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SUBSURFACE STRUCTURES BASED ON MICROTREMOR OBSERVATIONS IN LANDSLIDE AREA OF TANDIKAT, WEST SUMATRA, INDONESIA

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ABSTRACT: The 2009 West Sumatra Earthquake (M7.5) caused landslides in Padang Pariaman, West Sumatra, Indonesia, and severe damage in Tandikat. Previous studies of the damage reported that the sliding surfaces are 2-m thick pumice layers above hard clay layers. In this study, we performed microtremor investigations at the landslide areas to estimate ground motion characteristics from horizontal to vertical (H/V) spectral ratios and subsurface structures from phase velocity dispersion curves of array measurements. The predominant periods of H/V spectral ratios are distributed in the range of 0.1–0.4 s. The H/V spectral ratios in the damaged area exhibit sharp unimodal peaks and the peak values in areas without landslides are small. These results may reflect the difference in the velocity structures between the areas with and without landslides during the 2009 earthquake. Hard subsurface structures are suggested in the areas without landslides. However, soft surface layers with an S-wave velocity of 200 m/s or less are estimated over the entire area, even in areas without landslides, by subsurface structure models derived from array data. The layers, including pumice layers, represent remnants of prior landslides. We are concerned about future coseismic landslides caused by the deposits, even in the areas that did not experience landslides during this event. We hope the results will contribute to landslide disaster prevention in the area.

Keywords: Microtremor observation, Subsurface structure, Landslide, The 2009 West Sumatra Earthquake

1. INTRODUCTION

On September 30, 2009, at 5:16 pm local time, a magnitude 7.5 earthquake struck off the coast of Padang in western Sumatra, Indonesia, causing strong motions (Fig. 1) and extensive damage, primarily in Padang and Pariaman [1,2]. The distribution of landslides caused by the earthquake is shown in Fig. 2. In particular, the damage was severe in Tandikat, Padang Pariaman. Several flat-roofed houses and schools collapsed, killing many people, because of earthquake-induced landslides [3]. According to Wang et al. [3], the slip surfaces are composed of approximately 2-m thick pumice layers deposited on the top of solid clay layers.

Coseismic landslides have caused large-scale damage in recent years as shown above. It is important to understand the ground motion characteristics of landslide areas because landslides often recur in particular areas due to past landslide deposits. Microtremor surveys have been widely used to evaluate the ground conditions in landslide areas [e.g., 4] because sediments above the slip surfaces are very soft, creating a noticeable velocity contrast with the basement. We performed microtremor investigations at Tandikat, the location of an earthquake-induced landslide, to estimate landslide deposits.

2. OBSERVATIONS

Single-point microtremor observations were conducted at 11 sites in Tandikat, mainly in the area of observed landslides. A JU410 three-component accelerometer with a 24-bit recorder was used for data acquisition. We used the following specifications: an amplification factor of 100, a sampling frequency of 200 Hz, and a recording time of 10–15 min. Observations were made at TDK08, TDK10, and TDK11 at the same time.

We conducted array observations at two sites (TDKAR1 and TDKAR3) where landslides occurred and another site at high elevation (TDKAR2, as shown in Figure 3. Four JU410s synchronized by GPS clocks, four geo-phones (UD component only, natural frequency = 4.5 Hz), and a data logger HKS9700 (resolution = 27 bit) were used to conduct the measurements. One seismometer was placed at the center of a circle, and the other three were set in an equilateral triangle around the circumference. The specifications were as follows: a 200-Hz sampling frequency, a 1–10-m radius of the array, and a 15-min recording duration. The single-point observations recorded at TDK08, TDK10, and TDK11 formed an irregular triangular array synchronized by GPS to ensure synchronized observations. The results of this analysis are used in the TDKAR3 case.

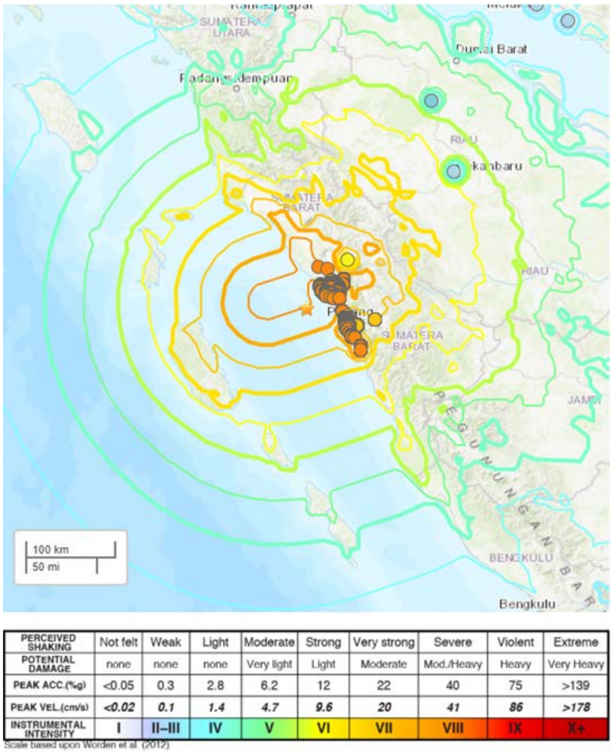

Fig. 1 Estimated seismic intensity distribution for the 2009 West Sumatra Earthquake [2]

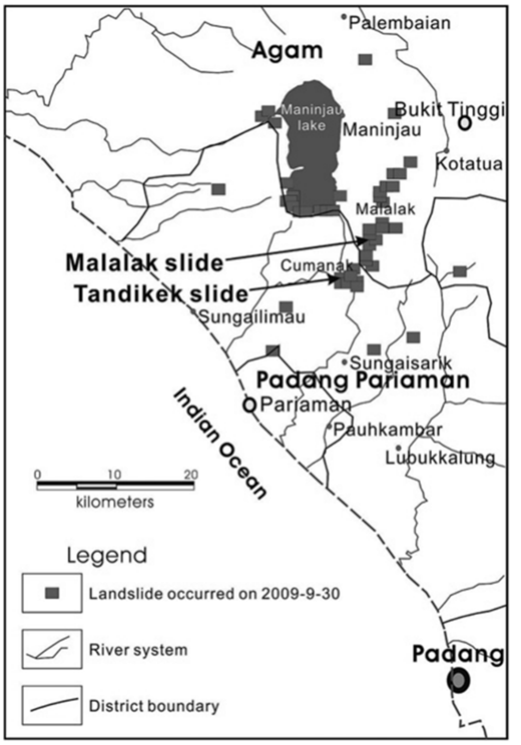

Fig. 2 Landslide distribution reported by the Geological Survey of Padang, Indonesia [3]

3. ANALYSIS

Fourier spectra were calculated from single-point observations of 20.48-s length segments and were smoothed using a log window with a coefficient of 20 [5]. Average spectra were evaluated from at least 10 stable sections. Horizontal to vertical (H/V) spectral ratios were calculated from the Fourier spectra, and the predominant periods were visually estimated. Many H/V spectral ratios were identified as unimodal with a single distinct peak. The predominant period distribution in Tandikat is shown in Fig. 3. Appendix fig. 1 shows H/V the spectral ratios in this study.

An analysis of the array observations was conducted with the following procedure: the phase velocity dispersion curves of the array observation records were estimated based on the SPAC [6] or CCA methods [7]. Using the open analysis tool [8], at least ten sections were selected by automatic extraction using the root mean square values of microtremor recordings with 10.24-s length segments. Only for the irregular triangle array of TDKAR3, 20.48-s length segments were used. Then, the power spectra of those sections were smoothed with a 0.3-Hz bandwidth Parzen window, and the average was estimated. Finally, the phase velocity dispersion curves were determined, and those obtained at each radius were integrated at each observation site, concerning their continuity.

Assuming that microtremors are Rayleigh waves, their propagation characteristics allow us to estimate subsurface structures [e.g., 9]. The subsurface structure models were estimated through trial and error to ensure that these phase velocity dispersion curves and the microtremor H/V spectral ratios obtained at the center of the array match the theoretical phase velocity dispersion curves and the theoretical H/V spectral ratios based on the Rayleigh wave fundamental mode, respectively. The S-wave velocities of the first layers were estimated from the minimum and constant phase velocity at high frequencies, and the base layer was fixed for Vs = 700 m/s. The number of layers was determined concerning previous studies [3] as shown in Fig. 4. Then, modeling was performed by modifying the thicknesses of layers. P-wave velocities were calculated using S-wave velocities [10]. The resulting subsurface structure model is presented in Table 1. Figure 5 shows the phase velocity dispersion curves of the fundamental mode of Rayleigh waves overlaid on those derived from array observations. Figure 6 shows the observed and theoretically calculated microtremor H/V spectral ratio at the center of the array observation sites.

4. ANALYSIS

4.1 Predominant Periods of the Horizontal to

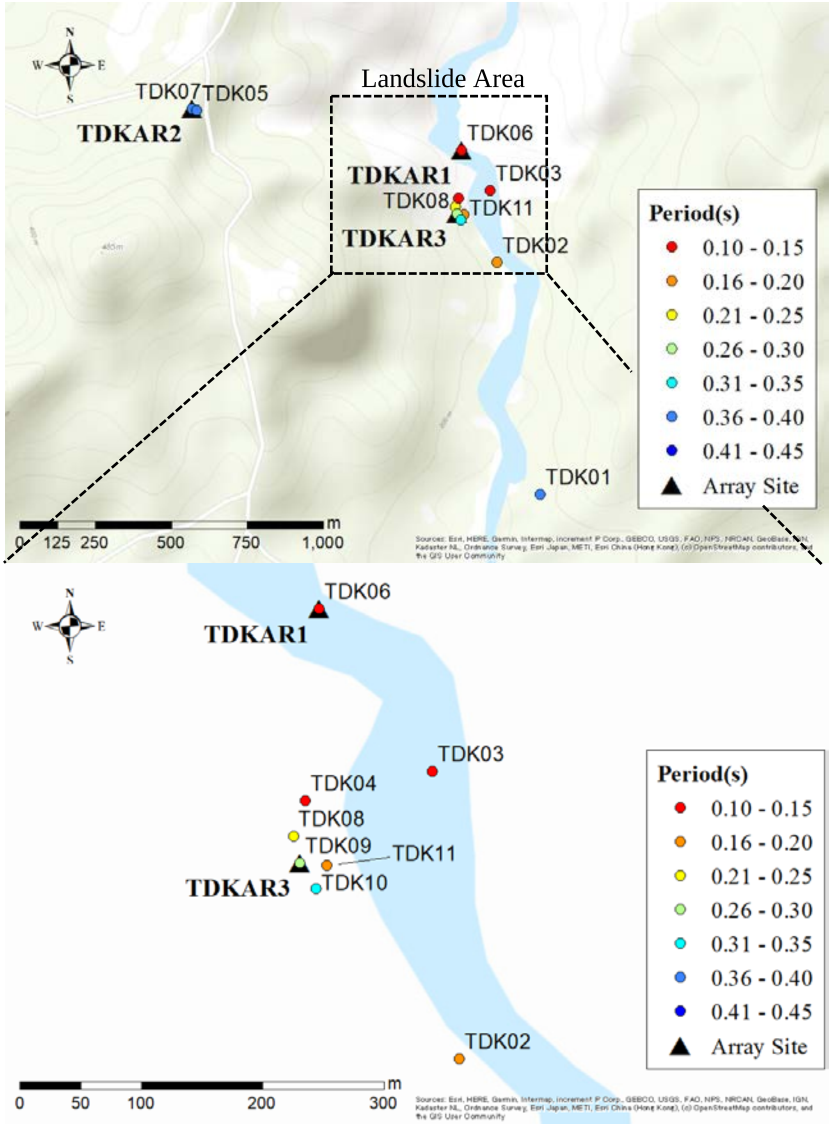

Fig. 3 H/V spectral ratios and predominant period distribution

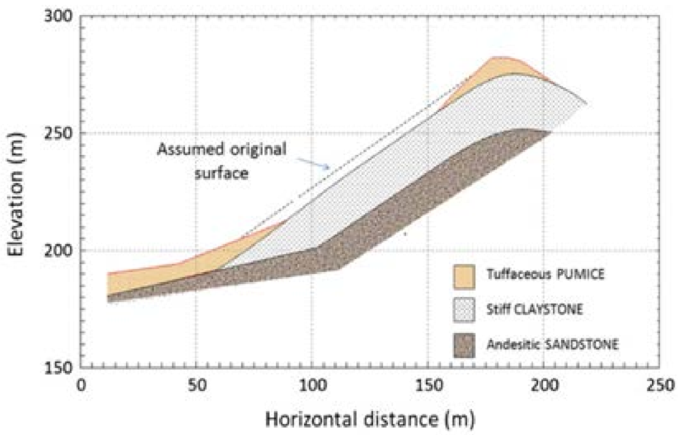

Fig.4 Interpretation of landslide sequences from geological surveys [3]

Vertical Spectral Ratios of Microtremors

Figure 3 shows that the predominant periods are approximately 0.4-s at TDK01, TDK05, and TDK07, which are far from the landslide areas. Besides, the periods are short at other stations. From TDK08 to 11 sites, the dominant period changes even in small areas, reflecting the quick change in layer thickness deposited by the landslide.

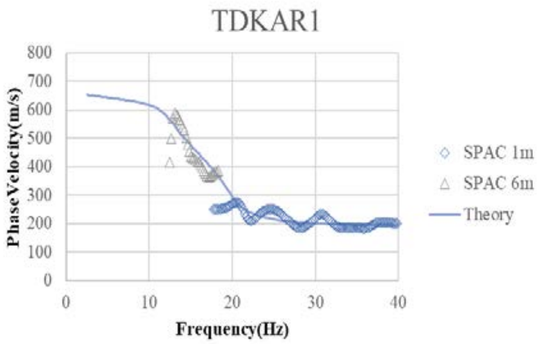

Table 1 Subsurface structures based on array observations

Site	Thickness (m)	density (t/m³)	Vp(m/s)	Vs(m/s)
TDKAR1	5	1.7	1430	200
	∞	2.1	2070	700
TDKAR2	6	1.6	1400	100
	10	1.8	1620	300
	∞	2.1	2070	700
TDKAR3	3	1.5	1350	50
	∞	2.1	2070	700

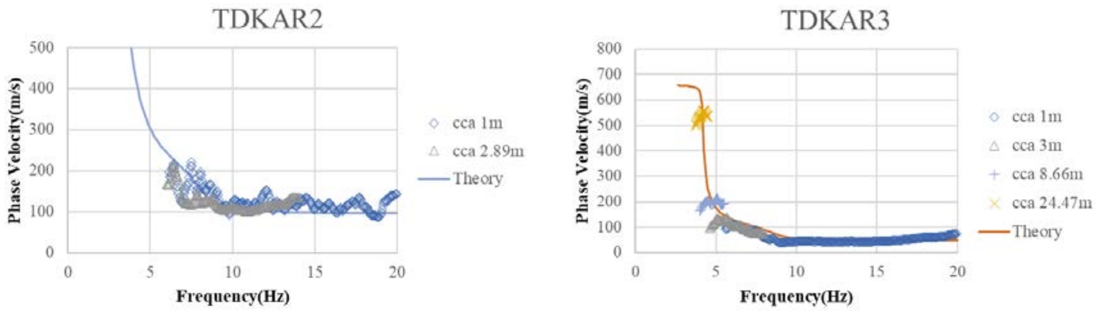

Fig. 5 Phase velocity dispersion curves

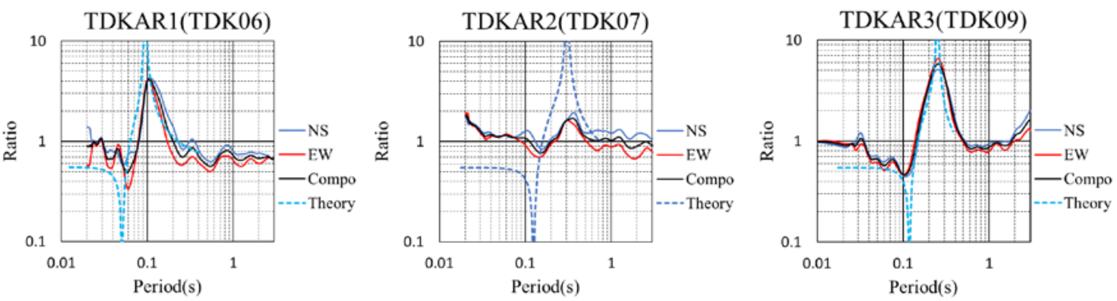

Fig. 6 H/V spectral ratios at the center of the array observation sites

According to Fikri and Wang [1], the landslides occurred along several valleys eastward of TDKAR2, as shown in Figure 3. In addition, the areas around TDK02, TDK03, and TDK06 are considered to be at the top of the landslide mass. Moreover, the sedimentary conditions are expected to be very complicated because of the confluence of several valleys. TDK01 is located on a flatland far from the collapse sites and is assumed to have a long period due to the presence of thick layers on the river terraces. Focusing on the spectral shape of microtremor H/V spectral ratios, we observed several single-peak H/V spectral ratios in the range of 0.1–0.4 s. The peak ratios of TDK05 and TDK07 are smaller than other stations. This suggests that the velocity contrast against the base layers is smaller than that in the observed landslide areas.

4.2 Estimation of Subsurface Structures

TDKAR1 and TDKAR3 have several meters of low-velocity layers with S-wave velocities of 100 m/s or less on the surface. Their S-wave velocities are different even at nearby stations, as shown in Table 1. In addition to these low-velocity layers, a 10-m thick intermediate layer with an S-wave velocity of 300 m/s was detected at TDKAR2. According to previous studies, the sliding surfaces are composed of approximately 2-m thick pumice layers on top of hard clay layers containing gravel [3]. Soft surface layers with S-wave velocities of 200 m/s or less are estimated over the whole area, including areas without landslides from the subsurface structure models in this study. The layers, including pumice layers, are past landslide deposits. TDK05 and TDK07 (TDKAR2) have longer predominant periods than the other sites because of the thick intermediate layer with an S-wave velocity of 300 m/s. Therefore, the intermediate layers are considered to be sediments that did not collapse due to the landslide in this area, raising concern for future coseismic landslides.

5. CONCLUSIONS

This study investigated microtremor observations in areas of Tandikat that had been damaged by landslides caused by the 2009 West Sumatra Earthquake. The relationship between subsurface structures and earthquake-induced landslide damages was considered. Consequently, the following findings are noted:

The predominant periods of microtremor H/V spectral ratios are distributed in the range of 0.1–0.4 s, and the peak ratios of H/V spectral ratios are small in areas without landslide damages. These results might reflect the differences in the velocity structures between landslide deposits containing sedimentary layers, such as clay, pumice, and bedrock layers. Subsurface structures without landslides are considered hard.

Surface layers with an S-wave velocity of 200 m/s or less were estimated from array observations. An intermediate layer with an S-wave velocity of 300 m/s was estimated at the site where no landslides occurred at this time. We are concerned about the possibility of future coseismic landslides due to the deposits. We would like to emphasize the importance of continuous monitoring of the deposits.

6. ACKNOWLEDGMENTS

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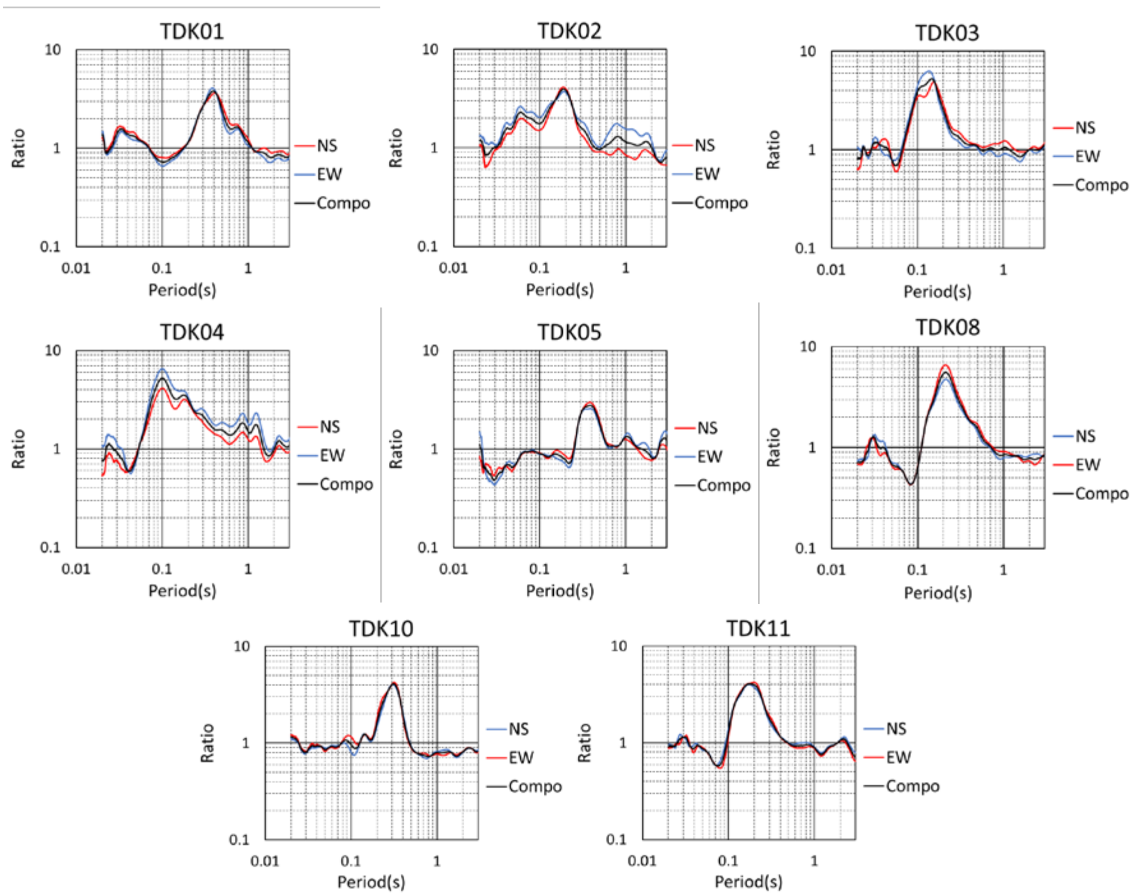

Appendix Fig. 1 H/V spectral ratios in this study

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