

A channelised long run-out debris slide triggered by the Noto Hanto Earthquake in 2007, Japan

Abstract A strong earthquake (M_j 6.9, M_w 6.6–6.7) at about 11 km depth hit the western shore of the Noto Peninsula on Honshu, Japan, at about 00:42 coordinated universal time (9:42 A.M. local time) on 25 March 2007 (the Noto Hanto Earthquake in 2007). The earthquake triggered only 61 landslides, with most traveling short distances. It caused one long run-out landslide in the Nakanoya district of Monzen town, Wajima city, Ishikawa Prefecture, when a portion of a deep-seated landslide transformed into a moderate debris slide down a channel. The rock slide occurred on a south-facing convex-shaped slope on a small spur where earthquake ground shaking likely was strongly amplified by topography. A portion of the rock slide reached a small channel floored by materials containing abundant groundwater. Constant-volume box-shear tests on normally consolidated saturated specimens revealed that the apparent angle of internal friction of the channel-floor material was 33–36° at 10-mm shear displacement and did not show much decrease in effective normal stress during shearing. In situ rock-sliding testing on the exposed channel materials showed a low kinetic-friction angle of about 21°. We suggest that an unsaturated portion of the rock slide slid down the channel, with sliding between the rock-slide mass and the channel floor. Because the slope angle of the travel path nearly equaled the kinetic-friction angle, the unsaturated rock slide mass may have traveled at a moderately slow speed, or it might have decelerated and accelerated. Slow speed is supported by accounts from local residents that suggest movement of debris continued for 3 days after the main shock.

Keywords Debris slide · Run-out distance · Topographic amplification · Earthquake

Introduction

At about 00:42 coordinated universal time (9:42 A.M. local time) on 25 March 2007, a strong, 11-km-deep earthquake hit the western shore of the Noto Peninsula in Ishikawa Prefecture on the island of Honshu, Japan (the M_j 6.9, M_w 6.6–6.7 Noto Hanto Earthquake in 2007, Japan Meteorological Agency 2007a; Fig. 1). Although the ground shaking must have been severe and the ground wet after rain, only 61 landslides were triggered by the quake (Goto 2007), including only four large ones, a small number compared with the M_j 6.8 Mid Niigata Prefecture Earthquake in 2004, which triggered more than 1,000 landslides of various types (Okada et al. 2005).

Most of the landslides in the Noto Hanto quake traveled short distances; however, a long run-out type, hereafter called the Nakanoya landslide, in the Nakanoya district of Monzen town, Wajima city, traveled 380 m. A deep-seated rock slide was triggered by the earthquake shaking, after which an unsaturated portion of it slid down the channel, striating the bed along the upper channel before it stopped at two check dams, by which time it had lost its

original structure because of the flow along the curved 250-m-long travel path.

The landslide was a rock slide–debris slide in the Cruden and Varnes (1996) classification. Although a portion of the rock-slide mass gradually lost its original soil structure during the downslope motion in which it changed into a type of flow, the ‘slide’ between the rock-slide mass and the channel-floor materials in the upper portion of the travel path appears to have been the key mechanism for the long run-out distance of this landslide. Local residents who live at the edge of the check dams reported loud noises, probably because of breakage of trees that continued for 3 days after the main shock, suggesting continued movement.

This paper first gives a brief description of the Noto Hanto Earthquake in 2007 and the Nakanoya landslide and then presents the results of in situ investigations (rock-sliding tests and sampling).

Geological setting and earthquake characteristics

The Nakanoya landslide lies in the northwestern part of the Noto Peninsula, in the Okunoto Hills, which consist mainly of Miocene sandstone, mudstone, conglomerate and tuff (Kurosedani stage: 16.5 to 16.0 million BP, and Higashibessho stage: 16.0 to 15.0 million BP; Kaseno 1992). According to a geological map by Kaseno et al. (1964), the Nakanoya landslide was initiated in sandstone and conglomerate (K_3), alternation of sandstone and mudstone (K_1), with Dacitic tuff (K_4) thinly sandwiched between them. The Noto Hanto Earthquake in 2007 produced four large landslides, all of them occurring in areas overlain by a thin layer of Dacitic tuff (K_4).

Although this region usually has heavy snowfall in winter, only a very small amount of snow was observed in the previous winter, and there was no snow cover in the Nakanoya district on 25 March 2007.

The hyetograph for March 2007 at nearby Monzen AMeDAS Observatory (Japan Meteorological Agency 2007b; Fig. 2) shows rainfall on 20, 22, 24 and 25 March just before the earthquake, totaling about 50 mm. Hence, the areas in which ground water was apt to accumulate, such as in the small channel at the foot of the Nakanoya landslide, should have been saturated or nearly saturated.

The triggering mechanism of the Noto Hanto Earthquake in 2007 was compression with a WNW–ESE axis. Modelling showed that the earthquake-source fault was a right-lateral reverse fault (throw of 1.1 m and heave of 1.2 m), and the fault plane had a dip angle of 63° SE (Geographical Survey Institute 2007). The main aftershocks were of M_j 5.3 at 18:11 (Local time), 25 March in Wajima city and at 7:16 A.M., 26 March, off the west coast of the Noto Peninsula. A part of the fault that is believed to have triggered the Noto Hanto Earthquake in 2007 is exposed about 500 m south of the Nakanoya landslide (Kanazawa University 2007).

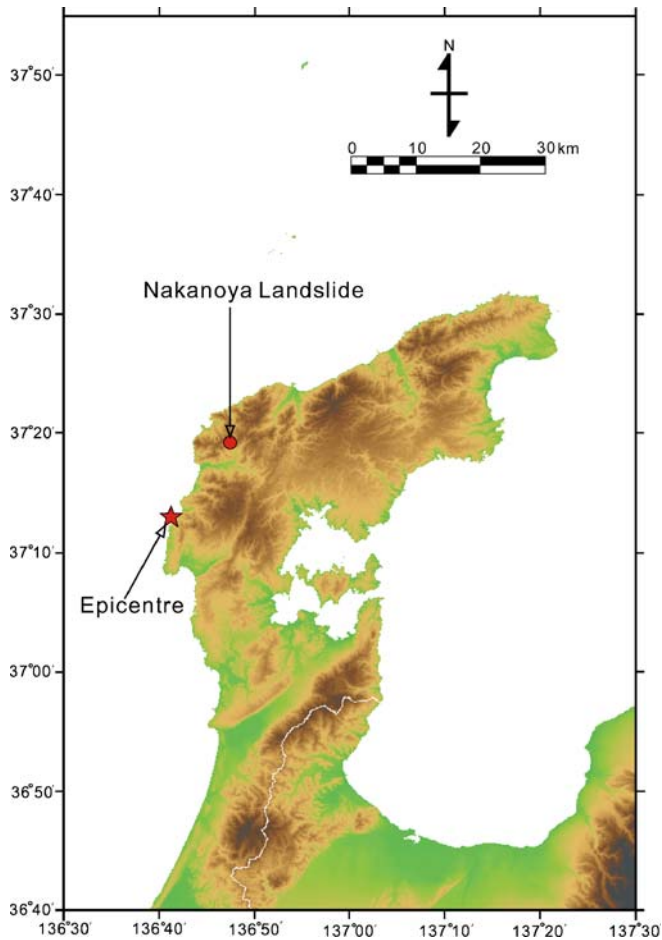


Fig. 1 Location of the Nakanoya Landslide on the Noto Peninsula in relation to the epicentre of the Noto Hanto Earthquake in 2007

Landslide description

The Nakanoya landslide headscarp is shown in Fig. 3. The dimensions of the source volume of the Nakanoya landslide were about 100 m long, 50 m wide and 15 m deep at maximum, with a

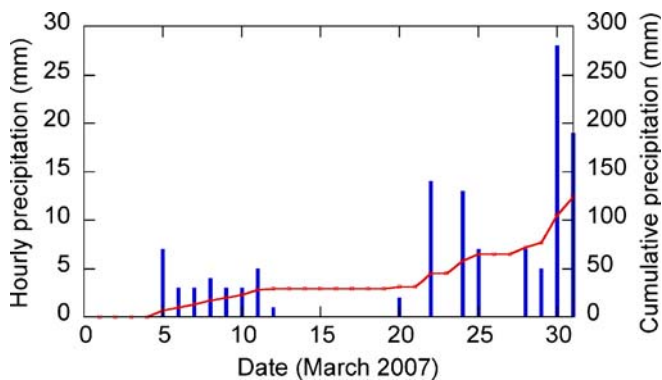


Fig. 2 Hyetograph of rainfall recorded in March 2007 at Monzen AMeDAS Observatory (monitored by the Japan Meteorological Agency)

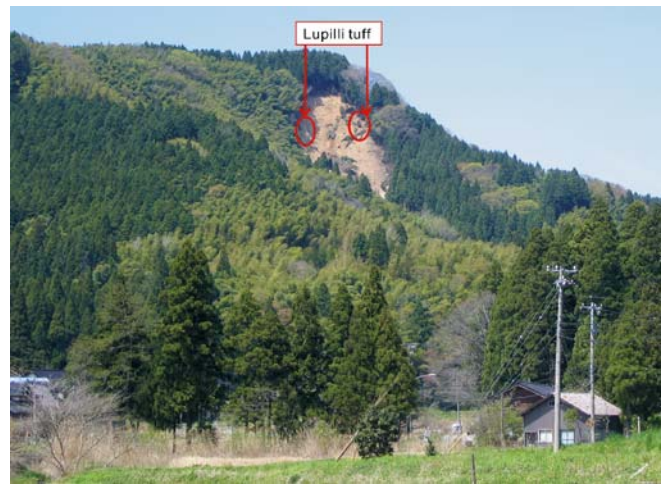


Fig. 3 Headscarp of the Nakanoya landslide on a convex slope on a small spur

total volume of about 10,000 m³. It originated from a convex slope on a small spur, exposing hard, lapilli tuff in the middle and lower sections of the source area.

Asano et al. (2006) pointed out that seismic acceleration is strongly amplified by topography, such that a convex slope would be expected to shake much more strongly. Furthermore, the Nakanoya landslide site was on the up-thrown side of the reverse fault; the ground accelerations should have been very high. Hence, we suggest that strong tremors on the up-thrown side of the fault as amplified by the topographical effect likely triggered the rock slide.

On 27 March, at our first investigation, groundwater exuded from the middle part of the rock-slide headscarp, and on 17 April, the middle part of the headscarp was widely wet. We assume that the hard lapilli tuff in the lower part formed a less permeable layer, so the sub-surface water came out from the middle part. When the unsaturated portion of the rock slide reached a small channel at the toe of the initial rock slide, it turned left and moved down the channel. It could have been as much as about 5 m thick when sliding down the channel.

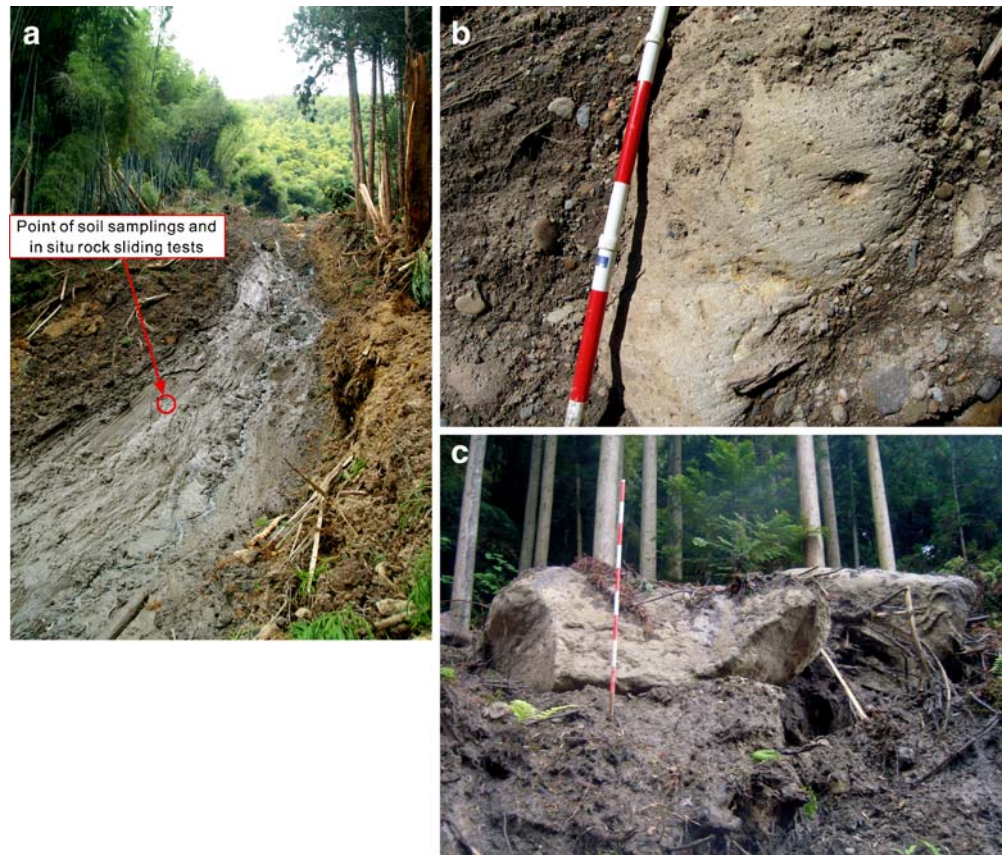
Soils in and around the channel must have contained a considerable amount of water. The unsaturated rock-slide mass slid on the channel-floor materials (Fig. 4a), leaving striations on the channel bedrock (Fig. 4b) and large rock blocks on the channel flanks (Fig. 4c). It traveled as much as 250 m down the channel towards the check dams, along a gentle slope of about 20° (Fig. 5), to form a deposit perhaps about 4 m deep behind the check dams.

Tests along the travel path

In situ rock-sliding tests were conducted, and soils were sampled in the upper portion of the travel path on 18 April and 25 May (see Fig. 4a). By manually sliding rock on the horizontal surface of the channel materials, an angle of kinetic friction ($\tan^{-1}\mu_k$) between the rock and the channel-floor materials was determined from the ratio of traction force to gravitational force (Fig. 6).

The tests were conducted with two blocks of lapilli tuff (Table 1). Although the weight and shape of the two blocks were different, the obtained kinetic-friction angle was about 21°, which was in general

Fig. 4 Views around the upper portion of the channel. **a** Soil surface along the travel path after sliding, **b** striations made by sliding and **c** large rock blocks left on the channel flanks. The width of each painted scale on the staff in **b** and **c** is 20 cm



agreement with the slope angle along the travel area. A point to note is that the soil surface after the tests was similar to that shown in Fig. 4a.

Undisturbed soils were sampled with 100-ml steel tubes (50 mm high) for tests of density, water retentivity and bulk permeability and with rectangular steel shear boxes (65 mm high, 100 mm wide, and 100 mm long) for box-shear tests. Although the exposed soils appeared oxidised (brown in colour), they appeared unoxidized (grey in colour) about 0.1 m below the surface on 18 April.

The relationship between saturation and suction is shown in Fig. 7. The water retentivity was measured by increasing the

suction on the saturated samples incrementally to reduce the saturation. The degree of saturation showed high values between 90 and 97% when the suction varied between 0.015 and 7.9 m. Permeability tests revealed coefficients of permeability for specimen 1 and specimen 2 of 8.7×10^{-7} and 1.2×10^{-6} cm/s, respectively. These findings indicate that the channel-floor materials had high

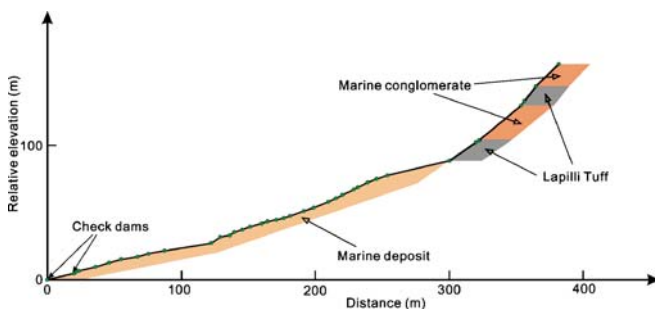


Fig. 5 Longitudinal section of the Nakanoya landslide

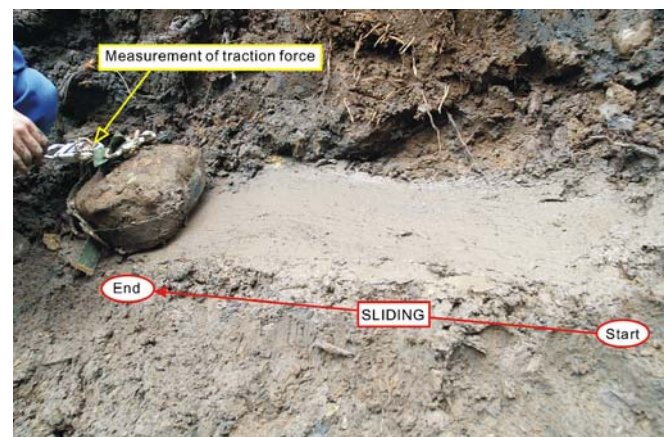


Fig. 6 In situ rock-sliding test and soil surface after sliding

Table 1 Summary of in situ rock-sliding tests

	Weight (kg)	T_{ave}^a (N)	$\tan^{-1} \mu_k$ (degrees)
1	10.0	39.2	21.8
2	18.0	68.6	21.3

^a Average traction force

water retentivity and low permeability. Hence, the channel floor retained a considerable amount of sub-surface water shown by the unoxidized colour even 3 weeks after exposure to air because of the landslide.

Three constant-volume box-shear tests on normally consolidated saturated specimens with shear speed of 0.050 mm/min (Table 2) revealed that the apparent angle of internal friction at the termination of the test of 10-mm shear displacement (ϕ_a) was between 33 and 36° (Fig. 8), which was much larger than the slope angle of the travel area (about 20°). A slight contractive deformation was observed immediately after the start of shearing. However, only a small reduction in effective normal stress was mobilised, and effective normal stress increased its values again after the phase transformation, irrespective of the total normal stress (5 to 50 kPa). This strongly suggests that the unsaturated portion of the rock slide did not shear internally but slid on the channel materials with a lower coefficient of kinetic friction, thus striating the upper portion of its path.

Because the driving force because of gravity on the slope of about 20° was close to the kinetic friction, the rock-slide mass slid slowly on the gentle slope or may have repeatedly decelerated and accelerated. Finally, it was stopped by the check dams after losing its previously intact soil structure during the motion over the curved travel path, breaking trees on its way.

Concluding remarks

A strong earthquake hit the western shore of the Noto Peninsula, Honshu, Japan, on 25 March, 2007. Relatively few (61) landslides occurred as a result, and there were only four large landslides. One

Table 2 Box-shear test conditions and results

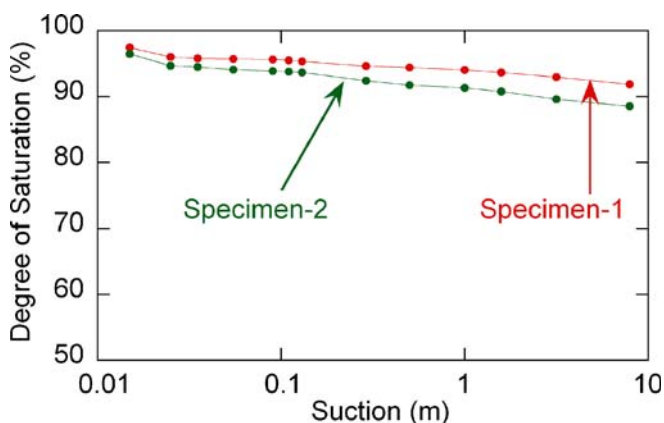
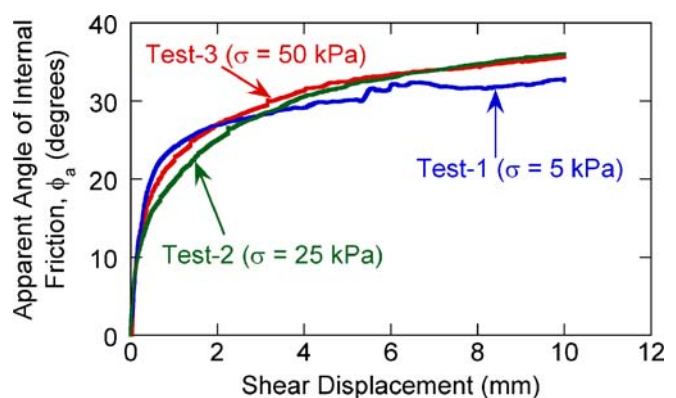
Test number	σ (kPa)	e_0	Φ_a (degrees)
1	5.0	0.84	33.0
2	25	0.81	36.0
3	50	0.78	35.4

of these, the Nakanoya landslide was a long run-out type (a deep-seated rock slide triggered by strong, topographically amplified seismic shaking) after which a portion of the rock slide slid downslope (making it a rock slide-debris slide) and traveled along a small channel until it was finally stopped by two check dams.

This landslide would have been classified as a debris flow based on aerial photo interpretation. When we visited the site, we wondered why the debris traveled such a long distance like a debris flow when the rainfall and snowfall were not heavy. Upon further investigation, we found that the channel-floor materials had high water retentivity and very low permeability, so the channel materials were close to a state of saturation.

The apparent angle of internal friction mobilised in the constant-volume box-shear tests on the saturated specimens of the channel materials was 33–36°, which was much larger than the slope angle of the travel area. The angle of kinetic friction between the rock and the channel-floor materials determined through in situ rock-sliding tests was about 21°, which was in general agreement with the 20° slope angle of the upper portion of the travel area.

Based on these findings, it appears that the unsaturated rock-slide mass reached the small channel below, then slid down the channel on the bed materials (Fig. 9). If this sliding had not taken place after the occurrence of the deep-seated rock slide, this landslide would have been as short as the other three large landslides triggered by the Noto Hanto Earthquake in 2007. Thus, sliding between the rock-slide mass and the channel floor was considered to be the key factor for the long run-out motion of the Nakanoya landslide.

**Fig. 7** Relationship between degree of saturation and suction**Fig. 8** Apparent angle of internal friction mobilised in the constant-volume shear-box tests

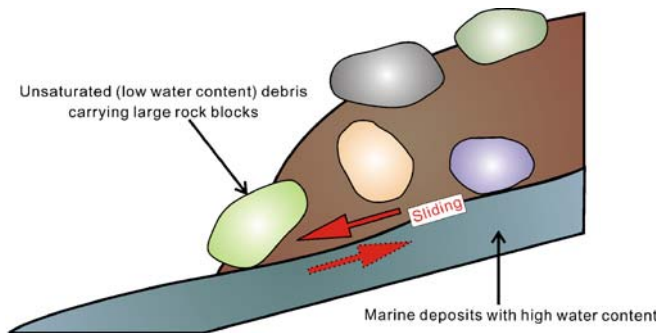


Fig. 9 Schematic illustration of the portion of unsaturated debris on channel deposits

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