Analysis of seismically triggered landslides in the 2004 Chuetsu event of Niigata prefecture, Japan

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Abstract: The 2004 Chuetsu event (Mw=6.6) generated landslides throughout a broad area in central Niigata, Japan. Most of them occurred in mountainous areas around the epicentre, and disrupted road traffic, destroyed homes and other structures, and caused other serious damage. Analysis of their spatial distribution is of crucial importance to understand what areas may susceptible to landsliding in the event of earthquakes. The authors thus analysed the frequency, distribution, and geometries of triggered landslides in a heavily affected area. More than 1000 landslides occurred in the landslide-prone area of green-tuff, with a geological structure of active folding which covers active faults underneath, and can be divided into following types, rock fall, disrupted soil fall, soil slide, soil slump and soil block slide as well as rapid soil flow and complex landslides. On the basis of Geographic Information Systems, the distribution of landslides was investigated statistically, to determine how the occurrence of landslides correlates with slope steepness, rock type and distance from the epicentre using an index of landslide concentration. The study concludes that the landslide concentration differs substantially among various geologic units, and has a strong positive correlation with slope steepness.

Résumé: L'évènement de 2004 (magnitude 6.6) a provoqué des éboulements dans une vaste zone à Niigata, au centre du Japon. La plupart d'entre eux se sont produits dans des régions montagneuses autour de l'épicentre et ont interrompu le traffic routier, détruisant des maisons et d'autres édifices, causant d'autres dégâts sérieux. L'analyse de leur distribution spatiale est d'une importante cruciale pour déterminer quels terrains sont susceptibles de s'ébouler en cas de tremblement de terre. Les auteurs ont donc analysé la fréquence, la distribution et la géométrie des éboulements dans une zone gravement affectée. Plus d'un millier se sont produits dans des régions herbeuses prédisposées à ce type d'évènement, avec une structure géologique de plissements actifs couvrant des failles actives. Ils peuvent être classés en plusieurs types: chute de rochers, affaissements de terrain, glissements de terrain ... ainsi que coulées rapides et éboulement complexes. Sur la base des Systèmes d'Information Géographiques, leur distribution a été étudiée d'une manière statistique, afin de déterminer de quelle manière ils sont corrélés au degré d'inclinaison des versants de montagne, au type de roche et à la distance à l'épicentre, en utilisant un indice de concentration des éboulements. L'étude conclut que la concentration des éboulements diffère de façon substantielle selon les formations géologiques, et a une corrélation très forte avec le degré d'inclinaison des terrains.

Keywords: Earthquake, landslides, geographic information systems, data analysis

INTRODUCTION

Earthquake shaking can cause landsliding activity on many scales, and such landslides claim toll death and property damage. To reduce this, seismically triggered landslides should be completely analysed to understand well the relationship between landslide occurrence and environmental factors. With the benefit of aerial photographs and field investigations, remote sensing and Geographic Information Systems (GIS) have significantly promoted the ability to map earthquake-induced landslides, for example, in California, El Salvador, Japan, and Italy (e.g. Wilson et al. 1985; Harp & Keefer 1990; Sassa et al. 1995; Wasowski & Del Gaudio 2000). In the last century, catastrophic landslides triggered by the Deixi earthquake (Mw=7.5) in China in 1933 killed 6,800 people, and 2,500 were drowned after landslide dams failed in this event (Li et al. 1986), and an example of the most destructive single earthquake-induced slide was a rock avalanche from Nevados Huascarán triggered by the 1970 Peru earthquake, which buried two cities and killed more than 18,000 people (Plafker et al. 1971). Various types of earthquake-induced landslides have posed hazards to human life and property; however, at least 90 percent of landslide deaths in historical earthquakes have been caused by rock falls, rock avalanches, and rapid soil flows (Keefer 1984). Understanding where these types of landslides are most likely to occur is crucial in reducing property damage and loss of life in future earthquakes. Therefore, this paper aims to present a statistical analysis of landslide distribution in an area of intense seismic landslide activity near the epicentre of the 2004 Chuetsu earthquakes of Niigata Prefecture, Japan, based on GIS technology, thus providing a good basis for furthering this understanding.

Statistical analyses of earthquake-induced landslide distribution have been performed after many earthquakes; several databases of landslides triggered by earthquakes have been compiled for areas of high seismic activity from 1811 to 1997 (Keefer 1984; Rodríguez et al. 1999). Numerous studies have focused on general correlations of landslide occurrence with slope steepness, distance from the earthquake source, and geologic units (Keefer, 2000; Khazai & Sitar, 2003), and the susceptibility of individual geologic units to seismic landsliding has also been quantified and ranked based on such analysis (Parise & Jibson, 2000). These studies have provided valuable insight into the characteristics of seismically triggered landslides. Thousands of landslides, as one of the secondary

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geotechnical hazards associated with the Chuetsu earthquakes, were triggered over a broad area and were of almost all types. Just a few days after the earthquakes, many kinds of aerial photographs and satellite images were made available, of which can be used for interpretation of landslide locations, and field investigations were conducted specifically in several seriously struck areas, where large-volume landslides dammed creeks. The Chuetsu earthquakes hence allowed us to statistically analyse the landslide distribution, and to understand contributions of geologic units, slope steepness and parameters of earthquakes, such as magnitude and distance from the epicentre, to landsliding.

The Study area

On October 23, 2004, a series of powerful earthquakes located near the western coast of northern Honshu Island struck parts of northern Japan, especially Niigata Prefecture, about 250 km north of Tokyo. The strongest magnitude was M_{JMA}6.9, as measured by the Japan Meteorological Agency (JMA) or M_W 6.6, as measured by the U.S. Geological Survey. The epicentre of the main shock was located at 37.28° N 138.88° E at a depth of 13.4 km, and many aftershocks including some M_{JMA}6 class events occurred (National Research Institute of Earth Science and Disaster Prevention (NIED), 2004a).

Most active faults in the area affected by the earthquakes are reverse faults that dip to NW. Despite the shallow activity of the present earthquakes, no active fault has been recognized in the aftershock area. Basically, it can be interpreted that the focal mechanism of those major earthquakes shows almost pure reverse faulting dipping NW/SE. This is consistent with historical solutions for major earthquakes in this area, such as the 1828 Sanjo earthquake, 1933 Ojiya earthquake, and 1961 Nagaoka vicinity earthquake (NIED, 2004a).

This area is tectonically very active with many folds and active faults trending NNE/SSW. Most of the areas affected by the earthquakes are underlain by Neogene-Quaternary sedimentary units, which consist of a sequence of claystone and siltstone that is relatively nondurable, with interbeded sandstone and minor conglomerate, partly associated with a minor amount of volcanic rocks (Geological Survey of Japan (GSJ), 1982). These rocks are typically poorly or moderately indurated, and are structurally deformed by pervasive folding and local faulting. Prehistoric landslide deposits are widespread, and thousands of landslides have occurred historically in and around this area (NIED, 2004b), characterizing geomorphic features. The landslides are dominant geomorphic features in the area. A terrace is well developed, and its deposits of gravel, sand and mud covered with a weathered volcanic ash layer, are located at three levels, some of which are interbeded with slope deposits (Yanagisawa et al., 1986). To some extent, step cultivation of paddy fields and fish ponds for carp feeding, have also formed the landscape of this area, and increased the risk of slope failures due to the infiltration of surface water into soil or rock.

Topography in the study area ranges from hilly to mountainous in the Higashiyama Hills, located in the south western part of the Niigata coastal plain along the Japan Sea. Annual precipitation ranges from about 136 to 255 mm. However, seasonal antecedent rainfall from July 1, 2004, through October 23, 2004, totalled 1055 mm in Nagaoka City, as compared to a mean value of 1106 mm for the vicinity of the earthquake-impacted areas. Thus, total rainfall for the four months prior to the earthquakes was four to five times the annual average for the area. Three months before the Chuetsu event, heavy rainfall of as much as 400 mm in 24 hours triggered more than 1000 landslides in the study area (Yamagishi et al., 2005); some of these landslides were reactivated by the earthquakes. The earthquakes occurred only a few days after Typhoon Tokage; the strong shaking of rain-soaked hillsides triggered numerous mudslides and debris flows.

LANDSLIDE CHARACTERISTICS

The Chuetsu earthquakes triggered thousands of landslides in the vicinity of the epicentre. Aerial photographs and satellite photos taken urgently after the earthquakes by several companies and the Geographical Survey Institute of Japan (GSI) were interpreted to provide extensive information on landslide locations, geometries, types, and characteristics. In this study, reports of landslides triggered by the Chuetsu event have been collected from a wide variety of sources, which has allowed comprehensive analysis of landslide distributions. The heavily struck area and its vicinity were chosen for detailed study; this area is located between 138°48΄E and 138°58΄E longitude, and 37°15΄N and 37°25΄N latitude. The spatial distribution of landslides was extracted from a map of earthquake-triggered landslides produced by the GSI (2004) just several days after the earthquakes. This broad area having widely scattered landslides encloses two zones of much more concentrated landsliding activities extending NE-SW, which coincided with local structural patterns of active folding and faulting. In these zones of great concentration, landslides occurred in siltstone, sandstone, and their thin-bedded alterations, which consisted of weathered, uncemented sediment that has been folded and uplifted. In addition, for the argillaceous bedrock materials, high antecedent moisture tended to cause softening and strength reduction, as well as elevated pore or joint water pressures and seepage forces, which resulted in increased landslide activity due to earthquakes.

After being rechecked from aerial photographs based on a spatial distribution map developed by the GSI, the landslides triggered by the earthquakes can be classified into six categories: (1) rock falls; (2) rock slides; (3) disrupted soil slides; (4) debris flows; (5) soil block slides; and (6) complex landslide (Cruden & Varnes 1996; Keefer 2002). The most widespread types of landslides induced by the earthquake were highly disrupted, relatively shallow slides and soil (debris) flows. The disrupted shallow slides consisted of regolith and highly weathered bedrock materials on very steep slopes flanking floodplains and along incised valleys and creek channels. In several cases, debris flows travelled long distance and blocked natural drainage courses, generating landslide dams. In some cases, slope failures were obviously controlled by pre-existing planes of weakness. However, as observed in the field investigation, other deep-seated failures were associated with certain soil deposits. In the study area, 1212 landslides triggered by the earthquakes covered 2.9% of the total surface area; of these, 641 were reactivated from pre-existing landslides.

However, preliminary observations indicated that some ancient landslides were not reactivated during the earthquakes. The volumes of nine earthquake-triggered landslides were estimated at more than 100 m^3 (http://www.mlit.go.jp/chuetsujishin/). Several of these large landslides blocked streams, forming landslide dams. The largest block slide, which was located in the Dainichisan Mountain five kilometres far from the epicentre, was reactivated from a pre-existing slide mass. As observed in the field investigation, this landslide was a typical rotational soil slide on a dip slope, which failed along a bedding plane. The landslide was as much as 650 m long, and its active area was about 0.2 km^2. The maximum depth of the sliding surface was estimated at 75 m.

Landslide dams were also remarkable phenomena triggered by ground motion in the Chuetsu event. For example, the Terano and Higashi-takezawa landslides moved rapidly to streams and, consequently, formed impoundments upstream. In the field investigation, it was found that these two large-scale landslides occurred on dip slopes, which were underlain by sandstone, mudstone, and their thin-bedded alternations, and they typically resulted from the reactivation of parts of previous landslides. It should also be pointed out that this kind of landslides obviously developed ponds on its surface, which seems to have provided water for soil liquefaction leading to flow-type failure of the debris.

STATISTICAL ANALYSIS OF LANDSLIDE DISTRIBUTION

A statistical analysis of landslide distribution was conducted for the landslides that were concentrated in the 275.55-km^2 study area. In general, the distribution of earthquake-triggered landslides is most strongly influenced by slope steepness, geology, and shaking intensity. This section notes correlations of landslide occurrence with each of these factors. The analysis was carried out using geologic maps digitally compiled by Takeuchi et al. (2004) and Digital Elevation Models (DEM) with a grid of 10 m produced by the Hokkaido Chizu Company Limited from GSI 1:25,000-scale topographic maps. In this analysis, landslide concentration (LC) was defined to express the influence of landslide occurrence, which is calculated as the number of landslides per square kilometre. The landslide concentration was

$$LC = 1212 \text{ landslides}/275.55 \text{ km}^2 = 4.4 \text{ landslides/km}^2$$

Landslide activity versus slope steepness

In general, steeper and higher slopes have greater higher susceptibility to landslide activity, even when the slope failure is not triggered by an earthquake. Within the study area, average slope steepness was calculated for each 10 m grid of DEM. For each 1˚ interval of slope steepness, its influence on landslide distribution was analyzed using percentage of landslide area. As shown in Figure 1, slopes in the study area are fairly evenly distributed from 5˚ to 30˚; above 30˚ areas of steeper slopes drop off abruptly. It can be noted that landslides occurred in grid cells with average slopes ranging from 0˚ to 50˚, but those slopes in a range of 20˚ to 35˚ were much more subject to landsliding, including more than 45% of the total area affected by landslides. Although slopes steeper than 50˚ occupied a smaller area, a number of landslides occurred on most of these slopes. Conversely, slopes ranging from 20˚ to 35˚ covered a much larger area, but percentages of landslide area are lower than those of slopes steeper than 50˚ because most of shallow and disrupted landslides occurred on the steeper slopes. It is interesting to note that the slope angle, at which landsliding most commonly occurred in the Chuetsu event, is much gentler than 45˚ at which most landslide occurred in the Chi-Chi (Taiwan) earthquake (Khazai & Sitar, 2003). However, 40% of failures occurred on slopes between 20˚ and 30˚ in the 1994 Northridge event (Parise & Jibson, 2000), and landslides triggered by the Loma Prieta earthquakes were strongly concentrated on slopes in the range of 30˚-45˚ (Keefer, 2000).

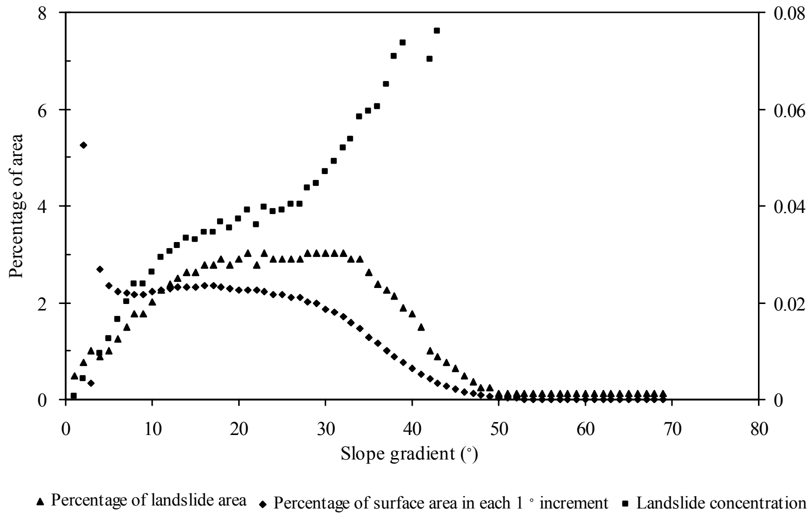

Figure 1. Relationship between landslide occurrence and slope steepness

Landslide versus geology

The study area is underlain by Miocene to Quaternary sedimentary rocks. It consists of a multilayered alternation of sandstone, siltstone and mudstone (Yanagisawa et al., 1986), which was deformed by a series of ENE trending folds. The distribution of landslides is zonal in the direction of folding, especially along two main fold axes. It was noted that many landslides were concentrated along a synclinal axis in Yamakoshi Village, while a number of landslides were distributed northwest of them far from an anticlinal axis. Also, it was noted that numerous landslides on steep slopes moved against the direction of the dip of the geological strata because of joints or other geological discontinuities across bedding planes. As the bedrock throughout the area of major landsliding is noted to be sufficiently weak under saturated conditions to permit development of continuous shear along curved surfaces or bedding planes, it can be observed that several deep-seated rotation slides occurred in the Chuetsu event, much like classical soil slumping.

Table 1 and Figure 2 show landslide occurrence by geologic units. It can be seen that 86.5% of landslides occurred in Tertiary sedimentary rocks (which are also subject to landsliding in many other parts of the world), although these units covered only one half of the study area. No landslide occurred in the Toyagamine Formation, two subunits of the Sarukuradake Formation and one subunit of the Hanzogane Formation, while the greatest areal extent of the Dainichisan landslide as observed was in the Kawaguchi Formation, which accounts for the biggest value in terms of percentage of landslide area. The Wanazu Formation had the most concentrated landsliding activity with 14.14 landslides/km^2, although the Wanazu Formation occupied only 4.5% of the total geological units. It is followed by the Kawaguchi, Ushigakubi, Shiroiwa and Oyama Formations. Regarding percentage of landslide area, the Shiroiwa, Ushigakubi and Wanazu Formations ranged from 4.6% to 6.0%, while the Kawaguchi Formation was ranked the highest with 8.2% of the area being affected by seismic landslides.

Table 1. Predominant lithologies, rock properties and percentages of exposure area for geologic units

Age	Geologic Unit		Description of lithology	Percentage of surface area (%)	Rock property
Q	Alluvium (A)		Gravel, sand, and mud	17.1	unconsolidated sediment
	Colluvium (C)		Debris, colluvium soil, and landslide deposits	2.4	
	Terrace deposits (Td)		Gravel, sand, and mud	9.9	
	Oyama Formation (Oy)		Gravel, sand, and mud	0.8	
	Uonuma Formation (U)	Ue	Silt and sand	4	
		Ud	Silt, sand, and gravel	2.7	
		Uc	Gravel, silt, and sand	6.8	
T	Wanazu Formation (W)		Sandstone	4.5	weakly cemented sandstone and mudstone
	Shiroiwa Formation (S)		Sandy siltstone and thin-bedded alternation of sandstone and siltstone	9.5	
	Suyoshi Formation	Ka	Hornblende andesite and dacite lava, and pyroclastic	0.5	weathered andesite and pyroclastic
		Sy	Tuffaceous sandstone and andesitic pyroclastic	2.9	
	Ushigakubi Formation	Um	Massive sandstone	6.2	weakly cemented sandstone and mudstone
		Uv	Andesitic pyroclastic	1	weathered andesite and pyroclastic
	Kawauchi Formation	Ks	Sandstone	0.4	weakly weathered sandstone and mudstone
		Ku	Mudstone interbeded with sandstone	6.8	
		Kl	Sandstone interbeded with mudstone	2.8	
	Araya Formation	Av	Andesitic pyroclastic	3.5	weathered andesite and pyroclastic
		As	Mudstone interbeded with sandstone	0.1	weakly cemented sandstone and mudstone
		Am	Massive mudstone	11.6	
	Toyagamine Formation	Tv	Andesite lava and pyroclastic	0.2	weathered andesite and pyroclastic
		Ts	Mudstone blocks	<0.1	weakly weathered sandstone and mudstone
	Sarukuradake Formation	Nd	Dacite lava and pyroclastic	1.4	weathered andesite and pyroclastic
		Ga	Andesitic pyroclastic	0.8	
		Sm	Hard shale, and shale interbeded with sandstone	0.6	weakly weathered sandstone and mudstone
	Hanzogane Formation	Hm	Massive mudstone	0.2	
		N	Rhyolite and tuff lava	<0.1	weathered andesite and pyroclastic

It is clear that a combination of slope steepness and geologic units may have jointly affected the distribution of landslides triggered by the earthquakes, hence, differences in slope steepness among geologic units were investigated by determining the distribution of slope steepness within each 5° interval for each unit. With regard to rock properties, geologic units can be grouped into the following subunits: (1) unconsolidated sediment, (2) weakly cemented sandstone and mudstone, (3) weakly weathered sandstone and mudstone, and (4) weathered andesite and pyroclastics, as shown in Table 1. It can be seen in Figure 3 that the subunits, for example, Ue, Ud, W, S, Um, Ku, Kl, Am and Sm, were frequently subject to landsliding on 30˚ slopes, while Uc, Sy, Ks and Av easily failed at 35˚. It can also be noted that slopes in the range of 40˚ underlain by the subunits of Ka, Uv, and Nd failed easily, while on slopes of about 10˚ terrace deposits and the Oyama Formation often were subject to earthquake-triggered landsliding. This result indicates that, as compared to rock mass, unconsolidated sediment was more frequently subject to landsliding even on the gentler slopes.

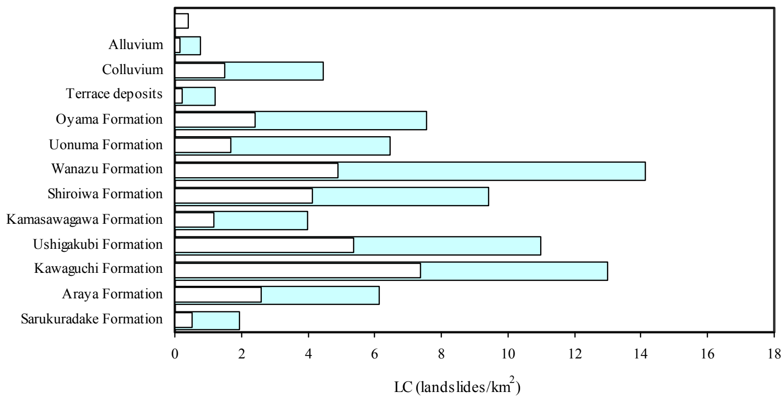

Figure 2. Correlation of landslide occurrence and geologic units by LC

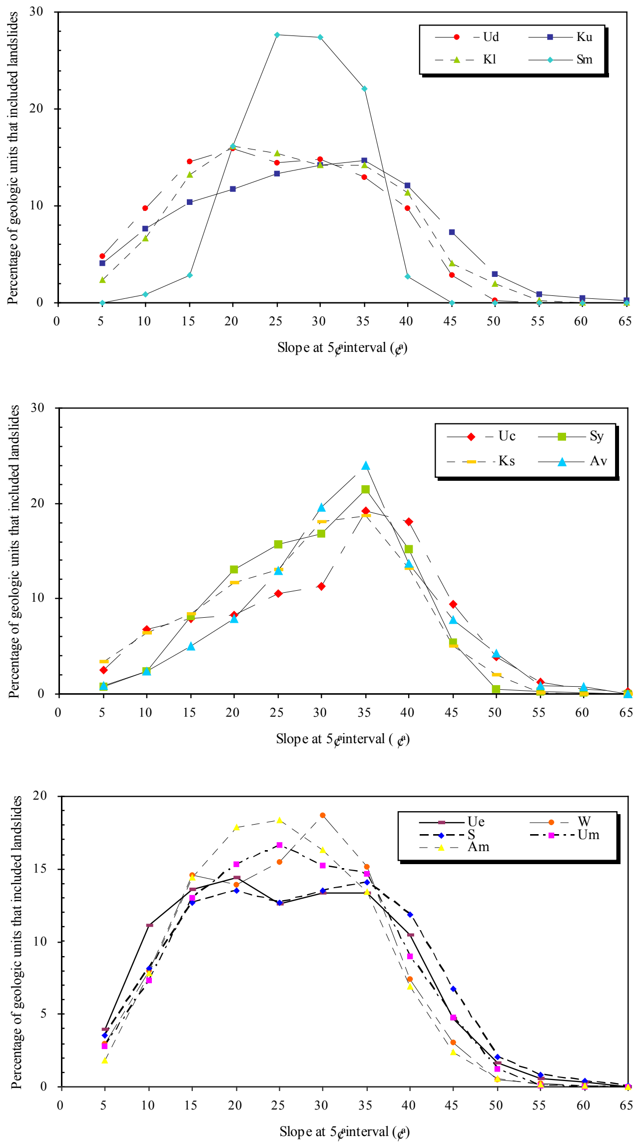

Figure 3. Percentage of landslide area within each 5˚ interval of slope steepness

Landslide activity versus shaking magnitude

The thresholds of minimum magnitude earthquakes that cause landslides were identified by Keefer (1984) and Rodríguez et al. (1999). As noted by Keefer (1984), many landslides can occasionally be generated by weak shaking on an imminently unstable slope, even if the earthquake magnitude is smaller than the threshold (Mw4.0). As would be expected, larger earthquakes tend to cause more abundant and more widespread evidence of landsliding than smaller earthquakes. Comparison with the historical earthquake-triggered landslides, which was included in the worldwide landslide databases covering the period 1811 to 1997 (Keefer 1984; Rodríguez et al. 1999), reveals that the area affected by landslides triggered by the Chuetsu earthquakes correlates with earthquake magnitude in a manner similar to historic earthquakes.

The maximum distance from the source of earthquakes of different magnitudes can be adapted as a valuable parameter for seismic landslide hazard assessment (Perkins 1997). The maximum distance (D) from the epicentre to landslides can be statistically calculated using $log\ D = 0.5M - 2.0$, where M is the earthquake magnitude (Kawabe et al. 2000), while approximate upper bounds for maximum distances of landslides from the epicentre were plotted by Rodríguez et al. (1999) and Keefer (2002). From the above equation, the maximum calculated distance of landslides from the epicentre in the Chuetsu earthquakes is 20 km. However, the actual maximum distance was about 18 km, which is smaller than calculated.

DISCUSSION AND CONCLUSIONS

The data and analyses presented herein provide useful insights into the correlations of the earthquake-induced landslides with geology, slope steepness, and earthquake shaking in the Chuetsu event. Although distributions of future earthquake-triggered landslides will depend strongly on earthquake magnitude, geologic and geomorphologic conditions, and focal mechanism, primary results obtained are reasonably expected to predict the areas where most landslides will occur in future similar events in Japan.

In the Chuetsu earthquakes, landslides predominantly occurred on slopes in the 20˚ to 35˚ range, and the increase of percentage of landslide area was especially pronounced for slopes steeper than 27˚. Compared to landslides triggered by the 1994 Northridge, California event and the 1999 Chi-Chi event in Taiwan, failed slopes in the Chuetsu event seem to be less steep. A possible reason is that the Chuetsu landslides were located using the areas of displaced material.

From the above analysis, the Uonuma, Wanazu, Shiroiwa, Kawauchi and Araya Formations were known to be the most frequent hosts of landslide activity on slopes of 30˚ to 35˚. Slopes in the range of 40˚ underlain by the Ka, Uv and Nd geologic subunits also failed easily. On slopes of about 10˚, terrace deposits and the Oyama Formation were especially subject to landsliding in the earthquake. In terms of susceptibility to landsliding, unconsolidated sediments easily failed even on gentler slopes, while weathered andesite and pyroclastics failed only on slopes steeper than 40˚. In further research, shear strengths of these units should be experimentally investigated to detect the correlations with landslide activity triggered by the earthquakes.

In terms of earthquake parameters, only magnitude and distance from the epicentre were analyzed to reveal their correlations with landslide occurrence, which coincided with previously studied cases. Although mechanism of the seismic fault has not been clearly identified, it was noted that the Miocene-Pliocene weathered sandstone, siltstone and mudstone played an important role in the generation of large scale landslides far from the epicentre. This also strongly implies that the study area experienced shaking well above the magnitude required to trigger landslides, and that factors other than the earthquake magnitude, such as geology and slope geometry under partly saturated conditions, controlled the landslide distribution near the epicentre.

Heavy rainfall in the days prior to the earthquake likely had a fundamental impact on the distribution and scale of landsliding, although no spatial correlations were found between antecedent rainfall and earthquake-induced landslide activity after overlaying maps of landslide occurrence and cumulative rainfall. As previously mentioned, the extent of the Chuetsu landsliding was very large (the landslide concentration was 4.4 landslides/km^2) as compared to other reported cases with the same earthquake magnitude. For example, the landslide concentration was 1.1 landslides/km^2 throughout an area of 11,000 km^2 in the Mw=6.7 Northridge event, although this concentration was calculated for the source area (Harp & Jibson, 1996). In the Chi-Chi event (Mw=7.6) only 0.88 landslides/km^2 were reported over an area of 11,000 km^2 (Hung, 2000). Generally, if the earthquake had rocked this area under normal moisture conditions, or relatively dry conditions, it is likely that the area affected by landsliding would have been significantly smaller. For the argillaceous bedrock materials in this active area, which were folded and faulted, high antecedent moisture would have tended to cause softening and strength reduction, as well as elevated pore-water pressures and seepage forces. Thus, landslide distribution was much more concentrated than in other reported cases subject to the same earthquake magnitude. It is also interesting that most of the large landslides observed, mainly soil slides, occurred due to ponds located above the source areas. It can be interpreted that these ponds, together with rice paddies tended to maintain a higher ground-water level, presumably leading to higher susceptibility of landslide occurrence on the slopes underlain by the weak and friable materials. Future evaluation of seismically triggered landslides should emphasize antecedent rainfall. Dynamic models should be developed that calculate slope instability based on geotechnical properties, slope geometry, and hydrologic conditions.

In conclusion, the Chuetsu earthquakes triggered thousands of landslides in the area of its epicentre. The value of landslide concentration was 4.4 landslides/km^2. Statistically, most landslides occurred in grid cells with average slopes ranging from 0˚ to 50˚, but slopes in the 20˚ to 35˚ range were the most subject to landsliding, including more than 45% of all the area affected by the landslides.

In terms of geologic units, the Wanazu Formation had the most concentrated landslide activity with 14.14 landslides/km^2; however, this formation occupied only 4.5% of the study area. This was followed by the Kawaguchi, Ushigakubi, Shiroiwa and Oyama Formations. With regard to percentage of landslide area, the Shiroiwa, Ushigakubi, and Wanazu Formations ranged from 4.5% to 6.0%, while the Kawaguchi Formation was ranked the highest: 8.2% of this formation was affected by seismic landslides. It can be seen that the geologic subunits of Ue, Ud, W, S, Um, Ku, Kl, Am and Sm were susceptible to landsliding on 30˚slopes, while Uc, Sy, Ks and Av were prone to landslide occurrence on 35˚slopes. It can also be noted that slopes of about 40˚ underlain by the Ka, Uv and Nd geologic subunits failed easily, while on slopes of about 10˚ terrace deposits and the Oyama Formation were susceptible to landslide activity.

Meanwhile, the area affected by landslides triggered by the Chuetsu earthquakes correlated with earthquake magnitude, and the maximum distance from epicentre of landslides triggered by the Chuetsu earthquakes was 18 km, slightly less than the distance calculated using the developed statistical equation.

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