



Shapes and Mechanisms of Large-Scale Landslides in Japan: Forecasting Analysis from an Inventory (WCoE 2014–2017)

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Abstract

Large-scale landslides with widths and lengths of 1 km or more have been reported in many parts of the world. Occurrences of large-scale landslides have recently tended to increase due to climate change and frequent seismic activity. To conduct research on proper measures for large-scale landslides, elucidation of the occurrence mechanism, for which there are as yet many unclear points, will be required in future. The Japan Landslide Society established a research committee that worked from 2011 to 2014 to elucidate the occurrence mechanisms of large-scale landslides. Analysis of examples of large-scale landslides collected from members of the research committee showed that a volume of moving body larger than $1 \times 10^6 \text{ m}^3$ and a maximum landslide thickness of more than 30 m are appropriate as the definition of a large-scale landslide. The shape of a large-scale landslide depends on the geology and age of the landslide site, and landslide activity and history affect the symmetry of the shape of a landslide. This paper presents some results of the WCOE (2014–2017) project titled “Emergency response support system for large-scale landslide disasters” by the Japan Landslide Society.

Keywords

Large-scale landslide • Kinematic structure • Landslide topography

Introduction

Many large-scale landslides, which have brought disaster to lives and properties, have occurred in Japan.

The Jizukiyama landslide (Fig. 1), which occurred in Nagano City in 1985, for example, was 350 m wide and 280 m long, with a maximum thickness of 60 m and a volume of $2.5 \times 10^6 \text{ m}^3$. The landslide buried facilities for

the disabled and housing-development apartments, and 26 lives were lost (National Research Institute for Earth Science and Disaster Prevention (NIED) 1986; Shinshu University Research Committee 1986). The Dozan river landslide, which occurred in Yamagata-prefecture in 1996, was 1100 m wide and 1200 m long. Its maximum thickness was 180 m, the volume was $1.0 \times 10^8 \text{ m}^3$, and the event caused damage to national roads and the Dozan River.

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The Sumikawa landslide, which occurred in Akita Prefecture in 1997, was 350 m wide and 650 m long, with a maximum thickness of 70 m. Some of the moving body, with a volume of $6.0 \times 10^6 \text{ m}^3$ (Furuya and Enokida 2004), partially moved down the river, damaging hot-spring facilities and national roads (Oyagi and Ikeda 1988).

Landslides have occurred at Akadani and Nagadono in the Kii Peninsula in 2011. The volume of the moving body at Akadani is estimated as $9.4 \times 10^6 \text{ m}^3$ (Sakurai 2013); that of Nagadono is $5.0\text{--}6.0 \times 10^6 \text{ m}^3$ (Sakurai et al. 2013).

In consideration of the occurrence of large-scale landslides such as those mentioned above, the Japan Landslide Society established the “Research Committee on Elucidating Mechanisms of Large-Scale Landslides” (hereinafter referred to as the Committee) in 2011 to contribute to the prediction of landslide occurrence, the planning of measures, and the development of analysis techniques, with a focus on large-scale landslides.

In the Committee, the main areas of research were the definition of large-scale landslides, characteristics of topography and geology, time-series kinetic structure, effect of groundwater at great depth, shear strength, and stability analysis techniques. A questionnaire was provided to each member to collect examples of large-scale landslides. The

instances include ones in which several landslide blocks are aligned (Furuya 2003). Here, 30 instances for which the landslide mechanism has been elucidated are collected to consider the characteristics of landslide kinetic structure and the shapes of landslide sites. For the kinetic structure, the “distribution pattern of displacement, velocity, and acceleration vectors of landslide moving body” defined by Oyagi (2004) is used.

Questionnaire Results

A total of 30 instances of landslides were collected using the questionnaire: 16 in rocks of Cenozoic age; the other 14 in rocks of Mesozoic and Paleozoic age. The landslides were assigned to groups to summarize the scale and the gradient of landslide sites in the occurrence areas (Fig. 2 and Table 1). Figure 2 shows landslide positions. In Table 1, the maximum landslide width (h), length (L), relative height (rh), gradient of landslide slope (θ), maximum thickness (t), volume (v), and gradient of sliding surface (α) are listed.

Figure 3 shows the dimension of landslides obtained from the questionnaire.

Fig. 1 Full view of the Jizukiyama landslide site (Shinshu University Research Committee 1986)



The maximum landslide width ranges from 190 to 2000 m. For landslides with a maximum width of 1000 m or longer, four instances in Cenozoic strata and one in Mesozoic and Paleozoic rocks are reported (Fig. 3a).

Landslide length ranges from 200 to 2100 m. There are nine instances in Cenozoic rocks and four instances in Mesozoic and Paleozoic strata of landslides that are 1000 m or more in length (Fig. 3b).

The relative height from the top of a main cliff to the bottom is between 45 and 500 m. For landslides with relative height of less than 100 m, four instances in Cenozoic rocks and one example in Mesozoic and Paleozoic rocks are reported. In contrast, for landslides with a relative height of 300 m or more, there is one instance in Cenozoic rocks and five in Mesozoic and Paleozoic rocks (Fig. 3c).

The gradient of landslide slope is 6–40°. There are seven examples in Cenozoic rocks and one example in Mesozoic and Paleozoic rocks of landslides with a slope smaller than

10°; in contrast, for slopes 20° or more, there are three reported instances in Cenozoic rocks and nine in Mesozoic and Paleozoic strata. The examples in Mesozoic and Paleozoic rocks display larger gradients (Fig. 3d).

The maximum landslide thickness is 30–180 m. For landslides with a maximum thickness of 100 m or more, there are six instances in Cenozoic strata and three in Mesozoic and Paleozoic strata; thus, there are slightly more occurrences in Cenozoic rocks than in older strata (Fig. 3e).

The volume of the moving body is a minimum of $7.0 \times 10^5 \text{ m}^3$ and a maximum of $1.0 \times 10^8 \text{ m}^3$. All 16 instances in Cenozoic rocks and 13 of 14 examples in Mesozoic and Paleozoic rocks have a volume of $1.0 \times 10^6 \text{ m}^3$ or more (Fig. 3f).

The gradient of the sliding surface is the slope immediately under the center of gravity of the landslide section; this parameter varies from 2° to 31°. There are seven examples in Cenozoic rocks and one example in Mesozoic and Paleozoic

Fig. 2 Instances of landslides obtained by using the questionnaire

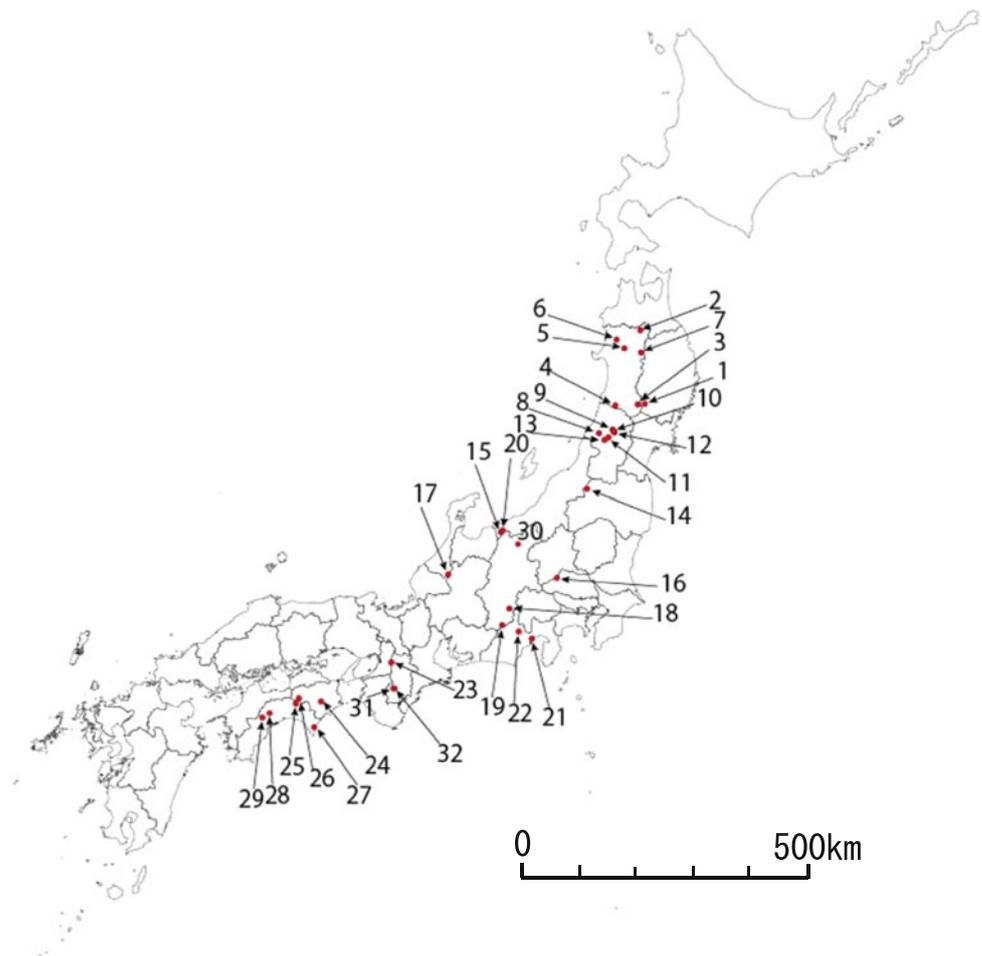


Table 1 Landslide scale based on the questionnaire results

Geological age	No.	Generating area						
		h (m)	L (m)	rh (m)	θ (°)	t (m)	v (m ³)	α (°)
Cenozoic era	1.	250	450	130	14.0	80	9.0E + 06	7.5
	2.	240	200	90	28.0	45	1.0E + 06	31.0
	3.	950	1200	200	6.5	55	1.0E + 07	11.0
	4.	1200	1000	250	15.0	165	6.0E + 07	15.0
	5.	800	1100	230	12.0	90	1.5E + 07	
	6.	280	250	45	25.0	45	1.5E + 06	
	7.	350	650	120	1.5	70	6.0E + 06	11.5
	8.	840	1140	150	8.0	122	4.9E + 07	4.5
	9.	470	750	100	13.0	100	1.0E + 07	
	10.	500	1000	50	6.0	45	1.3E + 07	4.0
	11.	500	750	70	6.5	40	1.0E + 07	5.5
	12.	2000	1500	350	10.5	150	8.0E + 07	14.0
	13.	1100	1200	190	8.0	180	1.0E + 08	2.0
	14.	1300	2100	150	8.5	140	4.8E + 07	3.5
	15.	250	1500	250	9.0	60	1.0E + 07	4.0
30.	350	280	100	22.0	60	2.5E + 06	10.0	
Mesozoic–Paleozoic era	16.	600	450	190	23.0	50	8.0E + 06	17.5
	17.	400	1200	500	21.0	130	2.1E + 07	14.0
	18.	270	300	90	12.5	30	1.0E + 06	11.0
	19.	350	450	170	20.0	48	5.4E + 06	11.0
	20.	200	500	130	12.5	60	6.0E + 06	12.0
	21.	350	400	200	28.0	65	3.6E + 06	24.5
	22.	400	900	260	23.0	60	2.0E + 07	15.0
	23.	400	650	100	4.0	70	9.0E + 06	12.5
	24.	190	390	180	40.0	30	7.0E + 05	18.0
	25.	700	900	440	26.5	65	1.7E + 07	25.0
	26.	400	350	100	16.5	35	2.0E + 06	12.0
	27.	640	1290	460	20.0	100	7.0E + 06	
	28.	1000	1050	450	20.0	160	1.0E + 08	13.0
	29.	400	1150	360	13.0	58	1.2E + 07	8.0

Blank fields for slide surface slope indicate places for which longitudinal section views were unavailable

rocks of landslides with a slope smaller than 10°; in contrast, for slopes 20° or more, there is one reported instance in Cenozoic rocks and two in Mesozoic and Paleozoic strata (Fig. 3g).

Discussion

Topography, Geology, and Scale

From the results of the questionnaire, in 29 of the 30 examples of landslides, the volume of the moving body is

1.0×10^6 m³ or more. Similarly, for maximum landslide thickness, all instances had a thickness of 30 m or more (Table 1). A volume of 1.0×10^6 m³ or larger was also treated as a large-scale landslide by Fujita (2004). These values, therefore, were regarded as a criterion for the definition of large-scale landslides by the Committee.

Shape of Landslide

From plane views of longitudinal and cross sections collected in the questionnaire, the shapes of landslide bodies in

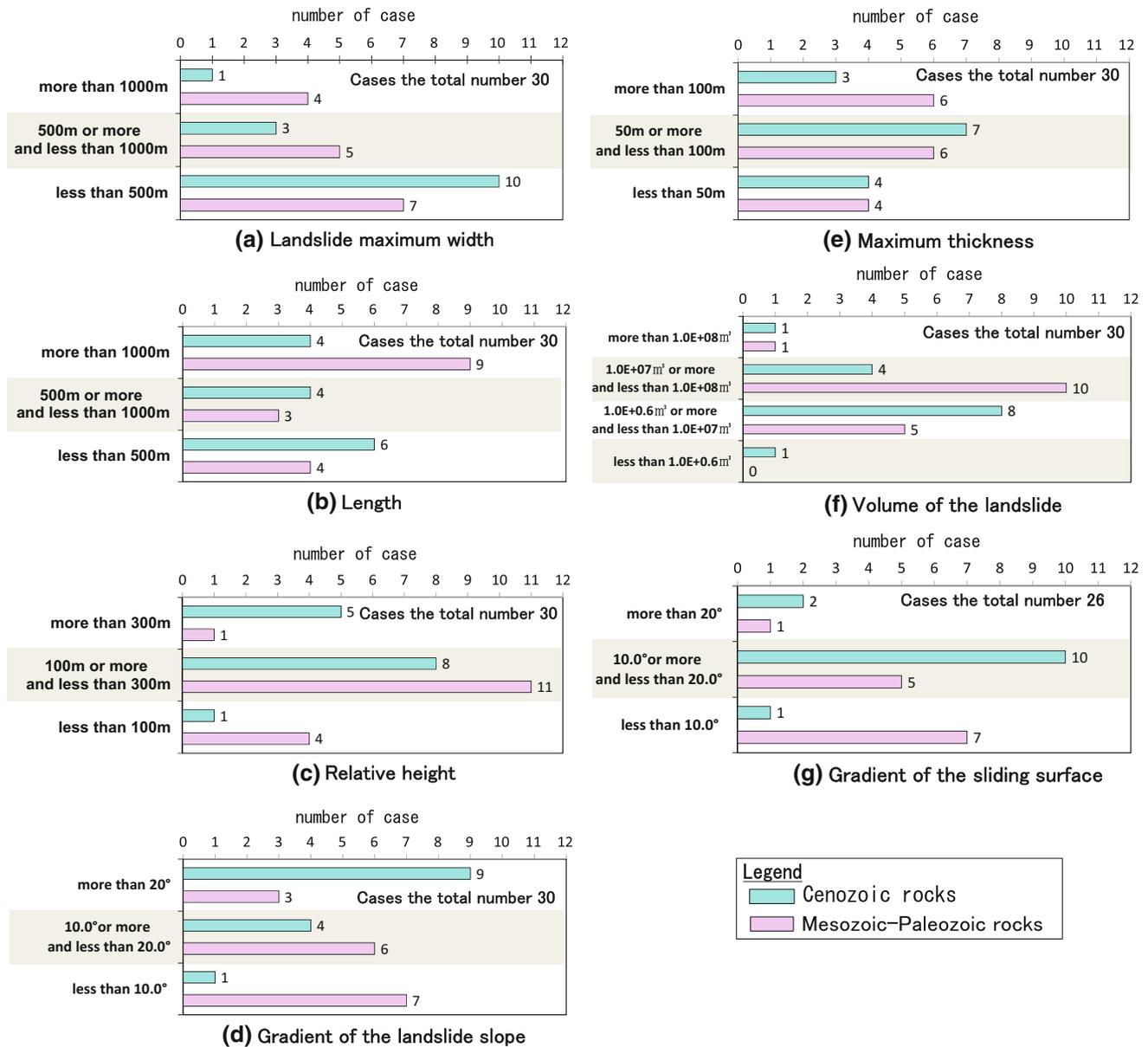


Fig. 3 Landslide dimensions from the questionnaire results

terms of geology were divided into symmetric and asymmetric (Fig. 4).

For plane shapes, a straight landslide direction was considered as symmetric and a bent landslide direction as asymmetric. For longitudinal-section shapes, cases in which the gradient of landslide slope and that of the sliding surface are equal on average were considered to be symmetric; those in which the thickness of the moving body at the top of landslide is different from that at the bottom and in which the dip of sliding surface at the toe part is opposite to that of the landslide

slope were regarded as asymmetric. For cross-sectional shapes, a ship-bottom shape and an isosceles-triangle shape were regarded as symmetric, and cases in which the landslide thickness slants to one side were deemed asymmetric. Landslides for which the shape was unclear were indicated by a question mark. When information became available, the section shape was added near the question mark.

For landslides in Cenozoic rocks, 11 of the 12 instances for which information is available are identified as asymmetric. Of these, 7 examples are asymmetric in planar view,

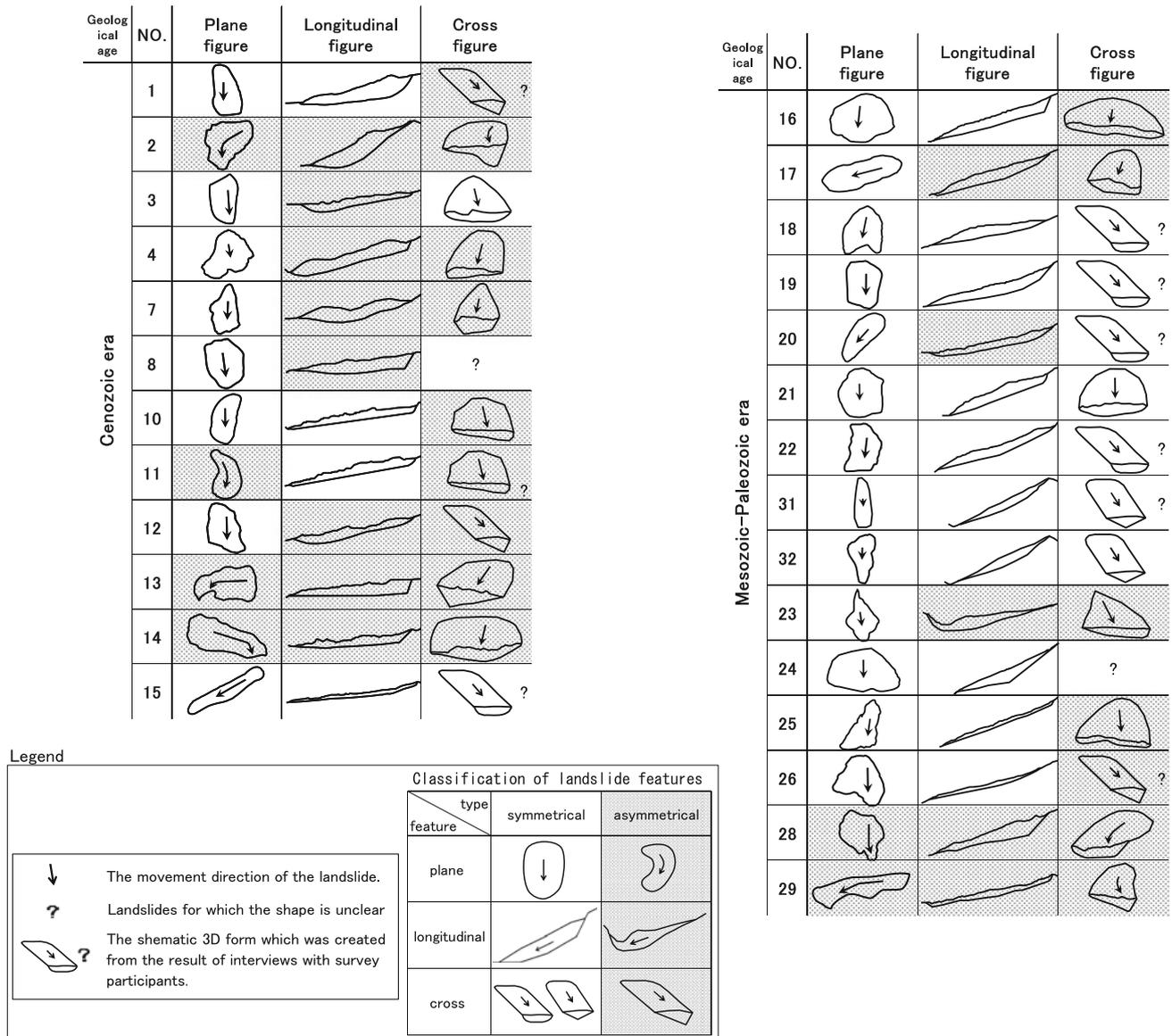


Fig. 4 Classification of landslide shape

in longitudinal section, and/or in cross-section. On the other hand, for landslides in Mesozoic and Paleozoic strata, 8 of the 15 examples are classified as asymmetric. Of these, 4 examples are asymmetric in shape, fewer than the number in Cenozoic strata.

Instances No. 7 in Cenozoic rocks and Nos. 31 and 32 in Mesozoic and Paleozoic rocks in Fig. 3 are landslides in which part or all of the landslide moving body slid downward. No. 7 is asymmetric in the longitudinal section and cross-section; Nos. 31 and 32 are symmetric in all views. Although the gradient of sliding surface of No. 2 is 31°, a steep slope, and the displacement over the last two years has

been 1 m, this example does not slide downward. It is suggested that a landslide with many asymmetric elements tends not to slide down easily and shows higher resistance, compared to landslides in which the planar, longitudinal section, and cross-sectional shapes are symmetric.

For example, Fig. 5 is a bird's-eye view from the northeast of the Tozawa landslide in Akita Prefecture (No.4 landslide in Table 1). It occurs in Cenozoic strata; is 1.2 km wide and 1.0 km long; has a maximum thickness of 165 m; and the gradient of its sliding surface is 15° (Table 1). This landslide is symmetrical in plan view and asymmetrical in longitudinal section and cross-section (Figs. 6 and 7).



Fig. 5 Full view of the Tozawa landslide site

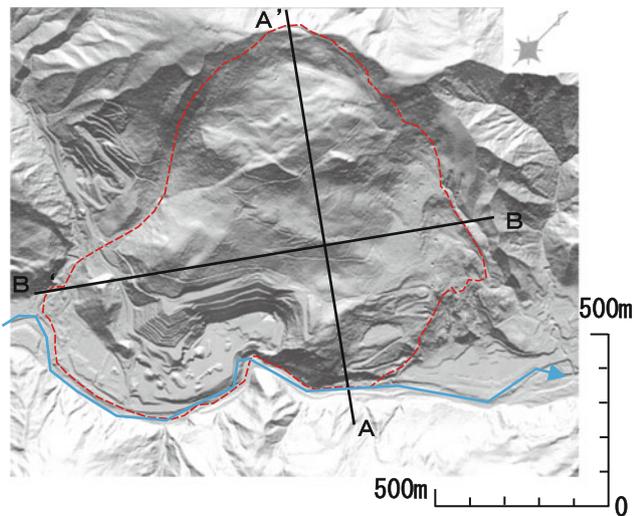


Fig. 6 Plan view of the Tozawa landslide site

For the movement state of the Tozawa landslide, the height of the sliding cliff is approximately 20 m, and the observed landslide movement was 0.4 m/year for 2002–2003. The river at the bottom of the landslide is now raised, but no downward sliding movement has occurred.

As an example of a landslide in Mesozoic and Paleozoic rock, Fig. 8 shows a view of landslide No. 25 in Table 1. The landslide is 700 m wide and 900 m long, and has a maximum thickness of 65 m and a slide surface of 25° in gradient. This landslide is symmetric in plan view and longitudinal section, but asymmetric in cross-section (Fig. 9). For the landslide, the difference in height of the sliding cliff is approximately 5 m, the observed landslide movement rate is 3 cm/year for 2007–2009, and the landslide is currently not sliding.

Fig. 7 Cross section of the Tozawa landslide site

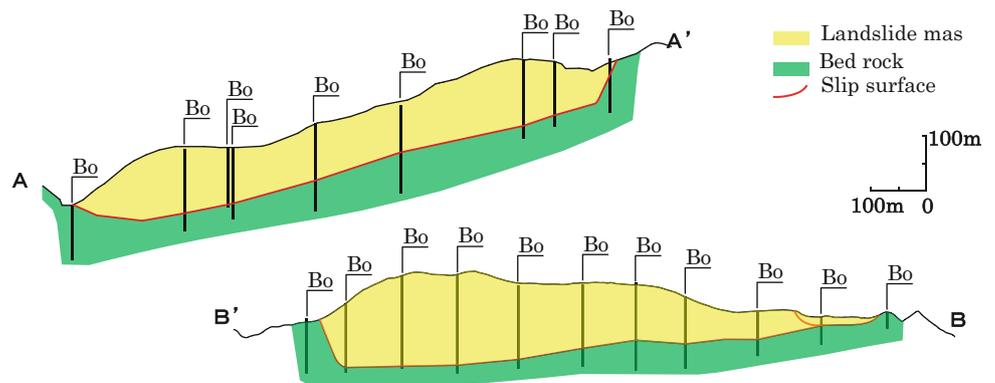


Fig. 8 Overall view of landslide No. 25

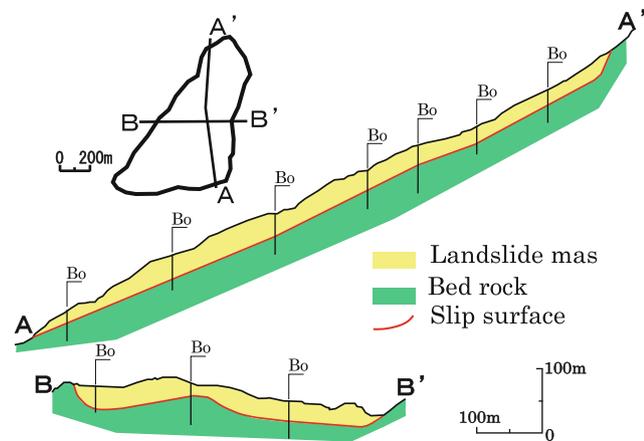
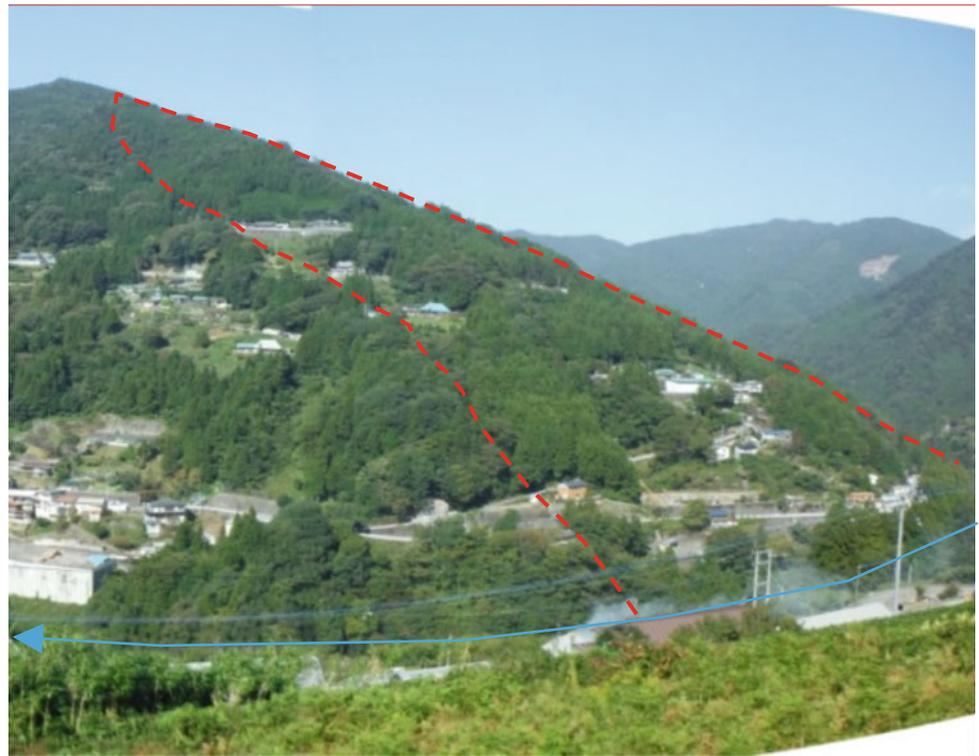


Fig. 9 Cross-section view of landslide No. 25

Landslide Kinematic Structure

Time-Series Displacement of Landslide

For some landslides, after small displacement has occurred for a certain time, the displacement velocity increases, leading to downward sliding; for others, the displacement velocity tends to increase and decrease, not leading to further sliding downward. Taking this information into consideration, landslide movement can be divided in a time-series

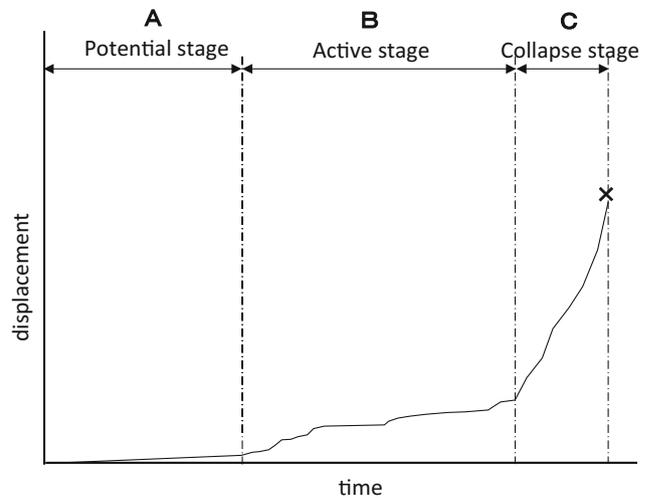


Fig. 10 Three stages of landslide displacement

manner into: period A, in which small landslide displacement that can be observed with creep by monitoring equipment occurs; period B, in which displacement that appears differently on the ground and within the structure takes place; and period C, in which the displacement velocity increases and part or all of the moving body slides down and collapses. Herein, period A is called the potential

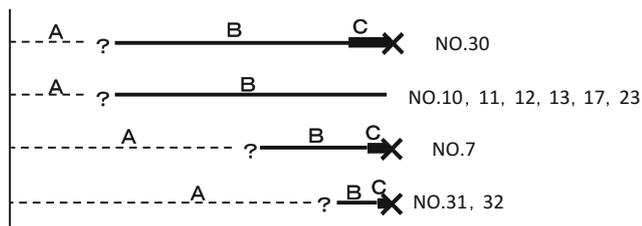


Fig. 11 Time-historical changes in the displacement stage of each landslide (A, B, C is shown in Fig. 10 No.7–32 is shown in Fig. 1)

stage of a large-scale landslide, period B is called the active stage, and period C is called the collapse stage (Fig. 10).

Examples of Landslide Movement History

As shown in Fig. 10, when the kinematic structure of a landslide is expressed as periods A, B, and C, in the case of landslide No. 30 in Table 1, after a period B lasting several years period C commenced, and part of the moving body slid down and flowed. For landslides Nos. 10, 11, 12, 13, 17, and 23 in Table 1, displacement increases during snow-melt and heavy rain; however, as these landslides have not collapsed at present, they are in period B. For the example of landslide No. 7 in Table 1, which occurred in a volcanic region, a period B of several years was confirmed (Oyagi and Ikeda 1988). After a period C lasting nine days, part of the moving body collapsed and moved for 1.5 km as a debris avalanche (Ogawauchi et al. 1988). Landslides Nos. 31 and 32 in Fig. 1 exhibited a period A, in which double ridges and a sliding cliff were formed, and a short period B; subsequently, sliding down and flowing out occurred (Sakurai 2013; Sakurai et al. 2013) (Fig. 11).

Summary

The results of the Committee's research can be summarized as follows.

- In the questionnaire to members of the Committee, which consists of technical and research experts, details of large-scale landslides in which the volume of the moving body was $1.0 \times 10^6 \text{ m}^3$ or larger were obtained for 29 instances, excluding one. A large-scale landslide, therefore, is defined herein as one in which the volume of the moving body is $1.0 \times 10^6 \text{ m}^3$ or larger and the maximum landslide thickness is 30 m or larger.
- There is a trend for the relative height, gradient of landslide slope, and that of sliding surface of large-scale

landslides to be smaller in Cenozoic strata than in Mesozoic and Paleozoic rocks.

- One of the factors controlling why some large-scale landslides do not slide down but displacement continues is asymmetry of shape (in any or all of plan view, longitudinal section, and cross-section) of the landslide moving body. This trend is particularly strong in landslides in Cenozoic rock. On the other hand, one of the factors causing Mesozoic and Paleozoic rock to sliding down relatively easily is that these landslides have a relatively symmetric shape.

Further analysis incorporating additional examples is required; there is a possibility that the characteristics of large-scale landslides deduced herein are also common in areas outside of Japan that have similar geology, topography, and evolution of geological structure. For large-scale landslides in which the scale of measures is apt to be large, monitoring of landslides and emergency measures suited to the characteristics of the ground of occurrence sites must be taken. It is necessary, therefore, for landslide experts to share detailed information on large-scale landslides.

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