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DETERMINED SOIL CHARACTERISTIC OF PALU IN INDONESIA BY USING MICROTREMOR OBSERVATION

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Abstract, The Palu city, which is located in the active seismic zone of the Palu-Koro fault. Several powerful earthquakes have struck Palu city at previous years. One of the greatest earthquake event occurred in year 2006 which 6.2 Mw, about more a hundred buildings and houses were collapsed due to this earthquake. Palu-Koro fault also produced several tsunami events in year of 1927, 1968 and 1996. The latest earthquake struck Palu on 2012 (7.2 Mw) and it produced local tsunami. Since no soil profile map of Palu region available, we performed single observations of microtremors at 122 sites in Palu. Its results enabled us to estimate the site-dependent amplification characteristics of earthquake ground-motion. We also conducted a 8-site microtremor array investigation to gain a representative determination of the soil condition of subsurface structures in Palu. From the dispersion curve of array observations, the central business district of Palu corresponds to relatively from soft soil to medium condition. Predominant periods due to horizontal vertical ratios (HVSRs) in Palu are in the range of 1.2 to 2.5 s.

Keywords: soil characteristic, predominant period, Palu koro fault, donggala earthquake

1. INTRODUCTION

The Indonesian archipelago is located at the boundary of three major tectonic plates, the Indo-Australian, Pacific, and Eurasian plates, stretching from Sumatra in the west to Papua in the east (Fig.1). Indonesia is at the collision point of these three crustal plates. The high subduction-related seismicity in this region means that tsunami and other earthquake hazards are also high. Indonesia has approximately 17,504 islands, with a total land area of 1.92×10^6 km^2 and a sea area of 3.26×10^6 km^2. It has experienced a large number of earthquakes in the past. According to catalogued events, the number of earthquakes that have occurred in this region exceeds 48,000 with a magnitude greater than 4.0 from AD 1779 to 2010 (Fig.1) [1] .

Most of the major historical earthquakes in Indonesia have caused significant damage to facilities ([2], [3], [4]. Many large earthquakes have occurred in the shallow seas of the area that can produce massive tsunami like the 2004 Banda Aceh event.

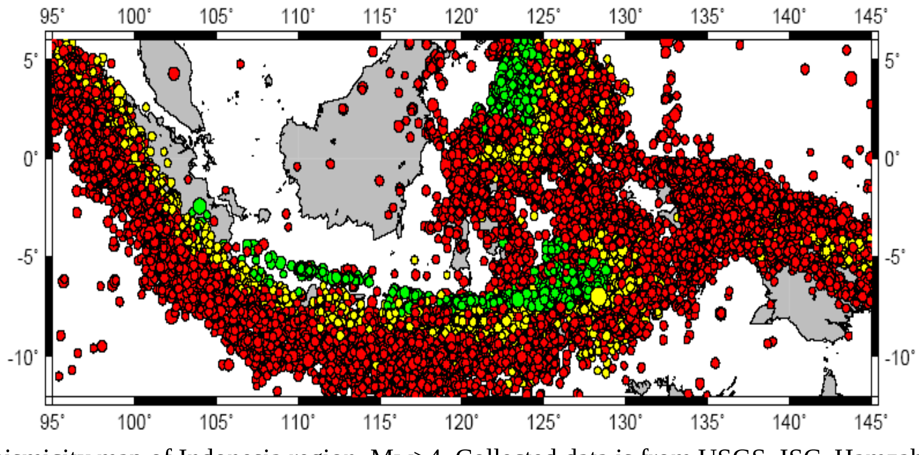


Fig.1 Seismicity map of Indonesia region, Mw>4. Collected data is from USGS, ISC, Hamzah& Puspito, BMKG, the period 1779 – 2012.

This earthquake off the coast of Sumatra resulted in hundreds of thousands of deaths and a million people homeless [5]. The most recent one is the Mentawai tsunami that occurred on October 25, 2010.

Sulawesi Island, one of eastern island of Indonesian region, it is located at the junction between the converging Pacific-Philippine, Indo-Australian Plates and the Eurasian Plate. Sulawesi tectonic evolution is resulted from successive collisions of continental slivers, island arcs, and oceanic domains with the Sunda land. Sulawesi is obliquely crossed by one of the main fault systems limiting the Eurasian Plate to the East, the left-lateral Central Sulawesi Fault System (CSFS), which comprises two fault zones, the NNW-trending Palu-Koro and the WNW trending Matano fault zones, connects, from north-west to south-east, the North Sulawesi Subduction zone (NSS) to the Banda Sea domain (Fig.2).

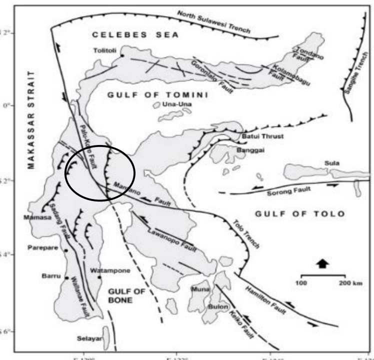


Fig.2 Geology and seismicity of the Sulawesi region,

The major active tectonics along the CSFS, particularly along the PKF [6],[7]. However, the seismicity of Sulawesi, as recorded by global seismic networks and some sources such Unites Stated Geological Survey (USGS), International Seismological center (ISC), Agency for Meteorology, Climatology and Geophysics (BMKG) and Hamzah Puspito from year of 1779 to 2010 (Fig.3b), Indonesian network and historical seismicity indicate a relatively low level of shallow seismic activity in Central Sulawesi [8]. In contrast with this low seismicity, PKF long-term slip rates as high as ±50 mm/yr has been estimated, on the basis of geodynamic reconstruction models (i.e. plate convergence rate along the NSS [9] and from paleo-magnetic studies [10]. Based on a 5 mm/year of slip rate, these estimates may integrate from different tectonic regimes and consequently variations of the slip rate on the PKF. In that case, the estimates are most likely inaccurate, particularly in a rapidly evolving complex area of a triple junction. Recently, the fared slip rate of the PKF was calculated at 38.8mm/yr from geodetic (GPS) measurements**.** Although poorly documented, historical seismicity in Central Sulawesi has been recorded since the 19th century. However, even if some damaging earthquakes have been reported within Central Sulawesi, few major earthquakes (Mw > 4.5) have occurred on the PKF and MF zones over at least the 100 years. Katili (1970) mentioned three earthquakes near the trace of the PKF.

Based on earthquake catalog, more than hundred earthquakes with magnitude more than 4 were recorded in Sulawesi area. These earthquakes clustered at the northern arm of Sulawesi and along the Palu-Koro Fault System. Several earthquakes known along Palu-Koro Fault system such as Gimpu earthquake in 1905, Kulawi earthquake in1907, Kantewu earthquake in 1934, off shore Donggala earthquake in 1968 which caused tsunami that destroyed 800 houses and killed 200 people at Donggala district. A damaging earthquake on the PKF in 1909 was reported by Hamilton in 1979, In addition, a recent reappraisal study [11] of the seismic history based on several catalogues [12], [13], [14] reported 28 major earthquakes around Sulawesi between 1845 and 1998. Considering the seismic activity along the Palu-Koro Fault system, it should be significantly important to mitigate the natural hazard of Palu city, by determining soil characteristic and its amplification during earthquake to whole Palu city since no existing of soil profile map in Palu city.

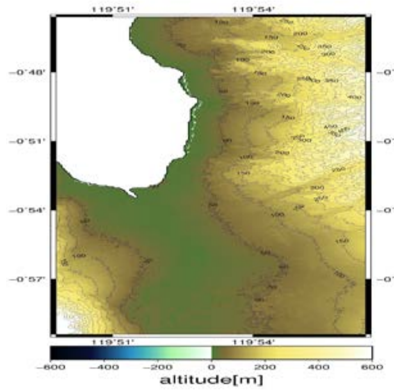


Fig.3 Altitude of Palu city area

2. SITE CHARACTERIZATION BY MICROTREMOR OBSERVATION

2.1 Single observations

A microtremor is a very small ground motion that can be recorded on the ground surface. It can be produced by a variety of excitations (e.g., wind, traffic, breaking sea waves). A full microtremor record can be described by one vertical and two horizontal components. Our analysis was conducted using the recorded by microtremor device. First, the horizontal and vertical spectrum ratios (HVSR) were computed for all sites. The peak period of the HVSR is known to correspond to the resonant period of the site. This method postulates the shape of the Fourier spectrum.

We performed 122 single site surveys that sampled every district of the city of Palu. These observations were carried out in 2012.

Eq. (1) shows the method used to calculate HVSR using the observed records.

$$\boldsymbol{HVSR} = \sqrt{\frac{F_{NSi}(\omega)^2 + F_{EWi}(\omega)^2}{F_{UDi}(\omega)^2}} \quad \textbf{(1)}$$

Where $\boldsymbol{F_{NSi}(\omega)}$ and $\boldsymbol{F_{UDi}(\omega)}$ denote the Fourier amplitude of the NS, EW and UD components of each interval, respectively, and $\boldsymbol{\omega}$ is the frequency. The locations of observations are plotted in fig.4. Microtremor was measured using a GPL- 6A3P sensor. The two horizontal (NS and EW) and the vertical (UD) components were recorded simultaneously for 10 minutes with a 100 Hz-200Hz sampling frequency.

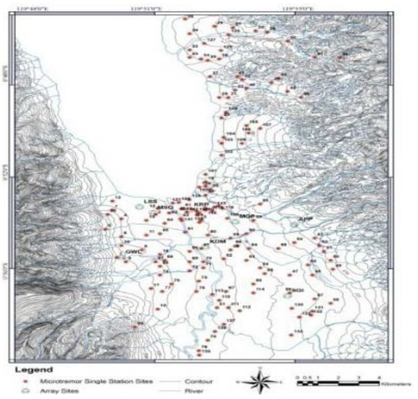


Fig. 4 Observation sites and predominant periods,

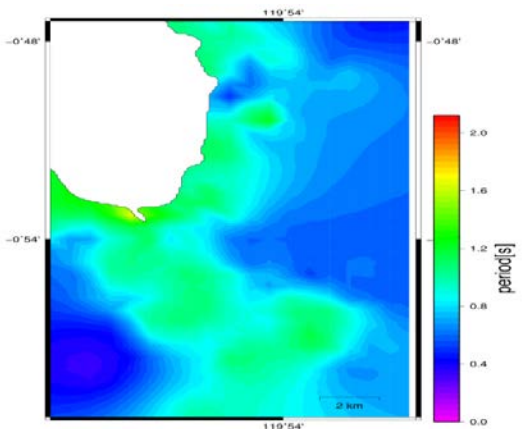
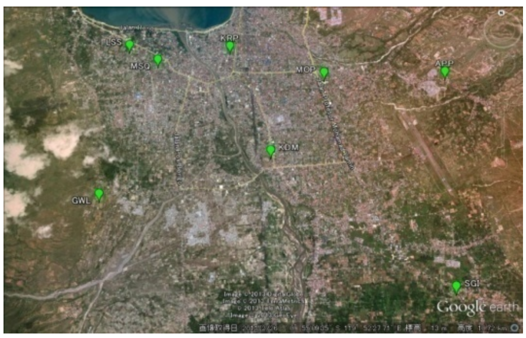


Fig.5 H/V ratio distribution

We estimated the distribution of the peak periods of the HVSRs for all sites in Palu using the ordinary kriging technique. From single observations, we obtained a predominant period of 1.2 to 1.8 s in the central business district and less than 1.0 s in the mountainous areas (Fig.5). These results indicate an affect related to the thickness of alluvium in the coastal area of Palu city, which decreases in thickness inland.

2.2 Microtremor array observations

The velocity of surface waves is well known to vary as a function of frequency (or period) due to dispersion. Since dispersion is a function of subsurface structure, the substructure can be estimated from a Rayleigh wave dispersion curve. We carried out microtremor array investigations using 8 sites at several districts in Palu (Fig.6). Dispersion curves were calculated using the SPAC method [15] to obtain a velocity structure from the microtremor recordings. An outline of the procedure follows. It is necessary to simultaneously record microtremors with an instrument array of at least three stations. The dispersion of a measured surface wave is a response to the subsurface structure directly below the array, and the estimation of the subsurface structure causing the dispersion is determined by means of inversion of Rayleigh waves. The basic principles of the SPAC method assume that the complex wave motions of microtremors are stochastic processes in time and space. A spatial autocorrelation coefficient for a circular array can then be defined when the waves composing the microtremor (i.e., the surface waves) are dispersive. Hence, the spatial autocorrelation is a function of phase velocity and frequency. Rayleigh wave records were measured for the 8-array observation sites using the SPAC method and inversion analysis was undertaken on the observed dispersion curves to estimate the soil profiles. In the inversion analysis, the Particle Swarm Optimization (PSO) algorithm was adopted to solve the non-linear optimization problem [16]. The basic



procedures of PSO are outlined below.

Fig 6**.** Array observation sites in Palu city.

The particle swarm concept originated as a simulation of simplified social system. The original intent was to graphically simulate the choreography of bird of a bird block or fish school. However, it was found that particle swarm model can be used as an optimizer, PSO simulates the behaviors of bird flocking. Suppose the following scenario: a group of birds are randomly searching food in an area. There is only one piece of food in the area being searched. All the birds do not know where the food is. But they know how far the food is in each iteration. So what's the best strategy to find the food? The effective one is to follow the bird which is nearest to the food. PSO learned from the scenario and used it to solve the optimization problems. In PSO, each single solution is a "bird" in the search space. We call it "particle". All of particles have fitness values which are evaluated by the fitness function to be optimized, and have velocities which direct the flying of the particles. The particles fly through the problem space by following the current optimum particles. PSO is initialized with a group of random particles (solutions) and then searches for optima by updating generations. In every iteration, each particle is updated by following two "best" values. The first one is the best solution (fitness) it has achieved so far. (The fitness value is also stored.) This value is called pbest. Another "best" value that is tracked by the particle swarm optimizer is the best value, obtained so far by any particle in the population. This best value is a global best and called gbest. When a particle takes part of the population as its topological neighbors, the best value is a local best and is called lbest. We estimate the subsurface structure of the model by solving a nonlinear minimization problem with the fitness function below.

$$v_{id}^{t+1} = \omega\, v_{id}^{t} + c_1 r_1\left(p_{id}^{t} - x_{id}^{t}\right) + c_2 r_2\left(p_{gd}^{t} - x_{gd}^{t}\right) \quad (2)$$

$$x_{id}^{t+1} = x_{id}^{t} + v_{id}^{t+1} \quad (3)$$

where v_{id}^{t} is particle velocity of the i^{th}component in dimension d in the interaction, x_{id}^{t} is the particle position of the i^{th} component in dimension d in interaction, c_1 and c_2 are constant weight factors, p_i is the best position achieved by particle i, p^g is the best position found by the neighbor of particle i, $r_1$and r_2 are random factors in the [0,1] interval and ω is the inertia weight. Before performing the inversion analysis, the subsurface structure was assumed to consist of horizontal layers of elastic and homogeneous media above a semi-infinite elastic body. The shear wave velocity and thickness of each layer are the parameters determined by the inversion analysis. The results enable us to determine the condition of shallow subsurface structures [17]. The outline of the SPAC method for the phase velocity calculation of Rayleigh waves follows.

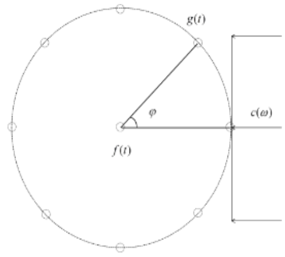


Fig 7. Microtemor array observation schema

$$F(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} f(t)\cdot exp(-i\omega t)\, dt = A_f(\omega)\cdot exp\left(-i\emptyset_f(\omega)\right) \quad (4)$$

$$G(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} g(t)\cdot exp(-i\omega t) = A_g(\omega)\cdot exp\left(-i\emptyset_g(\omega)\right) \quad (5)$$

$A_f(\omega)$, $A_g(\omega)$ and $\emptyset_f(\omega)$, are difference between the amplitude of $\emptyset_g(\omega), F(\omega)$, $G(\omega)$ respectively. Futher cross correlation in the frequency region of the two waveforms will be as follows.

$$C_{fg} = F(\omega)\cdot \overline{G(\omega)} = A_f(\omega)\cdot A_g(\omega)\cdot exp\left(i\Delta\emptyset(\omega)\right) \quad (6)$$

It shows the phase difference of $\Delta\emptyset(\omega)$

$$\Delta\emptyset(\omega) = \frac{\omega r}{c(\omega)} \quad (7)$$

$c(\omega)$is the phase velocity from the phase difference.

$$CC_{fg} = A_f(\omega)\cdot A_g(\omega)\cdot exp\left(i\frac{\omega r}{c(\omega)}\right) \quad (8)$$

The complex coherence of two waveforms is defined by the following equation.

$$COH_{fg}(\omega) = \frac{CC_{fg}(\omega)}{A_f(\omega)\cdot A_g(\omega)} = exp\left(i\frac{\omega r}{c(\omega)}\right) \quad (9)$$

$$Re\left(COH_{fg}(\omega)\right) = \cos\left(i\frac{\omega r}{c(\omega)}\right). \quad (10)$$

$$c(\omega,\varphi) = \frac{c(\omega)}{cos\varphi} \quad (11)$$

$$SPAC(\omega,r) = \frac{1}{2\pi}\int_0^{2\pi} exp\left(i\frac{\omega r}{c(\omega)}cos\varphi\right)d\varphi \quad (12)$$

$$Re\left(SPAC(\omega,r)\right) = \frac{1}{2\pi}\int_0^{2\pi} \cos\left(i\frac{\omega r}{c(\omega)}cos\varphi\right)d\varphi \quad (13)$$

$$J\left(\frac{\omega r}{c(\omega)}\right) = \frac{1}{2\pi}\int_0^{2\pi} exp\left(\frac{\omega r}{c(\omega)}cos\varphi\right)d\varphi \quad (14)$$

where $Jo(x)$ is the zero-order Bessel function of the first kind of x, and $c(\omega)$ is the phase velocity at frequency ω. The SPAC coefficient $\rho(r,\omega)$ can be obtained in the frequency domain using the Fourier transform of the observed microtremors.

$$Re\big(SPAC(\omega,r)\big) = J\left(\frac{\omega r}{c(\omega)}\right) \qquad (15)$$

From the SPAC coefficient $\rho(r,\omega)$, the phase velocity is calculated for every frequency from the Bessel function argument of equation. 15 and the velocity model can be inverted.

$$\overline{V_s} = \sum V_{si} \cdot \frac{H_i}{H} \qquad (16)$$

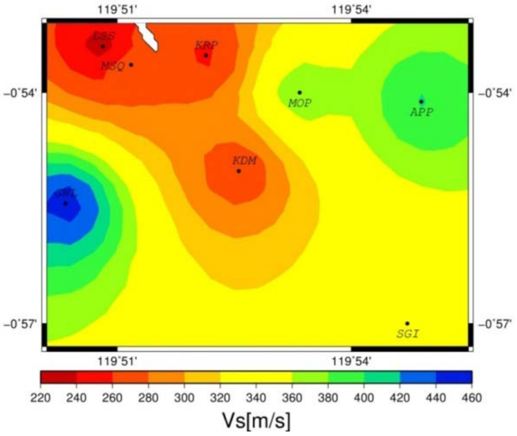


Fig. 8 Soil Profile, Shear velocity (Vs) for 1st layer in Palu city

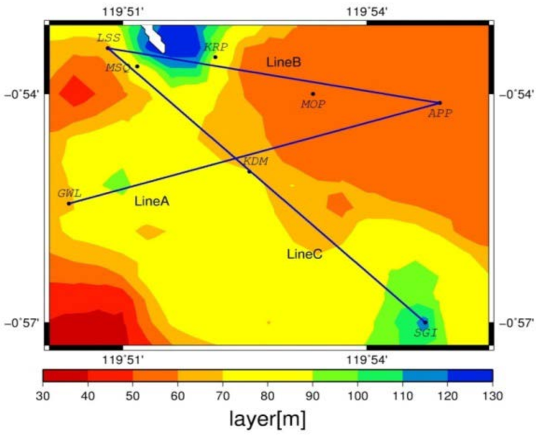


Fig. 9 Shear velocity (Vs) at 800 m/s (Engineering bedrock) in Palu city.

3. CONCLUSIONS

1. Our survey conducted in Palu city consisted of (1) microtremor observations (single and 8-channel arrays) in 2012, Palu has a thick alluvial layer in the coastal area (with a predominant period between 0.4 and 1.8 s) that thins toward the mountains (with a predominant period less than 1.0 s). The subsurface geology also changes slowly from soft soil in the coastal area to rocky conditions in the mountains.
2. According to microtremor observations, downtown Palu is underlain by soft soil conditions (V_s<400 m/s).
3. Consistent results concerning the soil condition were found based on predominant period observations. In its case, the coastal area was determined to have a soft soil conditions (V_s<400 m/s), a longer predominant period. These results provide critical information for making shaking maps, updating hazard maps, and developing disaster prevention countermeasures in Palu city.

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