Geomorphological and geological features of the collapsing landslides induced by the 2009 Padang earthquake

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Abstract

The Mw7.6 Padang earthquake in 2009 attacked the northwest of Sumatra, Indonesia, and triggered many landslides. We made satellite image interpretations, field investigations, and laboratory tests to identify the geomorphological and geological features of these landslides. As a result, we found that the number of landslides was 159, slid materials were pumice fall deposits, and their sliding surface was made in the base of the pumice layer, where pumice grains were mixed with the soil beneath the pumice bed. These landslides had the following characteristics: 1) they occurred in the areas with pumice fall deposits (Qhpt: Quaternary hornblende-hypersthene pumice tuff) with >3 m thickness, which was controlled by the distance from their source; 2) the pumice fall deposits had a slope-parallel layering, which had been cut at the foots of slopes; and 3) the mixed layer at the base of the pumice fall deposits was heavily weathered to be clayey materials with abundant halloysite. Interpretations of stereoscopic satellite images and field surveys showed that there are four terraces along the Magung River, and Qhpt covers widely distributed higher terraces (Lh) and middle terraces (Lm) but are cut by lower terraces (Ll1 and Ll2) as well as small nearby tributary gullies. This undercutting likely reduced the support of Qhpt beds from downslope. The mixed layers, in which sliding surfaces were formed, were heavily weathered and very weak. XRD analyses showed that pumice grains of the main part of Qhpt scarcely had halloysite but pumice grains and weathered debris flow deposits in the mixed layers were rich in halloysite. The geological history, which is volcanic eruption, weathering, and undercutting by river incision as stated above, is typical in tropical volcanic areas. That means we can make a hazard map of such a catastrophic landslide induced by earthquakes on the basis of geological development.

Keywords: 2009 Padang earthquake, Halloysite, Collapsing landslide, Pumice fall deposits, weathering

1. Introduction

The Mw7.6 Padang earthquake on 30 September, 2009 triggered many landslides, which were very rapid and highly destructive. Those landslides attacked valley bottom villages and killed at least 130 people (Fig.1). The landslides occurred during heavy rain, of which amounts were not recorded. We made satellite image interpretation and field survey to clarify landslide distribution, characteristics, and the relationship between landslides and the geological or geomorphological features.

2. Location

The epicenter of the 2009 Padang earthquake was located at 60 km offshore from Padang city; Central Sumatra of Indonesia (Fig. 2). Landslides occurred in the Tandikat area at an epicentral distance of 45-55 km (Fig. 2).

Fig. 1 Landslides triggered by the 2009 Padang earthquake (AP Photo/Dita Alangkara date：Oct 3. 2009).

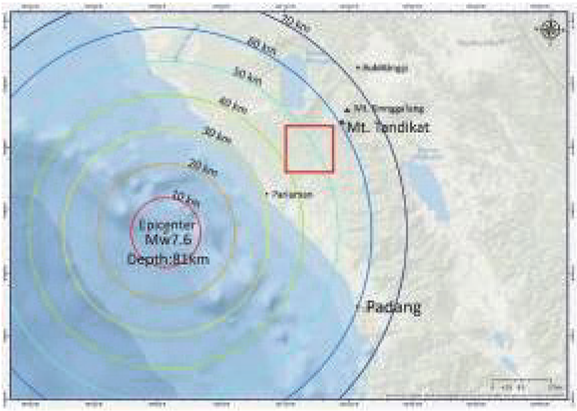

Fig. 2 Location of the epicenter of the 2009 Padang earthquake (USGS, 2009) and the landslide concentration area (red square).

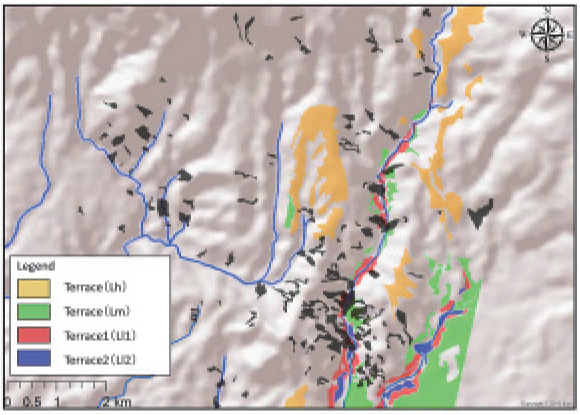

Fig. 3 Distribution of landslides (black) and river terrace.

3. Methods

3.1 Mapping of the collapsing landslide

To identify the distribution of landslides, we interpreted a Spot-5 Image with 10-m resolution taken 13 Oct, 2009. During the field surveys, we checked 14 landslides.

3.2 Classification of the topography

To classify the landscape, particularly river terraces and to clarify the landscape development, we made stereoscopic examination on ALOS PRISM images with a resolution of 2.5 m taken on 11 February 2012.

3.3 Field investigation

We made geological mapping, investigation on landslides with cone penetration tests (3kg weight 50 cm falling) and sampling for laboratory tests. Our field observations in and around Tandikat area were on 8/31 – 9/9, 2012, and 8/20 – 8/25, 2013.

3.4 Soil test and analysis

We made mineral analysis with X-ray diffraction, scanning microscopic observation (SEM), simple shear tests under the conditions of constant normal stress or constant volume, and measurements on physical properties (permeability, consistency limits, water contents, degree of saturation).

4. Results

4.1 Topography and landslide distribution

We found four terrace groups (high terrace, middle terrace, low terrace 1, and low terrace 2 in Fig. 3) and that landslides occurred on the valley slopes which were made by river incision of the high terraces. The slopes incised on the high terraces were recognized to be cut by the scarps of middle terrace and low terrace 1 on the PRISM images. Along the Maggung River, we observed that landslide slopes had been cut by the scarps of low terrace 1. Landslide slopes on nearby tributary catchments can be assumed to have been cut by small channels.

We identified 159 landslides on the Spot 5 image within 64 km^2.

4.2 Geology

The affected area is widely covered with pumice fall deposits just below the ground surface. This pumice fall deposits has been called as Qhpt and believed to be from Maninjau Caldera (Tjia and Muhammad, 2008), but the isopach map strongly suggests that Qhpt was from Tandikat Volcano (Fig. 4). The age of Qhpt is not specified but is younger than 0.08 Ma, which is the age of pyroclastic flow deposits older than Qhpt (Nishimura, 1980). The distribution of the pumice layer and the landslides indicates that the landslides concentrate in the areas where the pumice layer was 3.5-5.5 m thick. All of the 14 landslides we studied had a pumice layer with slope-parallel layering. Below the pumice layers are heavily weathered gravels or volcanic soils, the latter of which are distributed away from the terraces.

4.3 Sliding surface of landslides

Sliding surfaces were made within the base of the pumice layer, where pumice grains were mixed with soil, which is heavily weathered debris flow deposits (Fig. 5). Grains of pumice and soil in the mixed layer were very weak and easily smeared by finger and rich in hydrated 1.0 nm halloysite, while the pumice grains in the main part of pumice layer were hard and scarcely had halloysite. Pumice grains in the mixed layer had no remaining volcanic glass but consisted of halloysite, which had precipitated on the previous bubble walls to form a very fragile framework. According to the cone penetration tests performed on 2 landslide sites, mixed layer had the lowest penetration resistance. Permeability of the mixed layer and the debris flow deposits were about two orders smaller than the permeability of the pumice layer. Simple shear tests for the mixed layer under constant

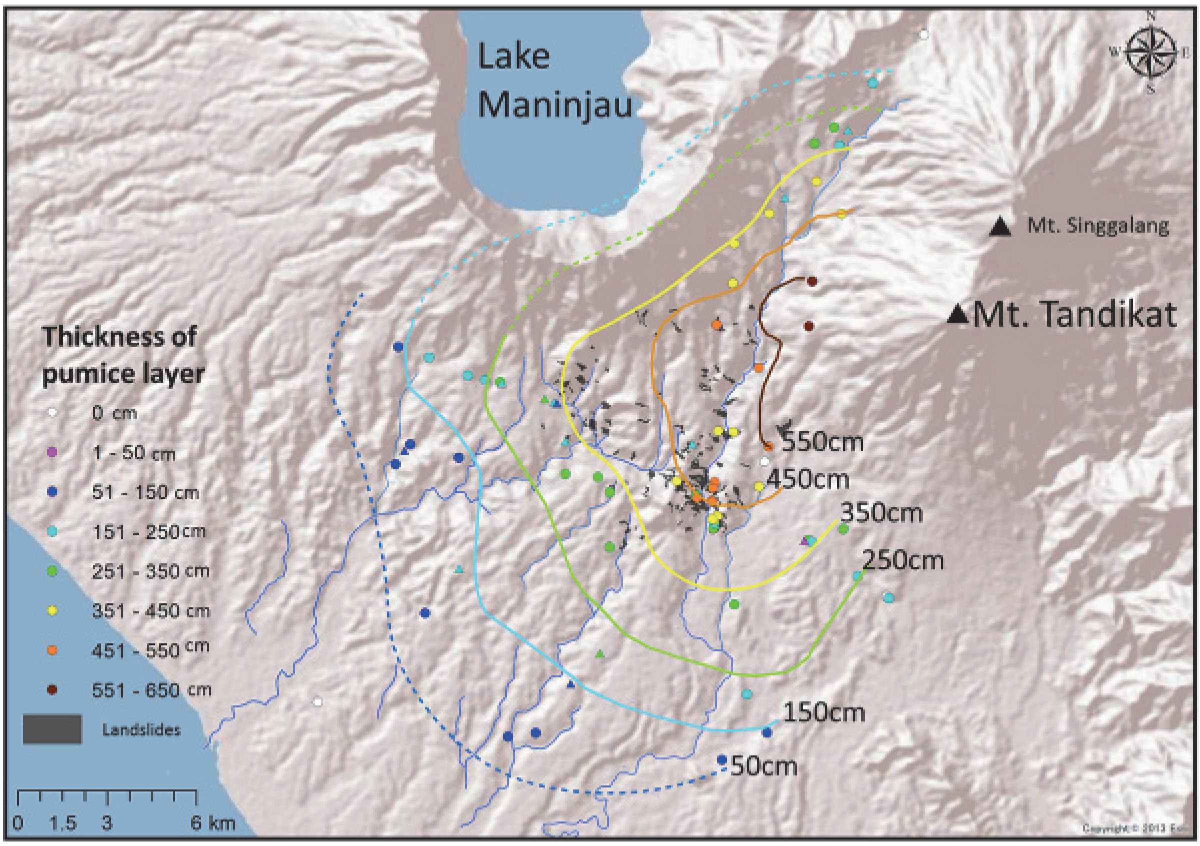

Fig. 4 Isopach map of the Qhpt and the distribution of landslides.

Fig. 5 Mixed layer and overlying pumice layer and underlying debris flow deposits.

volume yielded 18.2 kPa of cohesion and 15° of internal friction angle. Water contents were 95 % and higher than the liquid limit of 84%. Heavily weathered debris flow deposits below the mixed layer commonly contained gibbsite.

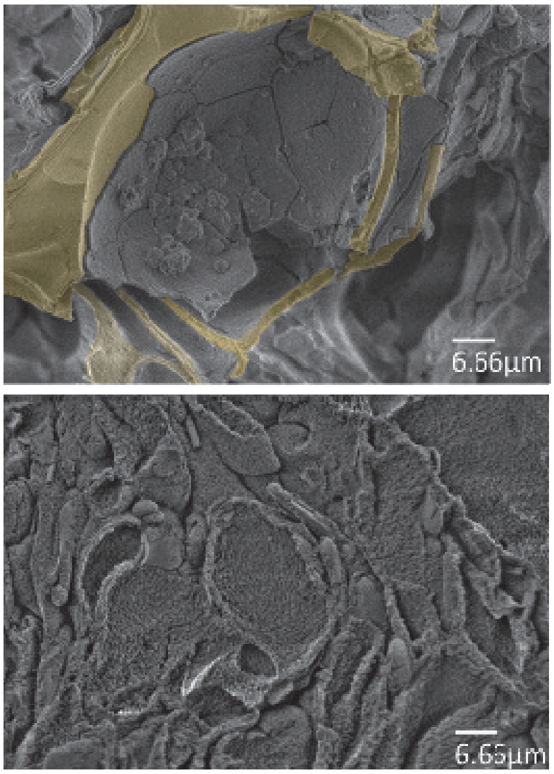

Fig. 6 SEM images of pumice grains. Upper: Pumice grains in the main part of the pumice layer. Volcanic glass (yellow) is covered by amorphous precipitate. Lower: Pumice grain in the mixed layer. No volcanic glass but small spherical halloysite.

5. Discussion

5.1 Mechanism of the weathering of the mixed layer

The sliding surfaces of the landslides we investigated were all within the mixed layer which is rich in halloysite, at the base of Qhpt layer. Halloysite is contained in the mixed layer and also soil of weathered debris flow deposits just below it, suggesting that it is made after the deposition of Qhpt. Soil much below the mixed layer was lack in halloysite but had gibbsite, which is the residue of intensive leaching. These occurrences suggests that once gibbsite is made by leaching, pumice grains deposited, and then water percolated from the ground surface, got SiO_2 from the pumice, then reached to the base of the Qhpt and reacted with the soil and pumice to form halloysite. The silica-rich water reacts with gibbsite-rich soil, forming halloysite, $Al_2Si_20_5(OH)_4 \cdot 2H_2O$ (Kleber, Schwendenmann et al., 2007). Similar reaction has been proposed for the halloysite formation in a paleosol where sliding surfaces were made during the 1978 Izu-Oshima-Kinkai earthquake (Chigira, 1982). Pumice grains in the mixed layer is dissolved to the water and halloysite is presumed to have formed on their surfaces.

5.2 Factor of the landslides occurrence from the viewpoints of geotechnics and landscape development

Infinite slope stability analysis has been done with parameters of slope angles and thickness of beds that slid. The strength parameters used for the sliding surface were 18.2 kPa of cohesion and 15° of internal friction angle. One example with a horizontal seismic acceleration of 250 gals is shown in Fig. 7, in which 9 of 10 landslides: all landslides we measured slope angle in field survey, plotted had safety factors less than 1. This acceleration is consistent with that estimated in the affected area by the US Geological Survey.

Our field survey and stereoscopic examination of PRISM images strongly suggest that major geological causes of the landslides were slope-parallel layering of the pumice fall deposits, undercutting by river incision, and the weathering of the mixed layer at the base of the pumice fall deposits. This undercutting reduced the support of pumice fall deposits from downslope. These factors can be considered in the contexts of landscape development (Fig. 8), which in sequence was the deposition of debris flow, weathering, volcanic eruption and the deposition of pumice fall deposit, the interaction between percolating water and the materials in the mixed layer and beneath, and undercutting by river incision. Such a history could commonly occur in tropical volcanic areas.

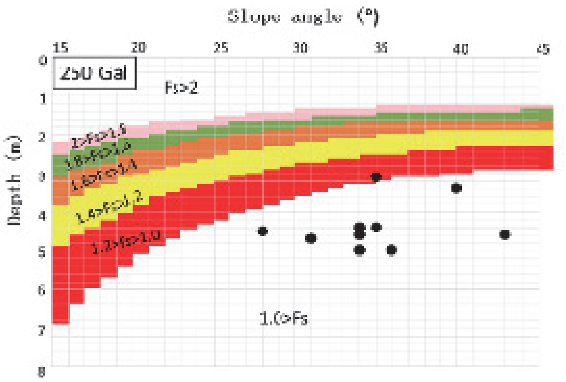

Fig. 7 Safety factors obtained from infinite slope stability analysis with parameters of slope angles and the depth of a sliding surface.

6. Conclusions

The 2009 Padang earthquake triggered many landslides. We have investigated the factors of landslides based on field survey and laboratory tests.

As a result, we found that these landslides had the following characteristics: 1) they occurred in the areas with pumice fall deposits with >3 m thickness, which was controlled by the distance from their source; 2) the pumice fall deposits had a slope-parallel layering, which had been cut at the foots of slopes; 3) pumice and soil grains in the mixed layers at the base of the pumice fall deposits were heavily weathered to be clayey materials with abundant halloysite; and 4) sliding surfaces were made in the weak mixed layers.

The geological history, which is volcanic eruption, weathering, and undercutting by river incision, is common in tropical volcanic areas. That means we can make a hazard map of such a catastrophic landslide induced by earthquakes on the basis of geological development.

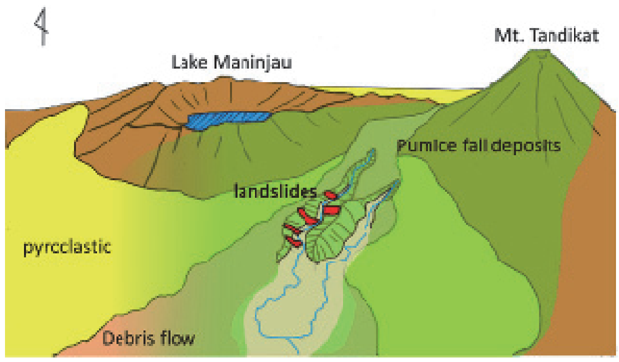

Fig. 8 Bird eye's view of the schematic of the topographic development.

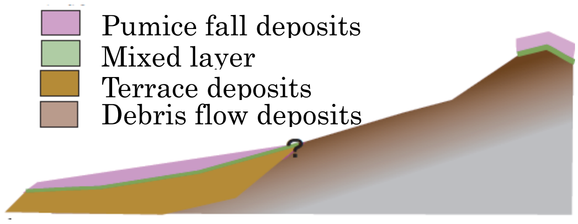

Fig. 9 Conceptual image of the geological profile of the slope.

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