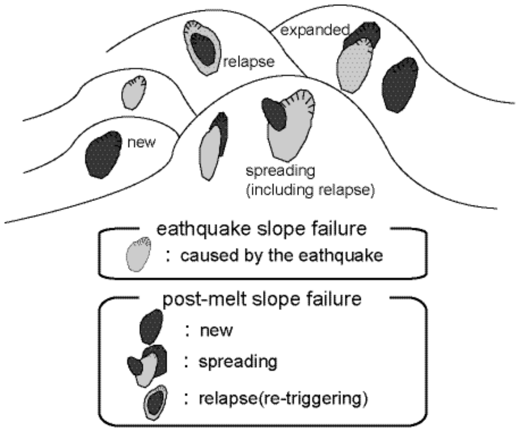

Fig. 2. Classification of slope failures

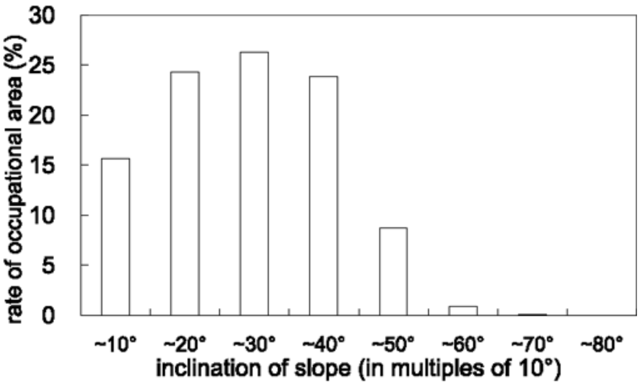

Fig. 3. Relative proportion of slope inclination in the Imo River basin

2. Spreading: slope failures spreading in head or side part of previous failure by the earthquake
3. Relapse (re-triggering): collapse of internal section (rupture surface) of earthquake slope collapse

The third type of slope failure (relapse) tends to involve failure to a greater ground depth but little or no increase in surface area.

The quantitative analysis of slope collapse characteristics was conducted using large-scale aerial photographs and a digital elevation model (DEM) based on laser profiler (LP) data for the river basin region as a whole. Slope failure characteristics before and after the earthquake, were analyzed based on the DEM and aerial photographs shown in Table 2, identifying slope collapse sites by comparing photographs from prior to the earthquake (No.1) with those taken immediately afterward (3). Similarly, conditions before and after the winter snowfall period were analyzed by comparing photographs (3) and (5).

For the numerical analysis of earthquake slope failure, a DEM was constructed using existing grid intervals (Hokkaido-chizu co., ltd., 2000) of east- west 10 m and north-south 10 m shown in (2), and another using lattice intervals of 1 m based on the LP data shown in (4). The analysis of post-melt slope failure, meanwhile, involved constructing DEMs with 1 m lattice intervals based on LP data in (4) and (6).

By comparing the photographs and DEM, it was possible to determine the conditions of collapses both directly after the earthquake and subsequently after the winter snowfall period.

The basic topographical characteristics of the Imo River basin prior to the earthquake were determined by converting the 10 m DEM in (2) into a DEM with 5 m intervals, then calculating the slope inclination and bearing direction from the highest and lowest points within each 5 m $\times$ 5 m cell.

The degree of undulation (relief energy) is generally defined as the altitude difference between the ridge or summit of mountain and the bottom of valley. Analyzing mesh size was determined as the double length of the mean horizontal distance between the ridge and the bottom of valley. The mean horizontal distance is determined in 300 m $\times$ 300 m cells as drainage area divided by the total river length beyond the primary valley in the Imo River basin.

The topographical characteristics of slope failure sites were analyzed by identifying topographical features from digital orthographical images combining aerial photographs with post-earthquake LP data, then

Table 2. Data of aerial photographs and DEMs

No.	Year/Month/Date	Data	Scale/Size	Note
1	1998/9~11	aerial photograph	1/20000	Grasping the slope failure distribution before the earthquake
2	2000/6	digital elevation model	5m◊5m (10m◊10m)	Digital elevation data (5m DEM) converted from 10m DEM based on 1/25000 topographical map before the earthquake
	2004/10/23			occurrence of the earthquake
3	2004/10/24	aerial photograph	1/10000	Grasping the slope failure occurred by the earthquake
4	2004/11/26	digital elevation model	1m◊1m	Digital elevation data (1m DEM) based on the LP measurement after the earthquake or before snow term
	2004/12~2005/4			snow term
5	2005/5/11,17	aerial photograph	1/10000,1/5000	Grasping the slope failure ocurred newly during the snow term
6	2005/5/11	digital elevation model	1m◊1m	Digital elevation data (1m DEM) based on the LP measurement after the snow term

Table 3. The number and area of slope failures occurred in Imo River basin

	slope failures occurred by the earhquake (a)	slope failures occurred newly during snow term				ratio against the slope failure occurred by the earthquake (%)	
		new (c)	spread (c)	relapse (d)	total (b+c+d)	(c+d)/a	(b+c+d)/a
number of slope failures (N)	1,419	822	435	191	1,448	44.1	102
total area of slope failures (m^2) (A)	1,477,818	194,892	186,995	62,360	444,247	16.9	30.1
the average area of a slope failure (A/N)	1,041	237	430	326	307	72.6	29.5

calculating the area of collapse from DEM data, and finally calculating the slope inclination and bearing direction. The area was taken from the aerial photographs since it was measured on the diagrams. Geological data was taken from 1:50,000 scale digital geological maps Ver.1 (Takeuchi et al., 2004) and 1:50,000 geological map (Yanagisawa et al., 1986 and Kobayashi et al., 1991) for the Chuetsu Uonuma district.

Result

Slope failure in the Imo River basin — number of incidents and total land area

Table 3 provides basic statistics for slope failures identified in the Imo River basin. 1,419 slope failures were caused by the earthquake. And a further 1,448 by the subsequent snow melt, Of those caused by snow, 822 represented new slope failures and 435 spreading slope failures, while 191 represented relapse slope failures. Thus, the number of post-snowmelt slope failure was almost the same number of slope failures caused by earthquake. Some 44% of earthquake slope failures were subsequently spread or relapse until the winter snow melted. The area of slope failures due to snow was approximately 30% of the area of slope failures due to earthquake. The area of new and spreading slope failures accounts for roughly the same area but the area of relapse failures one-third of that. The average area of slope failures caused by snow was only 30% of the area of an earthquake slope failure. In terms of types of post-melt slope failures, spreading slope failures had the largest area.

These statistics show that snow caused as many slope failures as the earthquake, although the area of slope failures tended to be smaller.

Table 4. Rate of slope failure by area for each unit basin

number	name of unit basin	drainage area (m^2)	area of slope failures by the earthquake (m^2)	areal rate of slope failures by the earthquake (%)	area of slope failures newly collapsed during snow term (m^2)	areal rate of slope failures during snow term (%)
1	most upper reaches	2,729,037	19,480	0.7	10,737	0.4
2	tributary 1	1,032,820	9,983	1.0	9,023	0.9
3	residual basin 1	4,635,901	419,499	9.0	90,140	1.9
4	seiganji river	679,055	36,175	5.3	9,665	1.4
5	residual basin 2	1,072,040	81,408	7.6	22,570	2.1
6	reikosawa river	3,061,404	173,120	5.7	58,583	1.9
7	residual basin 3	772,803	39,543	5.1	10,478	1.4
8	higashikawa river	2,609,874	164,587	6.3	38,805	1.5
9	residual basin 4	292,027	6,824	2.3	1,968	0.7
10	maesawa river	1,701,013	64,116	3.8	15,003	0.9
11	residual basin 5	269,873	712	0.3	1,206	0.4
12	kamisawagawa river	3,045,012	162,569	5.3	47,197	1.5
13	tamontagawa river	816,306	31,200	3.8	11,675	1.4
14	residual basin 6	890,927	63,521	7.1	15,325	1.7
15	imokawazawa river	3,045,379	30,687	1.0	18,231	0.6
16	residual basin 7	1,241,571	33,821	2.7	11,487	0.9
17	shiotanigawa river	4,412,068	96,005	2.2	44,347	1.0
18	residual basin 8	213,838	4,228	2.0	1,019	0.5
19	koimogawa river	2,263,750	17,632	0.8	16,083	0.7
20	residual basin 9	1,884,635	16,434	0.9	5,198	0.3
21	tributary 2	616,767	5,239	0.8	4,517	0.7
22	residual basin 10	655,585	1,035	0.2	990	0.2
	Imo River basin	37,941,685	1,477,818	3.9	444,247	1.2

Topographical characteristics of slopes and slope failure regions in the Imo river basin

The inclination of slopes in the river basin area was analyzed by calculating the number of 5 m meshes in each inclination category (in multiples of 10°) and multiplying this by the lattice area to determine the relative proportion of each category within the river basin as a whole. The same approach was used to calculate the respective proportions of slope failures caused by earthquake and snow within each inclination category. The inclination of a slope failure region after earthquake was defined as the angle between the horizontal plane and a straight line drawn between the highest and lowest points within the region. Figures 3 and 4 show the results. Most slopes in the Imo river basin have an inclination of between 10° and 40°. Within slope failure regions, failures caused by earthquake were most common at slope inclinations in the range 30°–50°, which is virtually equivalent to the inclination most vulnerable to earthquake (as shown in Table 1). However, earthquake slope failures also occurred in locations with lower inclination in the range lower than 30°. Failures caused by snow were most common at slope inclinations in the range 40°–50°. Thus, inclination of slope failure caused by snow is higher than by rainfall (as shown in Table 1), and overlaps the range for earthquake, suggesting that the earthquake has had an effect on the slope failures due to snow.

In the Imo River basin, the height of the highest point or knick line (concave) relative to the river bed or knick line (convex) is defined as the relief height. In terms of frequency, around 90% is 100 m or less, while 20–60 m accounts for around 60% (see Figure 5).

Figure 6 shows the relative height of the highest tip of a slope failure in relation to the height of the slope where the failure occurred. Many earthquake slope failures originate at the top of the slope, generally in ridge-type and parallel-type slopes. Post-melt slope failures also tend to originate at the top of the slope. However, new failures were found on valley-type slopes that were unaffected by the earthquake, as in the case of ridge-type and parallel-type slopes. Spreading slope failures was identified mainly at the head part of earthquake slope failures but also in the side part, while relapse of slope failures that occurred during earthquake was commonly found in the top to middle parts.

Geology type versus slope failure

Table 4 shows the slope failure rate by area caused by earthquake and snow for each unit river basin within the Imo river basin area. Figure 7 shows the distribution of slope failure rates in each unit river basin.

The general trend was similar for both causes of slope failure: a unit river basin with a high slope

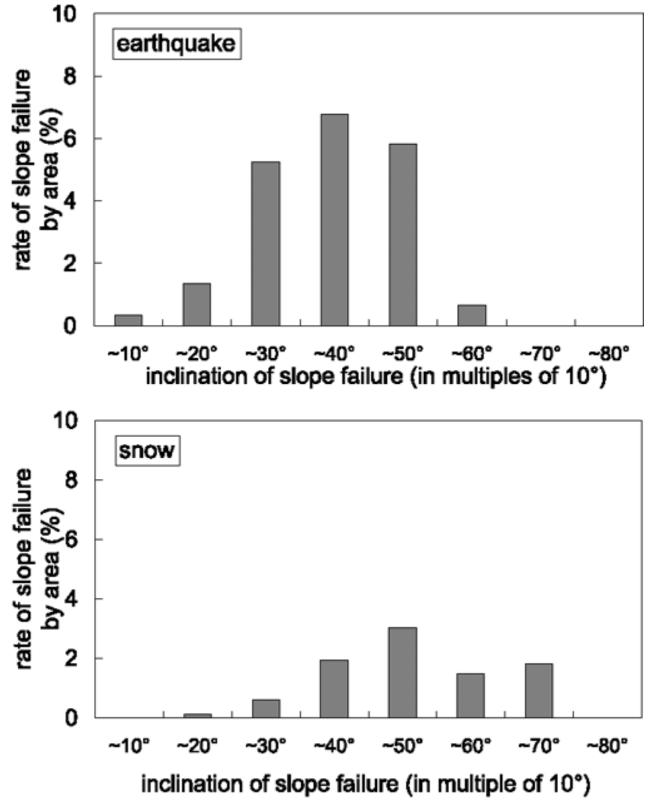

Fig. 4. Rate of slope failure by area in the Imo River basin

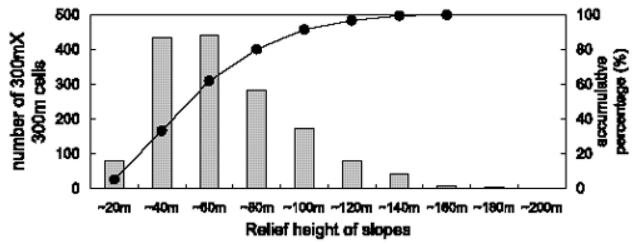

Fig. 5. Distribution of slope relief in the Imo River basin

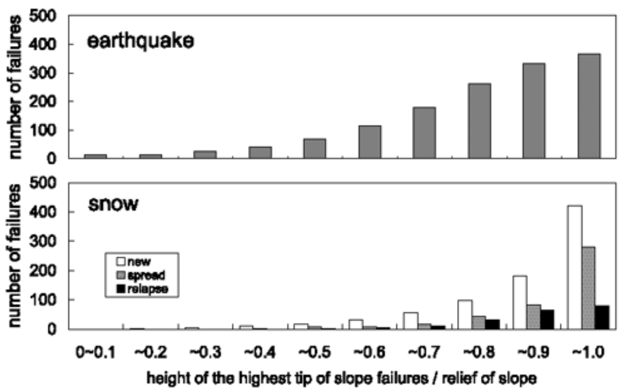

Fig. 6. Relative height of slope failures by the earthquake and snow

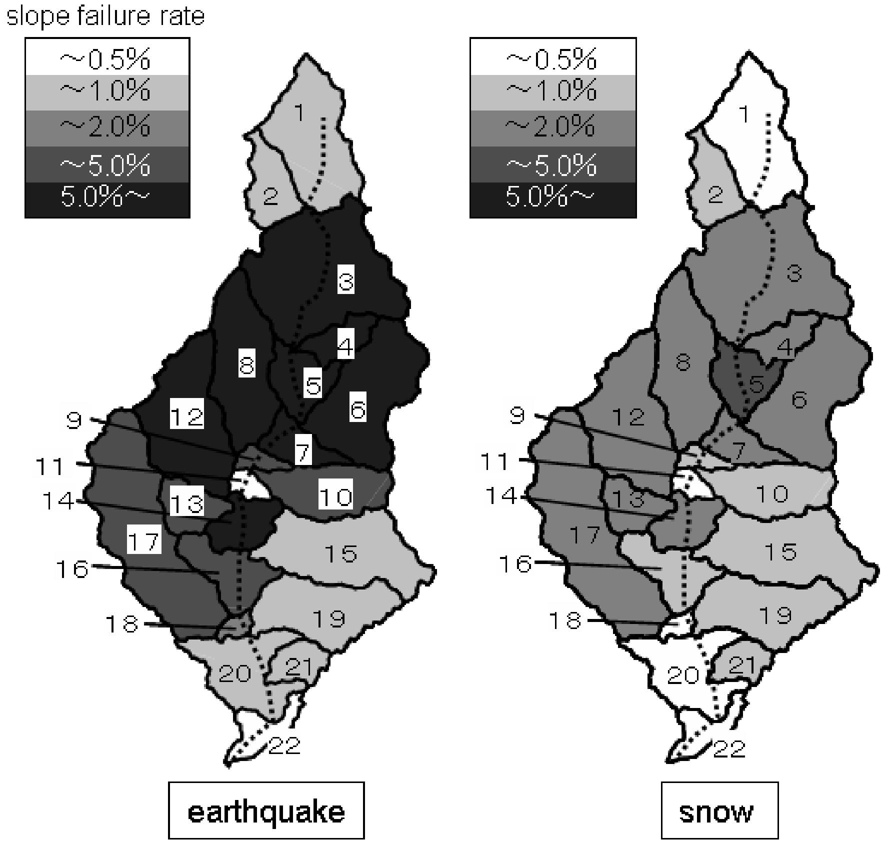

Fig. 7. Distribution of slope failure rates in each unit basin

failure rate for earthquake was likely to have a high slope failure rate for snow too. Units 3–10, 12–14, 16 and 17 had a high slope failure rate for earthquake, while units 3–8, 12–14 and 17 had a high slope failure rate for snow. These units are all adjoining the middle reaches of the Imo River basin. Slope failures caused by the earthquake accounted for 3.9% of the total land area of the Imo River basin, while slope failures caused by snow accounted for 1.2%. The slope failure rate by area for snow is around one-third of that for the earthquake. The total slope failure rate by area for earthquake and snow combined was 4.9%, taking into account that relapse collapses caused by snow involved little increase in area.

Figure 8 shows the five main types of geology found in the unit river basins. The slope failure rate is higher in sandy and muddy soils, particularly those consisting of sandstone or sandstone alternating with mudstone. The slope failure rate tended to be lower in regions with less of this type of geology. To examine the relationship between geology and slope failure in the river basin more closely, a more in-depth comparison was conducted in which the geological categories were sub-divided in accordance with the numerical geological maps described above.

Figure 9 shows the area of each geological category as a proportion of the total for the river basin, and the slope failure rate by area in each category.

Slope failure rates were higher — both for earthquake and snow melt — in sandstone and mudstone regions, especially those featuring sandstone, sandstone alternating with mudstone, sandy siltstone or sandstone alternating with siltstone. The geology represented in (8) — predominately sandstone with alternating sandstone and mudstone — had the highest slope failure rates for both earthquake and snow melt despite accounting for only a small proportion of the river basin, indicating that this geology type is highly vulnerable to slope failure. The slope failure rate tended to be lower in unit river basins with less of this type of geology.

Table 5 compares the slope failure rate by area in the Imo River basin as a whole with slope failure rates associated with previous earthquakes (NILIM and PWRI, 2006). The scope of this study encompasses a range of areas, so direct comparison is not possible; however, it is clear that slope failure rates for the Chuetsu Earthquake in Niigata prefecture are relatively high. In some cases, the snow melt slope failure rate is higher than the earthquake slope failure rate.

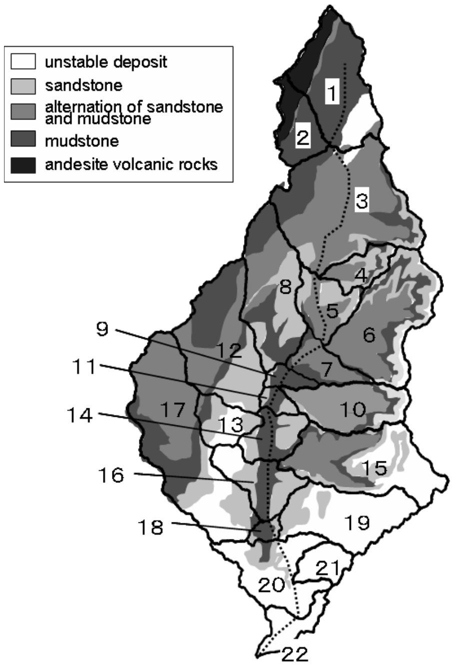

Fig. 8. Geology and unit basins in the Imo River

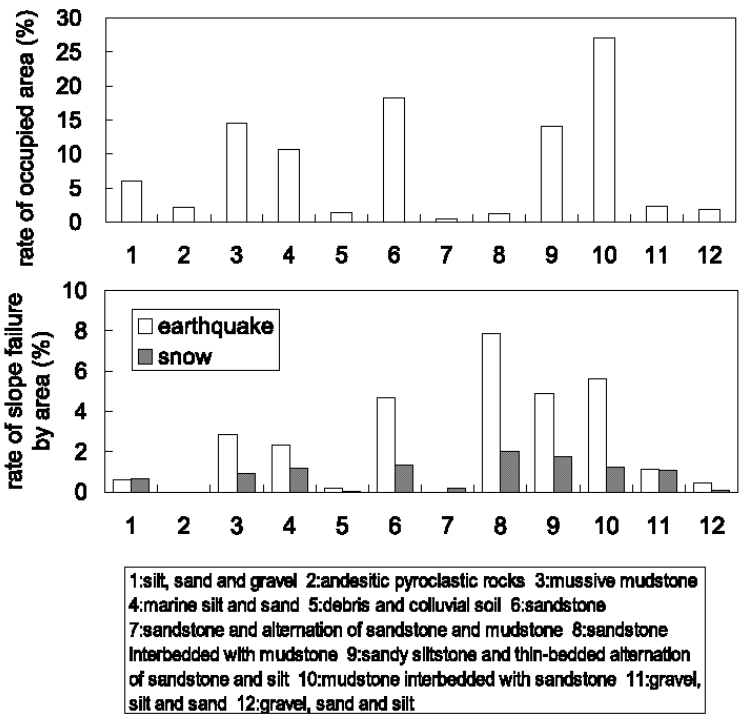

Fig. 9. Rate of occupied area and slope failure with detail geological categories

Geological structure versus slope failure

We analyzed the relationship between slope failure and particular geological structures such as "sliding ground" and "receiving ground" in the Imo River basin.

The geological structure of each slope failure region was analyzed in terms of the direction of maximum inclination θ and apparent inclination of the stratigraphic surface γ based on the inclination and direction of stratigraphic surfaces and geomorphic surfaces. The results were used to classify the ground geology as sliding (where $0^\circ < \gamma < \theta$), high-angle ($\theta < \gamma < 90^\circ$), or receiving ($90^\circ < \gamma < 180^\circ$). The orientation of strata in slope failure locations was determined via interpolation based on strata direction and inclination data taken

Table 5. Comparison of slope failure rates by area with the previous earthquakes

number	name of unit basin	drainage area (m^2)	area of slope failures by the earthquake (m^2)	areal rate of slope failures by the earthquake (%)	area of slope failures newly collapsed during snow term (m^2)	areal rate of slope failures during snow term (%)
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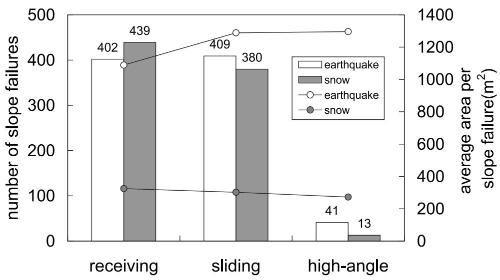

Fig. 10. Geological structure and slope failures

from 1:50,000 geological maps. Regions without defined strata (numbers 1, 2, 5, 11 and 12 in Figure 11) were excluded from the analysis. Figure 10 shows the results.

The general trends were similar for slope failures caused by earthquake and by snow. The incidence of slope failure was equally high for both sliding and receiving ground, and low for high-angle ground. When average volume per slope failure is taken into account, it can be seen that slope failures caused by snow were generally smaller in area than those caused by earthquake, as noted earlier. Slope failures due to earthquake tended to be slightly larger on sliding and high-angle ground, while post-melt snow failures were the same size across all categories. There were 16 slope failures due to earthquake involving an area of more than 10,000 m^2, and these occurred on both sliding and receiving type ground and located n unit river basins 3–8, 10 and 12 which had high rates of slope failure.

Conclusions

This study analyzed slope failures caused directly by the Mid Niigata Prefecture Earthquake and subsequent slope failures associated with the snow season. The winter of 2004–2005 brought the highest snowfalls for 19 years. The impact on sediment generation was thus greater than normal. The main conclusions from the study are as follows:

- Though there was little area of slope failures before the earthquake, many areas of slope failures were formed by the Chuetsu Earthquake. In addition, collapse areas expanded during the snow term. So slope failures occurred during the snow term were taken an influence by the earthquake strongly.

- The rate of slope failure due to earthquake was 3.9% relative to the total land area of the Imo River basin, while the slope failure rate due to snow was 1.2%. The total combined slope failure rate by area after all snow had melted was 4.9%. Snow caused around the same number of slope failures as the earthquake, but the post-melt slope failures were smaller — around 30% the size of earthquake slope failures.
- Both earthquake and post-snowmelt slope failure rates were higher in areas with sandstone and mudstone ground.

In order to evaluate the impact of earthquake in mountainous regions, it is necessary to perform a long-term tracking study of sediment movement, particularly with respect to movement of collapsed ground after an earthquake.

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