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Earthquake-induced rapid long-traveling flow phenomenon: May 2003 Tsukidate landslide in Japan

Introduction

An earthquake with a moment magnitude of 7.0 occurred in northern Japan on May 26, 2003. The epicenter was located at latitude 38.806°N and longitude 141.685°E, at a depth 70.4 km (National Research Institute for Earth Science and Disaster Prevention, Japan 2003). Although no deaths or missing persons were reported, 174 persons were injured, and some structures were damaged (Fire and Disaster Management Agency of Japan, 2003).

Landslides were also triggered by the earthquake, and among which a massive landslide occurred in the Tsukidate area, northwest of Sendai, the capital city of Miyagi Prefecture (See Fig. 1, hereinafter we call this landslide the Tsukidate landslide). The Tsukidate landslide partially destroyed two houses. Although two people were partially buried by the displaced landslide mass, both were subsequently rescued. The landslide was triggered on a gentle slope with the sliding surface inclination of approximately 13.5 degrees. The displaced landslide mass traveled a long distance of about 130 m, and finally spread and deposited on a horizontal rice paddy, thus showing some typical characteristics of rapid long traveling flow phenomenon. Because this landslide was triggered by an earthquake without rainfall, the fluidization behavior of the landslide attracted the attention of researchers in various fields. Those ICL member organizations, which are promoting IPL-M101 project (Areal Prediction of Earthquake and Rain Induced Rapid and Long-traveling Flow Phenomena), and the Japan Landslide Society jointly organized an investigation team and completed a field survey on this landslide four days after the disaster. Field investigation and laboratory experimental study on the possible mechanism of this landslide were performed and are presented in this paper.

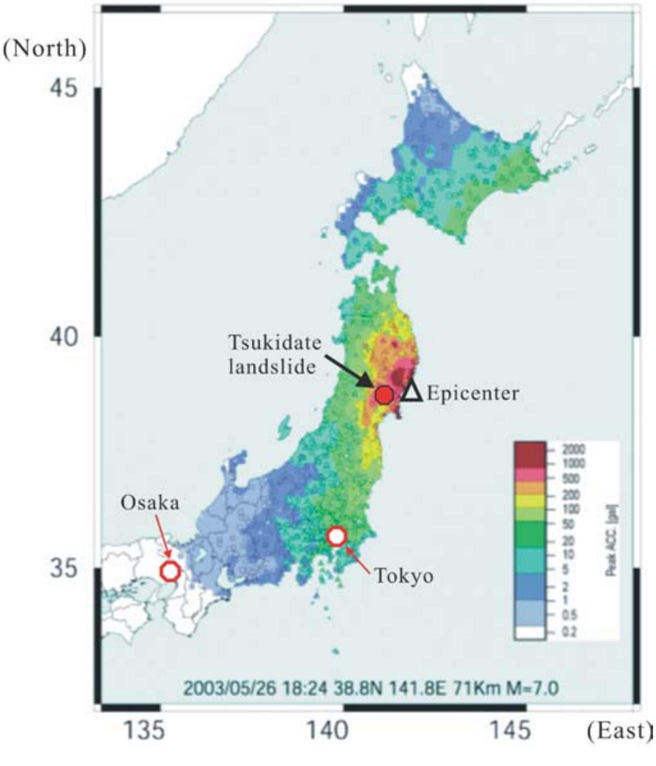

Fig. 1 Location of the Tsukidate landslide as well as the earthquake epicenter (after National Research Institute for Earth Science and Disaster Prevention, Japan 2003)

Tsukidate landslide

According to the records of the High Sensitivity Seismograph Network Japan (Hi-net), which is operated by the National Research Institute for Earth Science and Disaster Prevention (NIED), Japan, the maximum acceleration exceeded 1,000 gal in the vicinity of the epicenter. Because the Tsukidate area is very close to the epicenter (see Fig. 1), it is believed that the Tsukidate landslide was triggered by the strong seismic ground motion.

Figure 2 shows views of the Tsukidate landslide, where Fig. 2a is an oblique air photograph of the front view taken by the Yomiuri Shimbun (a newspaper company) helicopter just after the earthquake. Figure 2b shows another oblique side view (taken by Kokusai Kogyo Co., Ltd). In this photo it is evident that the road on the right side is almost parallel to the landslide, indicating the nature of gentle slope. Figure 3 is a view from the toe of the landslide, which was taken four days after the event (at our survey time). As shown in Figs. 2 and 3, the landslide mass slid out of the source area, traveled a long distance, and finally spread and deposited on the rice paddy below the slope. The bamboo originally on the source area was transported with the landslide mass; however, most were standing almost vertically on the rice paddy with a thin soil layer of landslide mass below, as seen clearly in Fig. 3. From the deposition area on the horizontal rice paddy, it is inferred that the displaced landslide mass displayed significant energy (great velocity) when it left the gentle slope.

From the images presented above, a question may be raised why this landslide was triggered on such a gentle slope and traveled such a long distance. To examine the triggering mechanism, it is necessary to have a better understanding of the geological background of the slope. Comparing the present contour map of this area to that of about 40 years ago (Fig. 4), it is clear that the source area of this landslide was located on a filling ground, where a gully was buried for developing residential ground. Within the red circle in Fig. 4a, a gully is clearly visible. However, since this gully was buried about 40 years ago, it is no longer visible (see Fig. 4b). Figure 5 presents a stereo-pair of air photographs of the Tsukidate landslide site. These air photographs were taken by the Geographical Survey Institute of the

Fig. 2a,b (**a**) Oblique front view of the Tsukidate landslide (photo courtesy of the Yomiuri-Shimbun); (**b**) oblique side view of the landslide (Photo courtesy of Kokusai Kogyo Co., Ltd)

Fig. 3 View from the toe of the Tsukidate landslide. The source area was covered by a blue sheet to minimize the potential for a second rainfall-triggered-disaster. Bamboo originally on the source area was still standing almost vertically on the deposited landslide mass after a long traveling distance

Ministry of Land, Infrastructure and Transportation, Japan, in 1976 after the gully had been buried. No gully could be identified within the red circle where the Tsukidate landslide was located.

Portable dynamic cone penetration tests (DCPT) were performed along the centre line of the landslide to obtain the strength properties of the soils at the source, the traveling path as well as the deposition areas. A detailed contour map of the Tsukidate landslide area after the landsliding is given in Fig. 6a (courtesy of Aero Asahi Corporation, Japan). This map with a contour interval of 50 cm was obtained by means of an airborne laser scanner after the landslide event. The locations of DCPT test points are plotted on Fig. 6a. Among these test points, three tests, Nos.6, 7, and 9 were located outside of the landslide: Nos. 6 and 7 were located on the upper part of the scarp, and test No. 9 was 44 m east of the scarp. The test results for these three locations are presented in Fig. 6b in the form of the deduced *N*-value against the soil depth. Usually, a greater *N*-value means greater shear resistance, which depends on the soil type, soil density, etc. It is inferred that the penetration for test No. 6 had been performed within the filling (Fig. 6a), since the *N*-values were small for the whole penetrating process of 400 cm. Test No. 7 showed a sharp increase in *N*-value after a cone penetration depth of about 330 cm, indicating that the penetration had reached bedrock. Test No. 9 showed a sharp increase in the *N*-value with increase of soil depth at a soil depth of 100 cm. Therefore, it was confirmed that the source area of this landslide was located within the fillings characterized by very low resistance.

Using the total station equipment, the central longitudinal section of the landslide from the source area to the deposited area of the paddy was surveyed (Fig. 7). The landslide descended 27 m over a horizontal distance of 180 m (from the head scarp to the toe). The original ground surface was inferred from the shape of the neighboring ground surface. It is seen from Fig. 7 that this landslide originated from a gentle sliding surface with an incli-

Fig. 4a,b Contour maps of the Tsukidate area in 1962 (**a**) and 2001 (**b**), respectively. The Tsukidate landslide was triggered within the red circle in May 2003

Fig. 5 Stereo-pair air photographs of the Tsukidate landslide site before the earthquake, taken by the Geographical Survey Institute of Ministry of Land, Infrastructure and Transportation. Source area of the Tsukidate landslide is located inside the red circle

nation of about 13.5 degrees and moved with an average apparent friction angle of about 7.3 degrees.

To examine the triggering mechanism of the landslide, soil samples were taken from the filling in the source area, which was mainly composed of pyroclastic deposits. Figure 8 shows the sampling site on the left side (seen from the upper slope to down slope) of the landslide. As revealed in this photograph, the pyroclastic deposits changed in color from brown (due to oxidization) to blue-gray (due to deoxidization). This means that the iron contained in the soil was not oxidized during the exposure to groundwater. As such, it was concluded that abundant groundwater existed within the source area. Because it is obvious that the liquefaction phenomenon was the main reason for this long runout landslide, laboratory tests were performed on these soil samples from the source area with an emphasis on the liquefaction potential of the filling soils.

Laboratory experimental examination

Undrained cyclic ring-shear tests were performed on the samples from the source area. During the sample preparation, gravels in the sample greater than 2 cm were sieved out. The grain size distribution of the sample after sieving is presented in Fig. 9. The sample in the field had a specific gravity of 2.61, dry density of 1.1 g/cm^3, void ratio of 1.38, and a unit weight (γ_t) of approximately 15.7 kN/m^3 with a water content (at sampling time) of 45.7% by weight.

A newly developed ring shear apparatus with the shear box sized 350 mm in outer diameter, 250 mm in inner diameter, and 150 mm in height, was used in this research. The sample was saturated by means of CO$_2$ and de-aired water, and then was normally consolidated under stresses corresponding to the sliding surface at the source area as shown in Fig. 7. After consolidation, the sample was subjected to the seismic loadings shown in Fig. 10 in an undrained condition. Detailed information on the design of this apparatus as well as its operating procedures can be obtained from Wang and Sassa (2002) and Sassa et al. (2003).

Because the tests aim to examine the liquefaction potential of the soil in the source area, a soil element on the sliding surface with the overlain soil layer being 3-m thick was selected as the study target. In calculating the acting stresses (normal and shear stresses) on the sliding surface, a slope angle (θ in Fig. 6) is measured approximately as 13.5 degrees from Fig. 7, and a saturated unit weight (γ_{sat}) for the soil mass in the field was calculated as 16.5 kN/m^3 by the measured properties of the sample, i.e., $\gamma_{sat}=(e/1+e)+\gamma_d$, where, γ_w: unit weight of water, was regarded as 9.8 kN/m^3 during calculation; γ_{sat}: unit weight of saturated soil; γ_d: field dry unit weight of soils; and e: field void ratio of soils.

The test results are presented in Fig. 10, in the form of time series data (Fig. 10a) and effective stress path (Fig. 10b). As shown in Fig. 10a, the shear strength showed a great reduction within one cycle of cyclic loading, and reached a low value of approximate 9 kPa, whereas the monitored pore-water pressure kept increasing with time and finally almost reaching the same as the normal stress. Shear displacement reached about 49 m within the shear time of 115 seconds. From Fig. 10b, it is seen that the effective stress path reached the failure line in the first cycle of shearing, and thereafter moved leftwards almost horizontally. This probably was due to the fact that the shear failure was localized in the shear zone, and it took time for the pore-water pressure generated within the shear zone to propagate to the effective places for pore-water pressure transducers (detailed information on the pore pressure measurement system can be ob-

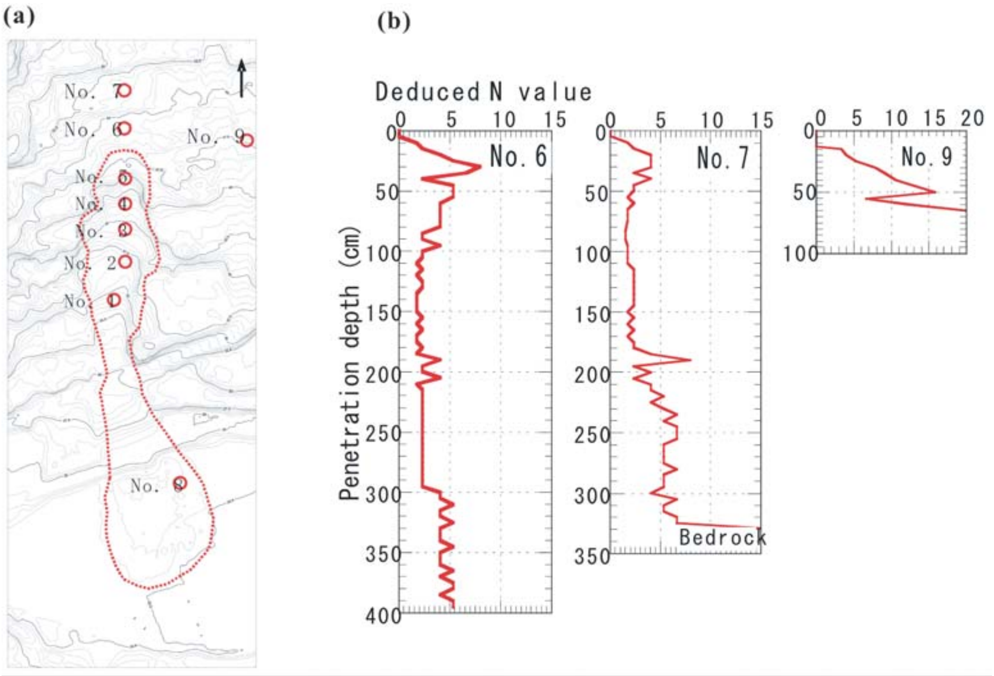

Fig. 6a,b (**a**) Contour map of the Tsukidate landslide area after the earthquake obtained by airborne laser scanner (Courtesy of Aero Asahi Corporation, Japan. The contour interval is 50 cm, and the red line shows the landslide area), and the locations of portable dynamic cone penetration tests; (**b**) In-situ penetration test results: deduced *N* value against soil depth

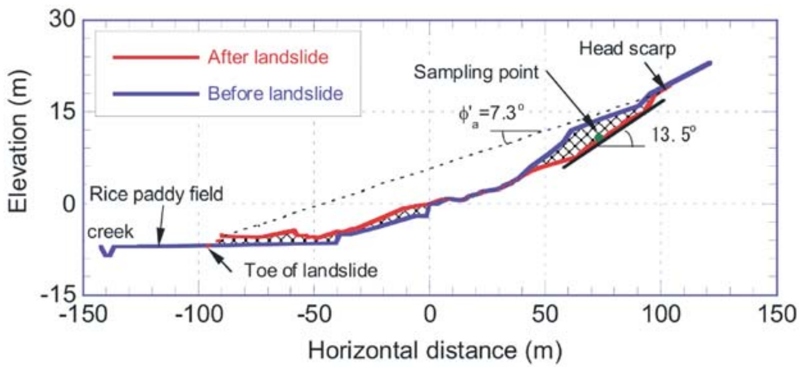

Fig. 7 Longitudinal cross section of the Tsukidate landslide obtained by non-prism total station survey (in red line). Blue line is the section before the landslide estimated from topographic maps. Apparent friction angle, which is the slope angle of the line from head scarp to the toe of landslide, is only 7.3 degrees. Origin of this figure was the location of Total Station used for the survey

Fig. 8 Sampling in the source area

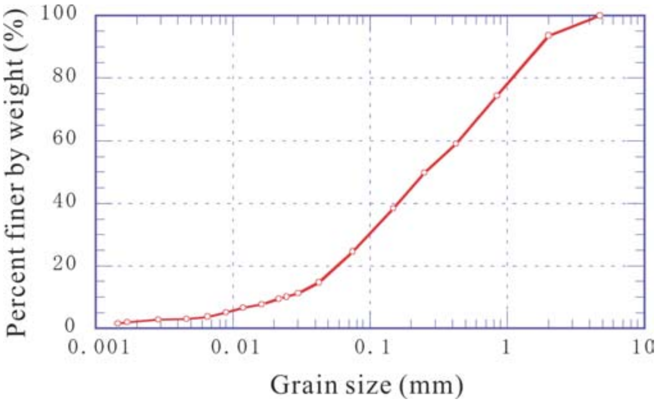

Fig. 9 Grain-size distributions of sample from the source area

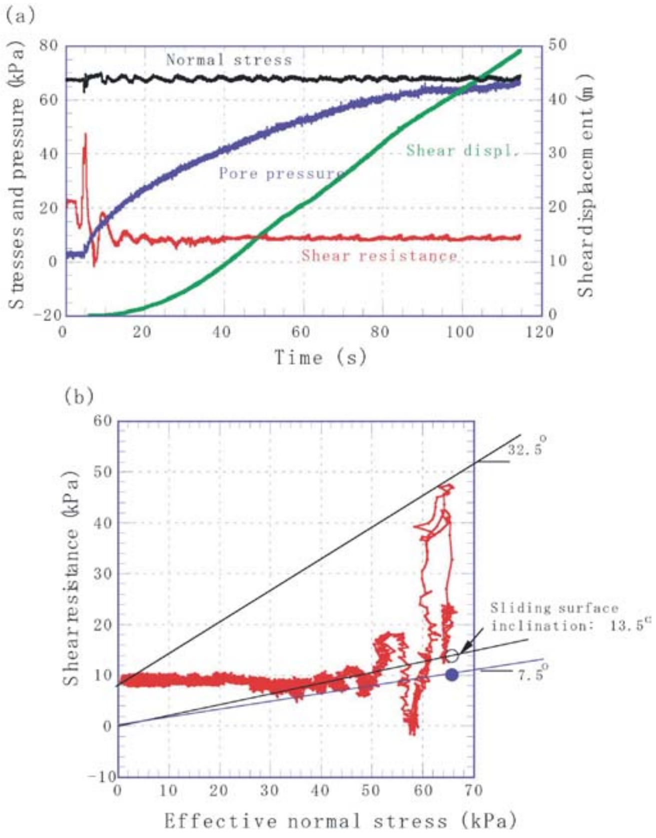

Fig. 10a,b Undrained cyclic ring shear test on the saturated sample taken from the source area (B_D=0.97). (**a**) Time series data of normal stress, shear resistance, pore-water pressure, and shear displacement; (**b**) Effective stress path

tained in Sassa et al. 2004). The apparent friction angle was about 7.5 degrees, showing a good consistency with the apparent friction angle of the landslide as shown in Fig. 7.

Summary and conclusions

1. The Tsukidate landslide originated on a gentle slope of approximately 10 degrees, and was a typical long traveling flow phenomenon triggered by an earthquake.
2. The landslide was triggered in the filling of a gully, which was buried for the purpose of developing residential ground some decades ago. In-situ penetration test results revealed that the filling material is composed of pyroclastic deposits with low deduced *N*-values, namely, with very low shear resistance.
3. Standing groundwater existed at the source area and it saturated the filling material. Undrained ring-shear test results revealed that the filling material was highly liquefiable. It is inferred that due to seismic loading, a certain excess pore-water pressure built up within the saturated sliding surface, which then led to the failure of the slope. After failure, high excess pore-water pressure was generated with the increase of shear displacement. This finally resulted in a great reduction in the shear resistance and rapid movement.

Acknowledgements

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