Investigation of the Distribution of Long-Traveling Landslides

Nobuhiro Usuki,[1)] Yoshinari Tanaka[2)] and Takahisa Mizuyama[3)]
1) Asia Air Survey Co., LTD, Manpukuji 1-2-2, Asou-ku, Kawasaki, Kanagawa 215-0004 (usu.usuki@ajiko.co.jp)
2) Kitac Co., LTD, Shinkou-cho 10-2, Niigata, Niigata 950-0965 (y.tanaka@kitac.co.jp)
3) Graduate School of Agriculture, Kyoto University, Oiwake-cho, Kitashirakawa, Sakyo-ku, Kyoto 606-8502 (mizuyama@kais.kyoto-u.ac.jp)

Abstract

Most landslides move slowly and only over a short distance. However, some landslides travel over a long distance. These are called long-traveling landslides. This type of landslide tends to cause severe, widespread damage. This study presents an overview of the actual state of long-traveling landslides in Japan. The spatial distribution and characteristics of these movements are reported. The ratio of the horizontal traveling length of a landslide to the horizontal length of the original landslide is defined as the traveling coefficient (**Tr**), and it is used for the evaluation of landslide movements. Landslide movements are classified into three types: fully fluidized ($\mathbf{Tr} \geq \mathbf{0.9}$), partly fluidized ($\mathbf{0.3} \leq \mathbf{Tr} < \mathbf{0.9}$), and non-fluidized ($\mathbf{Tr} < \mathbf{0.3}$). Tr is influenced not only by the volume of a landslide, but also by other factors.

Keywords: landslide, long-traveling landslide, spatial distribution, movement characteristic

Introduction

Some sliding soil masses become fluidized and travel over a long distance, although they have not yet reached a debris flow level. Normally, long-traveling landslides tend to cause severe damage, as seen in the landslide that occurred at Mt. Zizuki in Nagano Prefecture in July 1985. Sasa et al. (2000) studied highly fluidized, long-traveling landslides from the viewpoint of moving rate, etc. However, we focused on the traveling length of landslides. Past research on the traveling length of landslides includes: prediction of traveling length of collapsed soil (Moriwaki, 1987); prediction of traveling length of landslides through case analyses (Kusumoto et al., 2003); and topographical conditions related to landslides with large displacements (Morishita et al., 2003). These studies advanced mainly from a statistical approach, but they did not treat the kinematic aspects of landslide movements. This paper presents an overview of the actual state of long-traveling landslides in Japan, with focus on their characteristics, distribution, and the relationship with soil constants.

1. Target Data for the Survey of Traveling Length of Sliding Soil Masses

Landslides selected as the target data for this study were those that were triggered by rainfall, snowmelt, and other natural causes, and whose soil masses moved spatially continuously. Of the primary landslide disasters occurring in Japan (376 landslides: 1947–2000), 109 landslide disasters that have the following reference materials were selected for this study: plane drawings describing the state of landslide occurrence; data on the geology of the landslide site, scale of the landslide, volume of the landslide, and traveling length of the sliding soil mass; and photographs and other data showing the state of landslide occurrence (that show the conditions of sliding soil masses). However, the following types of landslides were excluded from the selection process: [1] Landslides caused by an earthquake or artificial causes; [2] the type of landslide in which a sliding soil mass flows into a mountain stream, clogs it, and moves again as a secondary movement, which is usually known through hearings and field surveys; and [3] the type of landslide in which a landslide dam has been formed and then breached. The traveling lengths of these 109 landslides were measured using the geometry shown in Figure 1.

2. Definition of Long-traveling Landslides

A histogram of the traveling lengths of landslides (**L2**) is shown in Figure 2. The traveling lengths of sliding soil masses vary widely, ranging from slight movement at the end of a soil mass to as long as 2,300 m.

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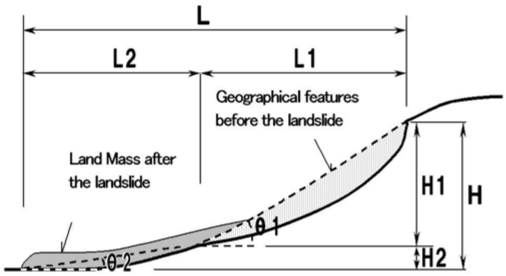

Fig. 1. Definition of factors on landslide movement.

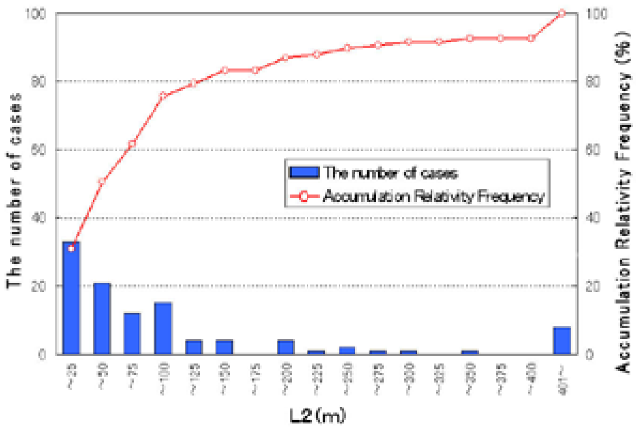

Fig. 2. Histogram of the travel distance of landslides.

In the present study, the ratio of the traveling length of a landslide (**L2**) to the length of its original landslide (**L1**) is defined as the traveling coefficient ($\mathbf{Tr = L2/L1}$), and it is used as the index to evaluate the traveling length of sliding soil masses. A histogram of the traveling coefficients is shown in Figure 3. The traveling coefficients are distributed in the range of $\mathbf{0 < Tr \leq 3.4}$. Landslides whose traveling coefficient is $\mathbf{Tr \geq 0.5}$, which accounts for about 20% of the accumulation relative frequency, are defined as long-traveling landslides. The average traveling length and the maximum traveling length of the landslides whose traveling coefficient is $\mathbf{Tr \geq 0.5}$ are about 350 m and 2,000 m, respectively. Of the target data, 22 landslides had a traveling coefficient of $\mathbf{Tr \geq 1.0}$ (which means that the traveling length is longer than the original landslide length).

Distribution of Long-traveling Landslides

Figure 4 shows the distribution of landslides with a traveling coefficient of about $\mathbf{Tr \geq 0.5}$. The occurrence areas of these landslides roughly coincide with the areas of Neogene formations and the areas of metamorphic rocks, both of which are susceptible to landslides. The 109 landslide areas surveyed also have a similar distribution tendency. These are the geological zones likely to cause a landslide, corresponding to the zones of "landslides at Tertiary formations" and "landslides at fractured zones" according to the landslide classification proposed by Koide (1955). Long-traveling landslides are mainly distributed in the Hokuriku and Shikoku regions, which are well-known landslide-frequent areas, but they are also widely distributed in other regions, particularly in the areas of Neogene formations and along the geological tectonic line. Here, the Motochi Landslide with a large traveling coefficient ($\mathbf{Tr = 2.76}$) and the Tamanoki Landslide with a small traveling coefficient ($\mathbf{Tr = 0.35}$) are introduced in Figures 5 and 6.

1) Motochi Landslide (Rebun Town, Hokkaido)

- Date of occurrence: October. 11, 1994
- Geology: sandy and gravelly tuffs from the Neogene Period
- Traveling coefficient: $\mathbf{Tr = 2.76}$
- Outline

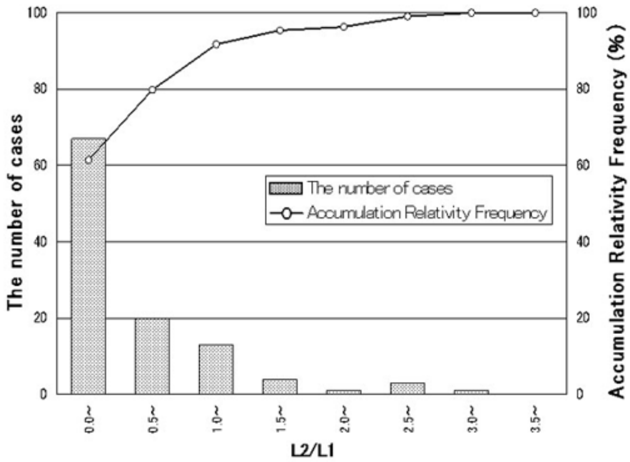

Fig. 3. Histogram of the traveling ratio (Tr).

The Motochi landslide occurred on the relatively gentle valley sandwiched by scarp and intrusive rocks, a location presumed to have many landslides in the past. The sliding soil mass flowed down this valley for 400–500 m, and its tip neared the coast, collapsing the houses of local residents. The damage was: 1 total collapse of a house; 1 semi-collapse of a house; and disruption to town roads.

The primary causes (topographical/geological causes) were that the site is a valley tending to store groundwater, and that the bedrock is severely weathered tuffs that easily become clayey. As a secondary cause (provoking cause), it is considered that the large amount of rainfall, 1.5 times the annual average and about 5 times that of the previous year, on the preceding days triggered the landslide.

2) Tamanoki Landslide (Oumi Town, Niigata Prefecture)

- Date of occurrence: February.15, 1985
- Geology: Pre-tertiary tuffs, Quaternary talus accumulation
- Traveling coefficient: Tr = 0.35
- Outline

At the Tamanoki landslide site, a steep slope at the end of a mountain facing National Route No. 8 collapsed, and earth and debris rapidly ran down the slope. The damage was: 10 killed; 4 injured (both severely and lightly); 5 total collapses of houses; 5 semi-collapses of houses; 1 total collapse of a shrine, 1 total collapse of a temple; and 3 total collapses of warehouses.

The primary causes were that the slope was steep, and consists of talus accumulation, and groundwater converged at the deep normal fault-type cracks around the sliding scarp that was caused by past landslides. As a secondary cause, it is pointed out that heavy snow with a depth of 150–160 m, started rapidly to melt about 15 days before the occurrence of the landslide. Because of this snowmelt, a large amount of melt-water percolated into the ground through the above-mentioned cracks, and triggered a landslide.

3. Characteristics of Long-traveling Landslides

3.1. Classification of Movement Types of Sliding Soil Masses

Landslides are usually classified based on the location of sliding movement, movement type, moving rate, and scale. The movement type is generally classified into: topple, fall, spread, flow, slide, creep, etc. Long-traveling landslides are considered to belong primarily to the flow type.

Here, we further attempted to classify the movement type of soil masses focusing on the conditions of these masses. The following three characteristics were found concerning the conditions of the sliding soil masses surveyed (see Figure 7).

① A sliding soil mass and its surfaces are hardly disturbed and moves as a mass(non-fluidized).

② A sliding soil mass and its surfaces are lightly disturbed. If trees are present in the landslide area, few of them are fallen.

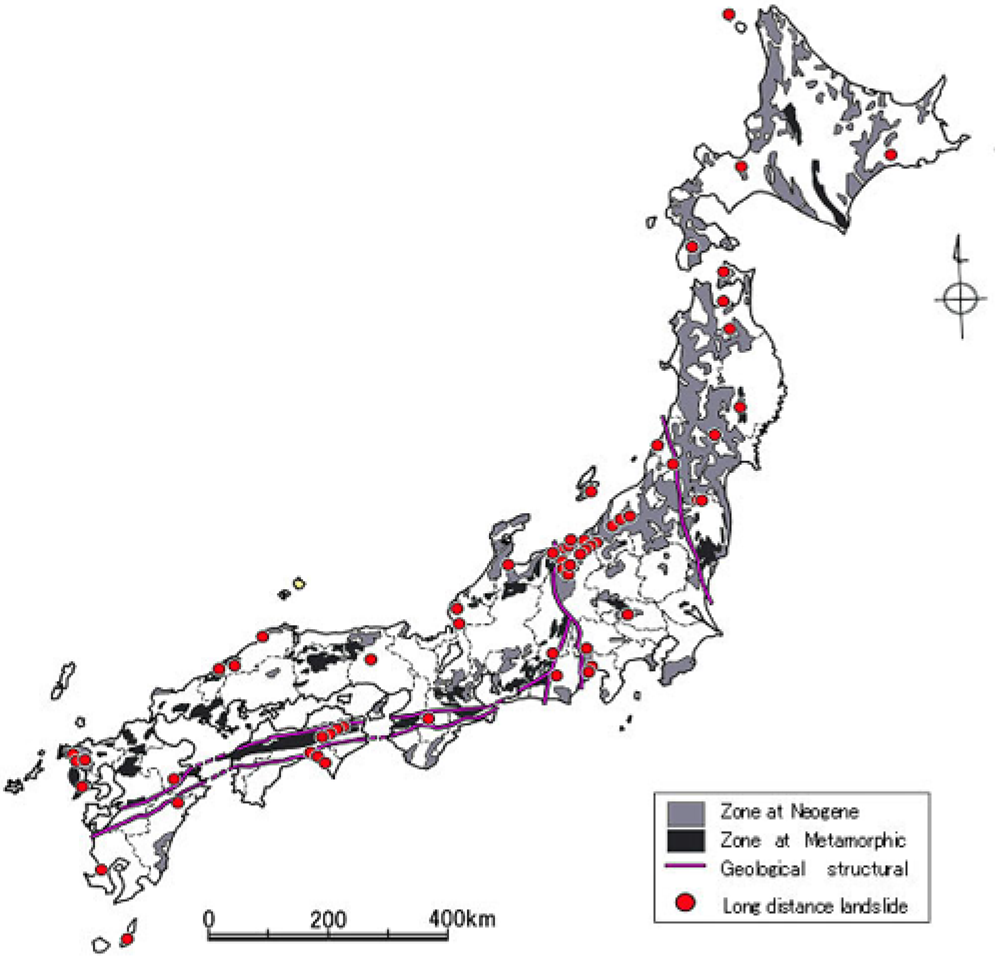

Fig. 4. Distribution of long-traveling landslide

③ The surfaces of a sliding soil mass are significantly disturbed, virtually not retaining its original form. If trees are present in the landslide area, most of them are fallen Of these three, ① is the case in which sediment moves as a mass taking the sliding plane as the boundary. In addition, the sliding soil mass retains its original form without sustaining serious damage to its internal structure. Cases ② and ③ are grouped into the following two types based on the conditions of fallen trees and the moving soil mass.

② The soil mass is deformed, but moves with its internal structure not completely ruptured (partly fluidized).

③ The internal structure of the soil mass is completely ruptured after the start of sliding, and flows down as it is (fully fluidized).

3.2. Gradient of Landslide Area, Gradient between Landslide End and Lower Area, and Traveling Coefficient

The relationship between the gradient of the landslide area ($\theta 1$), the gradient between the landslide end and the lower area ($\theta 2$), the traveling coefficient, and the fluidized conditions are shown in Figure 8. The gradient of the landslide area and the gradient from the landslide end to the lower area were evaluated using their ratios. It is found from the figure that fully fluidized landslides rather than partly fluidized landslides tend to occur at slopes with a gentler gradient. Even though the landslide end was a virtually flat area, the traveling coefficient was as large as $\mathrm{Tr} \geq 1.0$ in some cases. Therefore, there is no clear relationship between the gradient from the landslide end to the lower area, the traveling coefficient, and the fluidity conditions.

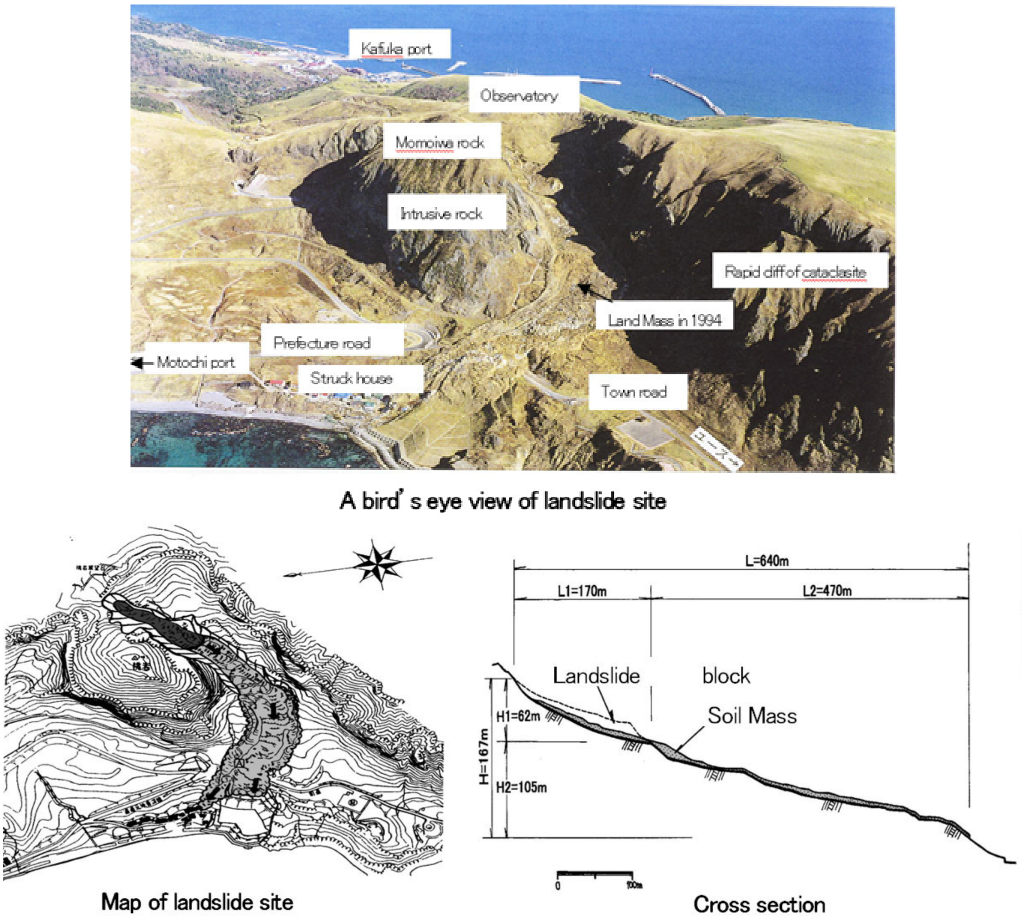

Fig. 5. Motochi landslide.

3.3. Equivalent Coefficient of Friction and Movement Type

The movements of sliding soil masses are classified into three types: fully fluidized, partly fluidized, and almost non-fluidized, as mentioned earlier. Then, the relationship between the equivalent coefficient of friction and the volume of sliding soil is described in Figure 9. The equivalent coefficient of friction is in the range of $\mu = 0.1$–0.9. However, it tends to become smaller as the volume of sliding soil increases, although this tendency is not very clear.

3.4. Volume of Sliding Soil and Movement Type

Figure 10 describes the relationship between the volume of sliding soil and the traveling length (L2) of each movement type of landslide. It has been pointed out that the traveling length of a landslide becomes longer as the volume of sliding soil becomes larger (particularly in the case of a debris avalanche, etc.). Although this tendency is seen in Figure 10, the plots of fully fluidized, partly fluidized, and non-disturbance-type landslides are also widely distributed. Therefore, concerning the fluidity of a landslide, factors other than the volume of sliding soil should be considered.

3.5. Traveling Coefficient and Movement Type

The movements of sliding soil masses are classified into three types, namely, fully fluidized, partly fluidized, and almost non-fluidized, and their traveling coefficients are described in Figure 11. The traveling coefficient is roughly **Tr** *geq* **0.5** for the fully fluidized type, $\mathbf{0.3 \leq Tr < 0.9}$ for the partly fluidized type, and $\mathbf{Tr < 0.3}$ for the almost non-fluidized type. Therefore, the classification of long-traveling landslides is possible to some extent with the use of the traveling coefficient and movement type.

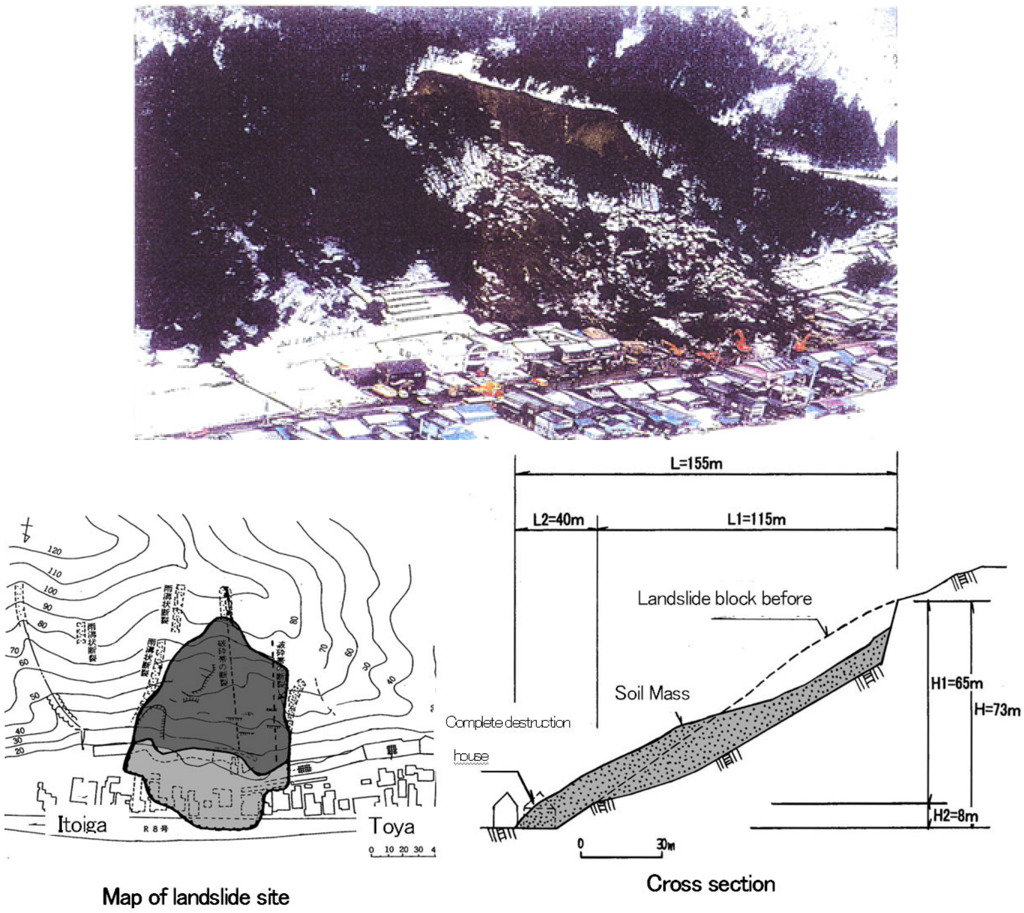

Fig. 6. Tamanoki landslide.

3.6. Characteristics of Long-traveling Landslides

Concerning the traveling length of sliding soil masses, a prediction method has been presented in which the equivalent coefficient of friction and the volume of sliding soil are used as the indexes and where their relationship (the equivalent coefficient of friction becomes smaller as the volume of sliding soil becomes larger) is utilized for prediction. This tendency seems to exist if regarded from the viewpoint of entire landslides, as seen in Figure 9, but the tendency is not necessarily obvious if attention is paid to the movement type. On the other hand, if focus is placed on the traveling coefficient and the movement type, long-traveling landslides can be classified clearly, as shown in Figure 11. This suggests that the movement type of the soil mass after the onset of sliding movement affects the traveling length.

4. Characteristics of Soil Constants of Long-traveling Landslides

The relationship between the landslides and soil constants was studied using the landslide data in Niigata Prefecture. The data in this prefecture were used because collecting soil test data of major landslides throughout Japan is difficult, and because the soil test results are well collected in the case of landslides in Niigata Prefecture.

4.1. Traveling Coefficients of Landslides in Niigata Prefecture

Of the primary landslide disasters occurring in Niigata Prefecture (1,387 landslides: 1982–2001), 131 landslides were selected for the current study based on the condition that the traveling length of the landslide, the length of the original landslide, and the topographical conditions of the area below the sliding could be identified. Landslides triggered by an earthquake or other artificial causes, and cases in which precursors of a landslide were found but the soil mass scarcely moved, were excluded from the selection process. A histogram depicting the traveling coefficients of these landslides is shown in Figure 12. As many as 57 landslides with a traveling coefficient of $\mathbf{Tr} \geq \mathbf{1.0}$ were found. The average traveling length and the maximum traveling length

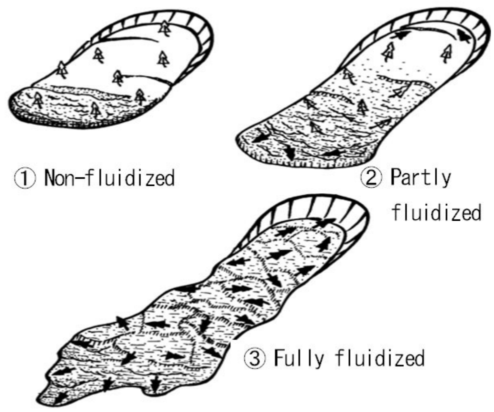

Fig. 7. Classification of landslides from their movement.

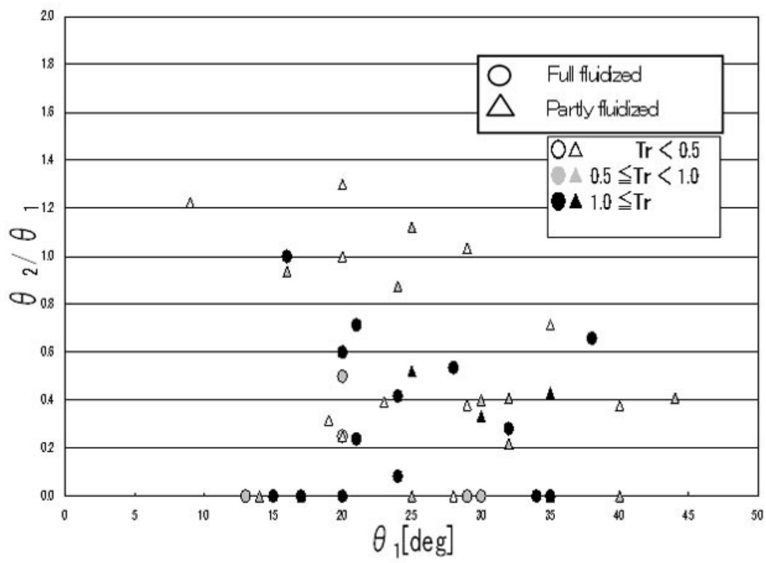

Fig. 8. Inclination of landslide and the lower side in end of landslide and traveling ratio.

were about 200 m and 1,000 m, respectively.

The conditions of sliding soil masses (fully fluidized, partly fluidized) were evaluated using past survey data and photographs, as well as the occurrence/non-occurrence of muddy flows. Landslides that became muddy flows were classified as the fully fluidized type, and the landslides in which a sliding soil mass was deformed but its internal structure appeared not ruptured from its surface conditions were classified as the partly fluidized type. The number of landslides classified as the fully fluidized type was 76. Their average traveling coefficient was **Tr = 1.7**.

4.2. Relationship between Traveling Coefficient of Landslide and Soil Constants

The landslides in Niigata Prefecture that received soil tests were grouped by geology (Uonuma Formation, Teradomari Formation, Nishiyama Formation, and Shiiya Formation), and their liquid limit was studied. The liquid limit was focused on in order to investigate the relationship between landslides and their material characteristics. Seventeen landslides that occurred adjacent to the soil test-received landslides and whose traveling coefficients were identified were grouped into the fully fluidized type and the partly fluidized type, and their relationship with the liquid limit was investigated. The results are shown in Figure 13. Although the relationship between the traveling coefficient vs. the plasticity index, effective stress, and total stress was also investigated, no clear characteristics were found. Regarding the relationship between the traveling coefficient and the liquid limit, it can be seen from Figure 13 that the liquid limit is less than 70 when the traveling coefficient is **Tr > 1.0** (fully fluidized), and 70 or more when the traveling coefficient is **Tr < 1.0** (partly

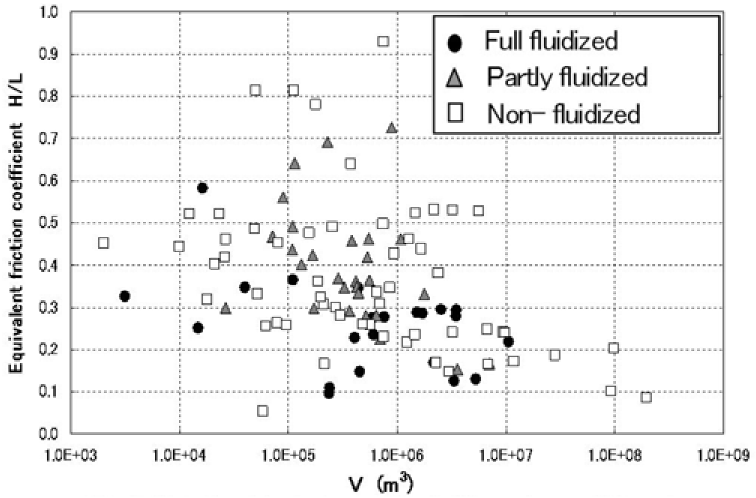

Fig. 9. Relationship between landslide volume (V) and the equivalentfrictioncoefficient(H/L)

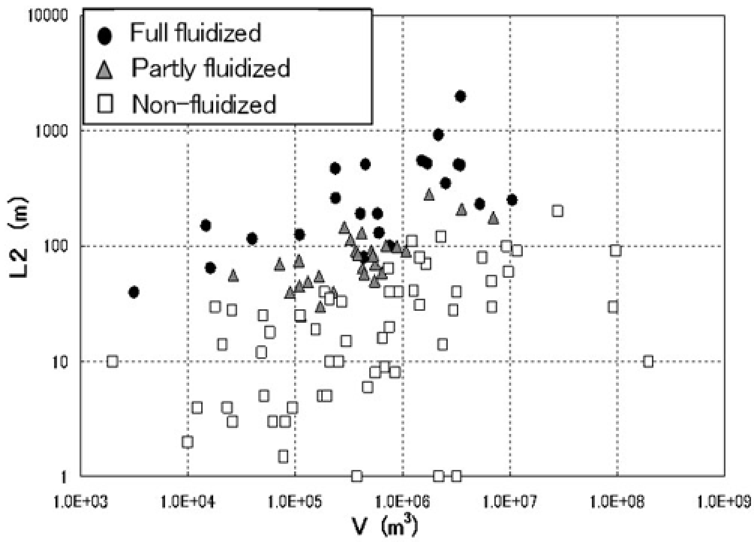

Fig. 10. Relationship between landslide volume (V) and travel distance(L2).

fluidized), showing a rather clear distinction. In general, soils containing silt and clay fractions with high liquid limit and plasticity index values are classified as high-plasticity clay in soil classification. These soils correspond to the soils of the partly fluidized landslide type. Meanwhile, the soils corresponding to the fully fluidized type have a smaller volume of silt and clay fractions and a relatively large volume of sand and gravel compared with the soils of the partly fluidized type. Although the water supply conditions and moisture conditions in the ground may have a significant effect on the fluidity of soil masses, the difference in liquid state, namely, the difference in the content of the sandy fraction, also has an effect on the fluidity and it is reflected in the traveling coefficient.

Landslides of the fully fluidized type contain a large amount of silt and clay fractions in the sliding soil mass, but they also contain a larger amount of sand and gravel than high-plasticity clay. Therefore, it is possible that the traveling length of the soil mass is further lengthened under the influence of this sand and gravel, in addition to the influence of the liquefied silt and clay fractions.

4.3. Long-traveling Landslides Triggered by the Niigata-ken Chuetsu Earthquake

When the Niigata-ken Chuetsu Earthquake occurred in October 2004, a number of collapses and landslides were triggered along the Imo River, which is a major landslide-prone area in Japan. In the Higashi-

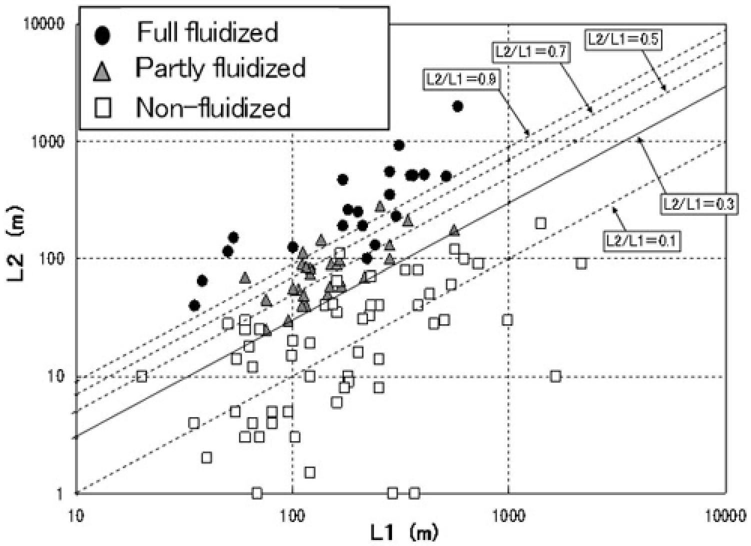

Fig. 11. Relationship between the length of landslide (L1) and travel distance (L2).

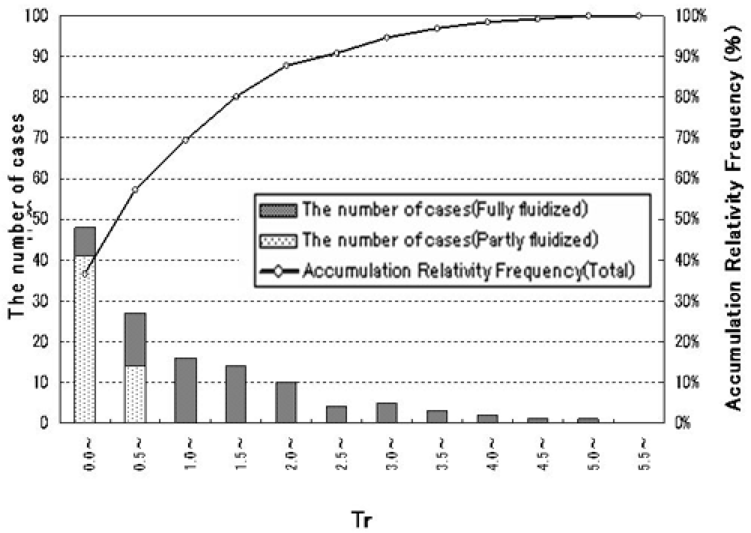

Fig. 12. Histogram of the traveling ratio

Takezawa area, a large-scale landslide dam was formed by the sliding soil mass that clogged the main stream of the Imo River, and the possibility of a secondary disaster by the breaching of this dam was imminent. Although landslide dams as serious as this were not formed, a number of landslides occurred along the Imo River. The largest of them that occurred near the Higashi-Takezawa area had a traveling length of 630 m.

[1] Traveling coefficient

Of the landslides occurring along the Imo River, 34 were selected through the reading of aerial photographs. Then, a histogram of their traveling coefficients was prepared, and the traveling coefficients were grouped by movement type. The results are shown in Figures 14 and 15. Of these landslides, landslides with a traveling coefficient of $\mathbf{Tr} \geq \mathbf{1.0}$ accounted for about 20%. The average traveling length and the maximum traveling length were 86 m and about 630 m, respectively. In particular, the traveling coefficient of the landslide that occurred near the Higashi-Takezawa area was $\mathbf{Tr = 2.8}$ and its traveling length was 630 m, far exceeding the values of other landslides along the Imo River.

[2] Conditions of long-traveling landslides occurring near the Higashi-Takezawa area

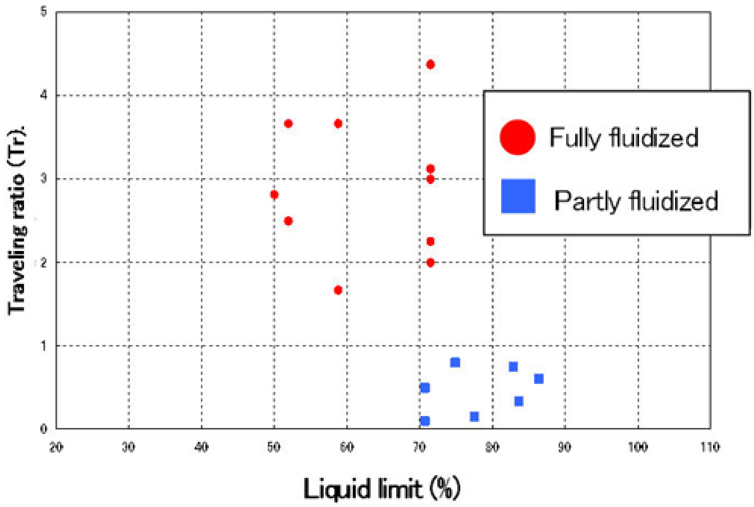

Fig. 13. Relationship between traveling ratio

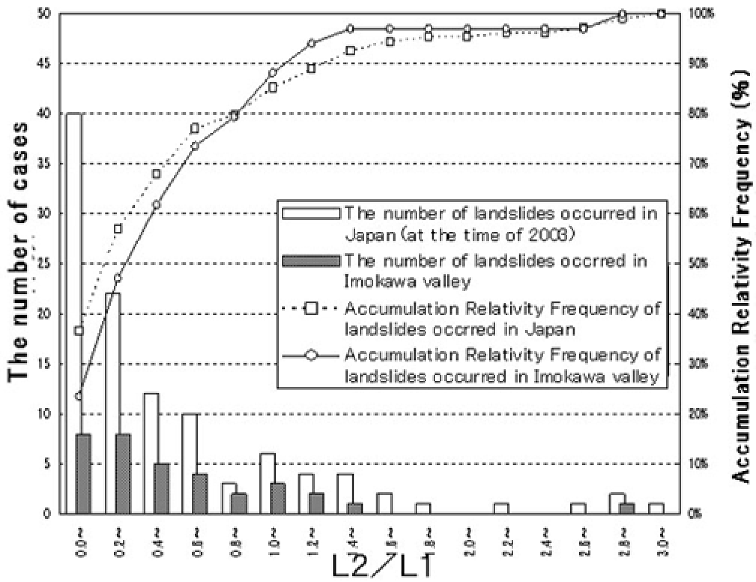

Fig. 14. Histogram of the traveling coefficient. (Landslides generated by Chuetsu earthquake)

The conditions of the moving soil mass of this landslide are shown in Photograph 1. The landslide was about 220 m long, 100 m wide, and the gradient of the landslide site was about 15°. The gradient between the landslide end and the stop position of the moved soil mass was about 6°. The sliding soil mass was the fully fluidized type (the internal structure was completely ruptured), and its movement stopped after flowing down about 630 m in the area with an elevation difference of 60 m. The maximum flow width was about 50 m. The flow depth was probably 5–10 m from the interpretation of aerial photographs.

[3] Results of soil tests

According to the results of soil tests conducted on the landslide that formed a landslide dam in the Higashi-Takezawa area (source: Erosion and Sediment Control Division, Research Center for Disaster Risk Management, National Institute for Land and Infrastructure Management), the soil was mostly sandy, with the sand fraction (0.075–2 mm) accounting for about 90%, which was found from grain size analysis. A consistency test was impossible because most of the samples were sand. The bedrock around the landslide locations along the Imo River consists of sandy siltstone and alternating beds of medium-grained and fine-grained sandstone. Therefore, although geological tests were not conducted on the long-traveling landslide

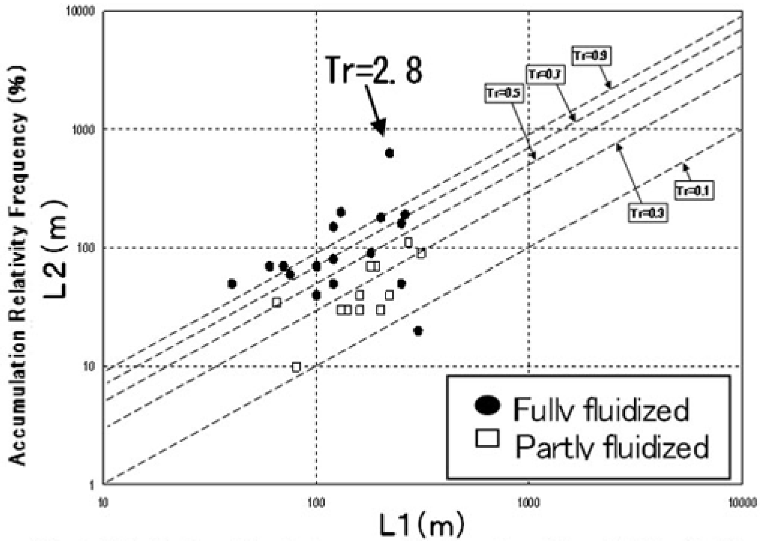

Fig. 15. Relationship between the length of landslide (L1) and travel distance (L2). (Landslides generated by Chuetsu earthquake)

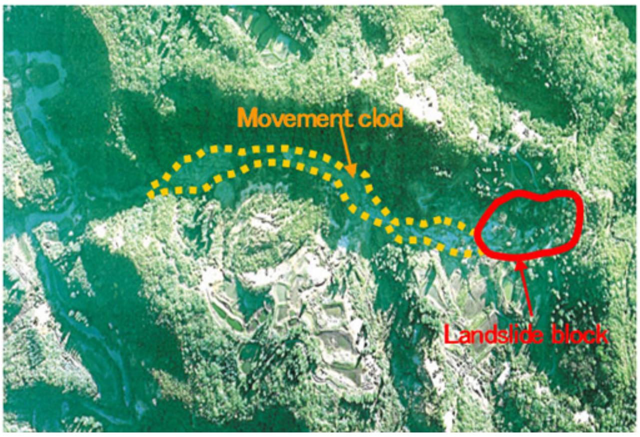

Photo. 1. Long traveling landslide generated in Higashi-Takezawa Niigata prefecture.

(**Tr = 2.8**) that occurred near the Higashi-Takezawa area, it is considered that the sliding soil mass of this landslide also consists of sandy materials. Furthermore, as rainfall of 96 mm was recorded at the Mitsuke gauging station on Oct. 20 and 21 before the occurrence of the earthquake, the ground probably contained much moisture. Consequently, it can be concluded that the landslide became the fully fluidized type with a large traveling coefficient, due to a combination of geological characteristics in this area, topographical conditions under which the landslide initiating point was the upper part of a valley, and the moisture conditions of the ground aggravated by the accumulation of rainfall in the days before the earthquake.

5. Problems to be addressed in the future

There is a relationship between the conditions of sliding soil mass (movement type) and the traveling coefficient. Long-traveling landslides are considered to take fully fluidized type movement in which the internal structure of the soil mass is completely ruptured after its movement starts. As factors that enlarge the traveling coefficient, namely, the factor causing the rupture of the internal structure that governs the fluidity, the following can be pointed out.

[1] Characteristics in terms of soil mechanics

[2] Distribution of moisture in the sliding soil mass

Concerning [1], the consistency of the soil affects the fluidity of a sliding soil mass. Concerning [2], water supply conditions, such as the presence of groundwater, have a considerable effect. In Figure 10, which describes the relationship between the soil amount and the traveling length of fully fluidized-type landslides, it is seen that the traveling length becomes longer as the amount of sliding soil increases, although this tendency is not very evident. If the amount of soil is large, a large amount of water is retained within the soil mass. Then, a highly saturated zone is formed along the sliding plane, and the degree of saturation at the end of the landslide is increased. The synergistic effect due to changes in the consistency, etc. is also produced with the rise in saturation level. As a result, it is presumed that once sliding action is triggered, the unstable sliding soil mass is ruptured, fluidized at a stroke, and then moves down over a long distance. In the future, it is necessary to further investigate the relationship between the causes of long-traveling landslides and their movement types, by incorporating more detailed information on topographical and geological conditions.

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REFERENCES

Survey Report on Landslide-related Warning and Evacuation (1989), SABO Technical Center (In Japanese)

Actual State of Sediment Disasters: 1983–1998 (1998), SABO Technical Center (In Japanese)

Statistics on the State on Landslides (Part 2) (1975), Reference No. 1121, Public Works Research Institute, Ministry of Construction (In Japanese)

Oyagi et al. (1991), a draft presented at the Committee on Topographic and Geologic Terminology, Japan Landslide Society (In Japanese)

Sassa, K. (2000) *Mechanism behind the Development of Fluidized Type Collapses*, Proc. of Symposium at the Kansai Chapter, Japan Landslide Society with the theme of "Occurrence, Movement, and Prediction of Fluidized Type Collapses", p.1–26 (In Japanese)

Hsu, K. J., (1975), Catastrophic debris streams generated by rockfall. *Geol. Soc. Amer. Bull.*, 86, 129–140

Hsu, K.J., (1978), Albert Heim: Observation on landslides and relevance to modern interpretation. *In* Voight, B., ed., *Rockslides and Avalanches*, Elsevier, 71–93

Scheidegger, A. E., (1973), On the prediction of the reach and velocity of catastrophic lamdslides. *Rock Mech.*, 5, 231–236

Japan Society of Erosion Control Engineering (supervised) (1992), Lecture on Erosion Control Engineering, Vol. 7/1 — Sediment-related Disaster Prevention Measures — Collapses, Landslides, Rockfalls, and Blown Sand Prevention Measures (1), Sankaido Publishing Co., p. 122–198 (In Japanese)

Japan Society of Erosion Control Engineering (supervised) (1992), Lecture on Erosion Control Engineering, Vol. 3 — Sediment Movements on Slopes, Sankaido Publishing Co., p. 302–310 (In Japanese)

The Japanese Society of Soil Mechanics and Foundation Engineering (edited) (1985), Soil Engineering Library 27 — Prediction and Countermeasures of Sediment-related Disasters, p. 27–64 (In Japanese)

Takei, A. (supervised) (1980), Landslides, Collapses, and Debris Flows — Prediction and Countermeasures, Kajima Institute Publishing Company, p. 192–226 (In Japanese)

Fujita, T. (2002), Landslides and Geology, Kokon Publishing Co., p.78–95 (In Japanese)

Slope Preservation Division, Erosion and Sediment Control Department, River Bureau, Ministry of Construction (supervised) (1995), Landslides in Japan, Published by Sabo Publicity Center, p.7 (In Japanese)

Niigata Prefecture (1989), Guidebook on Geology in Niigata Prefecture, p. 92–93 (In Japanese)

Landslide Countermeasures Association (2003), Round-table Talk on Landslides in Hokkaido (Part 2), Journal of Landslide Engineering, Vol. 29, No. 3 (87th issue), p.34–47 (In Japanese)

Moriwaki, H. (1987) *Prediction of Traveling Length of Collapsed Soils*, Journal of Landslides, Vol. 24, No. 2, p.10–16 (In Japanese)

Kusumoto, T., Fujimoto, M., and Nakamura, S (2003) *Study on the Prediction Method of Traveling Length of Landslides by Case Analyses*, Proc. of the 42nd Symposium of the Japan Landslide Society — Landslide in 2003, p. 105–108 (In Japanese)

Morishita, J., Oyamauchi, N., Ishii, Y., and Nakano, K. (2003) *Study on the Topographical Conditions of Landslides with Large Displacements*, Proc. of the 42th Symposium of the Japan Landslide Society — Landslide in 2003, p. 331–334 (In Japanese)