Topographic features of snowmelt-induced landslide locations with long travel distances in Japan

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Landslide masses can travel long distances, resulting in large-scale sediment-related disasters. To develop a method for detecting locations prone to a landslide with long travel distance, we first collected data of 76 previous snowmelt-induced landslides in Japan and analyzed their topographic features including landslide slope category (primary or reactivated) and travel path of the displaced mass (headwater valleys, floodplains, or slopes). A landslide whose travel distance was greater than the horizontal length of the collapsed slope was regarded as a landslide with a "long" travel distance. The results suggest that landslides with long travel distances often occur at slopes that have experienced past landslide events (i.e., reactivated landslide); the travel paths of these landslides were classified into "headwater valleys" category. The reactivated landslides and valley topography are important because (1) landslide mass loosened in reactivated landslide sites compared with primary landslide sites, (2) water flowing frequently along the valley prior to the landslide event mixed with the landslide mass, and (3) the valley topography prevented diffusion and dissipation of the kinetic energy of the landslide mass. Combination of these effects probably caused the liquefaction of landslide mass and, in some cases, transformation into debris flow, thereby resulting in a long travel distance. The importance of valley topography is in agreement with previous studies on rainfall-induced landslides, implying that the results of this study can be applied to rainfall-induced landslides also.

Key words: snowmelt-induced landslide, travel distance, travel path, reactivated landslide

1. INTRODUCTION

In Japan, frequent landslide disasters cause severe damage to human life, property, and infrastructure. One of the main causes of landslides is infiltration of snowmelt water into landslide blocks. Such snowmelt-induced landslides often occur in areas along the Sea of Japan due to heavy winter snowfall.

The cases where landslides travel long distances often result in large-scale sediment-related disasters. For example, in 1980, a snowmelt-induced landslide in Yamakoshi Village (now Nagaoka City), Niigata Prefecture, had a moderate horizontal collapsed slope length of 200 m but traveled as far as 480 m, maintaining the form of a block. This landslide destroyed prefectural and village roads and buried 25 ha of paddy fields [*Fujita et al.*, 1981]. A similar event in 1978 in Myoko Village (now Myoko City), Niigata Prefecture, had horizontal collapsed slope length of only 130 m, but the landslide mass transformed into debris flow to travel 6,500 m, leaving 13 dead, 1 injured, and 27 buildings destroyed completely or partially [*Shiraishi*, 1978].

For prevention and mitigation of such disasters, detection of areas prone to landslides with a long travel distance is very important. Although previous studies have reported detailed information on individual snowmelt-induced landslide disasters with long travel distances, including landslide scale and movement of landslide mass [e.g., *Tsuda et al.*, 1970; *Iwata*, 1973], studies that use large data of such landslide events and analyze topographic features of landslide locations have been rare.

As a first step in developing a method for detecting locations prone to landslides with long travel distances, we collected information about previous snowmelt-induced landslides in Japan and analyzed the topographic features of the landslide locations.

2. METHODS

2.1 Dataset

Data on 76 snowmelt-induced landslides that occurred in Japan between 1947 and 2012 were collected. The date of occurrence, location, horizontal length of the collapsed slope (*L1*, in meters), and travel distance of the displaced mass (*L2*, in meters) of each landslide (Fig. 1) were obtained from descriptions and figures in disaster-related project reports and/or the literature.

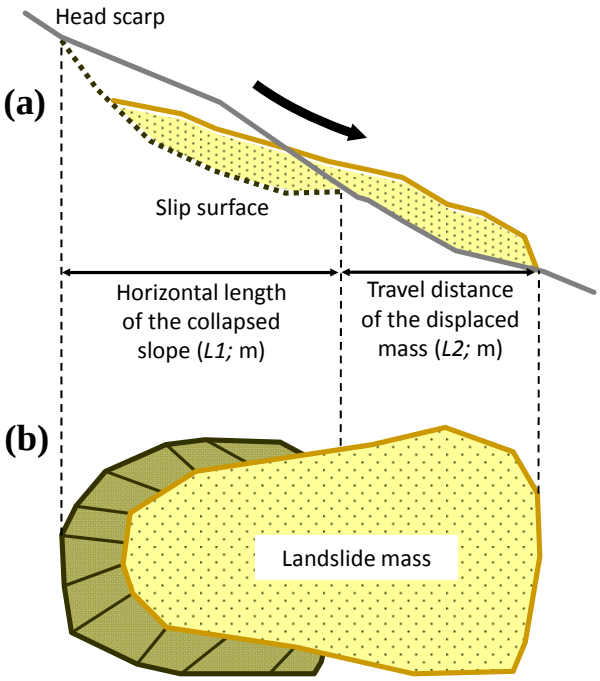

Fig. 1 Schematic diagram of a landslide: (a) cross-sectional view, (b) plan view

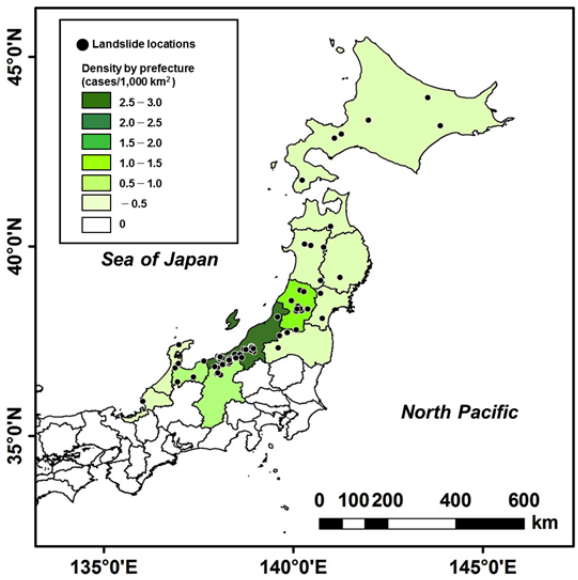

Fig. 2 Distribution of the studied 76 landslides and their density by prefecture

Fig. 2 shows locations of the studied landslides and density by prefecture. The studied landslides were distributed mainly along the Sea of Japan from Hokkaido to Fukui Prefecture, where snowmelt-induced landslides are common due to high winter snowfall. Thirty-four events were recorded in Niigata Prefecture, showing the highest density (2.70 cases per 1,000 km^2). Yamagata Prefecture has 10 cases, equivalent to 1.07 cases per 1,000 km^2.

Fig. 3 shows the frequency distribution and cumulative percentage of *L1*. The studied landslides have *L1* ranging from 30 to 3,600 m. Forty-seven (62%) landslides have *L1* less than 250 m, whereas 10 (13%) and 4 (5%) landslides have *L1* greater than 500 and 1,000 m, respectively.

Fig. 4 shows the frequency distribution and cumulative percentage of *L2*. The studied landslides have *L2* ranging from 0 to 6,500 m. Forty-eight (63%) landslides have *L2* less than 50 m, whereas 20 (26%) and 3 (4%) landslides have *L2* greater than 100 and 1,000 m, respectively.

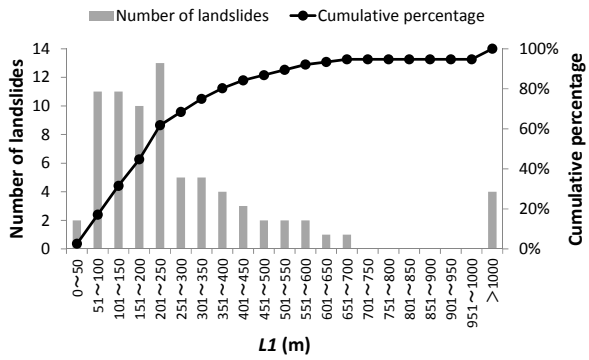

Fig. 3 Frequency distribution and cumulative percentage of *L1*

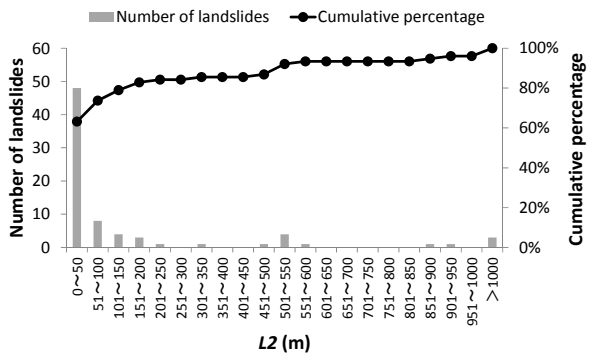

Fig. 4 Frequency distribution and cumulative percentage of *L2*

2.2 Classification of travel path

To examine the effect of displaced mass travel path on *L2*, we classified travel path of each landslide into three categories; "headwater valleys (HV)", "floodplains (including river beds; FP)", or "slopes (SL)", following the procedure given in *Kimura et al.* [accepted].

Plan curvatures and slope gradients were calculated using 10-m digital elevation models provided by the Geospatial Information Authority of Japan. River lines were determined by the river channels provided by the National Land Numerical Information Service of the Ministry of Land, Infrastructure, Transport, and Tourism.

Cells with a plan curvature ≤–1 (i.e., showing clear concave topography) continuously distributed over a 100-m length from the river lines were classified as HV. Along the river lines, except for HV regions, FP were delineated by the toes of surrounding slopes with gradient >10° on both sides of the river line. All other cells were classified as SL. Using this classification, travel path of each landslide was categorized. For more detail on the classification of travel path, see *Kimura et al.* [accepted].

Figs. 5–7 show examples of landslides of each

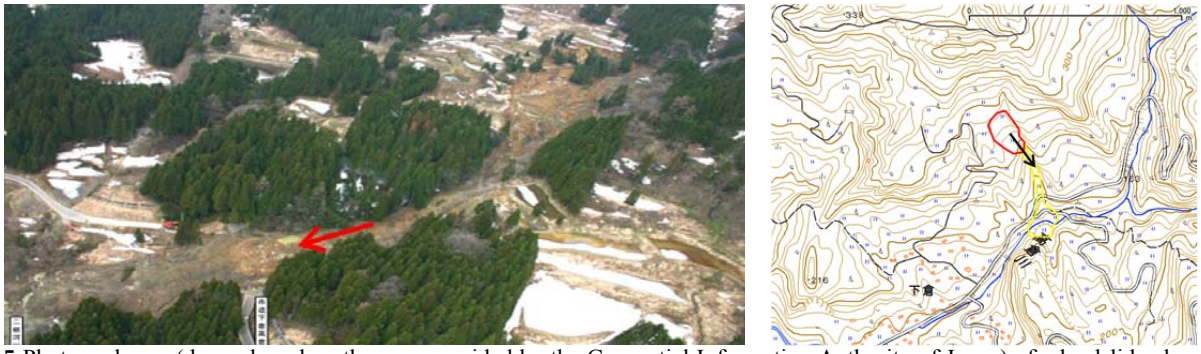

Fig. 5 Photo and map (drawn based on the map provided by the Geospatial Information Authority of Japan) of a landslide classified into the HV category: Shimokura landslide (Niigata Prefecture, Date of occurrence: April 10, 2005). The map has a contour interval of 10 m. Red and yellow lines in the map indicate the range of the collapsed slope and the displaced mass, respectively.

Fig. 6 Photo and map (drawn based on the map provided by the Geospatial Information Authority of Japan) of a landslide classified into the FP category: Kokugawa landslide (Niigata Prefecture, Date of occurrence: March 7, 2012). The map has a contour interval of 10 m. Red and yellow lines in the map indicate the range of the collapsed slope and the displaced mass, respectively.

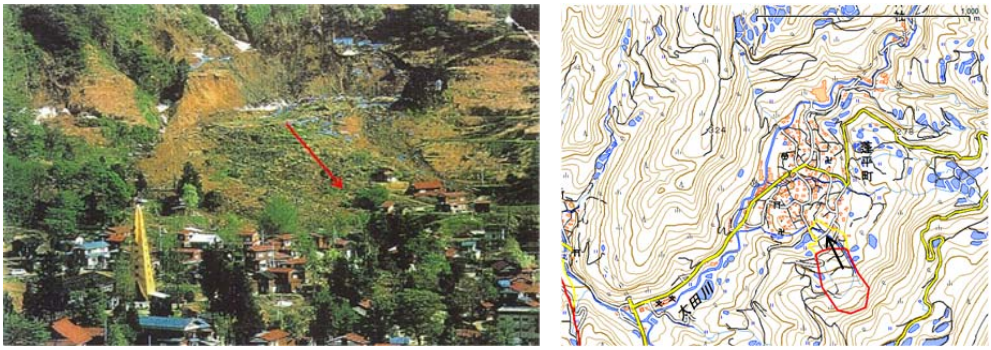

Fig. 7 Photo and map (drawn based on the map provided by the Geospatial Information Authority of Japan) of a landslide classified into the SL category: Yomogihira landslide (Niigata Prefecture, Date of occurrence: May 17, 1984). The map has a contour interval of 10 m. Red and yellow lines in the map indicate the range of the collapsed slope and the displaced mass, respectively.

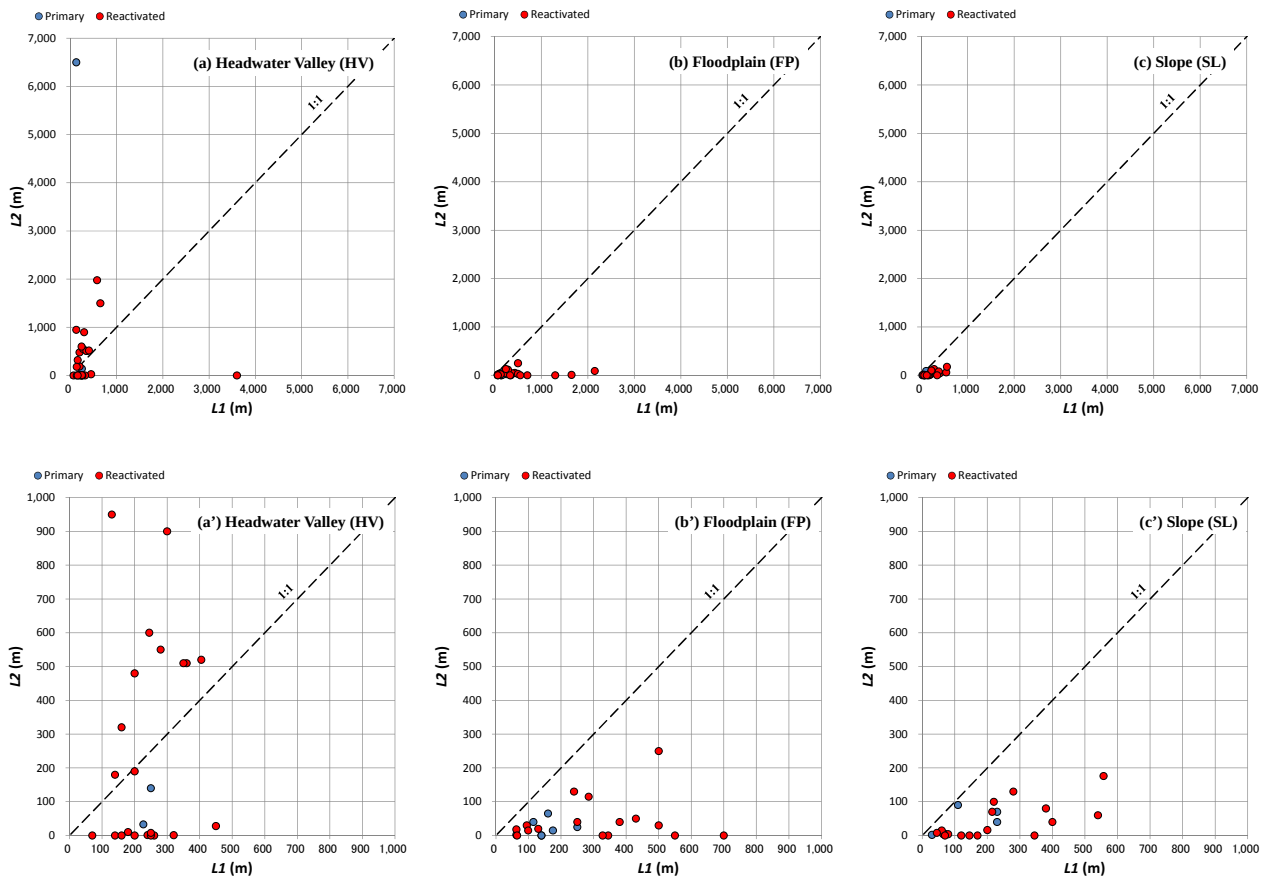

Fig. 8 Relationship between *L1* and *L2* for each travel path category

category (Fig. 5: HV, Fig. 6: FP, and Fig. 7: SL), demonstrating distinct topography of the travel paths.

2.3 Classification of landslide slope

Landslide slope category (primary or reactivated) of each landslide was investigated using the landslide distribution maps developed by the National Research Institute for Earth Science and Disaster Prevention. These maps were developed by studying topographic evidence of the past landslide events from aerial photographs. Landslides whose area of the collapsed slope totally or partially overlaps the area of displaced mass shown on the maps were regarded as reactivated, and the others were regarded as primary.

3. RESULTS

3.1 Travel paths

Figs. 8a–c show the relationship between *L1* and *L2* for all data in each travel path category. Figs. 8a'–c' show relationship between *L1* and *L2* for the range of 0–1,000 m. In this study, we define the landslides that had L2 greater than L1 (i.e., plotted above the 1:1 line in Fig. 8) as landslides with "long" *L2*.

Fig. 8 demonstrates that all events for the FP and SL categories are plotted below the 1:1 line, suggesting that their *L2* was not so long. For the HV category, however, only 15 landslides are plotted below the 1:1 line, suggesting that the remaining 13 landslides had long *L2*.

3.2 Landslide slope

To examine the effect of landslide slope category on *L2*, the events plotted in Fig. 8 were classified into two categories: primary or reactivated. Fig. 8 shows that majority of the landslides were reactivated in each travel path category, suggesting that the locations of these landslides are past landslide sites. As described above, all plots for the FP and SL categories are below the 1:1 line regardless of the landslide slope category. The 13 landslides plotted below the 1:1 line for the HV category include one primary landslide, but all others were reactivated.

4. DISCUSSION

Table 1 Summary of topographic features and the classification of travel distance of the studied 76 landslides

Travel path category	Landslide slope category	*L2* >*L1*	*L2* ≤*L1*	Subtotal	Total
HV	Primary	1	2	3	28
	Reactivated	12	13	25	
FP	Primary	0	7	7	26
	Reactivated	0	19	19	
SL	Primary	0	5	5	22
	Reactivated	0	17	17	
Total		13	63	–	76

Table 2 Summary of the predicted and observed classification of travel distance for the studied 76 landslides

		Predicted		
		L2>*L1*	*L2*≤*L1*	Total
Observed	*L2*>*L1*	12	1	13
	L2≤*L1*	13	50	63
	Total	25	51	76

4.1 Locations prone to snowmelt-induced landslides with a long travel distance

Table 1 summarizes the topographic features (i.e., travel path category and landslide slope category) and the classification of the travel distance (i.e., *L2*>*L1* or *L2*≤*L1*) described in the previous section. Although we studied a similar number of previous snowmelt-induced landslide disasters for the HV (28 landslides), FP (26 landslides), and SL (22 landslides) categories, all landslides that had *L2*>*L1* (13 landslides) were from the HV category. Moreover, 92% (12 landslides) of these 13 landslides were reactivated landslides.

To examine how well the two topographic features used in this study can predict the classification of the travel distance, the observed and predicted classification of the travel distance for the studied landslides are summarized in Table 2. Here, we predicted that the travel distance would be long (i.e., *L2*>*L1*) if (1) the landslide was reactivated and (2) the travel path is in the HV category.

Table 2 shows that the hitting ratio (i.e., the ratio of landslides whose classification of the travel distance was correctly predicted) is 82% (12 + 50 landslides). However, note that the false-alarm ratio (i.e., the ratio of landslides whose *L2* was predicted as >*L1* but was actually ≤*L1*) is slightly high at 17% (13 landslides). This result suggests that it is possible to use the two topographic features used in this study to predict landslide travel distance classification considerably well.

Hence, it can be concluded that slopes that have experienced past landslide events (i.e., reactivated landslide) and have travel path in headwater valleys (i.e., the HV category) can be regarded as prone to snowmelt-induced landslides with long travel distances.

4.2 Mechanism behind long travel distance

The previous section demonstrated that reactivated landslides and the HV category are important factors behind long travel distance. Detailed examination of the 13 landslides with long *L2* suggested that landslide mass was liquefied and sometimes transformed into debris flow, thereby travelling a long distance along valleys.

The effects of reactivated landslides and valley topography on liquefaction of landslide mass and transformation into debris flow can be inferred as follows. First, because reactivated landslide sites have experienced landslide events in the past, landslide mass at these sites loosened compared with primary landslide sites. This suggests that landslide mass can be easily broken up or liquefied during a landslide event. Second, water often flows along the valley prior to a landslide event, and snowmelt can increase the water flow considerably. Such stream water mixes well with the landslide mass. Third, valley topography confines the movement of landslide mass along the valley, preventing diffusion and dissipation of the kinetic energy of the landslide mass.

Sammori [2006] presented processes similar to the second and third effects described above. Combination of the above three effects likely contribute to the liquefaction of landslide mass and transformation into debris flow in some cases, resulting in long travel distances.

4.3 Comparison with previous studies

A few previous studies investigated the effects of topography on the travel distance of landslide mass. *Tsukamoto et al.* [1993] analyzed topographic features of sediment-related disasters, including

landslides and debris flows, caused by a heavy storm event in Kagoshima Prefecture in 1993. They demonstrated that transformation of landslide mass into debris flow with a long travel distance occurred at locations where the ratio of width to depth of a contour line is larger than 0.4–0.5 (i.e., showing valley topography). *Watanabe and Kaibori* [1999] investigated topographic characteristics of landslides and debris flows triggered by heavy rainfall in the northwestern part of Hiroshima Prefecture in 1988. They suggested that liquefaction and transformation of landslide mass into debris flow occurred where travel paths showed deep valley topography.

Although these previous studies exclusively examined rainfall-induced landslides whose mass transformed into debris flow in relatively small areas, their results are similar to those of this study. This implies that slopes having headwater valleys along travel paths are prone to landslides with long travel distances, regardless of the cause of the landslide (i.e., snowmelt or rainfall), because landslide mass can travel in the form of liquefied landslide or debris flow.

5. CONCLUSIONS

This study analyzed the topographic features of locations of snowmelt-induced landslides with long travel distances in Japan. The results suggested that such landslides tend to occur at slopes that have experienced past landslide events (i.e., reactivated landslide) and have travel paths in headwater valleys (i.e., HV category).

The results of this study can be used as the first method for determining locations prone to snowmelt-induced landslides with long travel distances.

However, because locations satisfying the topographic features used in this study may be found widely, additional criteria are needed to determine the potential locations more accurately. As some landslides triggered by rainfall or earthquake also show long travel distances, locations prone to such rainfall- or earthquake-induced landslides should also be analyzed with the criteria used in this study. Furthermore, developing a method to predict areas damaged by such landslides is very important. Future work should address these issues to contribute to preventing and mitigating large-scale sediment-related disasters.

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† The title or source is a tentative translation by the authors from the original.