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INVESTIGATION OF SUBSURFACE CHARACTERISTICS BY USING A V_{s30} PARAMETER AND A COMBINATION OF THE HVSR AND SPAC METHODS FOR MICROTREMOR ARRAYS

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ABSTRACT

Palu City is an active seismic area in Indonesia due to the very active *Palu-Koro* fault system. The development of the city area, therefore, must consider the risks induced by the seismic activities. The risk assessment has to be supported by information on subsurface characteristics. The aim of this study is to investigate the characteristics of the subsurface of the area by considering the value of V_{s30} (top 30 m shear-wave velocity). This parameter has been related to the estimation of the site's ground shaking during the occurrence of an earthquake. The measurements taken in the deep soil sediment include the microtremor array, using the spatial auto correlations (SPAC) method, as well as the site's dominant period measurement, using the horizontal-to-vertical spectral ratio (HVSR) method. All these parameters were local site parameters, which could be subsequently related to a description of the potential impact in an area near to the epicenter. The measurement of V_{s30} was conducted in collaboration between the Indonesian Agency for Meteorology, Climatology, and Geophysics (Badan Meteorologi, Klimatologi, dan Geofisika) (BMKG) and the University of Indonesia (Universitas Indonesia) (UI); the overall surveys included V_{s30} measurements at 44 sites, microtremor array surveys at 10 sites, and the dominant period measurements at 74 sites. The overall results indicated that there is a good correlation between V_{s30} and the dominant period. In general, Palu City is predominantly a class-D site, but the northwest part of the Palu area is a class-C site.

Keywords: HVSR; Microtremor array; V_{s30}; SPAC

1. INTRODUCTION

Palu is one the major cities in the eastern part of Indonesia, and its population and amount of infrastructure has increased steadily over time. The city should prepare for the consequences of this development, including the expansion of residential and commercial areas. Furthermore, the earthquake catalogs published by the Indonesian Agency for Meteorology, Climatology, and Geophysics (Badan Meteorologi, Klimatologi, dan Geofisika, BMKG) in 2016 show that a significant number of earthquakes have occurred in the Palu area (see Figure 1). Therefore, the regional planning and other policies for the area need to consider the seismic-resistant structural

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requirements.

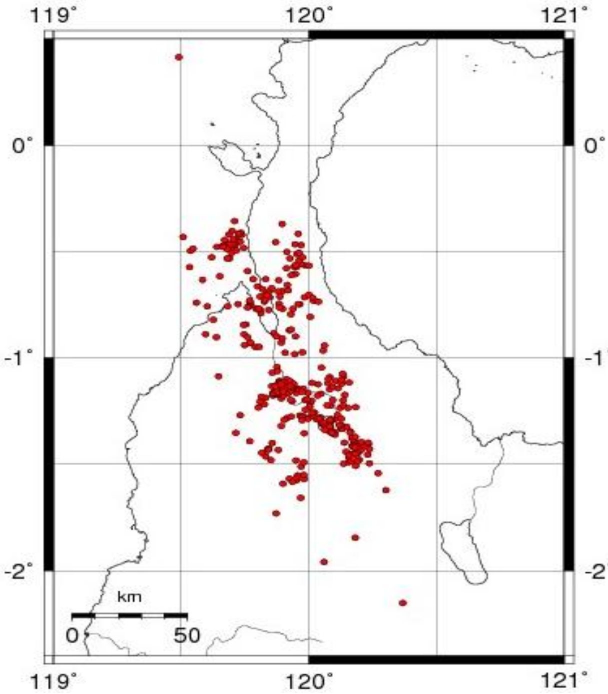

Figure 1 Distribution of epicenters along Palu-Koro fault in Central Sulawesi (BMKG, 2016)

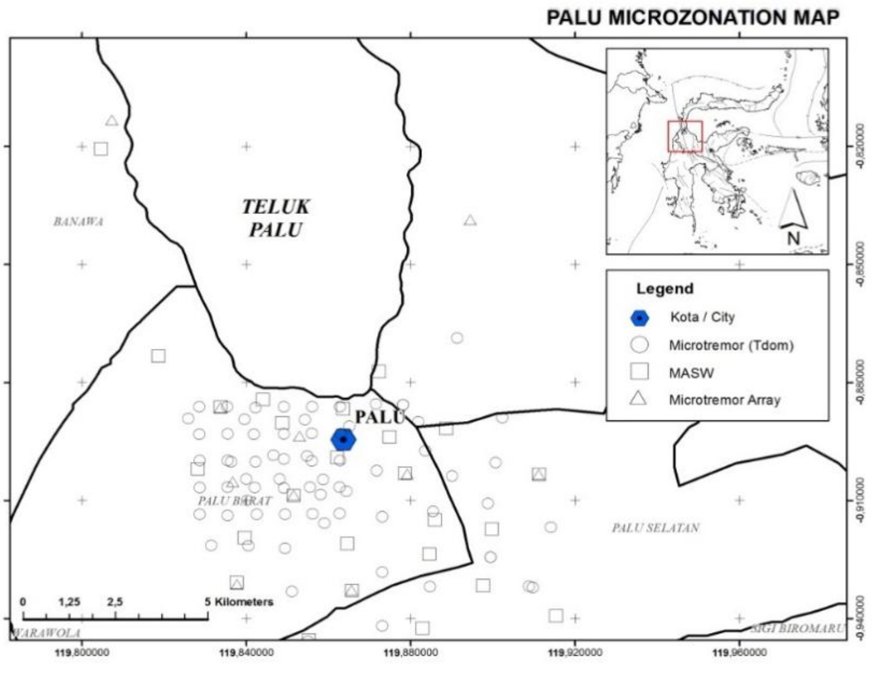

Figure 2 Configuration of instruments for T_{dom}, MASW, and the microtremor array

Seismotectonically, Palu is located close to the Central Sulawesi fault system, including the active Palu-Koro fault, as well as the inland Poso fault and Metano fault in the eastern part of Palu. Furthermore, data on the local site conditions in the western and eastern parts of Palu is different, indicating rather varied local site characteristics. Palu City has a complex type of focal mechanism, with a strike-slip fault as the predominant mechanism, particularly for the Palu-Koro fault. Sulastri et al. (2016) state that the Palu-Koro fault is one of the horizontal sinistral faults on the island of Sulawesi. The earthquake data and other collected data from the study indicate that the faults are likely to be normal and sinistral faults. Hamilton (1979) suggests that there are some fault segmentations, namely: (1) Palu-Koro fault; (2) Saddang fault; and (3) Trench fault. The geomorphological aspect of the area is very complicated, due to the Palu-Koro fault. In order to characterize the subsurface conditions of Palu, measurements of the dominant periods, shear-wave velocity profiles for the top 30 m of soil, and the bedrock depths have to be conducted. In Palu, earthquakes with a magnitude greater than 5.0 on the Richter scale can usually be felt by people. To reduce the seismic risks, mitigation efforts should be conducted immediately, including examining further the local tectonic conditions.

The numbers of measurement locations for the dominant periods (T_{dom}), multichannel analysis of surface waves (MASW), and microtremor arrays are 74 sites, 25 sites, and 10 sites, respectively. These locations are shown in Figure 2.

2. METHODS

The geotechnical characteristics of soil deposits play an important role in the modification of seismic ground motions, which are generally termed as the local site effects. The MASW method is a geophysical method that can be used to characterize the local site conditions, and it is shown to correlate with recorded strong ground-motion amplitudes and damage distribution (Roca et al., 2006). In this study, the MASW method was conducted using 24 geophones and an active source of a 10 kg hammer. The focus is on the surface wave propagation, which is used to measure the shear-wave velocity. Shear-wave velocity and therefore shear modulus is directly linked to material stiffness and is one of the most critical seismic engineering parameters (e.g., Park et al., 1999). Seismically, shear-wave velocity (V_S) is considered to be the best indicator for assessing the topsoil conditions. Although methods such as shear-wave refraction, downhole, and crosshole surveys can be also used, they are generally less economical than MASW in terms of field operation, data analysis, and overall cost.

The horizontal-to-vertical spectral ratio (HVSR) is a seismic approach used to investigate the response subsurface conditions using passive seismic imaging. The aim is to assess local dominant periods. This method was originally introduced by Nogoshi and Igarashi (1970), followed by Nakamura (1989), and it can effectively identify the amplification factor of a sediment layer to rock site ratio. This method can be used to estimate the parameter for fundamental resonant frequency. It is revealed by many (e.g., Ohmachi et al., 1991; Lermo et al., 1992; Field & Jacob, 1993) how such an HVSR of noise can be used to identify the fundamental resonant frequency and amplification factor of sediments (Nakamura, 2008). Most studies agree that HVSR allows the determination of the site resonant frequency with high reliability.

The spatial auto correlations (SPAC) method represents the change of velocity to a target depth using inverse processing. It uses an ambient noise waveform using four microtremor sensors in a triangle configuration (with the fourth sensor in the middle of the triangle) to make recordings during a one-hour period at each site. In one measurement, we deployed five configurations to estimate the target depth. The basic equation is given as Equation 1:

$$C(\omega) = Jo\left[\frac{2\pi f r}{v(f)}\right] \tag{1}$$

where $C(\omega)$ is the spatially averaged coherency, Jo is the Bessel function of the first kind and zero order, f is the frequency, r is the radius of the array, and $v(f)$ is the shear-wave velocity of the dispersion curve associated with one dimensional (1D) layered earth geology. It directly fits the coherency curves to the Bessel function by the iterative forward modeling of the shear wave of the profiles (Asten et al., 2004; Asten, 2006). It should be noted that the SPAC method has been implemented in a few regions of Indonesia, recently including Jakarta City (Ridwan et al., 2013).

All the parameters (T_{dom}, HVSR, V_{s30}, and SPAC) were analyzed using the aforementioned methods to obtain the observed values, and compared using a mapping analysis to describe and evaluate the relationships among the three parameters.

3. RESULTS

3.1. Interpretation of the HVSR Method

Figure 3a shows a sample of the recorded noise waveforms. After calculating the HVSR, the dominant period can be determined as shown in Figure 3b. In this particular example, the dominant frequency (the inverse of the dominant period) is about 3 Hz. The results are mapped in Figure 3c, indicating that most Palu areas have high dominant periods, including the southern part. Nevertheless, there are local areas (the eastern and northwest parts of Palu area to Donggala) having low dominant periods.

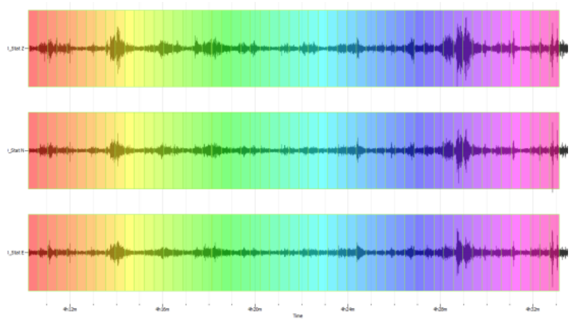

Figure 3a Example of microtremor data record

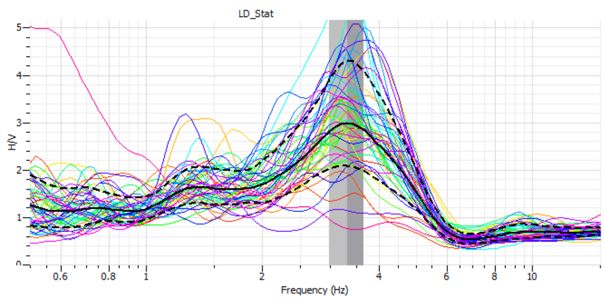

Figure 3b Example of HVSR curve

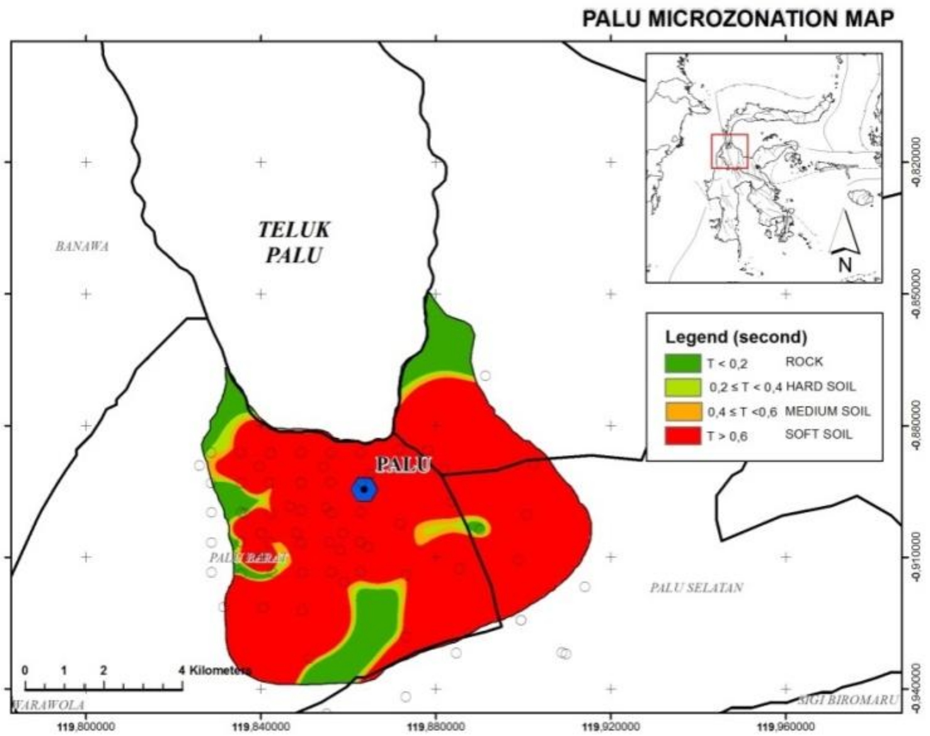

Figure 3c Distribution map of dominant periods in Palu and surroundings

The high dominant periods typically suggest that the area has deep or very deep sedimentary soil. Based on the V_{s30} classification proposed by Zhao et al. (2006) a $T_{dom} > 0.6$ s indicates that the condition is sedimentary alluvium and also probably deep sediment. The mapped results suggest that the Palu area and the coastline areas are alluvium or deep sediment. It can be interpreted further that these areas will experience strong ground motions during an earthquake event.

3.2. Interpretation of MASW

The MASW method was used to determine the average value of the shear-wave velocity to a depth of 30 m. The steps, process, and results of the MASW method are shown in Figure 4. The mapped results, as demonstrated in Figure 4e are generally similar to the mapped results for the dominant periods. The Palu area has a distribution of V_{s30} that is relatively lower than other areas. The average of V_{s30} is more than 200m/s.

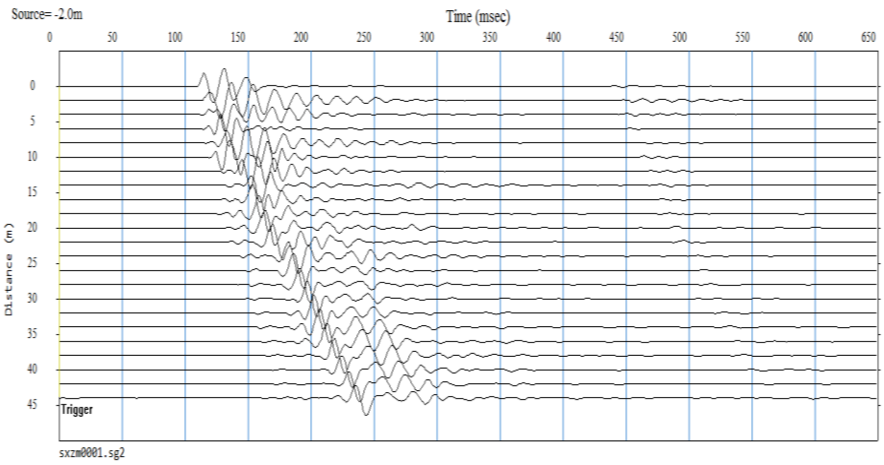

Figure 4a Example of MASW data record

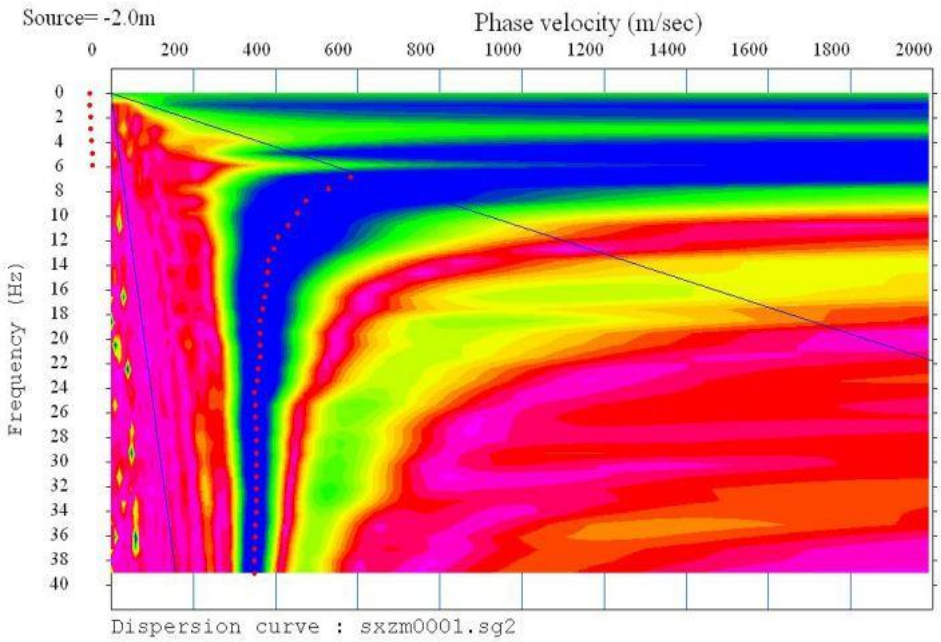

Figure 4b MASW dispersion curves

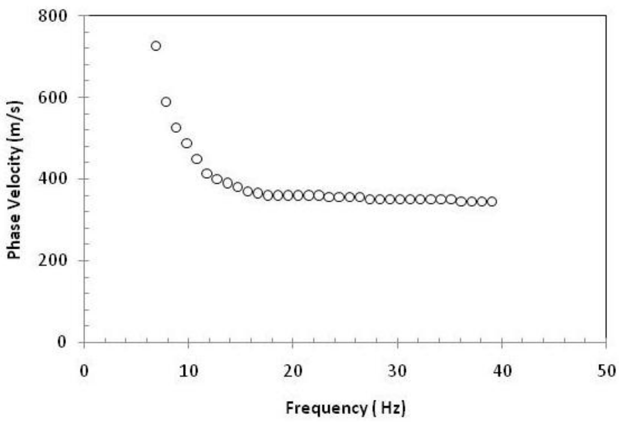

Figure 4c MASW dispersion curve

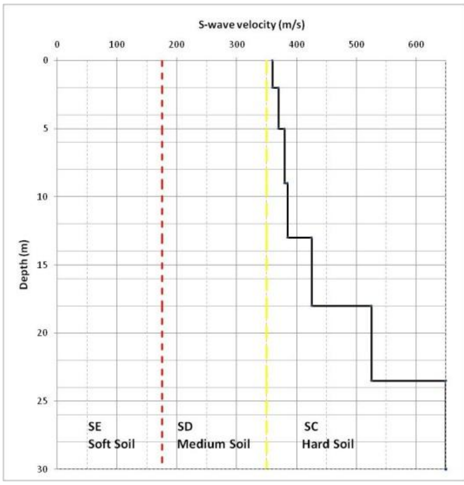

Figure 4d 1D shear-wave velocity profile

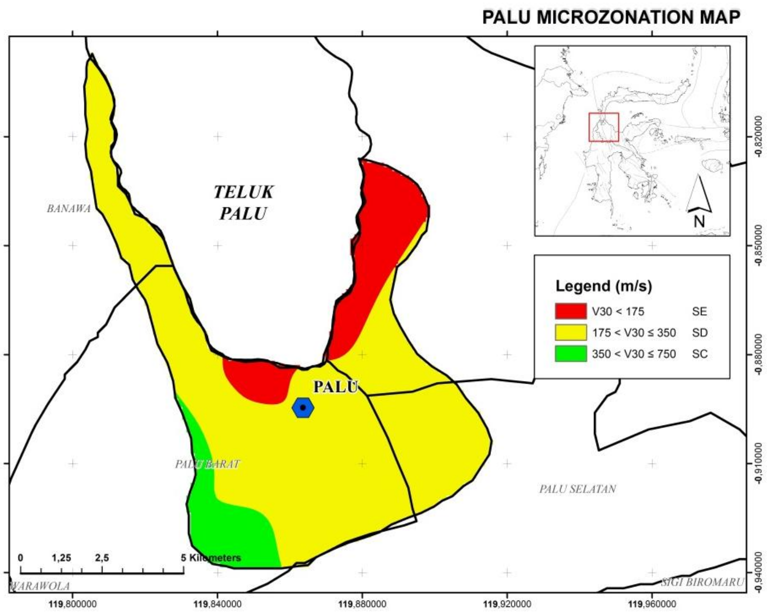

Figure 4e Distribution map of V_{s30} using the MASW method

3.3. Interpretation of SPAC

The SPAC method was carried out for ten sites. In each site, five test configurations, with array distance configurations of 62.5 m, 125 m, 250 m, 500 m and 1,000 m, were conducted. The observation period was one hour; however, for the shorter array distance configuration, the time required to record the noise waveforms was shorter. Figures 5a and 5b are the typical configuration and the typical recorded noise waveforms, respectively. It should be noted that the area covered by the SPAC method was not as large as those covered by the dominant period measurements or the V_{s30} parameter measurements. The estimated depth of engineering bedrock was calculated based on the analysis of the dispersion curve. In general, the mapped depths of engineering bedrock, as shown in Figure 5e are quite similar with the subsurface characteristics indicated by V_{s30} and T_{dom} measurements. The estimated depth of engineering bedrock in Palu was greater than that in the western and northwestern parts of Palu.

The resulting parameters for T_{dom}, V_{s30}, and SPAC appear, in general, to correlate with each other. This information could actually be used by engineers to consider the seismic design of buildings in the Palu region.

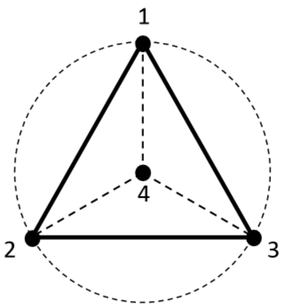

Figure 5a Array shape and location of the four sensors at the PKA01 site

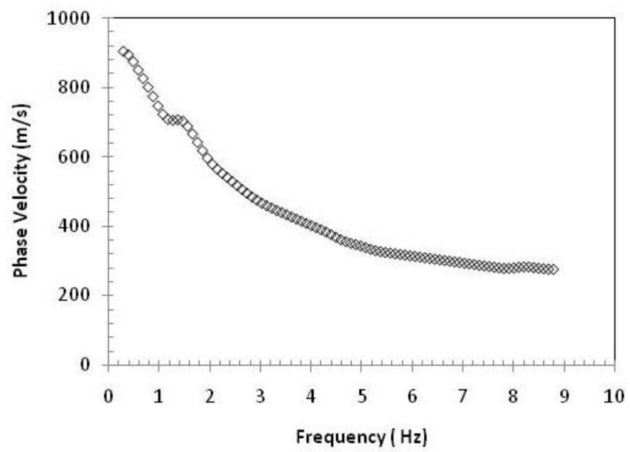

Figure 5c Microtremor array dispersion curve

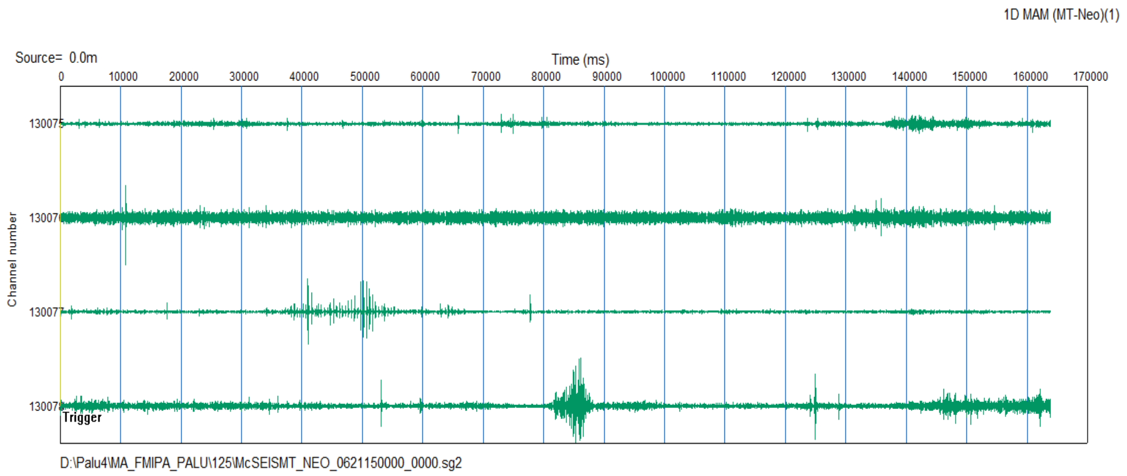

Figure 5b Example of a microtremor array data record at the PKA01 site

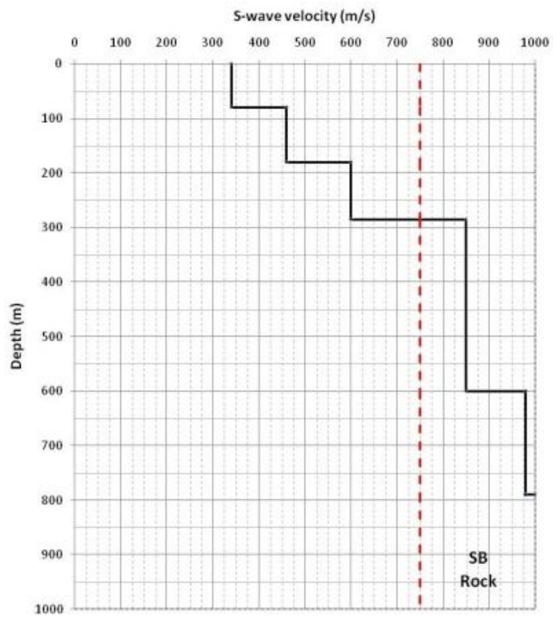

Figure 5d 1D shear-wave velocity profiles

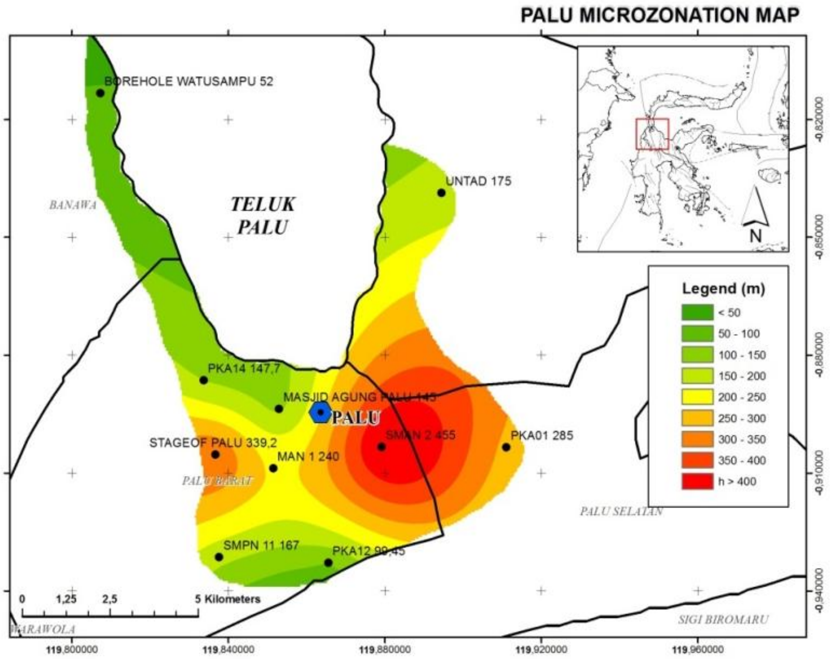

Figure 5e Distribution map of bedrock depths determined using the SPAC method

The Palu area appears to have sediment that is much thicker that western and northwestern part of Palu. The shallowest depth of engineering bedrock in Palu is approximately 200 m.

4. DISCUSSION

MASW is a non-invasive method of estimating the shear-wave velocity profile using surface wave energy. It utilizes the dispersive properties of Rayleigh waveform imaging of the subsurface layers. In an active MASW method, ground rolls (surface waves) can easily be generated by a source, such as a device used for creating vibration, being swept across the surface, or an impact source, such as a sledgehammer (Kesarwani et al., 2012). The entire procedure for MASW consists of three steps: (a) acquiring multichannel field records (or shot gathers); (b) extracting dispersion curves (one from each record); and (c) inverting these dispersion curves to obtain 1D (depth) shear-wave velocity (V_S) profiles (one profile from one curve). V_S profiling can be conducted in a 1D (depth) or 2D (depth and surface location) manner. The dominant periods (T_{dom}) were estimated using the HVSR method, and the ambient noise (passive seismic imaging) was used in the measurement process. Furthermore, MASW and microtremor arrays were used to measure the shear-wave velocity of the top 30 m of soil deposits and the depth of engineering bedrock, respectively.

This study aimed to describe in detail and comparing the results with the previous study by Thein et al. (2014). In detail, when conducting the deployment of a single microtremor measurement, there are many differences regarding the number of sensors and configuration, but the processing is similar. It is not for inversion method when proceed microtremor array data. Generally, when comparing, in spatial mapping, the information on the characteristics of the subsurface, they are not much different. Both of them use shorter and longer dominant periods to correspond with shallow and deep sediment soil, respectively. This information is not much different. The results show that in Palu City there is a longer dominant period than in the western Palu area. The mountain to the western side of Palu shows the typical shorter dominant period or high frequency. From the microtremor array to the southeast of Palu City, that area has deeper sediment than the areas to the west or north of Palu City, with a depth of sediment of about 400 m; this is deeper than previous research, which determined the depth to be less than 125 m. This study used three different methods, which could be used for engineering and city planning when really implementing the mitigation for earthquake hazards in Palu City, Central Sulawesi, Indonesia.

5. CONCLUSION

The small to moderate magnitude earthquakes induced by the Palu-Koro fault can cause damage, depending on the local site conditions. The damaging effects of local site conditions have been evident in recent earthquakes throughout the world. HVSR, MASW (V_{s30}), and the SPAC method have been used in this study to investigate the local site conditions of the Palu area and its surroundings. These methods have the advantage of cheaper costs and a non-invasive nature. The findings of this study were as follows: (1) The results of the MASW measurement indicated that the dominant local site conditions are alluvium and soft soil. The Palu area appeared to be predominantly alluvium, probably due to the location being close to the beach; (2) The T_{dom} results revealed the distribution of varying local conditions, with low dominant periods up to high dominant periods; (3) The results of the SPAC method identified that the depth of the engineering bedrock is about 200 m and appears to be deeper toward the southeast of the area. Furthermore, the depths in the northwest area are shallower than those in the southeast area of Palu.

Therefore, the results for the T_{dom}, V_{s30}, and SPAC parameters appear to be consistent with the other parameters.

6. ACKNOWLEDGEMENT

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