

# Estimation of Seismic Ground Motion Induced by the 23 January, 2005 Earthquake in Palu Region, Central Sulawesi, Indonesia

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**Abstract:** On January 23rd 2005, a strong earthquake with moment magnitude (Mw 6.3) hit the Palu City (Central Sulawesi area). The earthquake involved an area more than 800 km along the Palu Koro fault zone. In order to characterize the seismic ground motion of alluvium layers existing in the Palu City, eight sites of microtremor array measurements were performed. The shear wave velocity of the top layer is  $\leq 300$  m/s. Palu City had deposited on a thick alluvial layer in the coastal area. The subsurface geology also changes slowly from soft sedimentary layers in the coastal area to igneous intrusion and metamorphic rock in the mountains. Seismic strong ground motion was predicted based on the statistical Green's function method. Considering the damage produced by the 2005 Palu earthquake (Mw 6.3), we also estimated peak ground acceleration distribution at Palu City, with values ranging from 100 gal up to 500 gal on the PGA (peak ground acceleration) scale. Peak ground velocity becomes more than 0.3 m/s in some areas, which may likely lead to severe damage to buildings.

**Key words:** Seismic ground motion, Palu-Koro fault, microtremors, PGA.

## 1. Introduction

Sulawesi, eastern Indonesia, is a K-shaped island lying at the junction of Eurasian, Indo-Australian and Pacific plates. Sulawesi tectonic evolution results from successive collisions of continental slivers, island arcs, and oceanic domains with the Sundaland. The CSFS (Central Sulawesi Fault System), one of the major structures in southeast Asia, cuts across Sulawesi Island from northwest to south-east, connecting the North Sulawesi subduction zone to the Banda Sea deformation zones. One of the major structures in Central Sulawesi is the Palu-Koro fault system, which extends north-northwest to south-southeast direction

and cross cuts Sulawesi along 300 km, from Palu Bay southward turn to the southeast connecting to the Matano and Lawanopo Faults [1]. Based on ISC (International Seismological Centre), USGS (United States Geological Survey) catalog [2], Indonesian Institute of Meteorology, Climatology and Geophysics, more than hundred earthquakes with magnitude more than six were recorded in Sulawesi area. These earthquakes clustered at the northern arm of Sulawesi and along the Palu-Koro fault system. Considering the seismic activity along the Palu-Koro fault system it should be significantly important to mitigate the natural hazard of Palu city area, especially on earthquake mitigation. In this study, Palu, where a large earthquake is expected in the near future, is considered to be a target area. We carried out higher density single point observations and larger radius

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array observations. Based on the observed microtremor data, we calculated the distribution of the predominant and phase velocities of the Rayleigh wave.

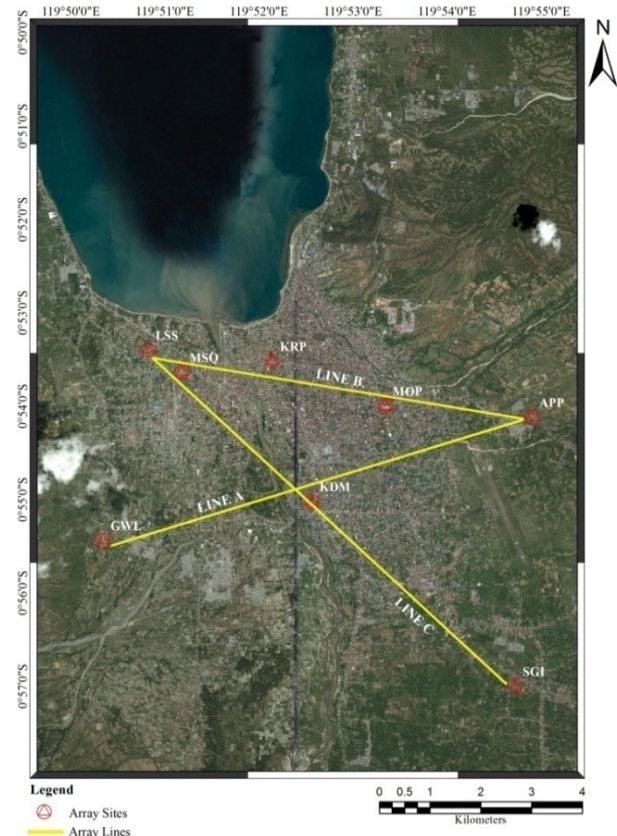
## 2. Geology

Evolution of Neogene kinematics along the Palu-Koro fault was confirmed based on microtectonics approach, i.e., sinistral strike-slip due to east-west compression, radial extensions caused by telescoping vertical movement of Neogene granitoid, and then left lateral with normal component displacement due to north-south extension/east-west compression which is still active actually [3]. Palu depression area is filled by mostly clay, silt, and sand deposits as alluvial deposit. The composition of gravel is granitic fragment to the northwest. West escarpment to the north consists of granite and granodiorite units, and to the south consists of schist-phyllitic units. East escarpment consists of molasses [4].

## 3. Microtremor Array Survey

We carried out array observations at eight sites in Palu (Fig. 1). Dispersion curves were calculated using the SPAC method. Four accelerometers were used in each array observation site. One was installed at a center of the circle with a radius,  $r$ . Other three were arranged on the circle with a shape of regular triangle. Observation duration time was 20-30 minutes and sampling frequency was 100 Hz. Sequential observations were conducted three times by changing the array radius;  $r = 3, 10$  and  $30$  m. The velocity of surface wave is well known to vary as a function of frequency (or period) due to dispersive characteristics [5]. Therefore, the substructure can be estimated from observed dispersion curve. Then, a sub structure profile was identified from the dispersion curve by using the particle swarm optimization [6, 7].

For line A (Fig. 1), the phase velocity corresponding to shallow ground with a high frequency range is about 369 m/s at APP (Airport Palu), about 423 m/s at GWL (Gawalise), about 318 m/s at KDM



**Fig. 1** Three survey lines for array observation (Line A, Line B, and Line C).

(Kadam), about 318 m/s at KRP (Karampe), about 279 m/s at LSS (Lasoso), about 348 m/s at MOP (Mayor of Palu), about 285 m/s at MSQ (Mosque) and about 317 m/s at SGI (Sigi Biromaru).

The soft ground extended beneath LSS, which is the nearest site to the coast. The ground beneath the sites higher than GWL has relatively hard surface soil compared with the plain along the coast. Since the minimum phase velocity in the high frequency range is around 300 m/s, the soil profile is very similar along line B and line C (Fig. 1). The dispersion curves obtained here had no discrepancies in the distribution of topography, altitude and predominant period. We could estimate subsurface sedimentary layers in the plains using these dispersion curves.

### 3.1 Results of Inversion

Line A, the  $V_s$  (shear wave velocity) structure along line A is shown in Fig. 2a. Looking at a surface layer at

GWL, the thickness of the first layer with  $V_s \leq 300$  m/s is about 26 m, however, the corresponding layer cannot be seen for KDM and APP. The thickness of the sediment is about 300 m/s at GWL, on the other hand, those at GWL, KDM and APP are 30 m, 10 m and 3 m of the array sites respectively, but the layer disappeared at the site near the mountain, GWL. As seen in the distribution of the predominant period of the H/V spectra, it can also guess at the existence of a rapid change in the subsurface structure between GWL and KDM. Line B, the  $V_s$  structure along line B is shown in Fig. 2b. The range of the shear wave velocity for the first, second, and third layers is assumed (I)  $V_s \leq 300$  m/s, (II)  $300 \leq V_s \leq 1,300$  m/s and (III)  $V_s \geq 1,300$  m/s. The thickness of the first layer is around 20 m to 60 m. The sediment thickness is about 125 m and almost uniform. This tendency is in good agreement with the results of the predominant period distribution characteristics. Line C, the  $V_s$  structure along line C is shown in Fig. 2c. At the sites in the plain, LSS, MSQ, KDM and SGI, the thickness of the layer with  $V_s \leq 300$  m/s is around 20 m to 60 m. Although it could construct a four-layered model for each line, it is still difficult to compile all the information because some layers of a site cannot connect to those of other sites; therefore, a three-layered model is introduced as an alternative.

### 3.2 Modeling of Subsurface Soil Structure

We could obtain  $V_s$  structures at array observation sites, however, the ground profiles are not uniquely determined. In this study, we proposed simple two layer model in Palu by averaging the first three layers of all array sites. Shear wave velocity of the first layer modeled is  $\leq 300$  m/s. By combining with the first peak of H/V data, we can obtain the thickness of the first layer. The technique used was the 1/4 wavelength principle, which can approximately be extended to multi layered media.

$$T = 4 H/V_s \tag{1}$$

where,  $H$  is a thickness of a layer,  $V_s$  shear wave velocity and  $T$  predominant period. The distribution of thickness for the first layer of which  $V_s$  is  $\leq 300$  m/s in Palu area is shown in Fig. 3, in which the rapidly varying area of the subsurface condition and dense observation area are enclosed. Tables 1 and 2 show the correlation between the subsurface geology and  $V_s$  and soil classification based on  $V_s$  from the regular triangle shaped circular array and SNI 1,726-2,002. In the east of the site, LSS, around a 75 m thick layer of sediment uniformly accumulated along the coast in the plain. The sediment becomes thinner from the coast to the eastern mountains. The boundary depth was around

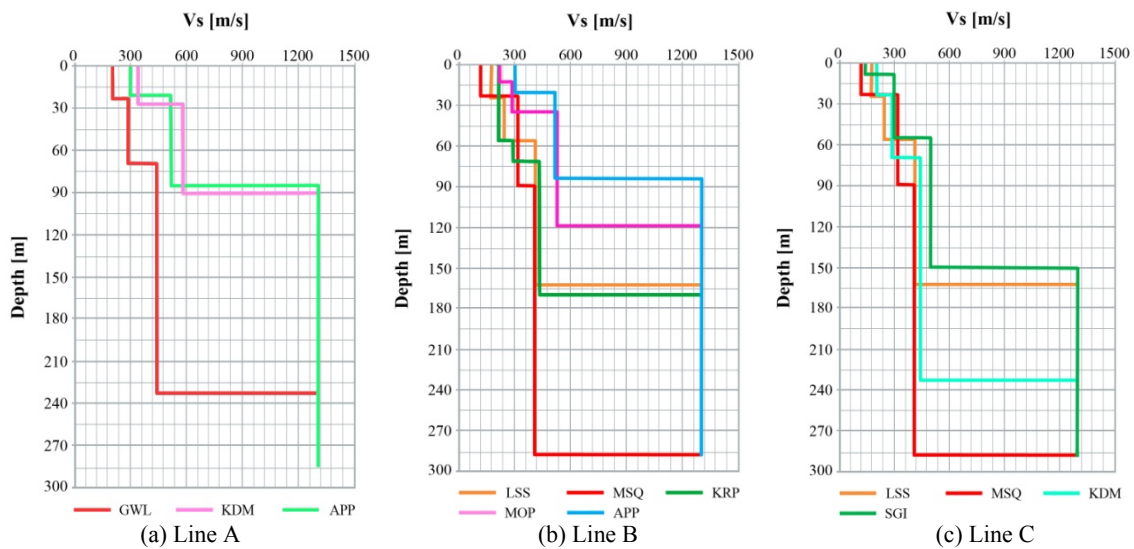
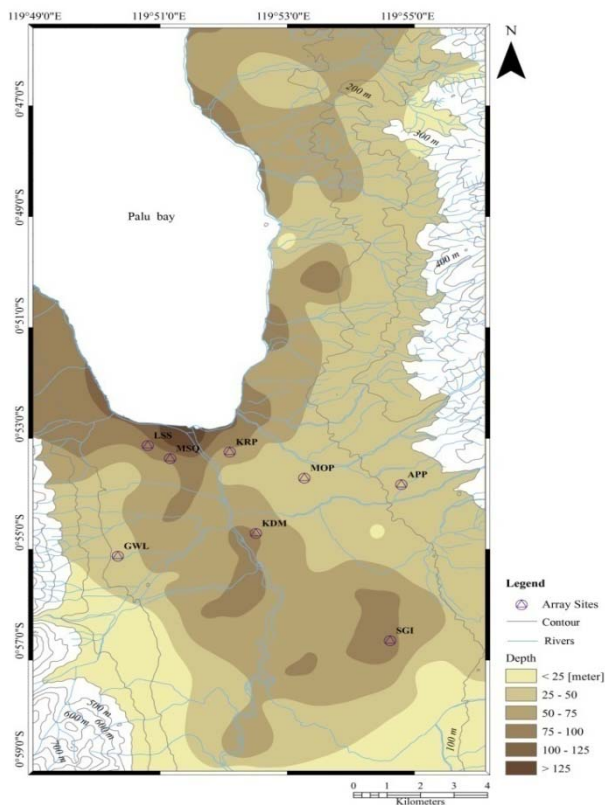


Fig. 2  $V_s$  structures of the ground along the survey lines (a) Line A, (b) Line B and (c) Line C.



**Fig. 3** Sediment thickness or depth of engineering bed rock in Palu City.

100-125 m and appeared very deep. In the west of the site, MSQ, the depth of the boundary drastically

changed from 75-100 m to 125 m. Rapid change can also be seen in the western part of the area near the GWL site because of the mountain location. Focusing on the site MSQ, although the elevation of surrounding area is almost at the same level, a sudden change in sedimentary layers can be seen. At present, since there are no detailed ground survey data in Palu such as deep boring, gravity anomalies, and seismic exploration, the existence of a hidden fault is just an estimation from microtremor observations. However, if a hidden fault exists beneath Palu City, we should prepare for a near-source earthquake here in Palu. For future work, additional dense array observations combined with other ground survey techniques need to be done to clarify the detailed subsurface structure, especially around the GWL site.

#### 4. Estimation of the 2005 Earthquake in Palu by Using Statistical Green's Function Method

The strong ground motion and amplification characteristics in Palu City had been computed by using synthetic waveforms of 2005 Palu earthquake

**Table 1** The correlation between the subsurface geology and  $V_s$ .

No	Array sites	Topography	Geology	Period (s)	$V_s$	Thickness
1	APP	Hilly	Molasse	0.6	369.7	< 50
2	GWL	Hilly	Alluvial deposits	0.56	423.7	< 50
3	KDM	Flat	Alluvial deposits	1.07	318.1	< 50
4	KRP	Flat	Alluvial deposits	1.32	318.0	50-75
5	LSS	Flat	Alluvial deposits	1.14	279.0	> 100
6	MOP	Flat	Alluvial deposits	0.59	348.0	> 100
7	MSQ	Flat	Alluvial deposits	1.23	285.7	> 100
8	SGI	Flat	Alluvial deposits	1.3	317.8	> 100

**Table 2** Soil classification based on  $V_s$  from the regular triangle shaped circular array and SNI 1726-2002.

No	Area	$V_s$ (m/s)	Weak soil $V_s < 175$ (m/s)	Medium dense soil $175 \leq V_s \leq 350$ (m/s)	Dense soil $V_s \geq 350$ (m/s)
1	APP	369.7			√
2	GWL	423.7			√
3	KDM	318.1		√	
4	KRP	318.0		√	
5	LSS	279.0		√	
6	MOP	348.0		√	
7	MSQ	285.7		√	
8	SGI	317.8		√	

as input bedrock motion below the alluvium sediments. The Irikura’s computer code was used to generate synthetic waveforms, mainly based on epicentral distance, magnitude and focal depth of earthquake [8, 9].

The USGS epicenter, magnitude  $M_w$  6.3 and focal depth 20 km are used for calculation of synthetic accelerograms at eight sites where microtremor measurements were conducted and interpolated Kriging sites in Palu City [10].

In this study, ground model is constructed by combining two layer model and average seismic bed rock model used in Japan, because there is no bed rock information in this area (Table 3). The fault model (Fig. 4) referred is an earthquake with moment magnitude of 6.3 on 23 January 2005 in Palu, Indonesia, of which epicenter was latitude 119.933 E and longitude -1.198 S. Fig. 5 shows data flow diagram of the statistical Green’s function method at Palu City.

4.1 Peak Time Domain Parameters

Historically, peak ground acceleration, PGA and a lesser extent peak ground velocity, PGV and peak ground displacement, PGD have been the most common peak time domain parameters used to describe strong ground motion in engineering practice. They represent the maximum absolute amplitude of ground motion scaled from a recorded or synthetic acceleration, velocity or displacement time series.

4.2 Response Analysis

When the layered ground model is constructed, we can calculate a transfer function (frequency response function) between seismic bed rock and ground surface. Here the layered media over bed rock is assumed to be two layers and to show linear behavior.

After obtaining the waveform at bed rock level by using statistical Green’s function model, its Fourier spectrum is multiplied with the transfer function of the surface layer. The time history of waveform at an arbitrary site can be simulated by inverse Fourier transform. Fig. 6 shows Fourier spectra of

accelerations at the surface (APP site).

Table 3 Macroscopic source parameters.

Source	Parameters
Latitude (°)	119.933 E
Longitude (°)	-1.198 S
Topdepth $d$ (km)	0
Bottomdepth (km)	20
Length $L$ (km)	40
Width $W$ (km)	20
Strike (°)	342.1
Slope (°)	90
Slipangle (°)	0
Moment magnitude	$M_w = 6.3$
Fault area (km <sup>2</sup> )	800
Shear wave velocity $V_s$ (m/s)	3000
Mean density $\rho$ (t/m <sup>3</sup> )	2.4
Modulus of rigidity $\mu$ (N/m <sup>2</sup> )	2.16E + 10
Averageslip (m)	0.21
rupture velocity $V_r$ (m/s)	3,000
High-frequency limit (Hz)	10

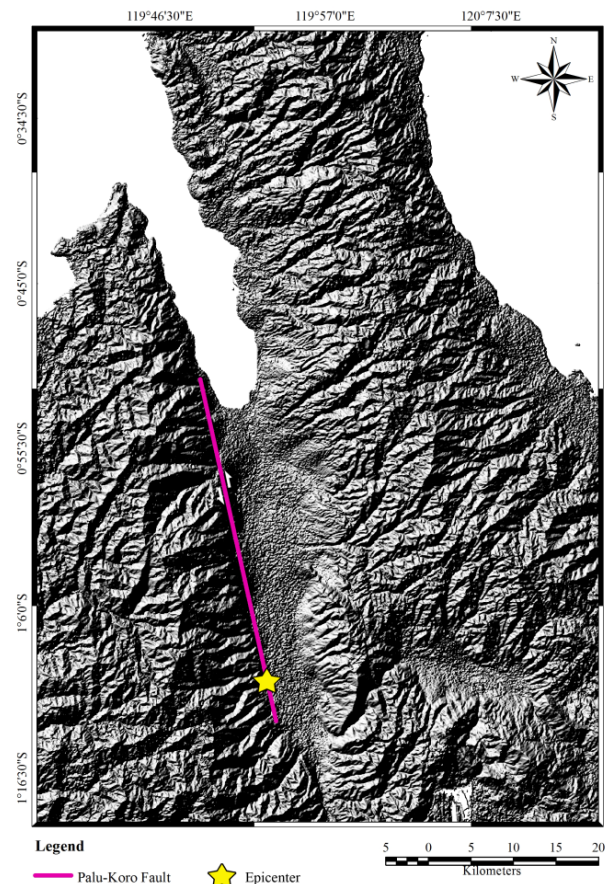


Fig. 4 Map of the Palu-Koro fault.

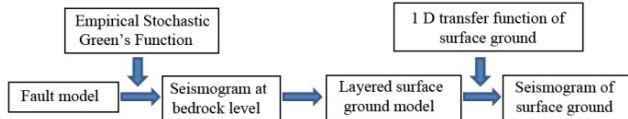


Fig. 5 Data flow diagram of the statistical Green's function method at Palu City.

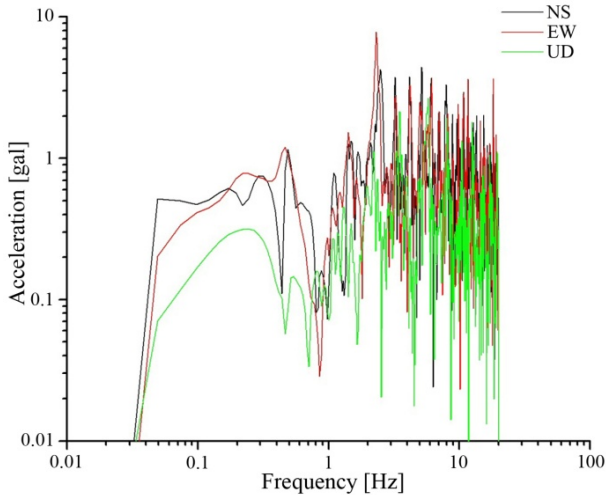


Fig. 6 Fourier spectra of accelerations at the surface (APP site).

## 5. Peak Ground Acceleration

Peak ground acceleration, PGA, is commonly used to describe ground motion because their natural relationship to inertial force induced in certain types of structures are closely related to it. Based on acceleration histories of response analysis, PGA values are determined. The most commonly used measure of amplitude of a particular ground motion is peak ground acceleration, PGA. It is the absolute value of horizontal acceleration. The vertical acceleration has received less attention in earthquake engineering than horizontal one because of the margin of safety against gravity induced static vertical forces. Through dynamic response analysis, PGA was determined based on response acceleration time histories of the arbitrary site. The Figs. 7-9 show the PGA map of Palu City by statistical Green's function method and response function of the surface ground. The PGA value is generally ranging from 150 gal to 500 gal. The central portion, high damage area, especially around Binangga of Palu show high PGA value, 400-450 gal. The PGA at Pengawu, Baliase and Tavanjuka are 300-400 gal. The PGA at

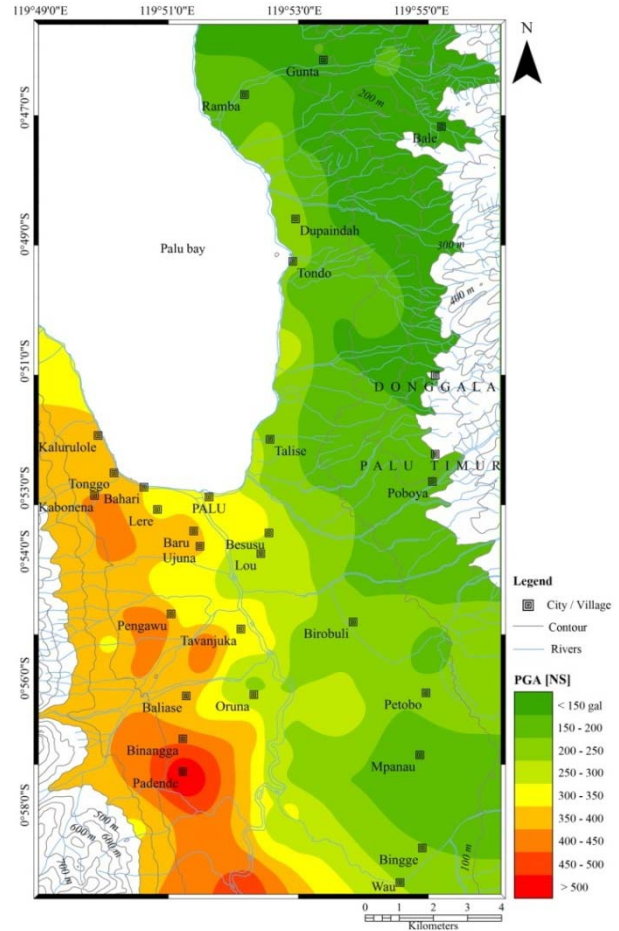


Fig. 7 PGA (north-south) map of Palu City derived from synthetic waveforms of Palu, 2005 Earthquake.

Tonggo and Kabonena are 350-450 gal while PGA is less than 350 gal in Palu and Talise areas.

## 6. Conclusions

The procedure employed and conclusions obtained in this study are as follows. Subsurface engineering bed rock in Palu City had been successfully determined based on data from microtremor array survey. Single-point and array surveys were conducted at 151 and eight sites respectively, which covered almost the whole city area. *H/V* spectra were calculated at all the single observation sites and a distribution of predominant periods was obtained. The Kriging method can be used for the interpolation of subsurface information such as predominant period, shear wave velocity and depth of irregular boundary. By conducting an inversion analysis for the calculation of

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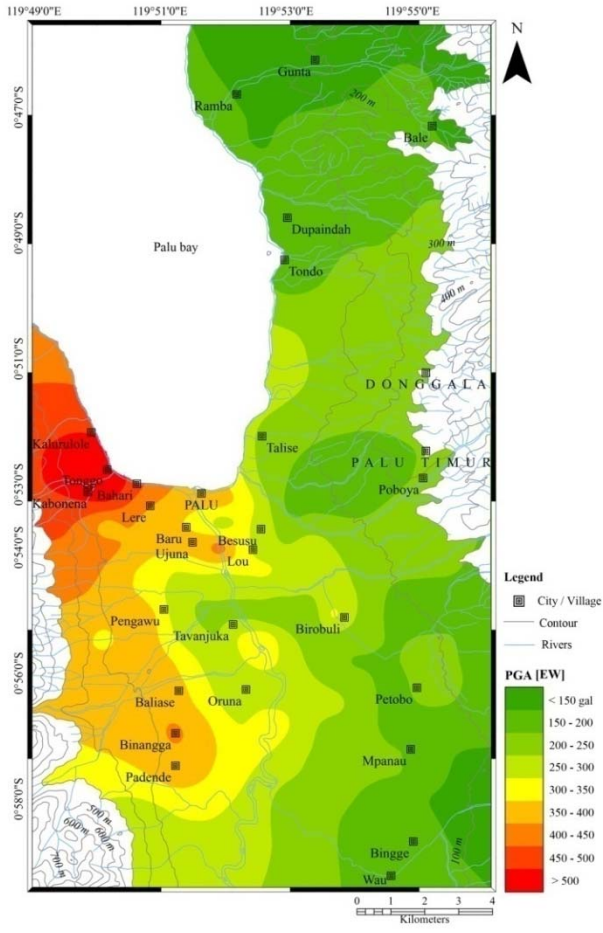


Fig. 8 PGA (east-west) map of Palu City derived from synthetic waveforms of Palu, 2005 Earthquake.

dispersion curves, the subsurface structure beneath the site can be estimated. It was constructed a four layered model in each array observation point. This research was reconstructed unified two-layered model by averaging the first three layers obtained from array observation. The shear wave velocity of the top layer is  $V_s \leq 300 \text{ m/s}$ . Three dimensional structure for shear wave velocities were (I)  $V_s \leq 300 \text{ m/s}$ , (II)  $300 \leq V_s \leq 1300 \text{ m/s}$  and (III)  $V_s \geq 3000 \text{ m/s}$ . By combining above two-layer model and the results of single point observation, the distribution of the first layer thickness of the sediment is obtained. It is well observed that S-wave velocity structure play an essential role in response analysis and determination of sediment thickness or depth of engineering bedrock. The shear wave velocity structure and map of  $V_s \leq 300 \text{ m/s}$  of studied area had been successfully determined together

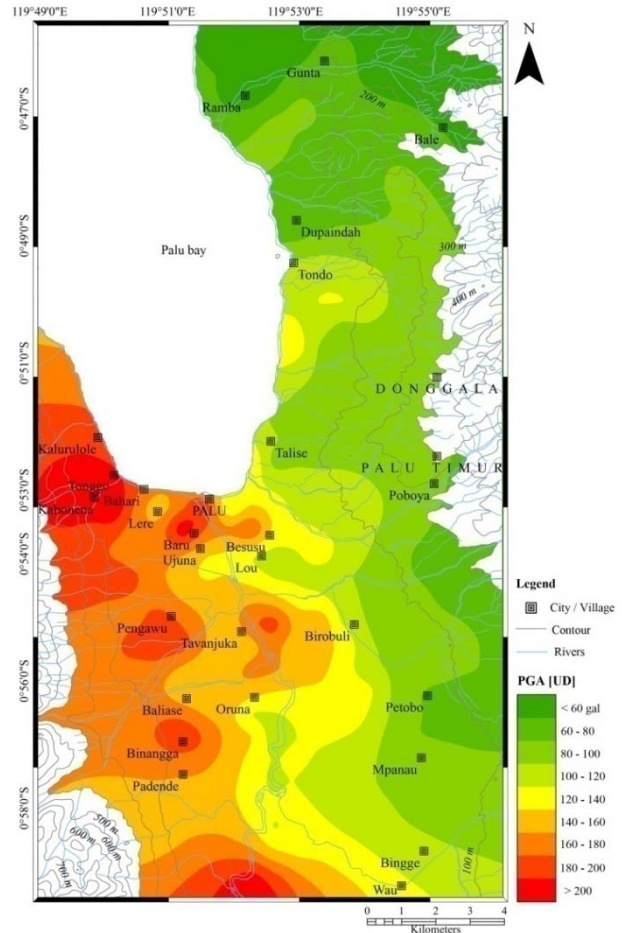


Fig. 9 PGA (updown) map of Palu City derived from synthetic waveforms of Palu, 2005 Earthquake.

with three dimensional model of sediment thickness or depth of engineering bedrock. The subsurface geology also changes slowly from soft sedimentary layers in the coastal area to igneous intrusion and metamorphic rock in the mountains. Strong ground motions were predicted based on the statistical Green's function method by using the proposed ground model. Peak acceleration becomes more than 500 gal in the some areas, which causes severe damage for buildings in high probability.

In this paper the alluvial subsoil of Palu City, Indonesia is investigated by microtremor measurements and processing in order to characterize the seismic ground motion in this city. Finally, the evaluated PGA maps should be used for seismic risk mitigation in Palu City. The mathematical application developed in this paper is interesting but the phenomenon of seismic

waves propagation is extremely complex one by permanent reflexion, refraction and interference of waves during propagation. In this context, any mathematical model is a pale representation of the physical phenomenon and results have only qualitative value. The degree of confidence in the results presented by authors, especially concerning PGA distribution at Palu City is limited. The future large array microtremors survey, geo-electrical investigation, cross hole in boreholes, sonic log test in boreholes and SASW (Spectral Analysis of Surface Waves) should conduct among the previous three survey lines in order to investigate thoroughly the whole City area. That kind of survey is in need to prepare adequate and satisfactory input data for future seismic hazard analysis in Palu City.

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