

## Tandikek and Malalak flowslides triggered by 2009.9.30 M7.6 Sumatra earthquake during rainfall in Indonesia

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### Abstract

Four earthquakes with magnitudes greater than M7.6 occurred in West Sumatra, Indonesia between 2004 and 2009. The M7.6 earthquake that occurred on 2009.9.30 was the smallest among them. Nevertheless, it triggered many flowslides in the Tandikek and Malalak districts and caused numerous fatalities. To investigate the mechanisms of the occurrence and rapid motion of these slides, we carried out field investigations and laboratory tests.

Our investigations found that flowslides occurred on steep slopes mantled by a pumice layer. A stiff clay layer with low permeability was present beneath the pumice. The most important factor was that it had been raining for three hours before the earthquake occurred, although the rainfall was of medium intensity. Laboratory tests on pumice samples with ring shear apparatus showed that: (1) The pumice layer was easily crushed; (2) The pumice layer could remain stable even in strong rainfall; (3) The pumice layer could resist strong earthquake motions in dry conditions; (4) Under fully saturated and undrained conditions, the pumice layer could be liquefied by earthquake triggering.

This study shows the worst scenario of the combination of rainfall and earthquake in the distribution area of the pumice, and calls for attention to a new type of geo-hazard.

**Key words:** earthquake, rainfall, pumice layer, permeability, liquefaction, flowslide

### Introduction

Earthquake activity is intense in southwestern Sumatra. As shown in Fig. 1, four major earthquakes occurred in the area between 2004 and 2009. The first and largest of these was the M9.3 earthquake that occurred on 26 December 2004. This earthquake caused a major tsunami disaster over a wide area, and 227,898 people lost their lives. A M8.6 earthquake occurred on 28 March 2005, followed by a M8.5 earthquake on 12 September 2007, and a M7.6 earthquake on 30 September 2009.

The 2009.9.30 M7.6 event was the smallest of these earthquakes, but it triggered many flowslides in the mountainous areas of Tandikek and Malalak. Those flowslides rapidly moved down slope, destroying villages at the fronts of the slopes, and killing many villagers.

Locations of the epicenter of this earthquake, Padang City, and the landslide area are shown in Fig. 2. We carried out field investigations in Padang City and the landslide area in March 2010. Building collapse was very severe in Padang City, and the collapse rate of buildings decreased with increasing distance from the epicenter. Almost no landslides occurred between the epicenter and Tandikek, including in Padang City, except for some small-scale rockfalls and soil slope collapses, even on steep mountainous slopes. How-

ever, extensive slides occurred in the Tandikek and Malalak districts (Fig. 2).

In this paper, we examine the cause of the Tandikek and Malalak landslides and the mechanism of their rapid motion and long travel, based on both field investigations and laboratory tests.

### Landslide distribution

Many landslides were triggered by the M7.6 2009.9.30 Sumatra earthquake. These moved for long distances at high speed, resulting in significant loss of life. Fig. 3 and Fig. 4 are maps showing the landslide distribution, as prepared by UN-OCHA (2009) and Badang Geological Agency, Indonesia. Thirty-three landslides were plotted in Fig. 3, whereas in Fig. 4 more than 60 landslides were plotted over a larger area. From Fig. 3, it can be seen that most of the landslides occurred at the mountain foot, at relatively low elevation.

A simplified geological map of the landslide area (Fig. 5) shows that lava and pyroclastic deposits are the main lithotypes present. In the area of concentrated flowslides, the bedrocks are Quaternary volcanic rocks (indicated as Qhpt and Qpt in the map). Previous work has found that the potential for flowslides to occur in pyroclastic strata is great, due to high grain crushing susceptibility (Wang & Sassa 2000). This is especially so in pumice layers.

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**Fig. 1.** Epicenter locations of four major earthquakes occurring around Sumatra between 2004 and 2009 (base figure from Google Map).

### Field investigation of the Tandikek and Malalak flowslides

Most of the landslides occurred around Cumanak village, Nagari Tandikek, Patamuan sub-district, Padang Pariaman regency. The distance from the epicenter is about 100 km. Padang is located almost midway between Cumanak and the epicenter. Among the landslides in the area, the Tandikek and Malalak flowslides caused most deaths. The common features of the two flowslides is that both occurred on steep source slopes of 30 to 40 degrees, movement was rapid, and villages located at the foot of the slopes were destroyed. This led to 132 and 32 fatalities at the Tandikek and Malalak flowslides, respectively.

The source and depositional areas of the Tandikek flowslide are shown in Fig. 6. The main scarp is steep, and the depositional area is very flat. The flowing process can be estimated from those photos. Fifty-seven houses were completely destroyed by the Tandikek flowslide, and no trace of them remains. The height of the main scarp was about 20 m, and the travel distance was about 220 m. From Fig. 6b, it is also evident that many other slope failures occurred on the steep slopes nearby.

A longitudinal section photograph of the Malalak flowslide (Fig. 7) illustrates the flat deposition of the sliding mass of the flowslide. The sliding mass moved out of the slope in the source area, and covered the gentle slope uniformly, as there was no resistance to the sliding mass. As also can be seen from Fig. 8a, the slope covered by the sliding mass was also very gentle, a typical character of flowsliding. In the source area slope, the structure of the sliding surface is almost the same as that in the Malalak flowslide (see Fig. 8b), with a pumice layer overlying the stiff clay horizon.

The soil structure of the unwelded pumice layer overlying stiff clay can be seen clearly in Fig. 9, an example from the Tandikek flowslide. The thickness of the pumice layer



**Fig. 2.** Location map showing the epicenter of the 2009.9.30 M7.6 earthquake, Padang City, and the Tandikek and Malalak landslides.

in both flowslides was about 1.5–2 m. The pumice layer easily collapses when cut by a shovel, showing a very loose structure. When eroded by rainfall, V-shape gullies form. Based on site observations, the pores are large and interconnected, and hence the permeability of the pumice layer is high. Water from rainfall can thus easily infiltrate the pumice layer.

To understand the factors causing the flowslides, we conducted interviews with the local people, because it is curious that no landslides occurred in this area during much stronger earthquakes such as the 2004.12.26 M9.3 event. Mr. Kader, a 50-year old local man who lost 10 family members in the Tandikek flowslide, including his father and two sons, told us that rainfall of moderate intensity began at about 2:00 PM, some three hours before the earthquake struck at 5:12 PM local time. For local people in tropical areas, moderate rainfall may equate to precipitation rate of 20–40 mm/hour. We suspected that the three hours of continuous rainfall may have contributed greatly to the flowslides. This theory will be examined by laboratory tests of soil samples taken from the Tandikek flowslide.

From the field investigations, we concluded that the flowslides occurred due to the following factors and processes:

- 1) Steep slope in the source area slope. The slope angle of 30 to 40 degrees is near the measured 35 degree average internal friction angle of the pumice layer;
- 2) Continuous rainfall for three hours. This rainfall could saturate the 2 m thick pumice layer;
- 3) The strong seismic motion from the M7.6 earthquake, even though the flowslide site was 100 km from the epicenter;
- 4) The special structure, with the pumice layer overlying a stiff clay layer. This structure not only makes saturation of the pumice layer easy, but could also easily maintain the soil in the sliding zone in an undrained condition when

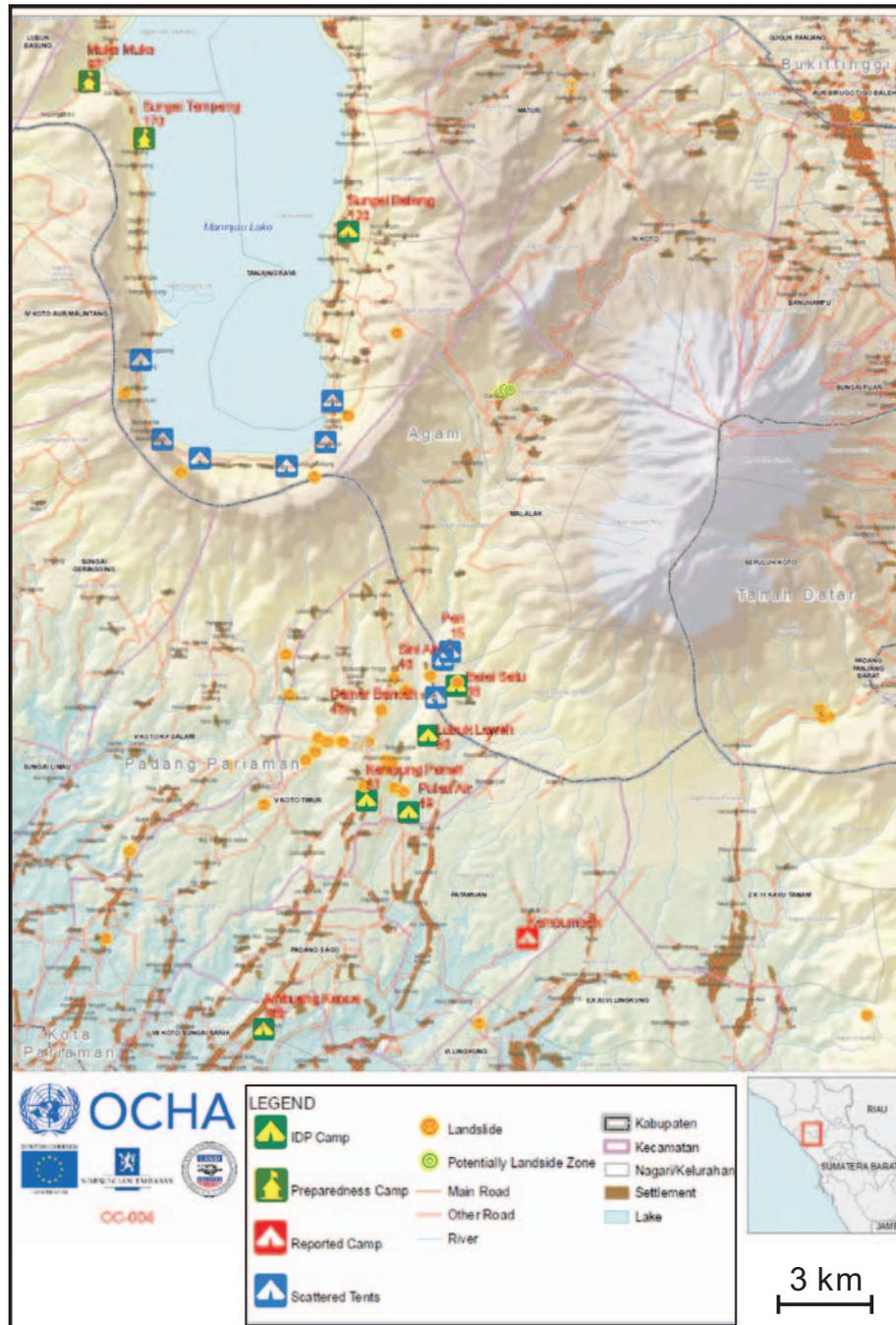


Fig. 3. Distribution of landslides triggered by the 2009.9.30 M7.6 Sumatra earthquake and IDP (internally displaced person) camp locations (from OCHA 2009).

the pumice layer slid on the stiff clay layer.

During our field investigation, we noted several important features of the pumice layer. Transported by wind rather than water, the pumice particles were very angular, and their surfaces were very rough. This means that the pumice layer can remain stable in the dry condition. This may explain why the pumice slope did not collapse when it was subjected to a much stronger earthquake in 2004. Although collapses occurred during that event, the collapse volumes were very small. Such small scale collapses were found near Padang

City, which was closer to the epicenter of the 2009 M7.6 earthquake. However, the rainfall at Padang was much different. According to a Japanese geo-disaster researcher who was in Padang City when the M7.6 earthquake occurred, rain was not falling there at that time.

The slopes in the Tandikek and Malalak areas can also remain stable during much stronger rainfall. Being in a tropical climatic zone, heavy rainfalls should be common. The Tandikek and Malalak slopes had been stable until the 2009 disaster even in more intensive rainfall. This strong

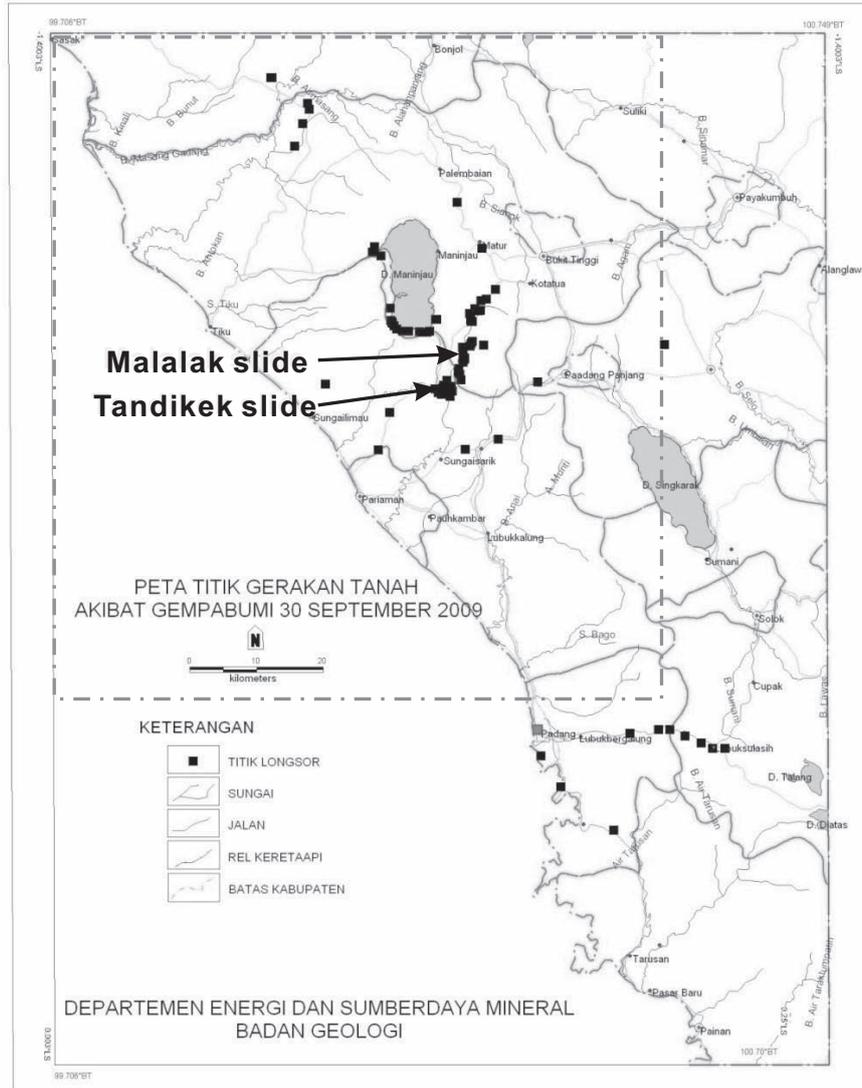


Fig. 4. Landslide distribution map made by the Badang Geological Agency, Indonesia. Dotted line rectangle is the area of the geological map shown in Fig. 5.

stability during rainfall may be due to the high permeability of the pumice layer. If possible, we need to measure the in-situ permeability of the pumice layer.

In the 2009.9.30 event many flowslides occurred on slopes which had been stable in stronger earthquakes, and in more intensive rainfalls. We presume that the cause of the 2009 flowslides was the unfortunate combination of the high rainfall and the earthquake. The worst scenario is that the pumice layer was saturated by the three-hour rainfall, and the collapse was triggered by the earthquake. Because of the two-layer structure, pore pressure generated in the shearing in the pumice layer could not dissipate, and the entire layer of the pumice liquefied. The sliding mass then flowed down without resistance, and was finally deposited on a gentle or flat slope.

To verify the above model, soil samples were taken from the source area of the Tandikek flowslide, and the soil mechanical properties of the pumice layer were investigated.

#### Ring shear test results on the initiation and motion mechanisms of the Tandikek and Malalak flowslides

The ring shear apparatus developed by Kyoji Sassa in the Disaster Prevention Research Institute of Kyoto University was used in this study (Sassa 1997; Sassa et al. 2003; Sassa et al. 2004). The ring shear apparatus was used because it can shear the sample for a long distance and thus can represent the long distance motion of a landslide. Furthermore it can maintain the sample in the undrained condition, which is an important characteristic of rapid landslides, and hence allow measurement of the excess pore-water pressure.

Three types of ring shear tests were conducted:

- (1) Shear tests on dry samples to measure the shear resistance of the pumice layer to resist earthquake, and to measure the grain crushing susceptibility of the pumice layer;
- (2) Shear tests on saturated samples to measure the shear resistance of the pumice layer and hence the capacity to resist heavy rainfall;

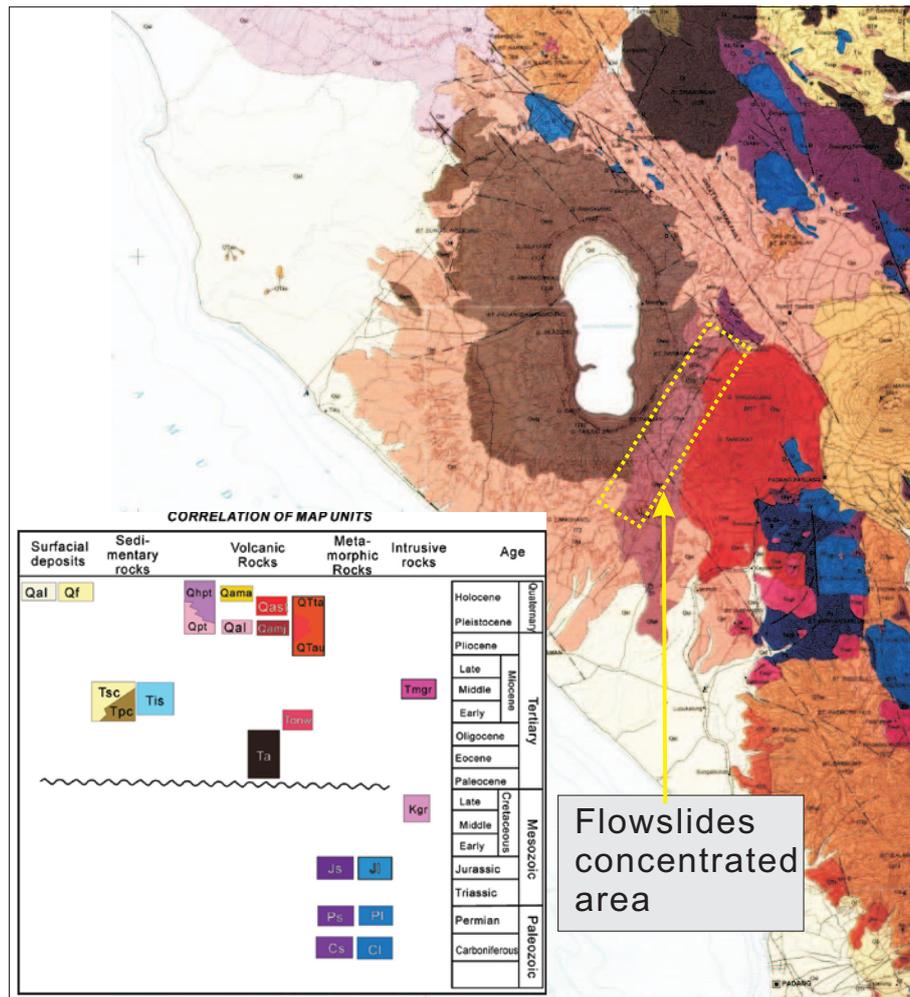


Fig. 5. Geological map of the landslide area and their surroundings.

(3) Shear test on saturated pumice with cyclic loading, to simulate the situation of a fully saturated sample shaken by a strong earthquake.

A normal stress of 30 kPa was used. This is the stress level of a 2 m thick pumice layer on a 35 degree slope. Also, to determine the effect of soil layer thickness, a normal stress of 100 kPa was used in test-1 and 2.

#### 1) Test results on dry pumice sample

Two tests were conducted on the dry pumice layer with normal stresses of 30 kPa and 100 kPa, respectively. After normal consolidation, the samples were sheared at a constant velocity of 0.1 mm/sec. The total shear distance for each test was 10 m. After shearing, samples at the shear zone were removed, and grain size distribution analyses were made for each sample.

Fig. 10 shows the shear resistance and sample height change with shear displacement at the normal stress of 30 kPa and 100 kPa, respectively. As shown in Fig. 10a, the peak shear resistance reached 40 kPa, representing a friction angle of 53 degrees. Considering the natural slope

of 35 degrees, the factor of safety is 1.89, reflecting high stability in dry conditions. Dilation occurred when the shear displacement was from 10 mm to 70 mm, a very large range of shear displacement.

Under the normal stress of 100 kPa, the peak shear resistance reached 100 kPa (Fig. 10b), the same value of the normal stress, and the corresponding friction angle was 45 degrees. At a natural slope angle of 35 degrees, the factor of safety decreased to 1.43. This means that with increase in thickness of the pumice layer, the ability to resist earthquake decreases. For the sample height change, the dilation range of shear displacement became shorter, ranging from 20 mm to 55 mm. This contraction is much larger than that in the test with normal stress of 30 kPa, suggesting that additional grain crushing occurred during the shearing at higher normal stress.

Fig. 11 shows the grain size distributions of the original pumice layer and the shear zone samples under normal stress of 30 kPa and 100 kPa. Grain crushing clearly occurred during the shearing, and the extent of grain crushing is much larger with a higher normal stress.



**Fig. 6.** Photos of the Tandikek flowslide. (a): The main scarp of the Tandikek flowslide. The slope angle was about 35 degrees; pumice layer distributed over stiff clay layer. (b): View from the source area of the Tandikek flowslide. The two remaining houses at the sides mark the boundaries of the flowslide.

With ring shear apparatus, the residual friction angle of the soil is easily determined. Fig. 12 is the result of residual friction angle analysis of the pumice layer. After shearing the sample to residual state under a normal stress of 100 kPa, the normal stress was decreased gradually, and the shear resistance then measured. The residual failure line is obtained when the normal stress decreased to 5 kPa, and the residual friction angle of 38.7 degrees is then derived. This value indicates that the pumice layer has high friction in the dry condition. If liquefaction does not occur in the soil, a flowslide cannot occur.

## 2) Test results on saturated pumice sample

Two undrained shear tests were conducted on fully saturated pumice samples. The normal stresses used were 30 kPa and 100 kPa respectively, and the shear velocity was 0.1 mm/sec.

Test results for the normal stress of 30 kPa are shown in Fig. 13. Fig. 13a shows time series data, and Fig. 13b is the effective stress path. The negative pore pressure caused by dilation during shearing can be easily observed in both figures. The apparent friction angle of the pumice layer at the point when the peak strength (52 kPa) was reached is calculated as 60.0 degrees, much higher than that at the dry condition (53 degrees). After shearing for more than 300 mm, the generated pore pressure was almost one third of the normal stress. This result indicates that the pumice layer is very strong even in the saturated condition, and thus the slope can remain stable even during heavy rainfall.

Fig. 14 shows equivalent results for the case where the fully saturated pumice layer was sheared under normal stress of 100 kPa in the undrained condition. High excess pore pressure was generated after shearing, and



**Fig. 7.** Longitudinal section photograph of the Malalak flowslide showing the long travel distance of the flowslides. Almost no sliding mass was left in the source area, and all of the sliding mass was deposited on a gentle slope.

relatively low shear resistance was reached. The test results show the effect of normal stress level on the mechanical behavior of soil. Although this case has no direct relationship to the 2009.9.30 flowslide disaster, the results hint that thick pumice slopes may be more dangerous than the thin pumice layer, if fully saturated.



**Fig. 8.** (a): Photograph taken from the toe of the Malalak flowslide. The slope covered with the sliding mass is very gentle, showing a flowsliding character. (b) : Soil layer structure in the source area of the Malalak flowslide: Pumice layer overlying a stiff clay layer containing gravels.



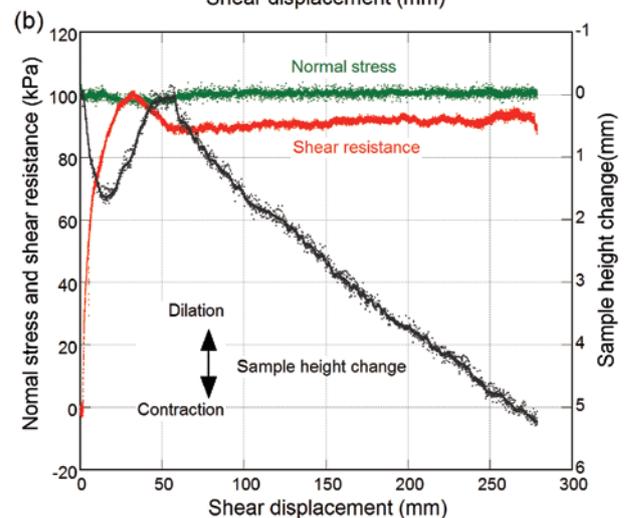
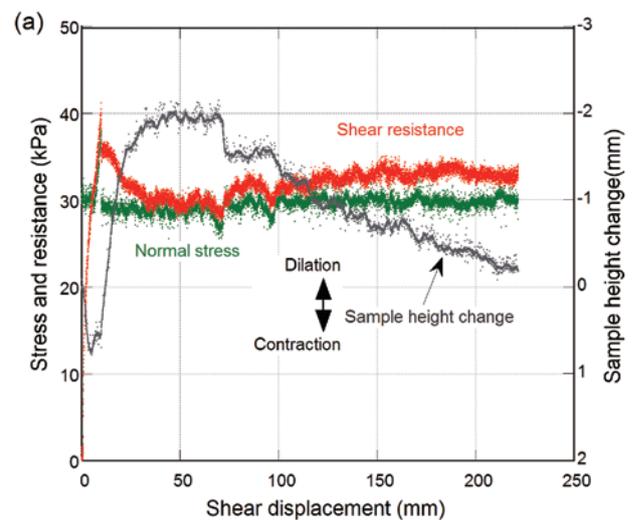
**Fig. 9.** Structure of the sliding surface in Tandikek flowslide: pumice layer overlying stiff clay layer with gravels.

### 3) Test results of cyclic loading on saturated pumice sample

The two series of tests described above show that the pumice layer slope has high stability during either rainfall or earthquake. The cyclic loading test is designed to clarify the mechanism of the slope behavior when an earthquake strikes a fully saturated slope.

The test procedure was:

- 1) Full saturation of the pumice sample, and confirmation of the degree of saturation with the  $B_D$  value (a pore pressure parameter in direct shear condition, as proposed by Sassa according to Skempton's  $B$  value) (Sassa 1988);
- 2) Normal consolidation of the sample at a normal stress of 30 kPa;
- 3) Application of an initial shear stress of 17.3 kPa to simulate the initial stress of a slope of 30 degrees;
- 4) Inputting a sinusoidal wave of shear stress for 10 cycles. The amplitude was not constant, but increased cycle by cycle to guarantee the pumice sample should fail, and to determine the change of shear resistance and pore pressure.



**Fig. 10.** Shear test results on a dry sample. (a) with a normal stress of 30 kPa; (b) with a normal stress of 100 kPa.

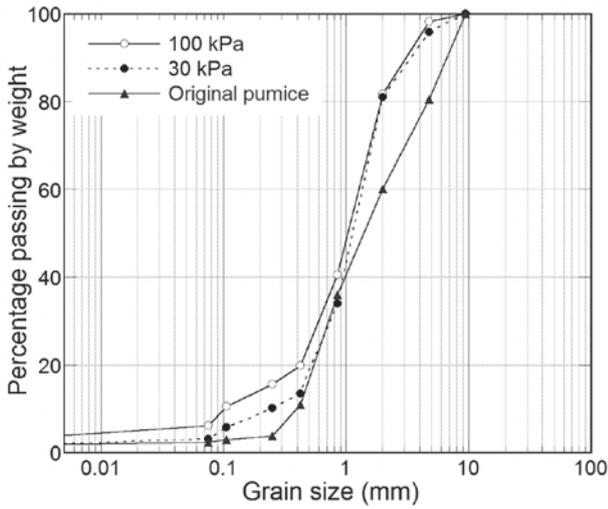


Fig. 11. Grain size distribution of the original pumice layer and sheared samples under normal stress of 30 kPa and 100 kPa, respectively.

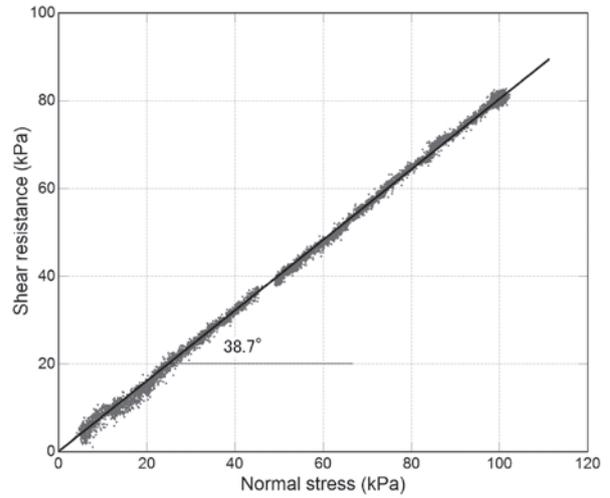


Fig. 12. Residual friction angle of the pumice layer.

The test results are shown in Fig. 15. The results confirm that the shear resistance never exceeded the normal stress, and the shear resistance decreased cycle by cycle during the cyclic loading, while the pore-water pressure increased gradually, and reached the value of normal stress when the cyclic loading ended (Fig. 15a). Almost complete liquefaction occurred in the pumice sample after the cyclic loading.

Although the stress paths in Fig.15b are quite complex, the effective stress path finally reached the original point, meaning complete liquefaction occurred in the sliding zone of the flowslide, when the slope failed due to the triggering force of the earthquake.

When the shear resistance of the pumice soil in the sliding zone of a landslide decreases to near zero, the landslide will transfer to a flowslide which moves for a long distance at high speed.

Summarizing the results of the three series of tests, we conclude that the slopes with a pumice layer can remain stable in a strong earthquake or during intensive rainfall, but become very unstable when both events coincide.

These test results have very important and practical implications for slope disaster mitigation. The occurrence of earthquakes occurring during heavy rainfall is a low-frequency event, and even the oldest people in villages may not have experienced any slope failure and disaster during their lifetime. Consequently, the general population is likely to think that the pumice-mantled mountain slopes behind their villages are stable, and that their homes and fields are not under threat. However, as occurred in Tandikek and Malalak, although those stable slopes can withstand strong earthquakes or intensive rainfall as separate events, their stability can be decreased dramatically by the coincidental combination of strong earthquake motion and moderately intense rainfall.

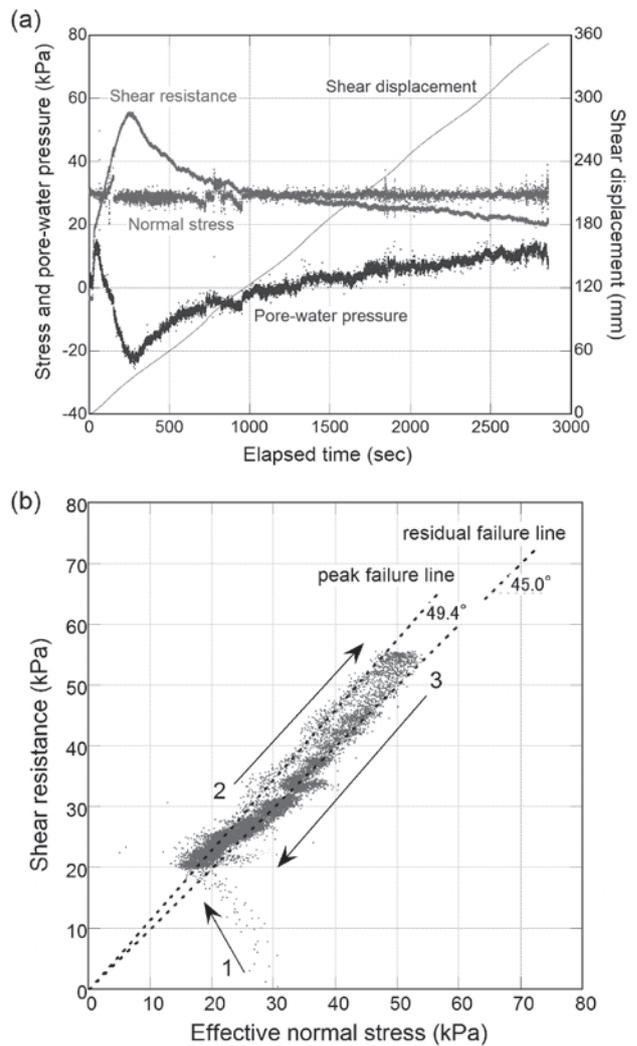
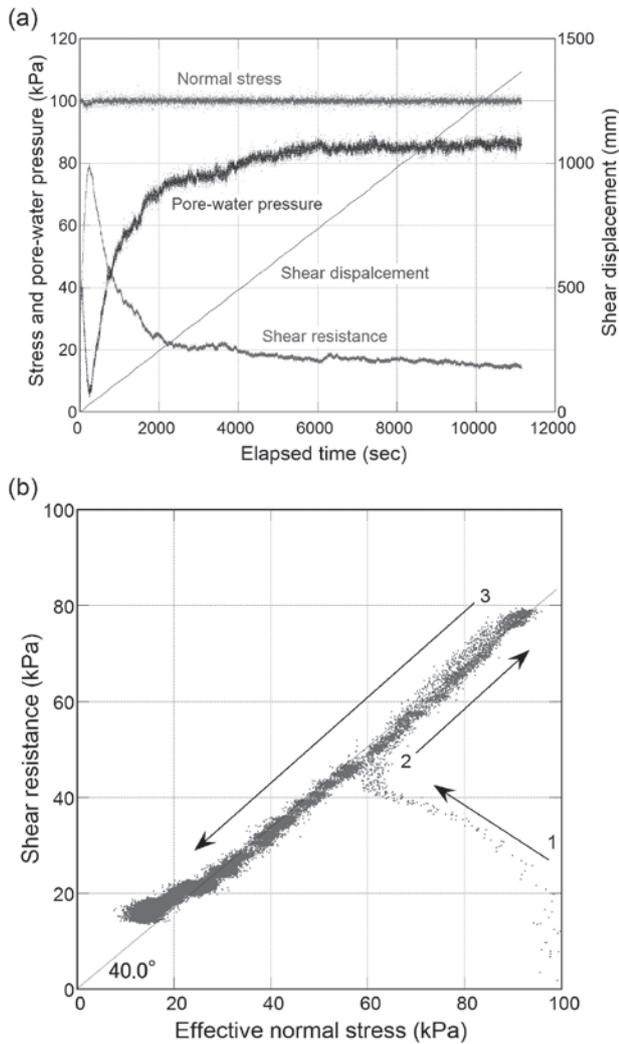


Fig. 13. Time series data (a) and stress path (b) of the undrained shearing test on a fully saturated pumice sample under normal stress of 30 kPa.



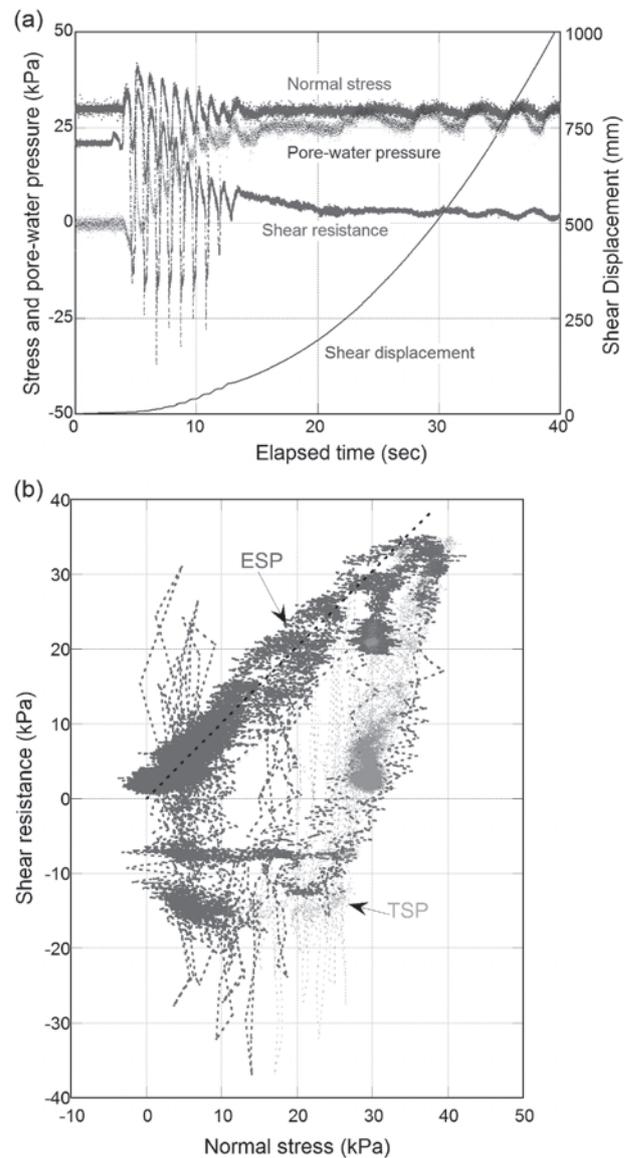
**Fig. 14.** Time series data (a) and stress path (b) of the undrained shearing test on a fully saturated pumice sample under normal stress of 100 kPa.

### Conclusions

Field investigations of the Tandikek flowslide and Malalak flowslide triggered by the 2009.9.30 M7.6 Sumatra Earthquake during rainfall, and ring shear tests on pumice samples from the Tandikek flowslide were used to investigate the initiation and motion mechanism of the flowslides. The worst combination of the following factors is the main reason for the flowslide occurrence and their rapid motion.

- 1) Steep slope in the source area;
- 2) Moderately intense rainfall before the earthquake;
- 3) Strong earthquake motion;
- 4) A two-layered structure which is easily saturated, but drains with difficulty;
- 5) A pumice layer with high susceptibility for grain crushing.

Through this study, we aim to call attention to similar slopes elsewhere. It is crucial to recognize the potential



**Fig. 15.** Time series data (a) and the stress paths (effective stress path (ESP) and total stress path (TSP)) (b) of the undrained shearing test on a fully saturated pumice sample under cyclic shearing.

danger in those slopes, and locate the local residents in safe places.

### Acknowledgements

Mr. Taufiq Wira Buana and Mr. Mas Maryono of Environmental Geological Center, Indonesia, and Dr. Atsuo Takeuchi joined the field investigation. Financial support from the Disaster Prevention Research Institute of Kyoto University to the first author when he was a staff member there is highly appreciated. We are grateful to Barry Roser of Shimane University for critically reviewing an early draft of the manuscript.

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(Received: Sep. 30, 2010, Accepted: Oct. 26, 2010)

## (要 旨)

注 発武・Muhammad Wafid A.N.・Fayu Zhang, 2010, インドネシア西スマトラ島における 2009.9.30 M7.6 地震によって発生した Tandikek 及び Malalak 流動性崩壊

インドネシア・スマトラ島南西部において、地震活動が活発である。2004 年から 2009 年の間、この地域周辺ではマグニチュード M7.6 以上の大地震が四回も発生している。その中に、2009.9.30 M7.6 の地震は一番小さいマグニチュードを有しているのに、Tandikek 及び Malalak 地区で多くの流動性地すべり災害を誘起し、地域に甚大な災害を及ぼした。災害の原因を解明するために、現地調査及び室内土質実験を実施したので、報告する。

人的被害最も酷いのは Tandikek 地すべり及び Malalak 地すべりによるものである。現地調査によって、下記ファクターの組み合わせが災害の原因になったと考えられる。1) 急峻な斜面地形 (30 - 40 度) (斜面土塊が臨界状態に近い状態にある) ; 2) 地震発生まで継続した雨 (軽石層を飽和させる) ; 3) 強い地震 ; 4) 斜面崩壊発生しやすい斜面土層構造 (難透水の粘土層の上に、粗な構造を持つ軽石層) ; 5) 粒子破碎しやすい軽石層 (過剰間隙水圧が発生しやすい)。また、これらの結論は室内リングせん断試験によって、確認できた。