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# Classification of the Geomorphology, Geology and Movement Types of Earthquake Landslides

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## Abstract

Various types of landslides have been induced by the past earthquakes in Japan and outside of the country. This study aims to classify the geomorphology, geology, and types of movement at the sites of earthquake landslides including those of the 2011 Tohoku Earthquake. Earthquake landslides show common movement types with similar geological properties. They are (1) translational slides in ridges and cuestas with Tertiary–Quaternary well-bedded sedimentary rocks, (2) flows in areas with unconsolidated Quaternary volcanic sediments, (3) shallow rotational slides at ridges in areas of volcanic rocks, and (4) rock failures and toppling in areas of granite, accompanied by the flow of weathered granite. Many of the earthquake landslides occur within a 30 km distance of the epicenter for earthquakes up to magnitude 7. A magnitude of 8 and above can often induce rock slides at locations over 100 km away. Flow of unconsolidated volcanic sediment and rock failures of consolidated bedrock occurred at locations 200–300 km away. These indicate that magnitude 8 is the line of demarcation at which the relationship between the distance from the epicenter to landslide sites and the movement types changes significantly. The scale of the earthquake fault may be the cause of it. Many recent earthquake landslides have also been observed at residential embankments in Japan.

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## Keywords

Earthquake · Landslide · Epicenter · Geology · Geomorphology

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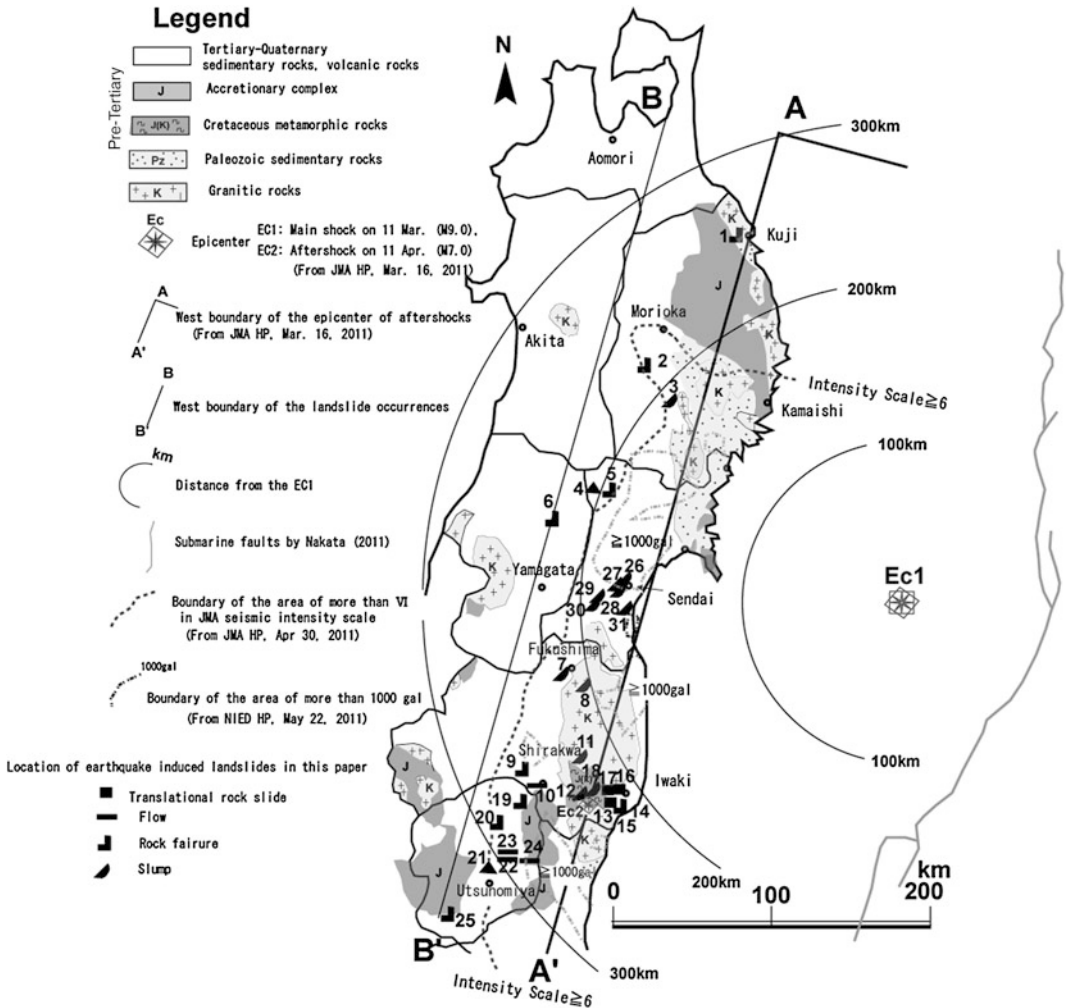
## 1 Introduction

Large-scale onshore earthquakes, inducing landslides of various types have occurred continuously, for the past 10 years in Japan. Abe and Hayashi (2011) previously reported on the relationship between the types of earthquake-induced landslides (henceforth, earthquake landslides) in Japan and the geomorphological

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**Fig. 5.1** Locations of the landslides by the 2011 off the Pacific Coast of Tohoku Earthquake and geological distribution

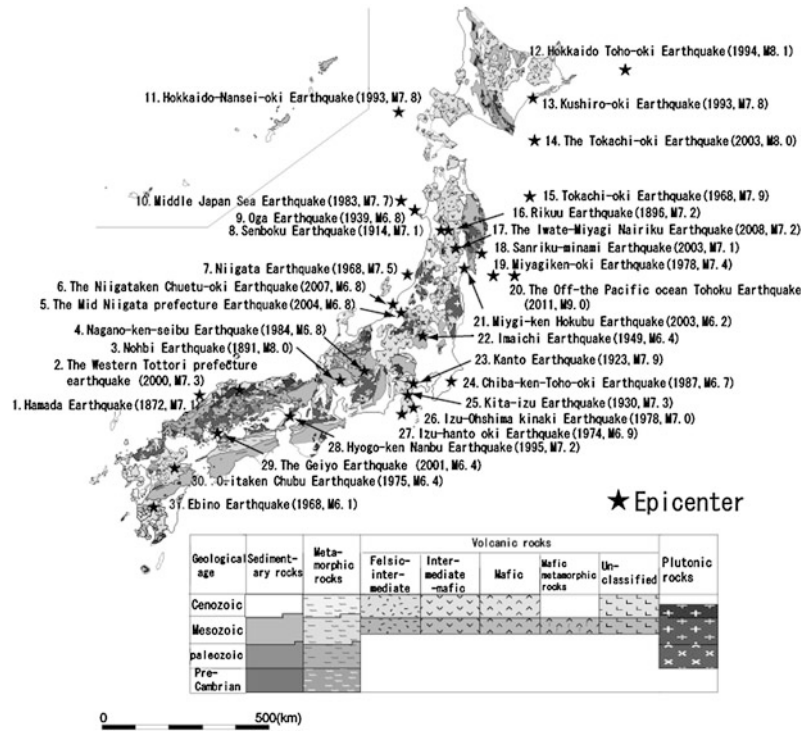
and geological properties of the landslide sites. Many earthquake landslides occurred across the Tohoku and northern Kanto regions following the 2011 large-scale Tohoku earthquake (*M*9.0) that occurred in the oceanic trench. This study analyzes the geomorphology, geology, and types of movement at the sites of earthquake landslides, including those triggered by the Tohoku earthquake.

The results of this study confirmed that earthquake landslides share common movements (with respect to the distance from the earthquake fault, i.e., epicenter) in areas with certain geomorphological and geological properties.

## 2 Overview of the Landslides that Occurred During the 2011 Tohoku Earthquake

Landslides that occurred during the 2011 Tohoku earthquake and its aftershocks were distributed along a belt extending from the Tohoku region to northern Kanto; many of which belong to the Tertiary and Quaternary geological system. The aftershock on April 11 (*M*7.0) was an onshore earthquake whose focus was located directly above the earthquake fault. This aftershock triggered landslides in the pre-Tertiary metamorphic rocks and Tertiary mudstone

**Fig. 5.2** Distributions of the epicenter of recent major earthquakes and geology in Japan



bedrocks. The area of landslide occurrence was approximately 600 km in length and 70 km inland from the western edge of the aftershock area. Tertiary pumice tuff bedrock failed, and a flow of Quaternary unconsolidated volcanic deposits occurred over 300 km inland from the epicenter. Slope movements also occurred in numerous hilly residential-area embankments in Sendai, Fukushima, and Iwaki. The intensity of the earthquake at these landslide sites was over 6 according to the Japanese Meteorological Agency (JMA) scale, and earthquake acceleration was in the range of 500–1,000 gal (Fig. 5.1).

from the 1872 Hamada earthquake up to the 2011 earthquake off the Pacific Coast of Tohoku (Abe and Hayashi 2011) (Fig. 5.2). Many of these recorded magnitudes of over 6. Of these, earthquakes with magnitudes over 8 included the 1994 Eastern Hokkaido Coastal earthquake (*M*8.1) and the 2011 Tohoku earthquake (*M*9.0). Many earthquake landslides occur at magnitudes above 5 on JMA scale (Usami 1996; Japan Meteorological Agency 2008) about half of these are on shore earthquakes.

On the basis of the work of Abe and Hayashi (2011), the geomorphological and geological characteristics and the movement types of earthquake landslides are summarized below.

### 3 Movement Types and Geomorphological and Geological Properties of Recent Earthquake Landslides in Japan

#### 3.1 Areas of Quaternary Unconsolidated Volcanic Deposits

Many large-scale earthquakes have been recorded historically in Japan. Thirty-one scientific articles have chronicled earthquake landslides—

In earthquake landslides caused by offshore earthquakes (e.g., the 1974 Izu Peninsula Coastal earthquake and the 1968 Tokachi-Oki earthquake) and onshore earthquakes (e.g., the 1949 Imaichi

earthquake and the 1984 Western Nagano earthquake), shallow disintegrative slides and flows of unconsolidated volcanic sediment (volcanic ash, pumice, scoria, etc.) have been known to occur (Okusa et al. 1978). In the Western Nagano earthquake, a large-scale landslide from Mt. Ontakesan evolved into a debris flow, reaching 12 km downstream (Inokuchi 1985). During the 2011 Tohoku earthquake, flow type landslides also occurred along hillsides and terrace cliffs of southern Fukushima Prefecture and northeastern Tochigi Prefecture.

### 3.2 Areas of Tertiary–Quaternary (Pleistocene) Sedimentary Rocks

Landslides during the 1914 Northern Akita Prefecture earthquake (Abe and Takahashi 1997) and the 2004 Chuetsu earthquake (Abe et al. 2006; Takahashi et al. 2005), and landslides on Okushiri Island during the 1993 Hokkaido Southwestern Offshore earthquake (Tanaka 1994), occurred as translational slides in well-bedded sedimentary rocks such as Tertiary mudstone and siltstone. These landslides include both primary and reactivated types (e.g., The Japan Landslide Society, 2007). During the 2008 Iwate and Miyagi inland earthquake, a large-scale translational slide moved ignimbrite cap rocks 350 m over alternate layers of sandstone, mudstone, and siltstone from Pleistocene volcanic caldera deposits (Moriya et al. 2010). These translational slides often occur in cuesta and mountain ridges, with a sandstone–mudstone–siltstone alternating layer as the sliding surface. Translational slides were observed to occur during the 2011 Tohoku earthquake in areas of Tertiary mudstone in places such as Iwaki, Fukushima and Matsushima, Miyagi.

### 3.3 Areas of Pre-tertiary Metamorphic and Sedimentary Rocks

Examples of earthquakes that induced landslides in areas of pre-Tertiary metamorphic and sedimentary rocks include the 1891 Nohbi earthquake, the 1994 Hokkaido Eastern Offshore Earthquake, and the 2011 Tohoku earthquake.

The Nohbi earthquake caused toppling along the earthquake fault over entire mountain slopes, with disintegrative slides occurring in many places from the head to the end of the slope (Tabata and Hara 1999). After the 1994 Hokkaido Eastern Offshore Earthquake, primary large-scale translational slides were reported to have occurred in the alternating layers of Cretaceous hard shale and fine-grained sandstone (Tajika 2009). During the April 11 aftershock of the 2011 Tohoku earthquake, slumps were confirmed in pre-Tertiary crystalline schists that were fractured near the earthquake fault.

### 3.4 Granite Belt

Earthquake landslides occurred in granite belts during the 1923 Kanto earthquake, the 2000 Western Tottori earthquake, and the 2001 Geiyo earthquake. Such cases were generally not found in relation to the 2011 Tohoku earthquake, except for a few small-scale shallow slides in the Abukuma Mountains. Many of the earthquake landslides in granite belts occurred due to disintegrative slides and flow of arenaceous granite.

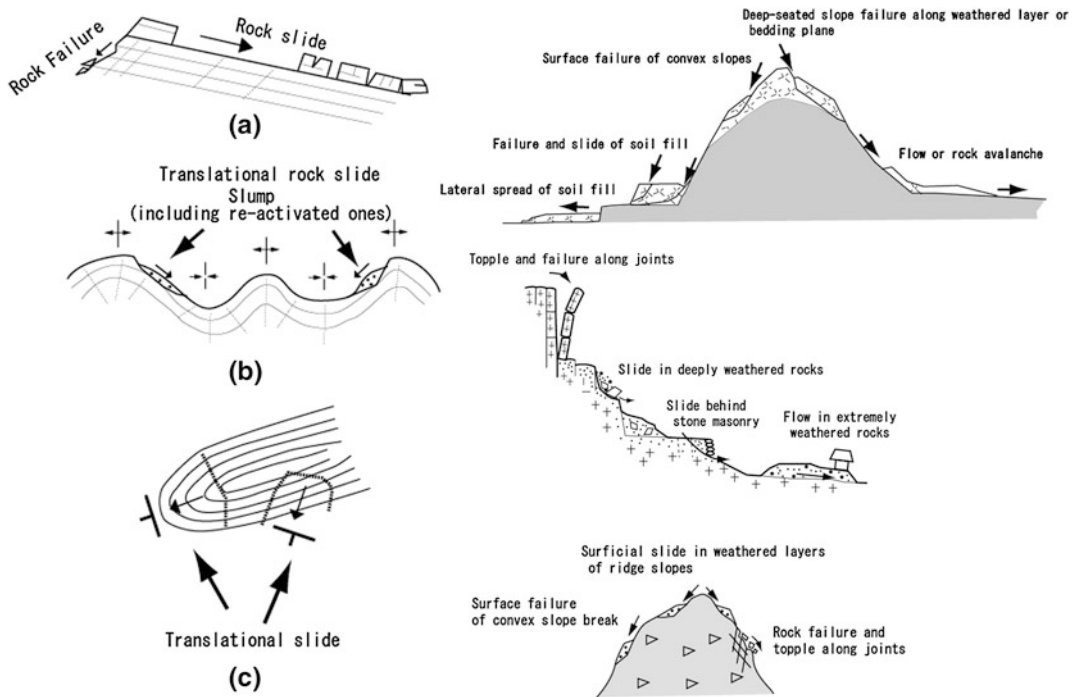
### 3.5 Distributional Area of Volcanic Rock Types

Shallow surface slides in the distributional area of Lower Miocene andesite and rhyolite during the 1896 Rikuu earthquake (Abe and Takahashi 1997) and toppling of molten basalt rocks during the 2000 Western Tottori earthquake (Yamashita 2002) are some of the reported cases in volcanic rock areas. Rock failures of pumice tuff also occurred in various parts of Fukushima Prefecture during the 2011 Tohoku earthquake.

### 3.6 Residential Embankments

Slope movement of residential embankments occurred at numerous sites. Both the 1978 Miyagiken-oki Earthquake and the 2011 Tohoku earthquake damaged such embankments in Sendai and Shiroishi in Miyagi Prefecture.

Figure 5.3 classifies the geomorphology, geology, and movement types of the landslides reported by Abe and Hayashi (2011) on the basis



**Fig. 5.3** Geology, movement type of earthquake landslides and their distance from the epicenter

of their similarities. The classification does not contradict the properties of landslides from the 2011 Tohoku earthquake.

#### 4 Distance from Epicenter, Geological Properties, and Movement Types of the Earthquake Landslides

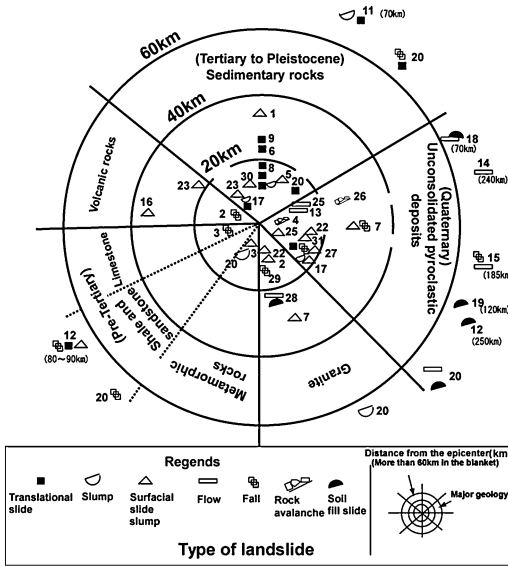
Landslides discussed in Sect. 5.3 typically occur within 30 km of the epicenter. However, flow often occurs over 100 km away from the epicenter in unconsolidated volcanic sediment. Landslides also occurred in embankments over 100 km away from the epicenter, thus extending the damage area. Figure 5.4 shows the relationship between the distance from the epicenter to the site of the landslide and the geology and movement types of the slides. In cases with earthquakes of magnitude 8 and larger, bedrock slides, rock failures and flows, and slope movement of embankments have occurred 200–300 km away from the epicenter. Examples include the 1994 Hokkaido Eastern

Shore earthquake, the 2003 Tokachi-Oki earthquake, and the 2011 Tohoku earthquake.

Figure 5.5 shows the same relationships as Fig. 5.4, but for earthquake landslides in regions outside Japan, on the basis of literature available from the 1971 San Fernando earthquake ( $M6.9$ ) (Abe 2012). As for the Japanese earthquakes, landslides were most likely to occur within a 30 km range from the epicenter, many slides were translational slides in well-bedded sedimentary rock, and flow of unconsolidated volcanic sediment was found at locations 150–250 km away.

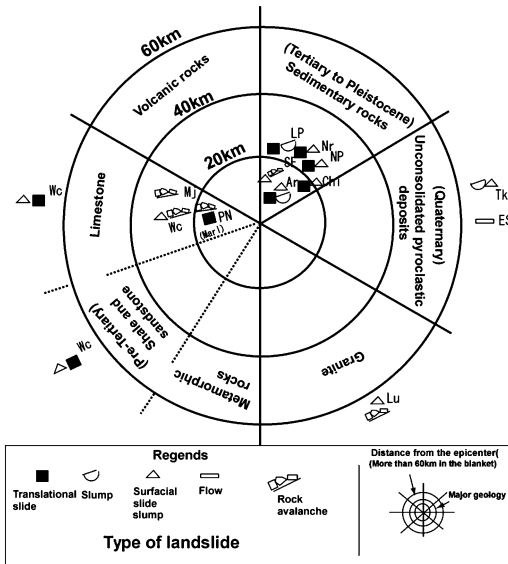
At the site of China's onshore Wenchuan earthquake, where a magnitude of 8 was recorded, limestone and pre-Tertiary sedimentary rock slides were discovered more than 60 km away from the epicenter, verifying that the relationship between the distance from the epicenter and the form of landslide outbreak becomes different when the earthquake is of magnitude 8 or above.

Thus, for the 2011 Tohoku earthquake, cases of rock failures and flow that occurred several hundred kilometers away from the epicenter were compared with past earthquake landslides

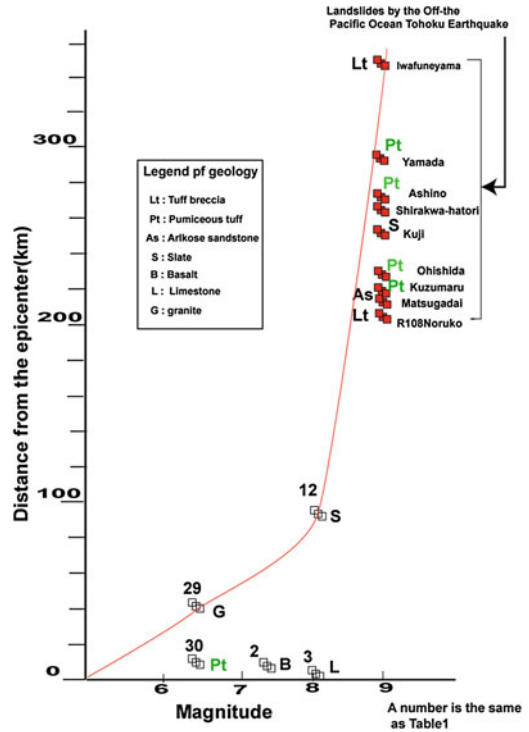


**Fig. 5.4** Geology, movement type of earthquake landslides and their distance from the epicenter (outside of Japan)

- |                                 |                                  |
|---------------------------------|----------------------------------|
| SF:1971 San Ferenando (M6.5)    | Nr:1994 Northridge (6.7)         |
| PN:1985 Papua New Guinea (M7.1) | Tk:1999 Turkey (M7.6)            |
| Ar:1988 Armenia (M6.9)          | Chi:1999 Chi-chi (M7.7-USGS-)    |
| LP:1989 Loma Prieta (M6.9)      | ES:2001 El Salvador (M7.6)       |
| Mj:1990 Manjil (M7.7)           | NP:2005 Northern Pakistan (M7.6) |
| Lu:1990 Luzon (M7.8)            | Wc:2008 Sichuan (M8.0)           |



**Fig. 5.5** Typical types of earthquake-induced landslides and their geological and topographical settings outside Japan. (1) Tertiary to Quaternary well-bedded sedimentary rocks (A) Cuesta, (B) Folding (C) Crest slope. (2) Quaternary unconsolidated pyroclastic deposits. (3) Granitic rocks. (4) Volcanic rocks



**Fig. 5.6** Magnitude and distance from the epicenter of earthquake-induced landslides in unconsolidated pyroclastic deposits

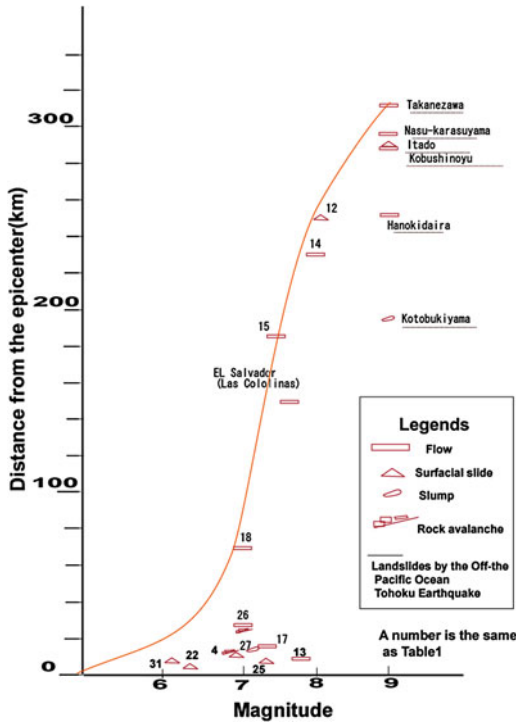
(Fig. 5.6 and 5.7). It was found that rock failures occurred at a distance of over 100 km away from magnitude 8 earthquakes, especially for pumice tuff rock failures and at undercut slopes along rivers. Flows also occurred in unconsolidated volcanic sediments at locations over 100 km away from the epicenter for earthquakes of magnitude 7 and beyond.

As noted before, there is a difference in distance between the fault and the earthquake landslide as well as their morphology from magnitude 8 and beyond.

## 5 Conclusion

Earthquake landslides show common movements in landslide sites with similar geological properties. The movement types can be summarized as follows: (1) translational slides in ridges and cuestas with Tertiary–Quaternary





**Fig. 5.7** Magnitude and distance from the epicenter of earthquake-induced rock failures

well-bedded sedimentary rocks, (2) flows in areas with consolidated Quaternary volcanic sediments, (3) shallow rotational slides at ridges in areas of volcanic rock, and (4) rock failures and toppling in areas of granite, accompanied by the flow of granite soil.

This study has evaluated the relationship between the distance from the epicenter and the type of earthquake landslides. Research has revealed that many of the earthquake landslides occur within a 30 km distance of the epicenter for earthquakes up to magnitude 7. However, it was also revealed that a magnitude of 8 and above can often induce rock slides at locations over 100 km away, and flow of unconsolidated volcanic sediment and rock failures of consolidated bedrock at locations 200–300 km away, indicating that magnitude 8 is the line of demarcation at which the relationship between the distance from the epicenter to sliding sites and the movement types of the slides changes significantly. This is possibly because of a significant difference in the location and epicenter of the earthquake as the

scale of the earthquake fault becomes larger. Upon evaluating the distance between the landslides and the faults, determining the position under the earthquake fault or under the seabed would become important.

Many recent earthquake landslides have also been observed at residential embankments.

Further research is needed to evaluate various issues, including the relationships between the location of the fault and that of the earthquake landslides, the physical and mechanical characteristics of unconsolidated volcanic sediment that cause flow to be induced far from the epicenter, the characteristics of the pumice tuff that lead to rock failures, and the relationship between earthquake movement and landslides in embankments.

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