Geoenvironmental Disasters

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Characteristics of tuff breccia-andesite in diverse mechanisms of landslides in Oita Prefecture, Kyushu, Japan

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Abstract

Heavy rainfall frequently occurred in Kyushu and triggers the landslides every year. This study observes the landslides which occurred in Oita Prefecture, Kyushu, Japan. The landslides in this study, consisting of the same soil materials, tuff breccia and andesite materials; however, the landslide mechanisms were different. Two landslides occurred caused by heavy rainfall in the different timing of the landslide occurrence, and another landslide occurred without the heavy rainfall or an earthquake occurs. Therefore, this study aims to analyse the physical and mechanical properties of tuff breccia and andesite materials with diverse landslide mechanisms. This study performed soil stratigraphic analysis and soil hardness measurements in the field, and performed physical properties, saturated permeability, mechanical properties, and XRD tests in the laboratory. This study found that characteristics of tuff breccia and andesite in diverse mechanisms of landslides were not very different, especially on the landslides caused by heavy rainfall. Furthermore, the landslide in the andesite and tuff breccia areas could be divided into three types based on the timing of the landslide occurrence, scale of the landslide, and landslide mechanisms.

Keywords: Andesite, Landslide mechanisms, Mechanical properties, Physical properties, Saturated permeability, Tuff breccia

Introduction

Heavy rainfall frequently occurred in Kyushu and triggers the landslides every year. The rainfall lead to the landslide because a lot of factors such as groundwater and moisture content could reduce the strength (Li et al. 2015). This study observes the landslides which occurred in Oita Prefecture, Kyushu, Japan. The landslides in this study consisted of the same materials. Figure 1 shows that the landslides in this study consisting of the same geological formation, igneous rock formation: andesite, basaltic andesite lava, and pyroclastic rocks from the Neogene period (Geology Survey of Japan 2020). The Yabakei landslide also consists of river deposits from the Holocene, Quaternary period (Geology Survey of Japan 2020).

However, the landslide mechanisms were different. The landslides in Ohtsuru and Ono, Hita City, were influenced by heavy rainfall whereas the landslide in Yabakei, Nakatsu City, was not influenced by earthquakes or rainfall. The discontinuous layer of permeability in tuff breccia layer was influenced the landslide in Yabakei (Kubota et al. 2018). Noviyanto et al. (2020) also reported that variations in volcanic rock and soil characteristics with clay-rich content can potentially form the sliding layer in the discontinuity layer.

The characteristics of tuff breccia and andesite at diverse landslide mechanisms in Oita Prefecture has not been studied in detail. Istiyanti et al. (2020) studied the physical properties of tephra layers and reported that the kuroboku and scoria layers have different physical properties of soil.

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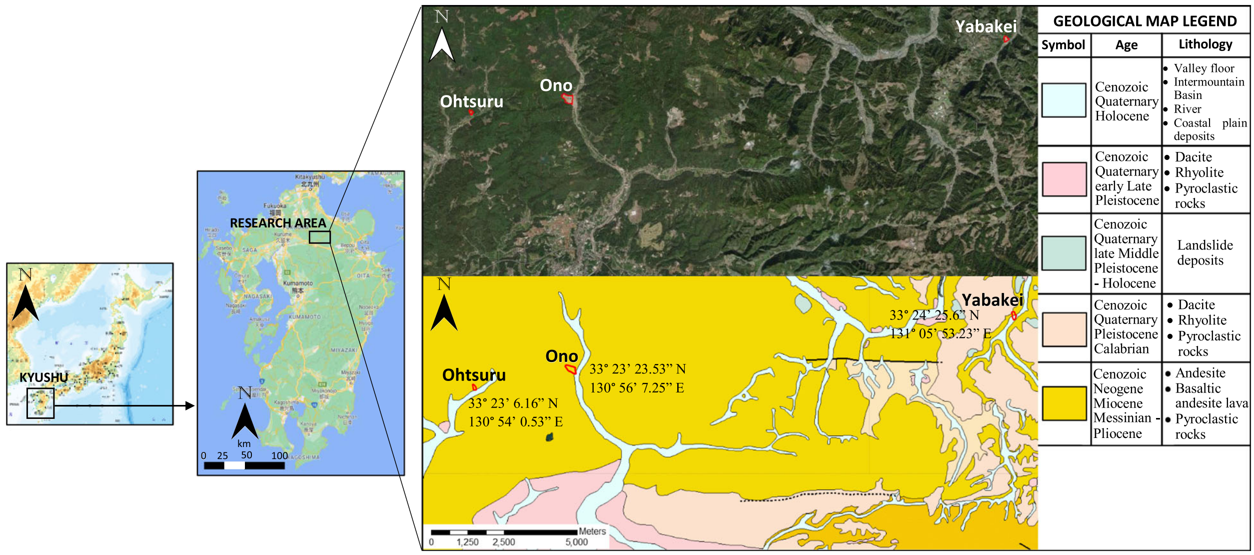

Fig. 1 Location of the landslides and geological map in this study (Geology Survey of Japan 2020)

The kuroboku layers have higher fine fraction content and plasticity index than the scoria layers, furthermore, sliding layer was located at N3–4 kuroboku layer. Therefore, this study aims to analyse the physical and mechanical properties of tuff breccia and andesite materials with diverse landslide mechanisms.

Research area

Three landslides that occurred in Oita Prefecture, two landslides in Hita City, and another landslide in Nakatsu City were selected as the research area. The landslides in Hita City are named Ohtsuru and Ono landslides, and the distance between these landslides was around 3300 m. Ohtsuru landslide occurred near Yanase, Hita City, and the Ono landslide occurred near the Ono River, Hita City in Joguyama Mountain (645 m). Another landslide, called the Yabakei landslide, occurred in the Yabakei area, Nakatsu City.

On 5th July 2017, a wide area in Hita City was affected by heavy rainfall (Fig. 2 (a)). The Ohtsuru landslide occurred during the peak rainfall on 5th April 2017 with the total rainfall on that day was 336 mm (Japan Meteorological Agency 2020). The Ohtsuru landslide was a shallow landslide and has a narrow slope (Fig. 3). Other landslides occurred surrounding the Ohtsuru landslide, on the opposite side of Ohtsuru landslide, and beside the Ohtsuru landslide (Fig. 4). These landslides were also shallow and have the narrow slope.

Large-scale landslides in Ono occurred the day after the peak rainfall on 6th April 2017 with the total rainfall of 66.5 mm (Japan Meteorological Agency 2020). Two collapses occurred in the Ono landslide; andesite was exposed in the lower collapse and weathered tuff breccia was exposed in the upper collapse (Fig. 5). The observation was performed in the upper collapse, and the soil sample was taken from this location. Ono landslide was occurred probably because the permeability behaviour in thick collapsed of soil layer which has a depth around 20 to 30 m (Ochiai et al. 2017). Ochiai et al. (2017) also reported that many cracks have occurred in the upper part of the landslide and some of them are considered to be old cracks and cliffs. Furthermore, Chigira et al. (2018) reported that the sliding layer was formed in the exposed layer, the reddish-brown layer. This reddish-brown layer is clayey tuff breccia and the clay probably forms on this layer and make the impermeable zone in this layer; the upper layer (andesite lava) is saturated and the water pressure increases near the boundary (Chigira et al. 2018). Figure 6 shows the topographic map and cross-section of the Ono landslide. The evidence of landslide activity in the past was also observed in the Ono landslide at the previous studies (Ochiai et al. (2017), Chigira et al. (2018).

The Yabakei landslide was a large-scale landslide (Fig. 7) that occurred on 11th April 2018 without the occurrence of heavy rainfall or an earthquake. Figure 2 (b) showed that heavy rainfall was not occurred from the March, one month before the landslide, in Yabakei area. The Yabakei area repeatedly suffered from landslides, and the landslides always occurred in the same location at Yabakei area (Yabakei landslide investigation committee 2018). The smectification process was observed on the sliding layer at highly weathered tuff breccia layer in the Yabakei landslide (Fig. 8) (Yabakei landslide investigation committee 2018), and this study observed that sliding

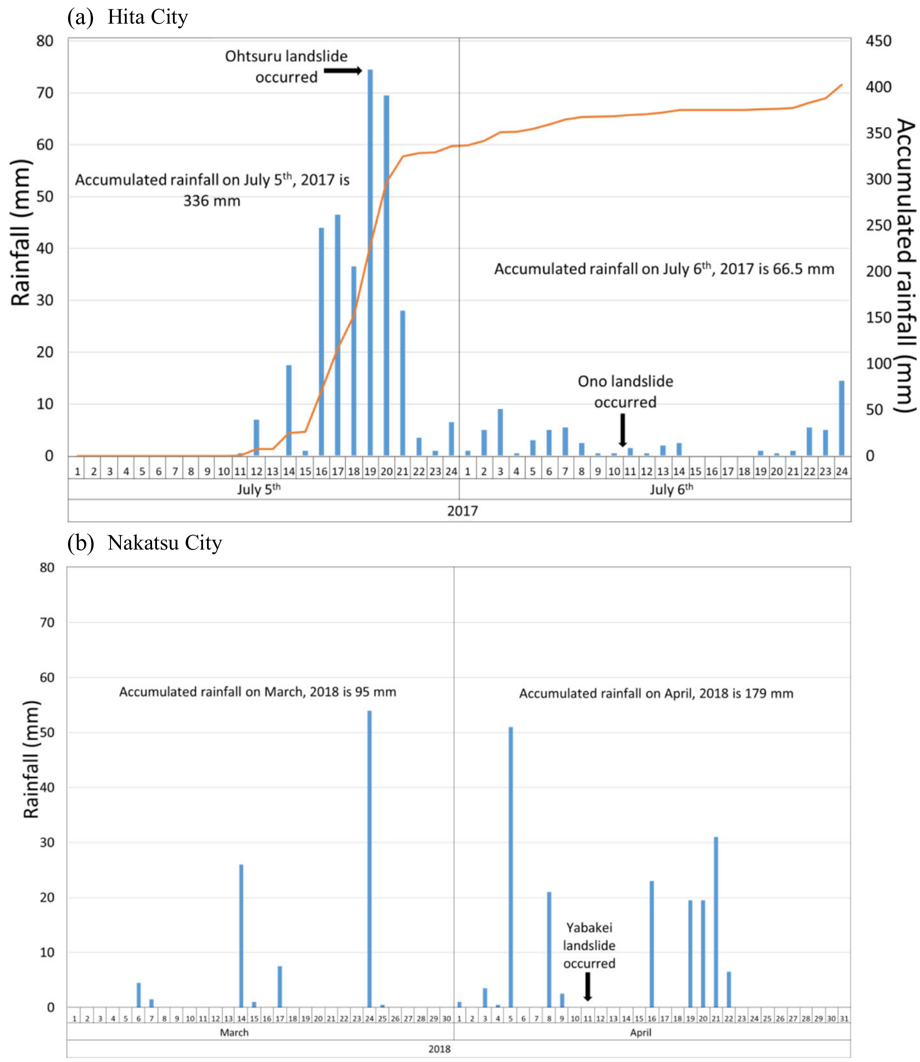

Fig. 2 Precipitation data on research area; (**a**) Hita City and (**b**) Nakatsu City (Japan Meteorological Agency 2020)

layer. In addition, Kubota et al. (2018) reported that the major cause of the Yabakei landslide was the weathered clay layer formed from the tuff breccia by a mineral-groundwater reaction, and groundwater was gushed out from approximately 20 m above sea level in the landslide with the surrounding bedrock was significantly altered and clayey.

Research methods

Field measurements

Soil stratigraphic analysis and soil hardness measurements were performed in the field. The stratigraphy analyses of each landslide were performed by scraping the surface to expose the soil layers, as shown in Fig. 9. The main soil layer in the Ohtsuru landslide was divided into 3 sub-layers from the surface to a depth of 6 m. Ohtsuru landslides consist of topsoil, highly weathered andesite, weathered andesite, and tuff breccia. Similar to the Ohtsuru landslide, the Ono landslide was divided into 3 sub-layers: weathered andesite, weathered tuff breccia, and tuff breccia. Unfortunately, because of the condition of the field which difficult to exposed the soil layers, the depth of the soil layers in the Ono landslide could not be identified. The soil layers in the Yabakei landslide also could not be exposed due to unfavourable conditions. Moreover, a depth of 1 m on the highly weathered tuff breccia was observed (Istiyanti and Goto 2020).

Soil hardness was measured using a Yamanaka-type soil hardness meter, which measures the soil hardness by inserting the device into the exposed soil layer at the site. Sasahara et al. (1995) reported that there is a strong positive correlation between the soil hardness and the shear strength parameters of soil in the Mohr–Coulomb failure criterion. Furthermore, Tokunaga and Goto (2017) found a discontinuity in the strength of pyroclastic materials in Aso volcanic mountains using a soil hardness

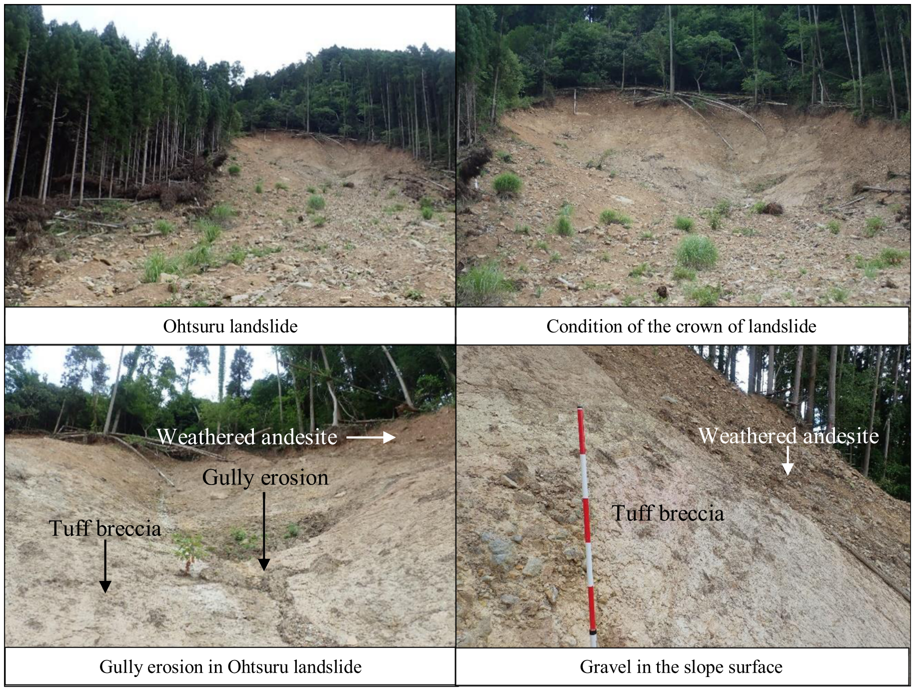

Fig. 3 Condition of Ohtsuru landslide (Photos taken on July 2018)

tester. In this study, the soil hardness values of each sub-layer at Ohtsuru and Ono, and highly weathered tuff breccia at the Yabakei landslide were measured. The undisturbed samples were collected from the centre of each soil layer to observe the characteristics of the tuff breccia and andesite in laboratory tests.

Laboratory tests

Tests for physical properties, saturated permeability, and mechanical properties were performed to observe the characteristics of tuff breccia and andesite. The tests for physical and mechanical properties were performed according to the laboratory testing standards of Geomaterials Vol. 1 (The Japanese Geotechnical Society 2015). Moreover, the test for saturated permeability properties was performed according to the methods for the permeability of saturated soils by Daiki (Daiki n.d.) using undisturbed samples.

Physical property tests of the soil performed in this study include the particle size distribution, liquid limit, and plastic limit tests. A particle size distribution test

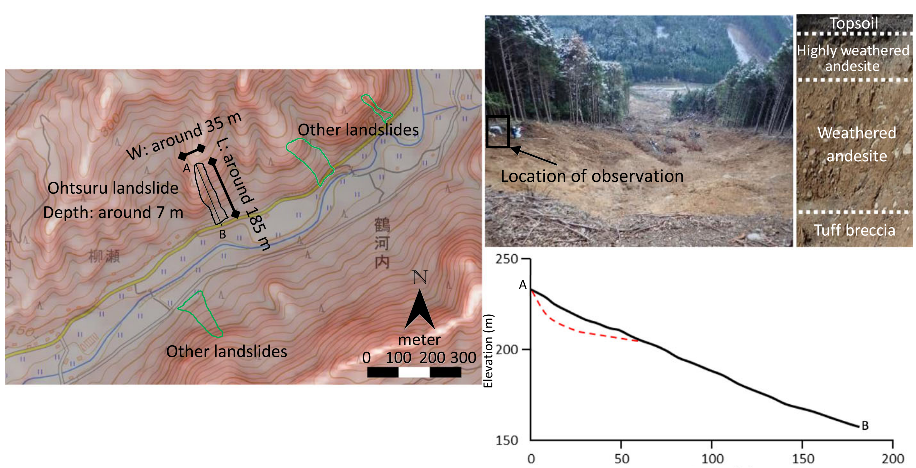

Fig. 4 Topographic map (Geospatial Information Authority of Japan 2020) with cross-section and photos of Ohtsuru landslide (taken on July 2017)

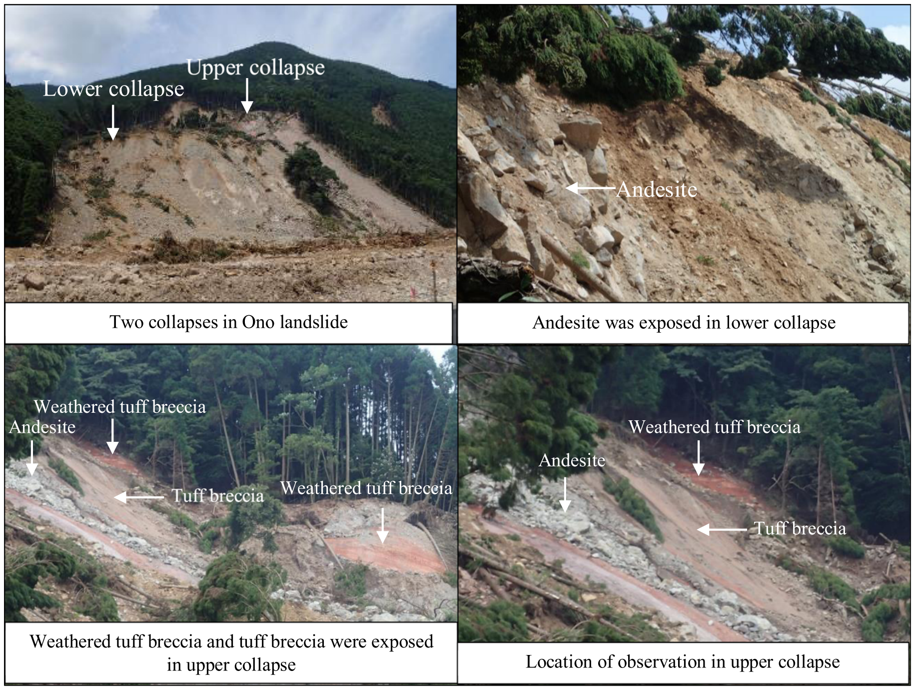

Fig. 5 Condition of Ono landslide (Photos taken on July 2017)

was performed to observe the relation between particle size (mm) and mass percentage passing (%) (JIS A1204 2009 cited in The Japanese Geotechnical Society 2015). The water content of the soil under different conditions, transition from plastic to the liquid state (liquid limit), and transition from plastic to semi-solid state (plastic limit) can be determined by the liquid limit and plastic limit tests (JIS A1205 2009 cited in The Japanese Geotechnical Society 2015). Furthermore, the mechanical properties were determined by the consolidated constant-pressure direct box shear test on soils (JGS 0561 2009 cited in The Japanese Geotechnical Society 2015) using undisturbed samples. This study also performed X-ray diffraction (XRD) tests to observe the clay minerals on tuff breccia and andesite; it was performed according to the randomly oriented powder

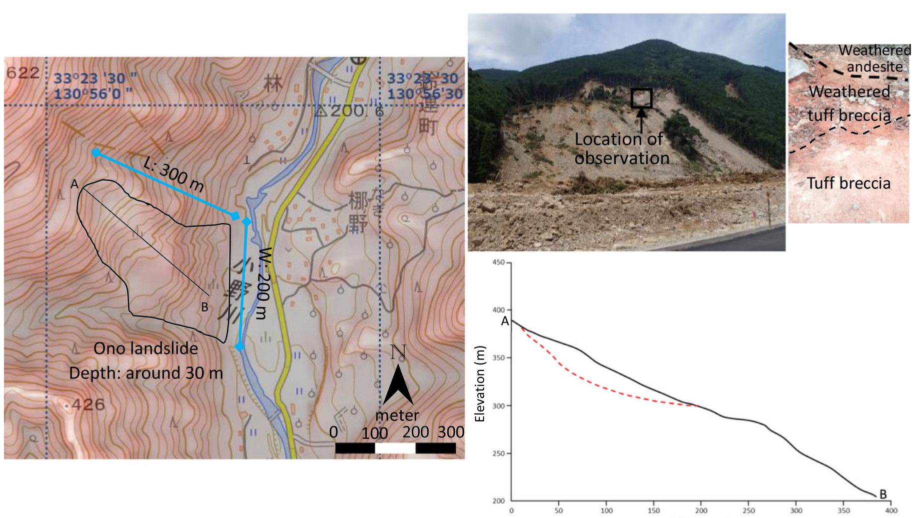

Fig. 6 Topographic map (Geospatial Information Authority of Japan 2020) with cross-section (modified Chigira et al. 2018) (photos taken on July 2017)

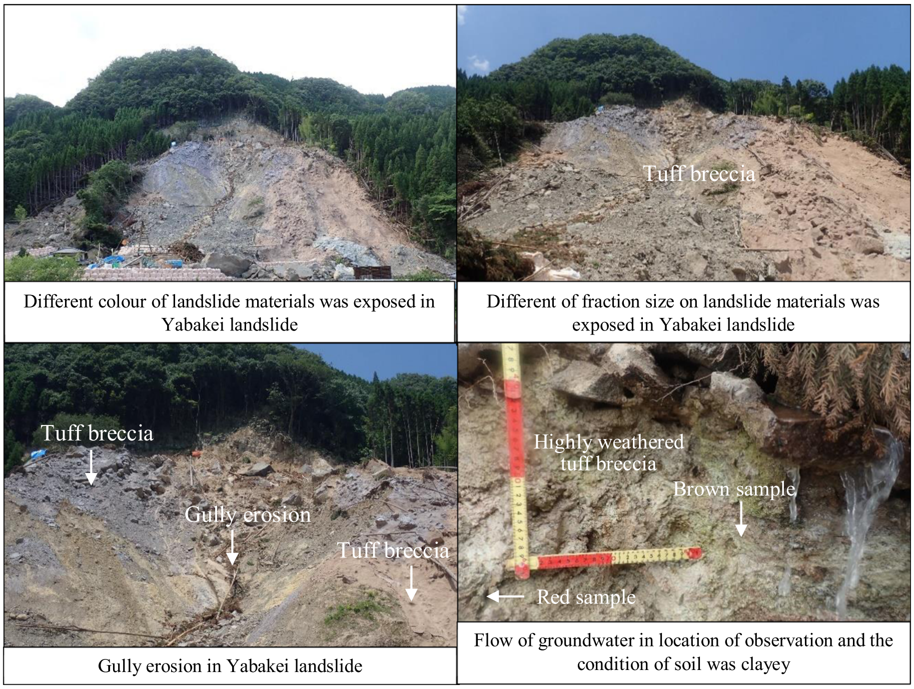

Fig. 7 Condition of Yabakei landslide (Photos taken on July 2018)

mounts, ethylene glycol treatment, and heat treatment methods from U. S. Geological Survey (US Geological Survey 2020).

Results

Soil hardness measurements

Figure 9 shows the soil hardness measurements during the field observation. An obvious difference in the soil hardness was observed between the tuff breccia and the upper layer in the Ohtsuru and Ono landslides. The soil hardness in the Ohtsuru landslide shows that the tuff breccia has the highest soil hardness value, and the weathered andesite has the lowest soil hardness value. Furthermore, the soil hardness in the Ono landslide also shows that tuff breccia has the highest soil hardness value, and the weathered tuff breccia has the lowest soil hardness

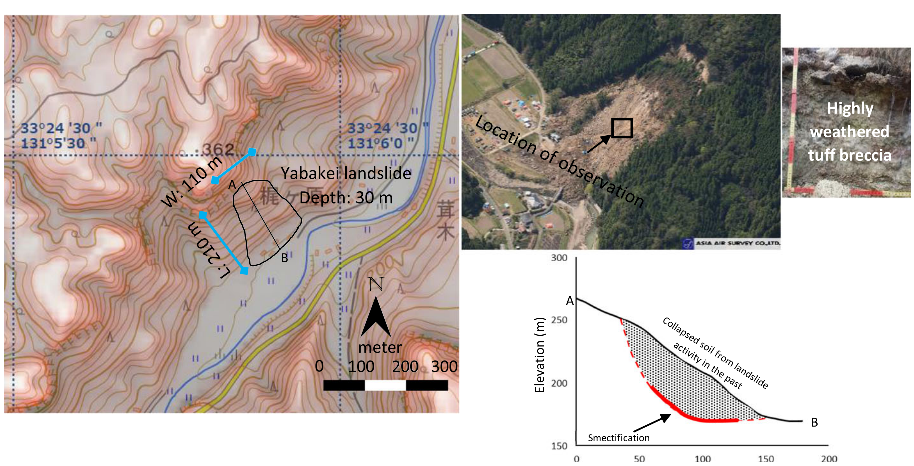

Fig. 8 Topographic map (Geospatial Information Authority of Japan 2020) with cross-section (modified Yabakei landslide investigation committee 2018), photo of slope from Asia Air Survey (2018), and photo of soil taken on July 2018

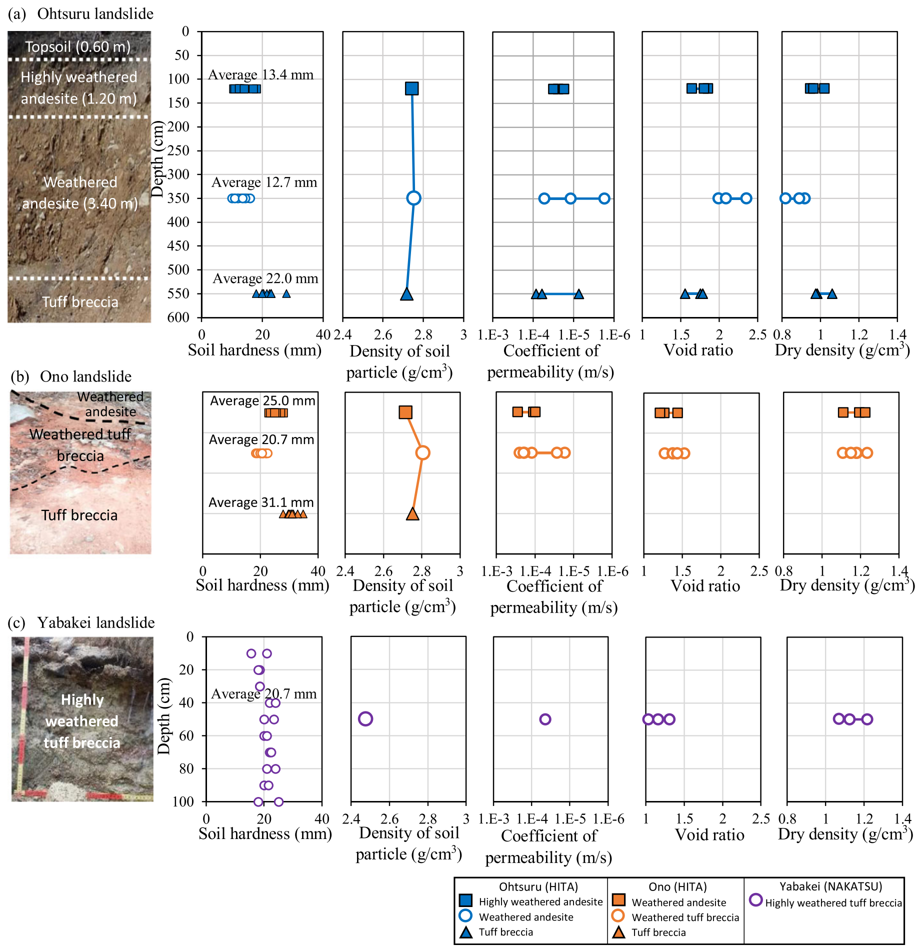

Fig. 9 Soil stratigraphy on the field, soil hardness, and saturated permeability properties values in (**a**) Ohtsuru landslide, (**b**) Ono landslide, (**c**) Yabakei landslide

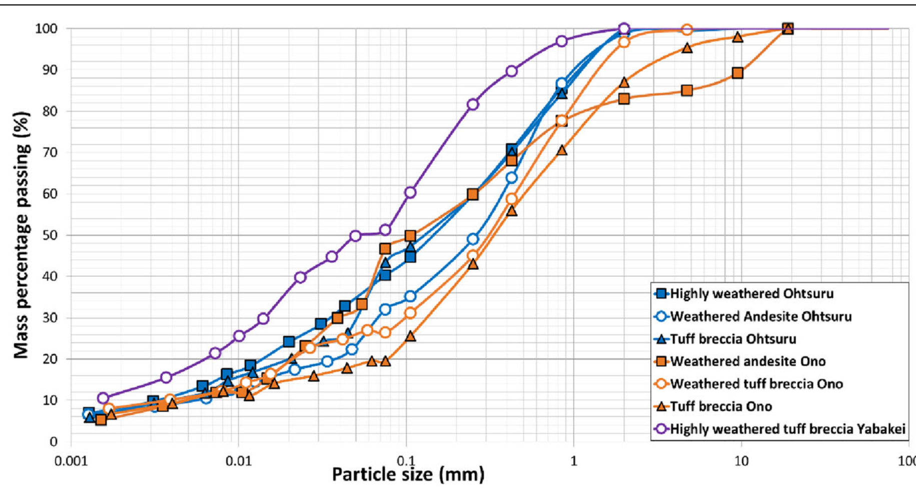

Fig. 10 Particle size distribution curves of soil materials

value (Istiyanti and Goto 2020). The soil hardness value in the Yabakei landslide was measured 1 m from the surface on the highly weathered tuff breccia layer. We could not observe other soil layers in the Yabakei landslide. Moreover, the highly weathered tuff breccia from the Yabakei landslide has a lower soil hardness value than the tuff breccia from Ohtsuru and Ono landslides.

Physical properties of tuff breccia and andesite

The density of soil particles (Fig. 9) showed that the soil materials from the Ohtsuru and Ono landslides have no dissimilarities; however, highly weathered tuff breccia from the Yabakei landslide has a low density of soil particles. The particle size distribution curve (Fig. 10) also shows no dissimilarities among the soil materials, and all the soil materials indicated a well-graded soil material. The particle size distribution curve for tuff breccia in the Yabakei landslide has the highest fine fraction content. Figure 11 shows the plasticity chart for classifying the soil materials using the liquid limit and plastic limit test results, which are separated among the sampling locations denoted by different colours, and sliding layers on each area are denoted by white circles with differently coloured outlines. The plotted data on plasticity chart showed that soil materials in the Ohtsuru landslide are inorganic silts of medium compressibility and organic silts. Furthermore, the plotted data of the Ono and Yabakei landslides are inorganic silts of high compressibility and organic clays.

The ratio of the plasticity index to the clay size fraction (percentage by weight of particles finer than 2 μm), termed the activity (Skempton 1953). Skempton (1953) also suggested three classes of activity: active, normal, and inactive, and subdivided them into five groups (Table 1). The greater the activity, the more important the influence of the clay fraction on the properties, and the more susceptible their values are to changes in factors such as the type of exchangeable cations and pore fluid composition (Mitchell and Soga 2005). The activity values are presented in Table 2 and the activity in soil materials from the Ohtsuru and Ono landslides have values of approximately 1–2. Moreover, the activity value in the highly weathered tuff breccia from the Yabakei landslide is greater than 3. The soil materials analysed in this study were active soil; however, the weathered andesite from the Ohtsuru landslide and the tuff breccia from the Ono landslide were normal active soil.

Saturated permeability properties of tuff breccia and andesite

Figure 9 shows the saturated permeability properties of the soil materials. This study measured the coefficient of saturated permeability on the highly weathered andesite, weathered andesite, and tuff breccia from the Ohtsuru landslide; on the weathered andesite and weathered tuff breccia from the Ono landslide; and on the highly weathered tuff breccia from the Yabakei landslide. The coefficient of saturated permeability, void ratio, and dry density from the test for the permeability of saturated soils showed no dissimilarities among soil materials.

Figure 12 (a) and (b) show the dissimilarities between the tuff breccia and andesite materials. Figure 12 (a) shows tuff breccia from the three landslides has the same range of coefficient of saturated permeability. The void ratio differed according to the weathering process, and highly weathered tuff breccia has a lower void ratio than tuff breccia. Furthermore, Fig. 12 (b) shows andesite materials from the Ohtsuru and Ono landslides have different coefficients of saturated permeability and void ratios. Andesite materials from the Ohtsuru landslide have a lower coefficient of saturated permeability and a higher void ratio than those from the Ono landslide. Different void ratios based on the weathering process are also observed in andesite materials from the Ohtsuru landslide; highly weathered andesite has a lower void ratio than weathered andesite.

Mechanical properties of tuff breccia and andesite

Tests for mechanical properties were performed on the highly weathered andesite from the Ohtsuru landslide, weathered andesite from the Ono landslide, and highly weathered tuff breccia from the Yabakei landslide. Two different colours were found on the highly weathered tuff breccia from the Yabakei landslide, and the direct shear test was performed on the red and brown samples of this layer. Direct shear test for the highly weathered andesite from the Ohtsuru landslide was performed at effective stress of 10–30 kPa. Direct shear test for the weathered andesite from the Ono landslide was performed at effective stress of 10–40 kPa, and that for the highly weathered tuff breccia from the Yabakei landslide at effective stress of 100–300 kPa. The relationship between the vertical displacement and shear displacement in Fig. 13 (b) shows that the weathered andesite in the Ono landslide has a dilative behaviour. Furthermore, the relationship between the maximum shear stress and vertical stress in soil materials is shown in Fig. 14. Unfortunately, the relationship between the maximum shear stress and vertical stress in highly

Table 1 Activity values in soil materials (Skempton 1953)

Classes of activity	Activity value
Inactive	< 0.5
Inactive	0.5–0.75
Normal	0.75–1.25
Active	1.25–2
Active	> 2

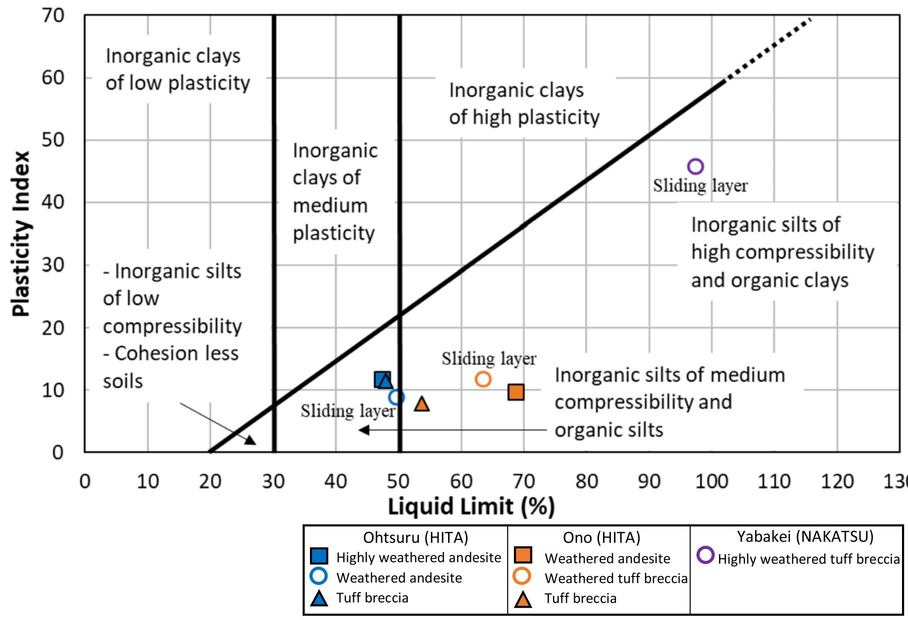

Fig. 11 Plotted data of soil materials on plasticity chart

weathered andesite from the Ohtsuru landslide could not be used in this study because of the dispersed test results.

Clay minerals in tuff breccia and andesite

A laboratory manual for XRD by the US Geological Survey (2020) divided the clay minerals into seven groups: chlorite, illite, kaolinite, mixed-layer clays, smectite, sepiolite, palygorskite, and vermiculite. Figure 15 (a) shows that the clay minerals in highly weathered andesite and weathered andesite from the Ohtsuru landslide consists of halloysite, illite, vermiculite, and montmorillonite. Furthermore, tuff breccia consists of halloysite, vermiculite, and montmorillonite. The content of clay minerals on soil materials from Ohtsuru landslide does not shows the dissimilarity.

In the Ono landslide (Fig. 15 (b)), the weathered andesite consists of sepiolite. Weathered tuff breccia consists of halloysite, sepiolite, montmorillonite, and dickite. The layer bed in the Ono landslide, i.e. tuff breccia, consists of halloysite, sepiolite, and montmorillonite. Moreover, highly weathered tuff breccia from the Yabakei landslide consists of illite, chlorite, and montmorillonite (Fig. 15 (c)).

Generally, the soil materials in this study consist of the smectite group minerals in each layer. Mitchell and Soga (2005) reported that the minerals of the smectite group have a prototype structure similar to that of pyrophyllite, consisting of an octahedral sheet sandwiched between two silica sheets. Water adsorbed onto the smectite between the unit layers and swell, and the smectite minerals are the dominant source of swelling in the expansive soils (Mitchell and Soga 2005). In addition, sliding layer in the landslides consist of the montmorillonite which is the expansive character of the group of smectite.

Table 2 Activity values in soil materials

Location of landslide	Soil materials	Activity	Type of soil
Ohtsuru landslide	Highly weathered andesite	1.46	Active
	Weathered andesite	1.19	Normal
	Tuff breccia	1.46	Active
Ono landslide	Weathered andesite	1.62	Active
	Weathered tuff breccia	1.39	Active
	Tuff breccia	1.11	Normal
Yabakei landslide	Highly weathered tuff breccia	3.82	Active

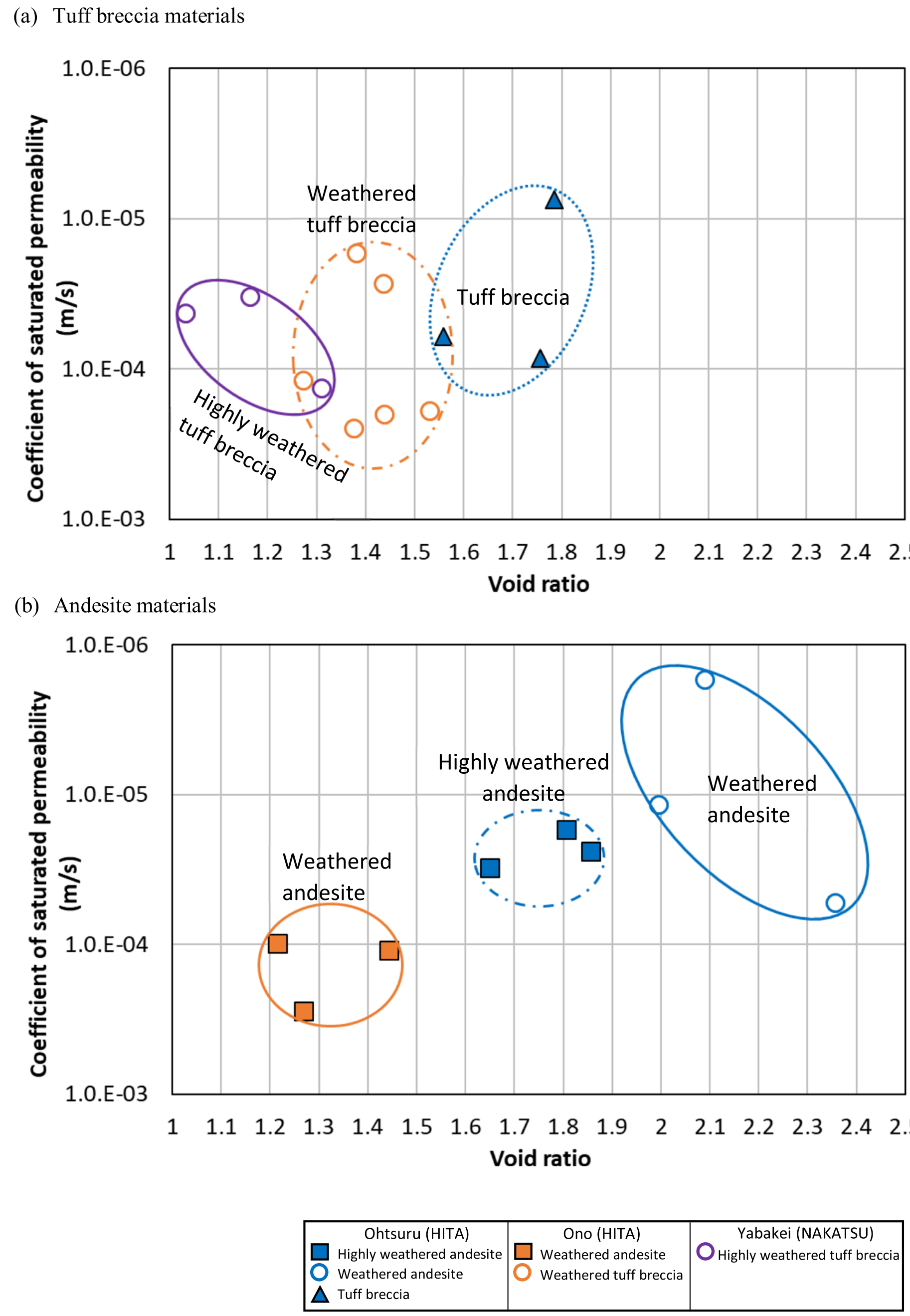

Fig. 12 Correlation between coefficient of permeability (m/s) and void ratio on (**a**) tuff breccia materials and (**b**) andesite materials

Discussion

Ohtsuru landslide

The sliding layer was located at the boundary between the weathered andesite and tuff breccia, approximately 5 m from the surface in the Ohtsuru landslide. An obvious difference in the soil hardness was observed between the weathered andesite and tuff breccia and showed the different strength on that layers. However, no dissimilarity was observed in the physical and saturated permeability properties. The upper layer, highly weathered andesite, exhibits a contractive behaviour. Unfortunately, the strength behaviour by the direct box shear test on weathered andesite and tuff breccia were not observed. Further study is needed to observe the strength behaviour by the direct box shear test in the Ohtsuru landslide.

Many shallow landslides occurred in the Ohtsuru area. The landslides occurred due to heavy rainfall and probably occurred during the peak rainfall. The mechanism of the Ohtsuru landslide may be influenced by the strength behaviour. The different strengths may be caused by the

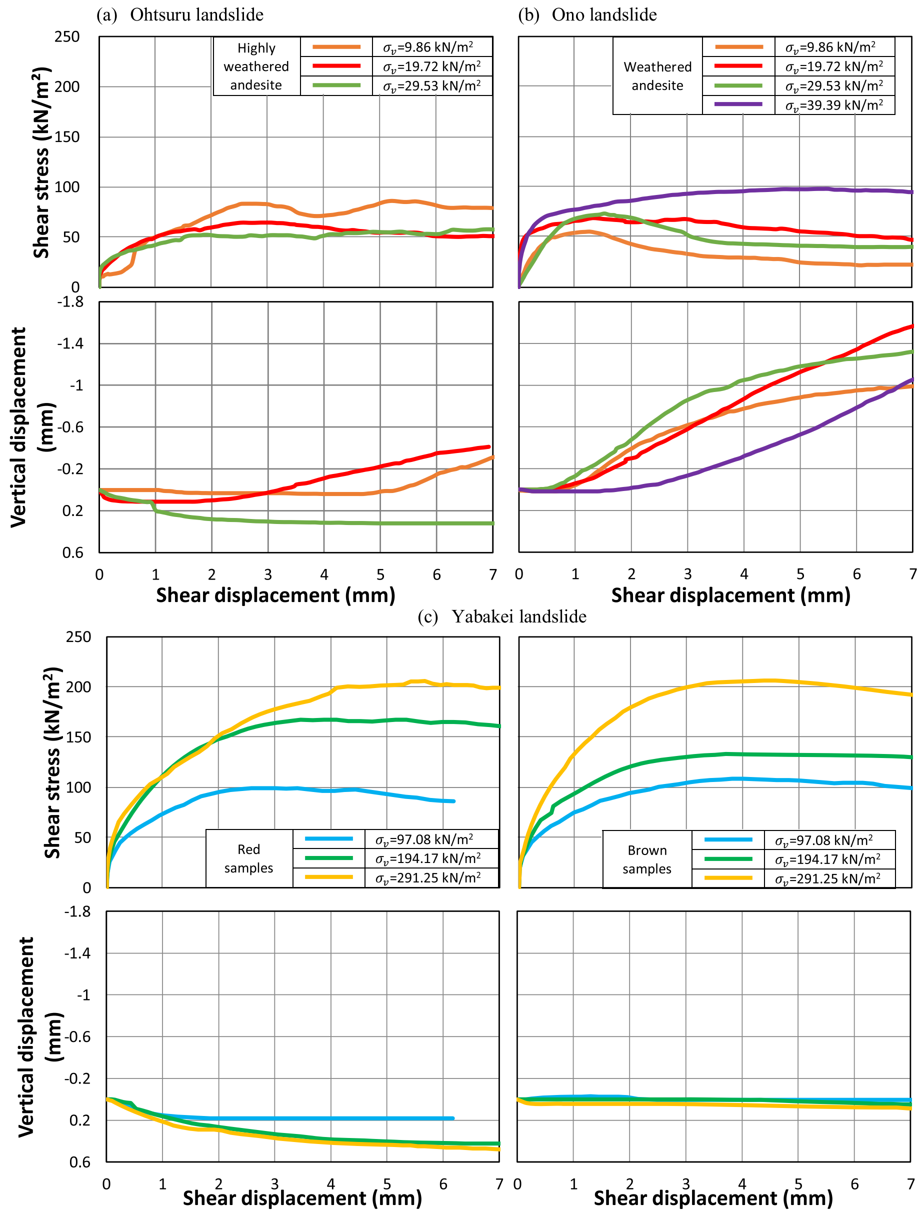

Fig. 13 Shear stress-shear displacement and vertical displacement-shear displacement behaviour in soil materials in (**a**) Ohtsuru landslide, (**b**) Ono landslide, (**c**) Yabakei landslide

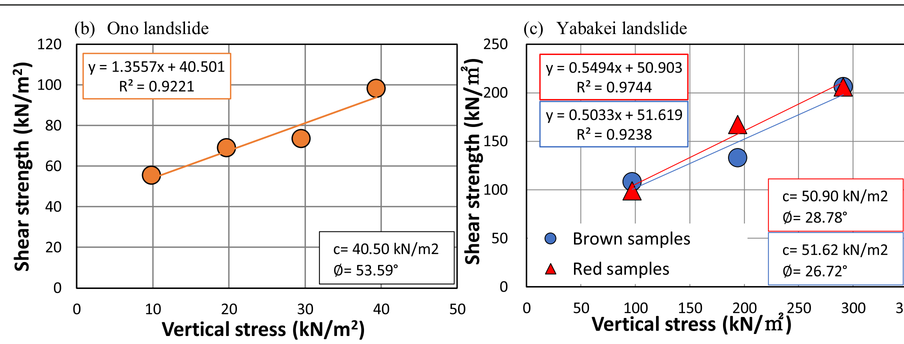

Fig. 14 Relation between maximum shear stress and vertical stress in soil materials in (**b**) Ono landslide and (**c**) Yabakei landslide

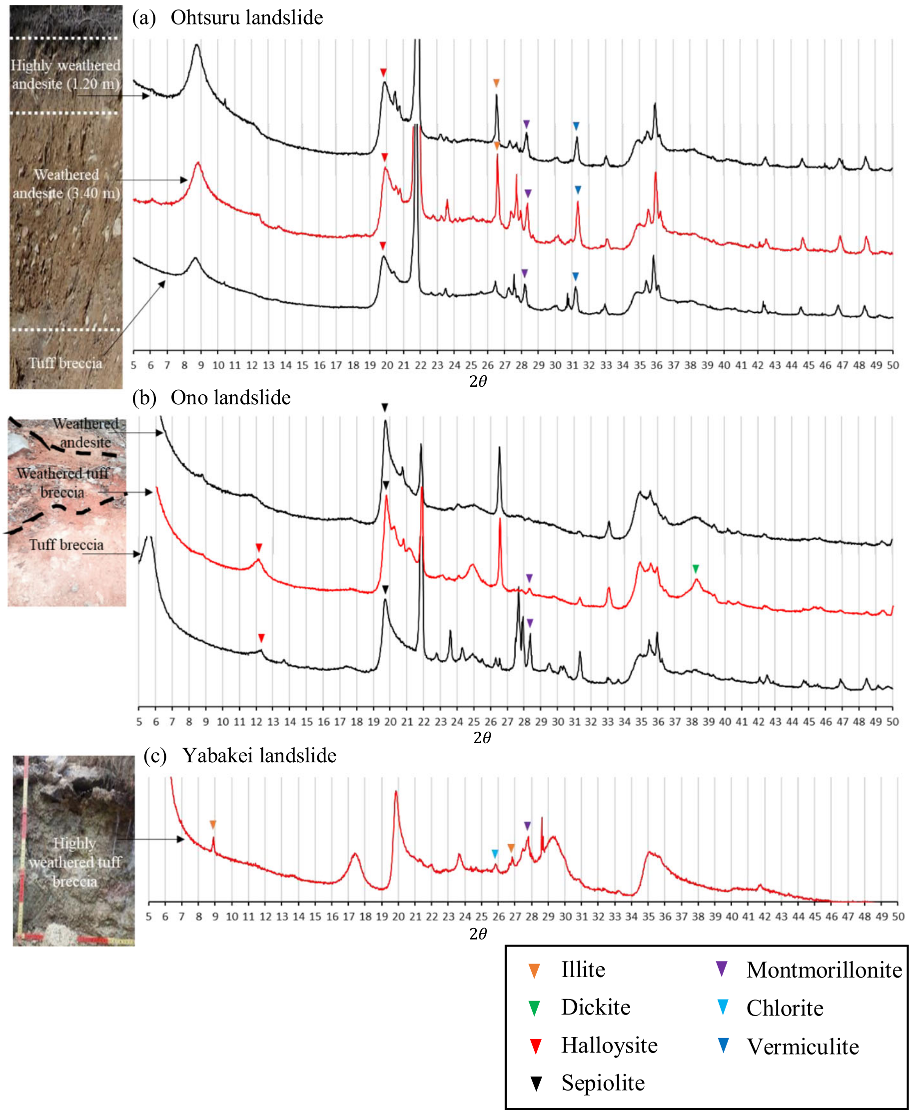

Fig. 15 X-ray diffraction on soil materials in (**a**) Ohtsuru landslide, (**b**) Ono landslide, and (**c**) Yabakei landslide

weathering process. The mechanism of other landslides near the Ohtsuru landslide could also be influenced by the same reason. Moreover, even though this study did not find any dissimilarities in permeability behaviour, this landslide occurred during the peak rainfall and is probably related to permeability behaviour.

Ono landslide

The sliding layer was located at a depth of around 30 m from the surface (Chigira et al. 2018) at the boundary between the weathered tuff breccia and tuff breccia, in the Ono landslide. An obvious difference in the soil hardness was also observed between the weathered tuff breccia and tuff breccia, and showed the different strength on that layers. However, no dissimilarity was found in physical properties. The upper layer, weathered andesite, exhibits a dilative behaviour. Unfortunately, the permeability behaviour of tuff breccia and the strength behaviour by the direct box shear test on the weathered tuff breccia and tuff breccia were not observed. Further studies are required to observe the permeability and strength behaviour in the Ono landslide.

The timing of occurrence of the Ono landslide, which occurred the day after the peak rainfall, could be influenced by permeability behaviour and the scale of the landslide. Furthermore, the landslide activity in the past could also influence this occurrence.

Yabakei landslide

Compared with the tuff breccia from the Ohtsuru and Ono landslides, the highly weathered tuff breccia from the Yabakei landslide has low strength and could be caused by the weathering process in this layer. The fine fraction content, plasticity behaviour, and activity value in this layer were also higher than those of tuff breccia from the Ohtsuru and Ono landslides.

For the soil permeability in the highly weathered tuff breccia from the Yabakei landslide, the permeability values of this study were higher than expected from field observations. The soil materials from the field observation were more clayey and should have had a low permeability. However, our results show that the highly weathered tuff breccia from the Yabakei landslide has a medium permeability, which could be caused by the landslide activity in the past, forming the complex layers. The strength behaviour of this layer exhibits a contractive behaviour.

The weathering process and landslide activity in the past could be the reason for this landslide. Landslide activity in the past caused higher weathering compared to the Ohtsuru and Ono landslides, due to which the fine fraction content and activity value increased and the strength of the soil decreased.

Types of landslide in the andesite and tuff breccia areas

Fan et al. (2017) classified the landslide dams associated with the earthquake in three types based on the composition material and sedimentological. Furthermore, this study also found that landslides in the andesite and tuff breccia areas could be divided into three types based on the timing of the landslide occurrence, scale of the landslide, and landslide mechanisms.

1) The landslide which occurred during the peak rainfall and it has the narrow slope. Generally, this type of landslide was found in the one area. This study also found the other three landslides in Ohtsuru area which have the same type with Ohtsuru landslide.
2) The large-scale landslide that occurred the day after the peak of heavy rainfall, such as the Ono landslide. The landslide activity in the past formed the low permeability zone and the infiltration of rainfall to the large-scale of slope was taking a several time. Therefore, the scale of the landslide and landslide activity in the past delayed the timing of the landslide occurrence.
3) The large-scale landslide that occurred without the occurrence of heavy rainfall or an earthquake, such as Yabakei landslide. The landslide activity in the past, which repeatedly occurred in Yabakei, made the groundwater gushed out. Furthermore, the weathering process in the soil high and the strength of the soil decreased.

Conclusions

Sediment disasters have frequently occurred in Oita Prefecture in 2017 and 2018. The characteristics of tuff breccia and andesite at diverse landslide mechanisms in Oita Prefecture has not been studied in detail, in addition, the landslides which observed on this study consisted of the same soil materials. Therefore, observations of the characteristics of tuff breccia and andesite in diverse landslide mechanisms in Oita Prefecture are of interest. This study performed soil stratigraphic analysis and soil hardness measurements in the field, and performed physical properties, saturated permeability, mechanical properties, and XRD tests in the laboratory.

Three landslides that occurred in Oita Prefecture were observed in this study. Ohtsuru and Ono landslides occurred caused by heavy rainfall on 5th July 2017 in a wide area in Hita City. Ohtsuru landslide occurred during the peak rainfall on 5th July 2017, and Ono landslide occurred in the next day, on 6th July 2017. Furthermore, different landslide mechanisms triggered the large-scale landslides in Yabakei, which occurred on 11th April 2018.

Characteristics of tuff breccia and andesite; physical properties, saturated permeability properties, mechanical properties, and the content of clay minerals in diverse mechanisms of landslides on this study were not very different, especially for the soil materials from Ohtsuru and Ono landslides. However, weathering process in Yabakei landslides formed the highly weathered tuff breccia which has high fine fraction content, plasticity index, activity value and low soil strength.

According to the results, this study found that landslides in the andesite and tuff breccia areas are of three types. The first type was a landslide with a narrow slope that occurred during the peak rainfall, such as the Ohtsuru landslide. This type of landslide was found frequently in the one area. The second type was the large-scale landslide that occurred the day after the peak of heavy rainfall, such as the Ono landslide. The scale of the landslide and landslide activity in the past delayed the timing of the landslide occurrence. Furthermore, the third type was a large-scale landslide that occurred without the occurrence of heavy rainfall or an earthquake, such as the Yabakei landslide.

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Authors' contributions
MLI, SG, and HO visited the landslide sites and selected a location to expose the soil materials, collected a sample, and conducted a field investigation to measure soil hardness. MLI and SG analysed and interpreted the soil behaviour regarding the materials at the landslide sites. The authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analysed during the study are available from the corresponding author upon reasonable request.

Competing interests
The authors declare that they have no competing interests.

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