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Research Paper

Sediment disasters caused by the 2016 Kumamoto Earthquake and regional disaster history

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ABSTRACT

In the 2016 Kumamoto earthquake, a lot of landslides, slope failures and debris flows occurred in mountainous regions around Mt. Aso. Most of the failed slopes were located near the earthquake faults caused strong vibrations. Although there was very little rainfall before the earthquakes, debris flows occurred along the mountain streams and eventually travelled long distances. It is noted that volcanic soil, being fragile and sensitive to disturbances, was widely distributed within the affected area. In this research, the conditions of large-scale failure, landslide, and debris flow are investigated to clarify the characteristics and history of earthquake-induced sediment disasters in the volcanic regions based on the results obtained from our investigation.

1. Introduction

Two earthquakes occurred over a two-day interval in Kumamoto Prefecture, southeast Japan, on 14 and 16 in April 2016. The earthquake foreshock occurred at 9:26 p.m. local time with a focal depth and magnitude of 11 km and *Mj* 6.5, respectively. The main shock occurred at 1:25 a.m. local time the following day with a focal depth and magnitude of 12 km and *Mj* 7.3, respectively. The magnitude of the main shock was equivalent to that of the Southern Hyogo Prefecture Earthquake in 1995 that caused serious damage, primarily in Kobe City. These earthquakes lasted for short periods of time. Aftershocks of intensity ≥1 were recorded 4,440 times as of 30 November 2017 (Japan Meteorological Agency, 2017). This number exceeds those that followed the Mid Niigata Prefecture Earthquake in 2004. Such seismic activity has never been previously measured in Japan.

Human loss and material damage from the earthquakes were enormous. A total of 88 lives were lost, 50 of which were direct casualties. The eastern suburb of Kumamoto City, Mashiki Town, experienced severe shocks, with intensity of seven, twice. In this town, many wooden houses were destroyed and people were crushed to death. Roads and bridges were also severely damaged in affected areas. A bridge over the Kyushu Expressway collapsed, stopping transport needed for restoration work. The earthquakes damaged cultural assets and historical buildings, such as Kumamoto Castle and the Aso Shrine. A tower in Kumamoto Castle was

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partially damaged and part of the stone walls collapsed during the earthquake. The main building of the Aso Shrine was crushed. Liquefaction occurred in the soft ground of the alluvial plains, natural levees, and rice and other crop fields. Furthermore, large-scaled failures, landslides, and debris flows occurred regionally around Minamiaso Village, causing nine fatalities.

A joint investigation team organized by the Japan Society of Civil Engineers (JSCE) and Japanese Geotechnical Society (JGS) conducted an emergency field survey. The results of the investigation were reported by Matsuda et al. (2016). In the investigation, we focused on the seismic faults conditions, slope failures and debris flows in the affected areas around Minamiaso Village. Furthermore, we investigated the history of disasters in the Kumamoto region based on regional archives. This paper provides a comprehensive examination of slope disasters caused by the earthquake and their frequency of occurrence.

2. Seismic activity and active faults

The source area of the 2016 Kumamoto Earthquake in central Kyushu is located under the NS extensional stress field created by the Philippine Sea Plate subducting beneath the Eurasian Plate. Many active faults and volcanoes are distributed in this area, as shown in **Fig. 1** (Nakata and Imaizumi, 2002). The Beppu-Haneyama fault zone and the Futagawa-Hinagu fault zone are well known major active faults in central Kyushu. In the 2016 Kumamoto Earthquake, the foreshock was caused by the movement of the Hinagu active fault. The main shock was caused by the movement of the Futagawa active fault in conjunction with the Hinagu active fault. The earthquake revealed right-lateral strike-slip surface faults extending from the southwest to the northeast. The total length of the fault series was approximately 31 km, and the maximum total fault displacement was close to 2.0 m at Dozon in the Mashiki Town and approximately 1.3 m near Tateno in Minamiaso Village. These coseismic ruptures represent the characteristic movement of the north-eastern portion of the Futagawa-Hinagu Fault zone. The magnitude and epicentre of the earthquakes were almost as predicted. Because this area has historically experienced powerful earthquakes several times, saying that people have suffered due to earthquakes would not be an exaggeration.

3. Sediment disasters caused by earthquakes

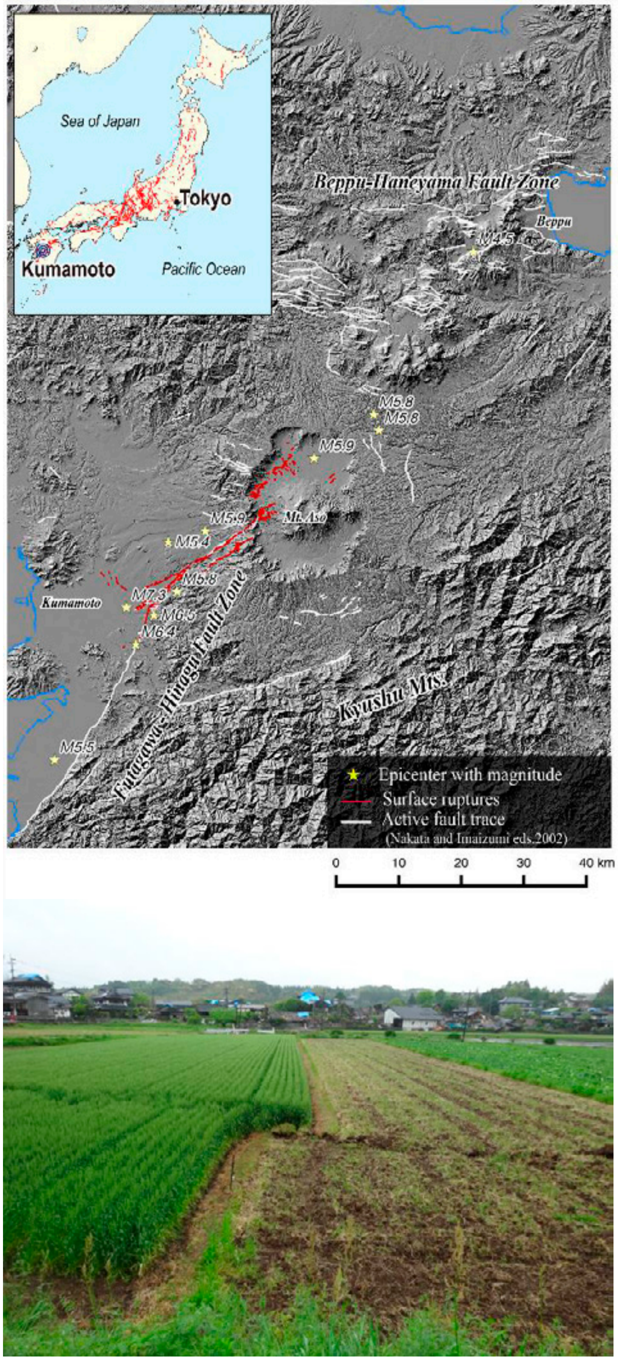

Fig. 1. Location of the epicentre with magnitude, surface ruptures, and active faults from the 2016 Kumamoto Earthquake (top; Nakata and Imaizumi, 2002).
A typical surface rupture, shown for Dozon, Mashiki Town (bottom).

Volcanic ash and lava were widely distributed in the mountainous region around Mount Aso. The fragile volcanic ash soil is sensitive to any disturbance. Small-sized slope failures were densely distributed in the volcanic soil ground, while large-scale failures were scattered over steep slopes inside the Aso caldera and outer crater rim. The number of sediment disasters totalled 190 in the region encompassing Kumamoto, Oita, Miyazaki, Kagoshima, Saga, and Nagasaki Prefectures.

However, most were concentrated in Kumamoto Prefecture. The sediment disasters included 57 debris flows, 10 landslides, and 123 slope failures as of 16 October 2017 (Ministry of Land, Infrastructure, Transport and Tourism, 2017). The sediment disasters that caused human fatalities were concentrated in the Minamiaso Village area.

This area receives high rainfall. The mean annual rainfall is 3206.2 mm and mean monthly rainfall in April is 237.7 mm, based on data from the Asosan observation station (AMeDAS Asosan, JMA). Thus, the areas around Mt. Aso are sources of water supply for Kumamoto City. Before the earthquake, the only precipitation that month had been 56 mm on 7 April 2016; there had been little rain until the foreshock occurred. Thus, the influence of rainfall on the sediment disasters can be considered negligible. However, it rained 21.5 mm and 56 mm on 17 and 21 April, respectively (AMeDAS Mashiki, JMA). When the accumulated precipitation reached 323 mm the 20-21 June, debris flows were reactivated in the mountain stream where they had occurred immediately after the main shock. Thus, secondary damage was caused by rainfall after the earthquake. In the report of Kitazono et al. (2016), the authors classified sediment disaster types as large-scale slope failure, landslide, slope failure, and debris flow.

3.1 Large-scale slope failure

A large-scale slope failure occurred in the vicinity of the Aso-ohashi Bridge in Tateno area, Minamiaso Village (Figs. 2-4). During the earthquake, a long slope slid from the mountain ridge, 755.8 m in elevation. The failed portion was estimated to be 700 m in length, 300 m in width, and 20 m in depth, with a 35–40° slope. A 206 m bridge constructed in 1970 across the Kurokawa River collapsed, cutting off road traffic and railways. Bridge piers, abutments, and foundations withstood the collapse. A combination of earthquake vibration, overloading of accumulated soils, and surface ruptures due to earthquake faults was considered the cause of the bridge collapse. Most sediment flowed into the river with some reaching the opposite bank in the Kawayo area. The earthquakes revealed regional surface faults, which were found to extend the line of the Futagawa fault.

The failed slope was composed of volcanic soil (Kuroboku soil), andesite tuff, andesite lava, and tuff breccia. Kuroboku soil is a type of organic clayey soil originating from volcanic ash. Volcanic ash at the surface ground failed and simultaneously the bedrock lava collapsed due to the strong vibrations. Slope failure resulted in a deeper and larger slide. Aerial photographs taken by the US armed forces in 1956 (obtained from the

Fig. 2. Image overview of large-scale slope failure covering the Aso-ohashi Bridge.

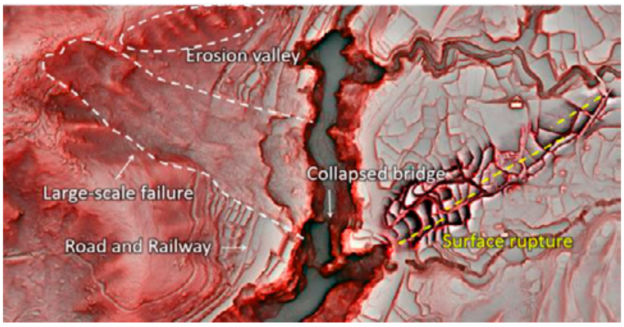

Fig. 3. Red relief maps and detail of large-scale slope failure. Original map obtained from Asia Air Survey Co., Ltd.

Fig. 4. Image showing surface cracks exposed on the opposite side of the large-scale slope failure.

Geospatial Information Authority of Japan) confirmed that erosional valleys had developed along the mountain ridgelines. Additionally, using unmanned aerial vehicles, we observed fissures and cracks on the ground and unstable rock masses along the ridge and side of a mountain.

Fig. 5. Image of the landslide at Takanodai.

Fig. 6. Image showing landslide sliding conditions with a distant view of the large-scale slope failure.

Fig. 7. Image showing a pumice fall deposit on the slip surface.

3.2 Landslide

A landslide slipped on a gentle slope (10-20°) of a mountain like dome at Takanodai in the Kawayo area, Minamiaso Village **(Figs. 5-7).** The Aso Volcanological Laboratory belonging to Kyoto University is located at the top of the dome. The landslide initiated from a dome hillside and travelled in three directions. Part of the massive soil reached a residential area, killing five people. Alternately stacked volcanic soil (Kuroboku soil, Akaboku soil), clayey soil, and pumice-fall deposits were observed at the main landslide scarp. A landslide slip surface could have developed inside the pumice-fall deposit or the boundary between the clayey soil and pumice-fall deposit. The landslide thickness was approximately 6 m to 10 m. Our observations taken at the estimated slip surface could not confirm the effect of ground water on landslide behaviour.

Fig. 8. Image showing an overview of surface failure.

Fig. 9. Image showing an overview of another surface failure.

3.3 Surface failure

Surface failure caused human fatalities in the Nagano area, Minamiaso Village **(Figs. 8-9)**. Massive soil movement devastated accommodations, such as the Onsen Log Sanso Hinotori where two guests in the lodge died. In this area, surface failure occurred at two sites: at a local water collection site formed by a depression and at a slope break along a mountain ridge. Pumice-fall deposit was confirmed present around the slip surface. The pumice-fall deposit observed at the main scarp was similar to that in the Takanodai area. Although it did not rain on that day, the sample was wet. This suggests that the pumice acted as a permeable layer.

3.4 Debris flow

Although there was little rain in the 51 h prior to the earthquake, debris flows were initiated in the mountain

Fig. 10. Image showing debris deposition area and toe that occurred after the earthquakes.

Fig. 11. Image showing the spread of sediment.

stream along the Sannoutani River **(Figs. 10-11).** The river was recognized as a torrential river causing debris flow to communities. The Kuroboku soil and gravel travelled along existing channels and spread in the lower reach of the stream. The source area of the debris flow was located upstream of Mt. Koeboshidake. Numerous surface failures occurred in the natural slopes of the mountain. This implies that the debris flow may have been triggered by the inflow of river water causing sediments to accumulate along the river. Subsequently, debris flows were reactivated along the same stream when it rained on 21 June, two months after the main shock.

3.5 Disaster record

Figure 12 shows the occurrence years for Mt. Aso eruptions and debris flows from AD 553 to AD 1900 based on descriptions of the "Kumamoto prefectural disaster record" issued by Kumamoto Weather Station (1952). Records of debris flows and landslides were respectively described as mountain tides and landslips in

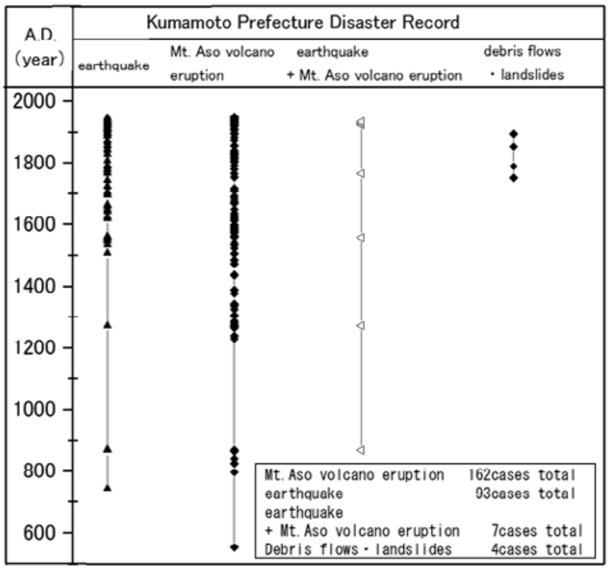

Fig. 12. Records of occurrence for Kumamoto prefecture region earthquakes, Aso volcano eruptions, and debris flows.

the disaster record. We found four sediment disasters and three earthquakes in the record. The occurrence interval for the four debris flows and landslides since AD 1751 is 38, 62, and 43 yr. Earthquakes also occurred three times, with intervals of seven, ten, and six years. There was only one record for Mt. Aso of a landslide associated with an earthquake, in 1854. Thus far, no prior relationships between earthquakes and debris flows have been found.

4. Conclusions

Several slope failures in surface soil composed of volcanic ash and lava were characterized in the region of the April 2016 Kumamoto earthquake. Typical failure types are summarized as follows:

1. The largest failure occurred at a natural slope near the Aso-ohashi Bridge. Volcanic ash in the surface soil and weathered lava bedrock collapsed due to strong vibrations. Slope failure resulted in a deep and extensive slide, classified as a deep-seated slide.
2. A landslide occurred on a gentle 10-20° slope in the Kawayo area. The failure had characteristic features of a fast and powerful landslide. Volcanic soil layers (Kuroboku and Akaboku soils), soft clay, and a pumice layer were deposited at the top of the slope. The pore pressure inside the slope was hypothesized to have increased during the strong vibrations, liquefying the soil on a slip surface and causing immediate slope failure and sliding. According to our observations, the landslide

occurred either between pumice layers or at the boundary between the pumice and clay layers.

3. Many surface failures took place at the steep slope around the central cone of Mt. Aso. The slope primarily consists of volcanic ash. Multiple surface failures occurred continuously in a lateral direction. A large amount of volcanic ash soil generated by the surface failures fell into a mountain stream. Debris flow occurred immediately following the earthquake and may have been triggered by river water. Numerous cracks and fissures are still recognized at ridges and sides of mountains, and unstable rock piles remain in mountain streams, scarps, and source areas. Therefore, the possibility of further collapse may initiate additional debris flows and is a hazard concern.
4. Based on historical disaster records, no prior relationships between earthquakes and debris flows have been found in this region.

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