Geological features of landslides caused by the 2018 Hokkaido Eastern Iburi Earthquake in Japan

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Abstract: Before dawn on 6 September 2018, a powerful earthquake with a Japan Meteorological Agency magnitude ($M_j$) of 6.7 hit central Hokkaido, causing more than 6000 landslides. As human damage, 36 of the 44 fatalities from the earthquake were from earthslides in Atsuma Town. Most slope movements were shallow earthslides of mantle-bedded tephra and soil layers, but some were deep rockslides involving basement rocks such as shale and mudstone of Miocene. Although the shallow earthslides were easily distinguishable in photos from satellites or airplane, the rockslides were more difficult to identify owing to their vegetation. Based on the quick interpretation of a high-resolution (0.5 m horizontal resolution) shaded relief map made from digital elevation model data by airborne laser survey and supplemental field surveys, we effectively identified 259 rockslides (196 certain ones and 63 possible ones) in Atsuma and Mukawa towns under newly invented identification criteria based on the scarp depth and positional relation between scarp and ridge topography. It was revealed that most rockslides were distributed within 10 km from the epicentre, while earthslides were distributed until 20 km north of the epicentre, and they seemed to be controlled by the thickness of mantle-bedded tephra and the soil layer. We also identified many traces of past rockslides and earthslides. The results show the possibilities for effective measurement of slope by clarifying the landslide distribution both this earthquake and past ones using high-resolution digital elevation model data.

At 03:07:59.3 JST (18:07:59.3 UTC) on 6 September 2018 (18:07:59.3 UTC on 5 September), a powerful earthquake hit the Eastern Iburi district of Hokkaido Island in Northern Japan. The earthquake was named the 2018 Hokkaido Eastern Iburi Earthquake by Japan Meteorological Agency (JMA). The JMA magnitude ($M_j$) was 6.7 and the moment magnitude ($M_w$) was 6.6, and the epicentre was 42.690° N by 142.006° E (Fig. 1b). The epicentre was about 65 km SE of Sapporo City and the hypocentre was at a depth of 37 km. A maximum seismic intensity of 7 by the JMA seismic intensity scale and 9.5 by the Modified Mercalli Intensity (MMI) of the US Geological Society (USGS) was recorded in Atsuma Town (Fig. 1b; USGS 2018). The maximum acceleration was 1796 gal on HKD127 of K-NET at Oiwake in Abira Town. The SE district of Sapporo City experienced seismic intensity lower than 6 by JMA and 6.7 by MMI (Fig. 1b).

The outline of the earthquake is shown in Table 1 along with that of the 2011 Great East Japan Earthquake. Forty-four people died (including earthquake-related deaths) and 785 people were injured. A cumulative total of 16 649 refugees spent time at 768 evacuation centres. Other important public facilities such as roads and waterworks were also heavily damaged. In particular, all of Hokkaido Island (2.95 million houses) experienced a complete power outage from the sudden stoppage of a major thermal power plant, Tomatou-Atsuma, south of the epicentre. Ground liquefaction caused the destruction and tilting of many houses in several embanked areas in Sapporo City. Notably, the earthquake caused more than 6000 landslides in hilly areas of Atsuma, Abira and Mukawa towns (Kita 2018; GSI Japan 2018; Yamagishi and Yamazaki 2018; Figs 2 and 3) and 36 people died as a result of shallow earthslides in Atsuma Town. A notably large rockslide intercepted the Hidaka–Horonai River in Atsuma Town and caused a lake to form upstream of the blockage. The total economic damage caused by the earthquake is estimated at about 162 billion yen (about US$1.48 billion).

The landslides caused by the Hokkaido Eastern Iburi Earthquake seem to be less well understood because of the large number of them and the difficulties of the field approach. Although rapid and widespread surveys using satellites and aerial surveys are effective for understanding landslides caused by earthquake, the methods for the detection and prediction of their localities have not yet been established. In this study, in order to clarify size, slope mechanism, total number and distribution of the earthquake-induced landslides, we carried out topographic analysis of landslides using high-resolution aerial laser survey data and field survey after the...
Our result will contribute to understanding the whole picture of the landslide disaster around the epicenter and also future mitigations of slope disaster by earthquake, as a case study of the high-resolution topographic analysis.

Geological setting

The basement rock around the epicentre mainly consists of Neogene sedimentary rocks that are conglomerate, sandstone and mudstone of the Fureoi Formation of Middle to Late Miocene, sandstone, hard shales and mudstone of the Karumai Formation of Late Miocene, and conglomerate, sandstone, hard shales and siltstone of the Moebetsu (Nina) Formation of Late Miocene to Early Pliocene (Fig. 1c; Matsuno and Ishida 1960; Kase et al. 2018). These are foreland basins fill deposits formed by a collisional event between the Northeast Japan Arc and Kuril Arc (Fig. 1c, d; Kawakami and Kawamura 2003; Kase et al. 2018). Several synclines, anticlines and faults oriented NW by SE are associated with westward motion of the Kuril fore-arc sliver by oblique subduction of the Pacific Plate (Kimura 1986; Kawakami and Kawamura 2003). As a front of this collisional tectonics, a zone of active faults, Ishikari-Teichi-Toen Fault Zone, is placed between Ishikari flatland and hilly and mountainous areas of Atsuma and Abira towns (Fig. 1b; AIST and HRO 2018). These basement rocks are widely covered with tephra and soil from 1 to 3 m in thickness (Fig. 4c; Uda et al. 1979; Hirose et al. 2018). In ascending order, pumice layers are Spfa-1 (34–31 ka; Machida and Arai 2003) from the Shikotsu caldera, En-a (17–15 ka; Machida and Arai 2003)
from the Eniwa Volcano, and Ta-d (8.7–9.2 ka), Ta-c (2.5 ka), Ta-b (1667 AD) and Ta-a (1739 AD) from the Tarumae Volcano (Furukawa and Naka-gawa 2010), located 40–70 km west of the area. These tephra layers are intercalated with soil (Fig. 4c). Around Atsuma Town, north of the epicentre, most of the landslides were classified as earthslides of thin, unconsolidated tephra and soil. Most of the collapsed slopes were covered by mantle-bedded tephra layers of Ta-d to Ta-a and/or En-a (Fig. 4c; Hirose et al. 2018). The En-a and Spfa-1 has been partially preserved on slopes around Abira Town (Fig. 4d; Hirose et al. 2018).

Weather conditions

The day before the earthquake, the powerful typhoon Jebi (designated as typhoon no. 21 of 2018 in Japan) struck Hokkaido Island. Despite heavy rainfall (about 200 mm per day) around Lake Shikotsu, about 50 km west from the Atsuma Town, there was a little rainfall in the epicentral area. The rainfall on the preceding day in Atsuma, Abira and Mukawa towns as recorded by the Automated Meteorological Data Acquisition System ranged from 10 to 20 mm. The antecedent precipitation (2 weeks) as recorded by the same system ranged from 50 to 70 mm in the three towns. Although these rainfalls might have adversely affected slope stability, they did not seem to be the direct cause of the thousands of landslides in these areas.

### Landslide classification and mechanism

Varnes (1978) classified slope movements in terms of materials and movement characteristics, and the ‘slide’ category is subdivided into three subcategories of rockslide, debris slide and earthslide by material. This study also follows these categories for the classification of landslides. In the 2018 Hokkaido Eastern Iburi Earthquake, more than 6000 earthslides (Kita 2018; Yamagishi and Yamazaki 2018; Wang et al. 2019) and more than 100 rockslides (Ito et al. 2019) were interpreted. The interpretation of earthslides was carried out mainly by satellite photos and that of rockslides was carried out rather qualitatively as a preliminary study without the identification criteria for rockslides, although high-resolution shaded relief maps were used, as in this study. The dense distribution of landslides was recognized in the hilly area of Atsuma and Abira towns NW of the epicentre (Figs 2 and 3). In Atsuma Town, the bases of the shallow earthslides were mostly the Ta-d tephra layer (Hirose et al. 2018). In the area of Abira Town, NW of Atsuma Town, the bases on the failed slope were partially recognized as En-a and/or Spfa-1 (Hirose et al. 2018). One of the largest rockslides blocked a branch of the Hidaka–Horonai River east of Atsuma Town (Figs 5 and 6), causing a barrier lake to form upstream. The largest rockslide slid 350 m of ridge topography, about 1000 m in length by 400 m in width by more than 70 m in depth. The basement consists of hard shale of
Fig. 2. Many hillside landslides in Atsuma Town. Comparison between aerial photograph on 3D-topographic map before the earthquake (upper: 20 October 2011) by GSI Japan and photo from an airplane after the earthquake (lower: 7 October 2019). Black arrow indicates the direction of the river current.

Fig. 3. Satellite image showing distribution of landslides caused by the 2018 Hokkaido Eastern Iburi Earthquake. Most of the brown-to-yellowish parts are shallow earthslides of tephra layers, but some include rockslides. They are widely distributed northwards from the epicentre. Note the scant distribution around the epicentre. White broken circles show distance from the epicentre. (Adapted from a SPOT satellite image provided by Pasco Corporation.)
Karumai Formation with about 10° dip towards the Hidaka–Horonai river that is typical dip-slope topography (Figs 5 and 6).

**Methods and materials**

To have a precise understanding of the overall picture of earthquake-induced landslides, it is very important to understand their distribution and mechanism quickly over a wide area for future prevention measures. In identifying landslides, it is very common to use a stereoscopic apparatus and photos taken from an airplane. The problem with this method, however, is revealed when there are many targets. While the earthslides in this case were easily distinguishable in photos from satellites or airplanes based on their brown to yellowish traces on whole slopes without using the stereoscopic method, interpretation of so many rockslides was complicated and took a good deal of time and effort.

Previous reports, such as Kita (2018), Yamagishi and Yamazaki (2018), Wang et al. (2019), Zhang et al. (2019) and Osanai et al. (2019), devoted much space to identification of shallow earthslides using aerial and satellite image and field survey, while not mentioning the number and distribution of rockslides except for one large one in Hidaka–Horonai river (Figs 3 and 5). The main reason for this is assumed to be that the earthslides caused serious damage and were very characteristic in this earthquake. However, another reason is assumed to be that rockslides are more difficult to identify at a glance because most of them are identified by crown cracks of tens of centimetres to several metres in width around top of the slide slope and because vegetation tends to cover them in Japan. It takes many hours to identify rockslides by field survey.

![Image](image-url)

**Fig. 4.** (a) High-resolution shaded relief map of an earthslide in Atsuma Town that has 40 m width, 100 m length and 34 m relative elevation. (b) Photos of the overview and (c) close up of lateral wall in the failed slope. Layers of Ta-b, Ta-c and Ta-d tephra intercalated with soil are recognized. En-a is absent on this slope. (d) Stratigraphic column in a flatland area in Atsuma Town (Uda et al. 1979). Age of each tephra after Machida and Arai (2003) and Furukawa and Nakagawa (2010). Locations are shown in Figure 3.
and low-level airborne survey in a large area. As we mentioned at the beginning of the chapter, it is important to understand the characteristics of both earthslides and rockslides in detail for future measurement.

In order to grasp the distribution of landslide disasters for the hilly area of Atsuma Town precisely, airborne laser surveys were carried out by the Hokkaido Regional Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism.

**Fig. 5.** The largest rockslide that intercepted the Hidaka–Horonai River. Upper-left shows topographic map before the earthquake and upper-right shows the aerial photo after the earthquake (modified after topographic map and photo form GSI of Japan). The red line shows the main slide body and the white broken line shows the position after earthquake in the upper-right. A transmission line (pale blue broken line in the upper-right) was displaced about 350 m by the rockslide. Lower figure shows the cross-section along the A–B white line in the upper figures. Black broken line shows the original ridge topography by GSI Japan and the red line shows that after the earthquake by this study.

**Fig. 6.** The inner part of the largest rockslide that intercepted the Hidaka–Horonai River. The central trail between slide blocks is made after the earthquake.
from 5 to 9 days after the earthquake. Figure 1c shows the surveyed area, which covers about 430 km² north of the epicentre. The horizontal resolution of the digital elevation model (DEM) data that were obtained was 0.5 m. We were able to use the data to create high-resolution shaded relief maps for the interpretation of rockslide topography, and we started to identify landslides, especially rockslides, with the newly established identification criteria. Geological field surveys were also carried out to confirm the results of the identification.

Figure 7 shows the comparison between a high-resolution shaded relief map of the area using this study and that by DEM with 5 m resolution which is published by the Geospatial Information Authority of Japan (GSI Japan). We can easily distinguish landslide traces and even a small path on slope by the former, while it is rather difficult to distinguish them by the latter. The following new criteria were used to identify rockslides and classify their types objectively and quantitatively using the high-resolution shaded relief map. The conceptual diagram and cross-section are shown in Figure 8.

1. The crown crack or scarp of the slide lies across the ridge line of a hill. They are classified into ridge type or slope type.
2. Although the crown crack or scarp dose not cross the ridge topography, the depth of the crack and scarp appears to be clearly greater.

![Fig. 7. Comparison result of shaded relief map between (a) DEM with 5 m resolution by the Geospatial Information Authority of Japan and (b) DEM with 0.5 m resolution by this study.](image)

![Fig. 8. Schematic model of (a) the shallow earth slides, (b) the rockslides, and (c) their cross sections.](image)
than that of the surrounding earthslide that less than 3 m in thickness in most cases. This is classified as shallow-type. We considered the landslide topography to be a rockslide if either criterion was clearly met, because the earthslides are thought not to cross the ridge topography of a hill owing to weak consolidation and the thinness of the tephra layer, and not to have a thickness of more than 3 m in the studied area (Figs 4 and 8a, c). We also subdivided rockslides into three types by their topography (Fig. 8b, c). If the crown clack or scarp crossed the ridge line with a high angle, it was classified as ridge-type. If it crossed parallel to low-angle, it was classified as slope-type. We regarded landslide topographies that satisfied only the second criterion as probable shallow-type (Fig. 8b, c). The depth of slip surface theoretically increases in the order shallow-, slope- and ridge-types in similar size (Fig. 8c).

To confirm the identification results (Fig. 9), we performed a geological field survey of the rockslides identified along the Hidaka–Horonai River in November 2018 (Figs 5 and 6), and along one branch of the Towa River (Figs 10 and 11) and one of the Ukuru River (Figs 12 and 13) in December 2018.

Results and discussion

Rockslides caused by the earthquake

Based on identification result using high-resolution shaded relief maps and supplemental field surveys, we interpreted 259 newly formed rockslide topographies caused by the earthquake (Fig. 9b; Table 2). They were subdivided into 109 ridge-type, 87 slope-type and 63 shallow-type. The number and size (as total and average area) of slide body of the shallow-type were smaller than those of ridge- and slope-types (Table 2). Figure 9b demonstrates their distribution, which clearly differs from that of the earthslides. These rockslides are densely distributed within 10 km from the epicentre correspond to the distribution of Karumai Formation (Fig. 9b). The earthslides are widely distributed 5–20 km northwestward from the epicentre, and a few are distributed near the epicentre (Fig. 9a; GSI Japan).
A possible reason for this may be that thick (>1–2 m) tephra and soils are distributed northwestward, whereas thin (<1–1.5 m) tephra and soils are distributed near the epicentre (Hirose et al. 2018). Therefore, the distribution of earthslides is thought to be strongly influenced by the total thickness of the tephra and soil on the basement. On the other hand, it is considered that the distribution of rockslides is strongly associated with topographic stability and geological settings in the area of strong ground motion around the epicentre.

The geological and topographical characteristics of the identified rockslides were verified in three locations by field observation and topographic analysis using the high-resolution DEM data. As described above, the notable rockslide in the Hidaka–Horonai river is the largest landslide (about 0.3 km² as slide area) caused by this earthquake and it is classified as a ridge-type rockslide with typical dip-slope structure consisting of hard shale of the Karumai Formation. (Figs 5 and 6). Figure 10 is a shaded relief map (a) and a cross section of ridge-type rockslide no 79 (b) of the left branch of the Towa River. We newly identified three rockslides at this site, which are the slope-type no. 68 and the ridge-type nos 75 and 79. Rockslide no. 79 is estimated to be 170 m in length by 85 m in width by more than 10 m in thickness (depth of slip surface), and the slide distance is estimated as 25–30 m.

Fig. 10. (a) identification results of earthquake-induced rockslide using a shaded relief map in the left branch of the Towa River and (b) cross section of ridge-type rockslide No. 79 (A-B line). The areas surrounded by rad line are identified rockslides of No. 68 as slope-type, No. 75 and No. 79 as ridge-type.

Fig. 11. Outcrop of the ridge-type rockslide (no. 79 in Fig. 10). (a) Overview of the scarp of the rockslide and adjacent shallow earthslide of mantle bedded Ta-d tephra layer; (b) sketch of scarp and (c) close-up photo of the scarp consisting of weathered basement of fine-grained sandstone covered by slope deposits consisting of highly weathered sandstone blocks in clayish matrix.
Here we observed basement of weathered sandstone to siltstone on scarp (Fig. 11), and the slide surface is in basement rock beneath the mantle-beded tephra and soil cover. Figure 2 lower also shows the aerial photo image of the same area as the shaded relief map of Figure 10a. There is dense vegetation on these identified rockslides, and we could not have easily identified them by photo from an airplane or satellite. The shape of No. 79 was probably detected from the airplane photo by the ground-coloured part surrounding the rockslide block because its movement is greater than those of nos 68 and 75. These three rockslides could be missing by simple distribution checks of failures and vegetation using photos from an airplane or satellite.

**Past landslide traces**

Using the high-resolution DEM data, we also found large number of old landslide traces (both rockslides and earthslides) which could be caused by past earthquakes or heavy rains. The interpretation of past earthslides is rather more difficult than that of past rockslides because they are more easily erased by surface erosion or weathering than the latter. Figure 12 is a shaded relief map in the Ukuru River with eight identified rockslides of ridge-type (nos 11, 64 and 78), slope-type (no. 91) and shallow-type (nos 180, 193, 201 and 252). The blue part is thought to be old rockslides. Ridge-type rockslide no. 78 is shown as a cross-section between A and B and also in the photo of Figure 13. Original surface is DEM data with 5 m in resolution by GSI Japan.

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**Fig. 12.** Identification results of rockslides using a shaded relief map in the Ukuru River. Location shows in Figure 3. Eight areas surrounded by red lines are identified to be rockslides of ridge-type (R; nos 11, 64 and 78), slope-type (SL; no. 91) and shallow-type (Sa; nos 180, 193, 201 and 252). The blue part is thought to be old rockslides. Ridge-type rockslide no. 78 is shown as a cross-section between A and B and also in the photo of Figure 13. Original surface is DEM data with 5 m in resolution by GSI Japan.

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The distribution of the identified rockslides is concentrated in the sandstones, siltstones (hard shales) and mudstones of Karumai Formation of Late Miocene with dip-slope structure.

In addition, careful identification also revealed some old earthslides. Figure 14 shows past and present earthslide topography by shaded relief map at the Sakuraoka area of Atsuma Town. However, when and how past rockslides occurred is still unknown. In Atsuma River, an old shallow earthslide was reported that had a similar structure to that of the earthslides at this time (Tajika et al. 2016). The age of the old earthslide has been estimated as 4.6–2.5 ka by 14C dating as a possible past activity of the Ishikari–Teichi–Toen Fault Zone (Tajika et al. 2016). It might be possible that the cycle and activity history of active faults in the Atsuma area can be estimated by dating of newly found old landslides.

**Table 2. Interpretation results of rockslide topography**

| Landslide Type | Certainty | Number | Total area (km²) | Average area (± SD) |
|----------------|-----------|--------|------------------|---------------------|
| Rockslide Ridge | Certain   | 109    | 2.10            | 0.020 ± 0.033 km²   |
| Rockslide Slope | Certain   | 87     | 1.61            | 0.018 ± 0.015 km²   |
| Rockslide Shallow | Possible | 63     | 0.46            | 0.007 ± 0.005 km²   |
| Total            |           | 259    | 4.21            | 0.016 ± 0.024 km²   |

**Fig. 14.** Past and present earthslide topography by shaded relief map at Sakuraoka area of Atsuma Town. Trace of earthslide of this time (New) breaks a small path on the slope, while that of the past one (Old) does not break it.

**Table 3. Summary of the characteristics of earthslide and rockslide**

|                  | Earthslides | Rocksides |
|------------------|-------------|-----------|
| Number           | >6000*      | >250      |
| Number of deaths and missing persons | 36          | 0         |
| Slope degree     | 20–30†      | 18–35     |
|                  | Not a few earth slides happened on a gentler slope (less than 20 degrees.) | Most rockslides happened under the dip slope structure, and the dip of the rock is most likely less than 30 degrees. |
| Distribution     | From 5 to more than 20 km north of the epicentre. Rare in the south and around the epicentre. It seems to be mainly controlled by the thickness of mantle bedding tephra and layers. | Most rock slides are within 15 km of the epicentre. It seems to correspond to the Neogene sedimentary rock area of sandstone and slate (Kurumai formation). |
|                  | 5; They were rapidly measured. Estimated volumes were 70 000, 50 000, 31 000, 30 000, and 15 000 m³, respectively ‡ | 1; Largest natural dam was on the Hidaka–Horonai River. Several years were thought to be needed for measurement. Estimated volume is several million cubic metres ‡ |

*Kita (2018).
†Umeda et al. (2019).
‡Fujinami et al. (2019).
Characteristics of earthslides and rockslides, and their measurement

Table 3 shows a comparison of earthslide and rockslide characteristics. The human damage caused by earthslides was much greater than that caused by rockslides. The distribution of earthslides was mainly controlled by the thickness of tephra and soil, and their mantle-bedded structure, while rockslides seem to be distributed at the dip-slope structure area of basement rock near the epicentre. The extent of liquefaction in earthslides is not fully explained. As for the slip surface of the earthslide, Kameda et al. (2019) reported a distinct example of liquefaction in the field and the existence of a halloysite-bearing volcanic layer. It has also been suggested that sliding surfaces in halloysite-rich weathered pumice fall (loam) could facilitate the effective transfer of landside mass (Umeda et al. 2019). As for rockslides, the existence of inter-bedded weak material or of the bedding plane itself might control the movement of rockslides because all rockslides that we could confirm had dip-slope structures.

In the area of earthslides, almost all materials on the slope failed except for the mountain ridge. In other words, there is seldom reserve material on the slope that could fail with the next earthquake or heavy rain. On the other hand, most rockslide bodies still existed on slope, and their stability had not been fully researched except for some distinct rockslides like along the Hidaka–Horonai River. It is very important to analyse both the distribution of earthslides and rockslides caused by this earthquake and past events for future measurement of landslides. In this study, we clarified that the high (0.5 m) resolution DEM and shaded relief map comprise a rapid and powerful investigation tool to provide the description and history of the earthquake-induced landslide disaster, while the 5 m-resolution DEM by GSI is not quite satisfactory for the investigations.

Conclusion

We newly identified 259 hidden rockslides triggered by the 2018 Hokkaido Eastern Iburi Earthquake in Atsuma Town area using high-resolution DEM and a shaded relief map. The rockslides were subdivided into 196 certain rockslides of ridge-types (109) and slope-types (87) and 63 possible rockslides as shallow-types. Thousands of earthslides caused by the earthquake were distributed in the northern area away from the epicentre, and were thought to be influenced by the local distribution of the thick and mantle-bedded tephra layers. On the other hand, the distribution of rockslides was found to differ from that of earthslides. Rockslides were densely distributed near the epicentre and occurred in unstable topography with dip-slope structures consisting of fine-grained sedimentary rocks of the Late Miocene. This suggests that the mechanism of the rockslides would be explained by the relationship between the geology, topography and strong ground motion around the epicentre.

We also distinguished many past landslide traces using high-resolution DEM and a shaded relief map, and clarified the importance of analyzing both the distribution of earthslides and rockslides caused by this earthquake and past events for future measurements.

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