Shear Behavior of Pumice Fall Deposit and the Seismic Triggering Mechanism of the Takanodai Landslide

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Introduction

On April 14, 2016, a Mw 6.3 foreshock struck the Kumamoto region in Kyushu, Japan. Approximately 28 hours later, it was followed by a Mw 7.0 mainshock, which caused severe damage to the affected area. In the Aso region, nearly 3000 landslides were identified within an area of 20 km², indicating an extremely high landslide density. The ground surface is predominantly covered by volcanic ejecta and gravelly materials. Among many landslides, a long travelling slope failure was observed at the foot of Aso Volcano, where the slope angle is relatively gentle.

The Takanodai Landslide

The Takanodai landslide occurred on the gentle western flank of a small parasitic cone of Aso Volcano, with the Aso Volcanological Laboratory of Kyoto University located at the top. The landslide is approximately 480 m in length and 700 m in width (Fig. 1). The mobilized mass developed into three major landslide blocks during motion. The slope angle before the mainshock is estimated to be about 15 degrees.

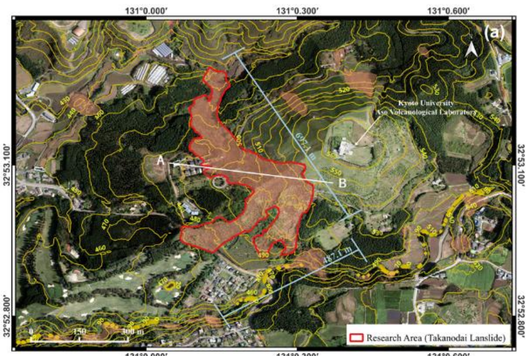

Fig. 1 The Takanodai Landslide (DEM data and Air photography provided by GSI).

Based on field investigations, the slip surface at the head scarp of the landslide was identified to be at a depth of approximately 8 m and a white weathered pumice fall deposit layer was outcropped. This white weathered layer experienced partial clay mineralization. Representative samples of the weathered pumice deposit were collected, and a series of laboratory tests were subsequently conducted

Physical Properties of the Pumice Deposit

The particle size distribution indicates that the material can be classified as a gravel sand. The hydraulic conductivity is as low as 1.75×10^{-6} cm/s.

Results of Ring Shear Tests

As shown in Fig. 2, in the stress space, the peak shear strength of the specimens increases with increasing normal stress. However, under both drained and undrained conditions, all specimens subjected to monotonic shearing exhibit a rapid strength reduction once the shear stress exceeds the peak value. The residual friction angle approaches zero, indicating that the residual shear strength is provided almost entirely by apparent cohesion. These two mechanical behaviors are highly consistent with the characteristic features of static liquefaction.

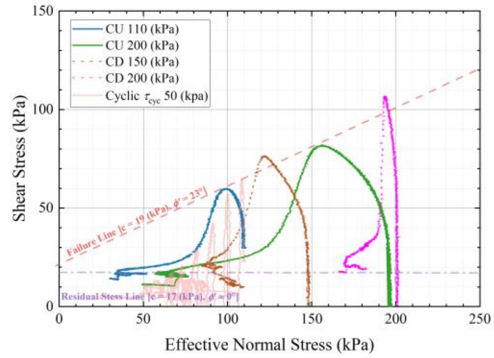

Fig. 2 The stress paths under different normal stress and drainage conditions.

It is also noteworthy that, under drained conditions, the stress path didn't follow a purely vertical trajectory. Instead, a certain amount of excess pore water pressure (EPWP) still accumulated during shearing. This accumulation implies that the EPWP generated within the shear zone cannot dissipate timely with shear displacement, reflecting the inherently low hydraulic conductivity of the material. Therefore, considering that the sensor was not directly connected to the shear zone, it is inferred that the measured EPWP is significantly lower than the actual value. This discrepancy indicates that static liquefaction had already occurred during shearing, which resulted in a sudden reduction in shear strength and a residual friction angle approaching zero.

Under cyclic loading with an amplitude of 50 kPa, which was determined based on the mainshock, the specimen experienced rapid failure within five cycles. Meanwhile, the EPWP increased sharply with each cycle. At the end of cyclic loading, the residual friction angle also approached zero. In contrast, under cyclic loading with an amplitude of 35 kPa determined from the foreshock, the EPWP

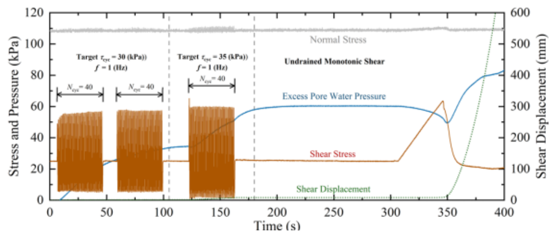

Fig. 3 Ring shear test results under cyclic loading with an amplitude of 35 kPa.

accumulated slowly, and only minor displacement was observed. No failure occurred during the test, as shown in Fig. 3.

Slope Stability and Runout Analysis

The stability and runout behavior of the Takanodai landslide were analyzed using a modified Newmark method. Based on the results of the ring shear tests, the yield acceleration was determined as a function of shear displacement. As shown in Fig. 4, Under the mainshock loading, the seismic acceleration significantly exceeded the yield acceleration, resulting in large displacement accumulation and continuous acceleration of the sliding mass.

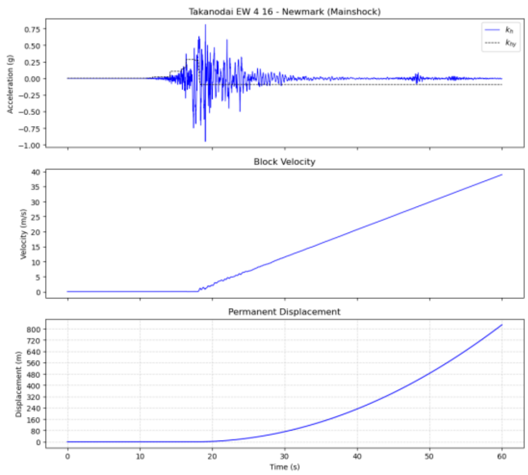

Fig. 4 Results of the Newmark analysis for the Takanodai landslide under mainshock loading.

Conclusion

(1) Under monotonic shearing, the saturated pumice deposits experience static liquefaction, which leads to a sudden reduction in shear strength and a residual shear friction angle approaching zero.

(2) The strong acceleration during the mainshock of the Kumamoto earthquake caused the failure of pumice deposits and triggered the Takanodai landslide.

(3) The high mobility of the Takanodai landslide originated from the liquefaction of the pumice deposits.