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# Estimation of Earthquake Ground Motion in Padang, Indonesia

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ABSTRACT: Several powerful earthquakes have struck Padang during recent years, one of the largest of which was an M 7.6 event that occurred on September 30, 2009 and caused more than 1000 casualties. Following the event, we conducted a questionnaire survey to estimate the shaking intensity distribution during the earthquake. About 500 residents of Padang were interviewed. The residents received explanations for each item on the questionnaire from the interviewers, and answers were filled in directly on the answer sheets. From this survey we produced a map of the shaking intensity distribution in Padang. In addition to the questionnaire survey, we performed single observations of microtremors at 110 sites in Padang. The results enabled us to estimate the site-dependent amplification characteristics of earthquake ground-motion. We also conducted a 12-site microtremor array investigation to gain a representative determination of the soil condition of subsurface structures in Padang. From the dispersion curve of array observations, the central business district of Padang corresponds to relatively soft soil condition with $Vs_{30}$ less than 400 m/s, the predominant periods due to horizontal vertical ratios (HVSRs) are in the range of 2.0 to 4.0 s, and the seismic intensity obtained is upper 5 (5+) in the $JMA_i$ scale. By making these observations, we can obtain a relationship between soil types, predominant periods and seismic intensities.

Keywords: Peak Ground Acceleration, Seismic Intensity of the Japan Meteorology Agency, Padang Earthquake, Microtremor Observations.

## 1. INTRODUCTION

Seismic intensity is one of the simplest and most important parameters for describing the degree of ground shaking during an earthquake. Sometimes it has a strong correlation with the human response to ground shaking, observations of damage, and earthquake effect. In this study, we adopt the seismic intensity scale of the Japan Meteorology Agency ($I_{JMA}$) scale, an instrumental seismic intensity that was first adopted in Japan after the 1995 Kobe earthquake. Its scale runs from 0 to 7, with ten classes including lower 5, upper 5, lower 6 and upper 6. We propose the use of the instrumental $I_{JMA}$ to make initial and fast estimations of damage following a seismic event.

The city of Padang, located on the west coast of Sumatra in western Indonesia, lies close to the Sumatran subduction zone that is formed by the subduction of the Indo-Australian Plate beneath the Eurasian Plate. Relative motion of the plates occurs at a rate of about 50 to 70 mm/year and this is the main source of subduction-related seismicity in the area [1]. Based on our catalog, seven giant earthquakes have occurred in this region since records began: 1779 (Mw 8.4), 1833 (Mw 9.2), 1861 (Mw 8.3), 2004 (Mw 9.2), 2007 (Mw 7.9 and 8.4) and 2009 (Mw 7.6). The hypocenter of the Padang earthquake that occurred on September 30, 2009 was located in the ocean slab of the Indo-Australian Plate at -0.81°S, 99.65°E and at a depth of 80 km. It produced a high degree of shaking and the tremor was felt in the Indonesian capital, Jakarta, about 923 km from the epicenter. The tremors also were felt in neighboring countries such as Malaysia and Singapore [2]. The earthquake caused landslides and collateral debris flows in the hills surrounding Lake Maninjau. A major landslide in Gunung Nan Tigo, Padang Pariaman completely destroyed some villages and forced road closures.

This 1900-km-long active strike-slip fault zone that runs along the backbone of Sumatra poses seismic and fault hazards to a dense population distributed on and around the fault zones [3]. The Sumatran Fault is highly segmented. It consists of 20 major geometrically defined segments and the slip rate along the fault increase to the northwest, from about 5 mm/yr [3]. This fault also has generated large destructive earthquakes, e.g., 1892 (Mw 7.1), 1943 (Mw 7.6) and 2007 (Mw 6.4). These faults are capable of generating strong ground motion in the future that would greatly affect vulnerable structures. According to our catalogs, the Sumatran Fault produces a very high annual rate of earthquakes, many of which occur in the shallow region under the island of Sumatra (**Fig. 1**).

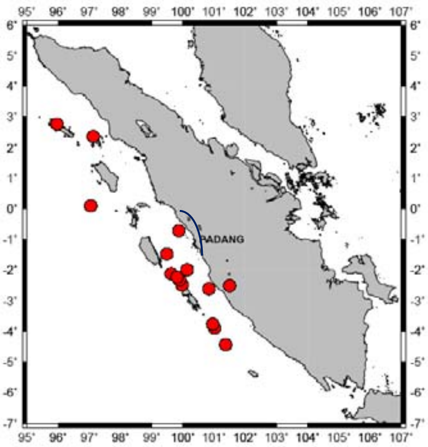



**Fig.1** Seismicity of Sumatra Island from 2005 to 2010, Mw>6.5, <100km depth of hypocenter, and Padang City.

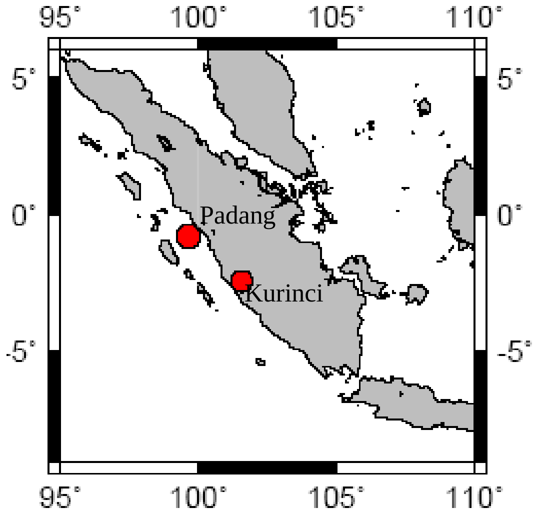
## 2. REGIONAL GEOLOGY AND RECENT EARTHQUAKES

The city of Padang, with a population of 856,814 people as of 2008, is the capital of West Sumatra province. The location of the city center is at 100.38°E, 0.95°S. The main part of Padang is situated on an alluvial plain between the Indian Ocean and the mountains. For the most part, the mountainous area is formed of Tertiary sedimentary rocks with outcrops of metamorphic rocks seen in some places. The alluvial plain spreads along the base of the mountains and is roughly 10 km wide in the east-west direction and 20 km wide in the north-south direction.

The topography of the Padang region (**Fig.4(a)**) is very similar to the tsunami-damaged area of Miyagi Prefecture in Japan, that was inundated by as much as 4-5 km from the coast after the March 11, 2011 Mw 9.0 Tohoku earthquake off the east coast of Honshu. In Padang, about 600,000 people live in the coastal area (covering about 60 km$^2$). The population density is very high, about 8500 people/km$^2$. The city is located on the coast of the Indian Ocean between the Sumatran Fault and the Sunda Trench Fault. Both faults are active with slip rate ranging from 10 to 27 mm/year [3]. According to our catalog, 2995 events with a magnitude greater than 4 occurred in this region from AD 1779 to 2010. The seven giant earthquakes mentioned previously have all been strongly felt here. For example, the source of the 2009 Padang earthquake was located in the ocean slab of the Indo-Australian Plate.

It produced extensive shaking and severe damage to houses and buildings in Padang and Padang Pariaman, because its epicenter was about 60 km offshore from Padang (**Fig. 2(a)**). As the Padang earthquake was an intra-slab earthquake at intermediate depth with a comparable magnitude, the event did not generate a tsunami of significance [4]. Due to this earthquake, 1117 people were reported killed, 1214 severely injured, 1688 slightly injured, and 3 were left missing in West Sumatra. The earthquake also destroyed many houses, buildings and infrastructure (heavily damaged houses numbered 114,797, with 67,198 moderately damaged and 67,837 slightly damaged). In Padang, 5458 buildings sustained damage [5]. This event occurred at the end of the working day, just 15 minutes after offices and schools closed; if it had struck earlier, the number of causalities would definitely have been higher as a result of building collapses. Several hours after Padang earthquake, 1$^{st}$ October 2009, Sumatran fault line generated Mw7.1 and 10km depth. Due to this earthquake destroyed many houses and building (heavily damaged houses numbered 600, with 550 moderately damaged). **Fig.2(a)** shows Padang earthquake and Kurinci earthquake.

There are four accelerometers in Padang. Three were donated by Engineers Without Borders Japan (EWBJ) and installed in 2008, and the other was installed by the Indonesian Government's Bureau of Meteorology, Climatology and Geophysics (BMKG). However, only one ground motion record is available for the Padang earthquake. Due to an electric power cut during the earthquake, only the BMKG device recorded the time history of the earthquake. The observed record shows about 20 s of strong shaking with a peak ground acceleration (PGA) of 0.3 g and a predominant period of 0.5 s (**Fig. 2(b)**). response spectra at law period is greater then Indonesia code for rock condition (0.83g) (Fig.2b).The location of this station is a mountainous suburb about 12 km in from the coast. The subsurface condition at this station is rocky; the average shear wave velocity for the upper 30 m of the subsurface here, $V_{s30}$, is 1200 m/s [6].

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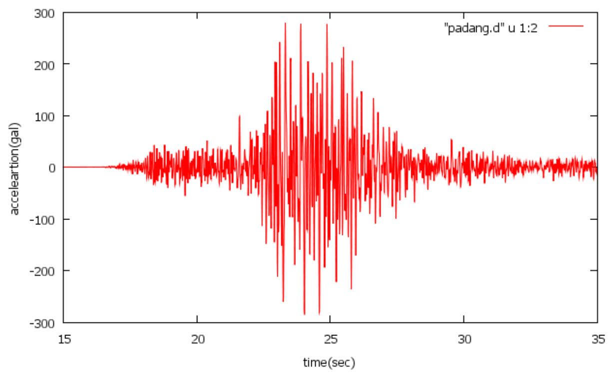


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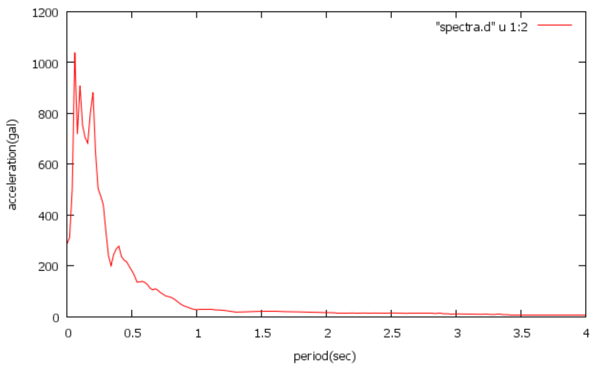



(b)

**Fig.2** Seismicity and time series. (a) two giant earthquake in Padang Mw7.6 and Kurunci Mw7.1, (b) time series of Padang earthquake, (c) response spectra due to Padang earthquake.

The paucity of measured ground motion information for this earthquake results in a need for transforming observed data (seismic intensity) into parameters that are more useful for engineering purpose (e.g., engineering ground-motion measures)[7]. From seismic intensity, we can evaluate historical earthquakes, assess seismic hazard and damage, correlate different intensity scales, and rapidly assess the severity of ground shaking [8]. In additional, we performed a 12-site microtremor array observations to determine the shear velocity of subsurface structures at several districts in Padang. From these observations, we obtained relationship between soil types, predominant period and seismic intensity.

## 3. DAMAGE FROM THE 2009 PADANG EARTHQUAKE

The city of Padang covers an area of about 695 $km^2$ and is divided into 11 districts: B. T. Kabung, K. Tangah, Kuranji, L. Begalung, L. Kilangan, Nanggalo, P. Barat, P. Selatan, P. Timur, P. Utara, and Pauh. 51.0% of the land is forested, 28.52% is used for farming, 9.54% for housing and 7.1% for rice fields [9]. The population of more than 857,000 is increasing by 2% per year. The K. Tangah district has the highest population and most extensive area compared with the other districts in the city.

The central business area of Padang is close to the coast and consist of several district: P. Barat, P. Utara, P. Selatan and P. Timur, B.T. Kabung, K. Tangah. The downtown area is utilized as a center of political and commercial activities. Although the Padang earthquake affected all districts of the city, the major damage occurred downtown, because about 80% of population lives near the coast.

The majority of houses in the city are one- and two-storey non-engineered structures. These structures are typically built of confined masonry, with reinforced-concrete (RC) frames acting as confinement for the brick masonry walls. There are three general categories of houses in Padang: permanent houses (RC), semi-permanent houses (mix of RC and wood) and traditional houses (wood). Unfortunately, no detailed damage statistics are available for each type of building, so we cannot classify the category of the house.

This earthquake also affected lifelines in Padang. The strong ground shaking destroyed public water distribution pipes leading to 2,906 reported leakage points in total [10]. Damage to pipelines forced the cessation of water delivery to consumers for several weeks.

## 4. SITE CHARACTERIZATION BY MICROTREMOR OBSERVATION

### 4.1 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 microtremor. First, the horizontal and vertical spectrum ratios (HVSR) were computed for all sites (**Fig. 3)**. HVSR (Horizontal-Vertical Spectra Ratio) is consists in estimating the ratio between the Fourier amplitude spectra of the horizontal (H) to vertical (V) components of ambient noise vibrations recorded at one single station.

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 [11].

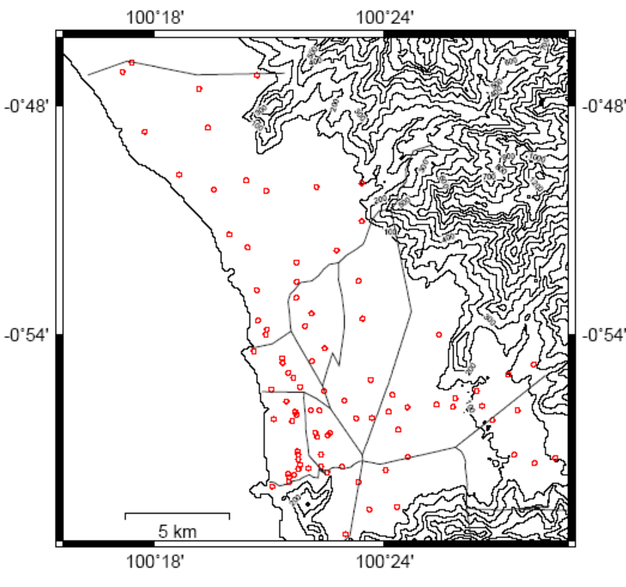
Equation. (1) shows the method used to calculate HVSR using the observed records.

$$HVSR = \sqrt{\frac{F_{NSi}(\omega)^2 + F_{FWi}(\omega)^2}{F_{UDi}(\omega)^2}} \qquad (1)$$

where $F_{NSi}(\omega)$ and $F_{UDi}(\omega)$ denote the Fourier amplitude of the NS, EW and UD components of each interval, respectively, and $\omega$ is the frequency.

We performed 110 single site surveys that sampled every district of the city of Padang. These observations were carried out in November 2008, September, November, and December 2009 and January 2010. The locations of observations are plotted in **Fig.3**. 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 sampling frequency.

We estimated the distribution of the peak periods of the HVSRs for all sites in Padang using the ordinary kriging technique (**Fig.3**). From single observations, we obtained a predominant period of 2.0 to 4.0 s in the central business district and less than 1.0 s in the mountainous areas. These results indicate an affect related to the thickness of alluvium in the coastal area of Padang city, which decreases in thickness inland.

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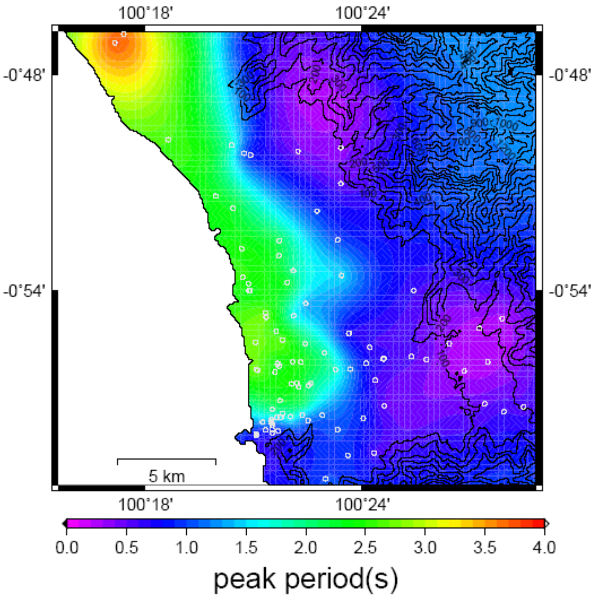



**Fig. 3** Observation sites and results of HVSR.(a) Microtremor single observation sites at every district in Padang, (b) Distributed HVSR ratio.

### 4.2 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 12 sites at several districts in Padang (**Fig.4(a)**). Dispersion curves were calculated using the SPAC method [12] 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 12-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 [13]. The basic procedures of PSO are outlined below.

We estimate the subsurface structure of the model by solving a nonlinear minimization problem with the fitness function below.

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

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

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 $\omega$ 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 [14]. The outline of the SPAC method for the phase velocity calculation of Rayleigh waves follows. The spatial autocorrelation function is defined as

$$\emptyset(r,\theta,\omega) = \overline{u(0,0,\omega,t) * u(r,\theta,\omega,t)} \quad (4)$$

where $\overline{u(t)}$ is the average velocity of the wave in the time domain, and the harmonic waves of frequency $\omega$ of the microtremor have the velocity wave forms $u(0,0,\omega,t)$ and $u(r,\theta,\omega,t)$, observed at the center of the array $C(0,0)$ at point $X(r,\theta)$ on the array.

The spatial autocorrelation coefficient $\rho$ is defined as the average of the autocorrelation function $\emptyset$ in all directions over the circular array:

$$\rho(r,\omega) = \frac{1}{2\pi\emptyset(0,\omega)} \int_0^{2\pi} \emptyset(r,\theta,\omega) d\theta \quad (5)$$

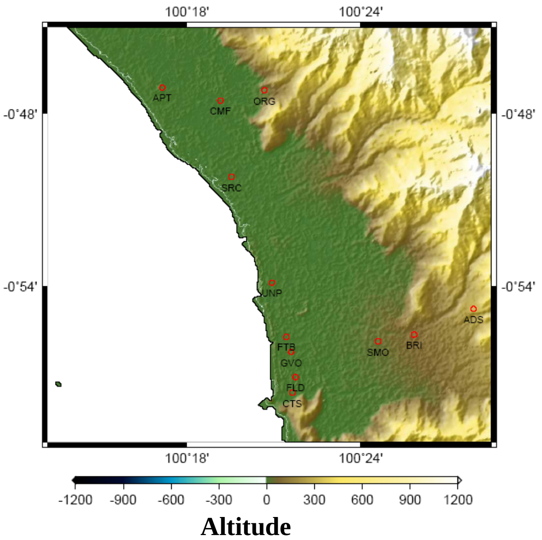
where $\emptyset(0,w)$ is the SPAC function at the center $C(0,0)$ of the circular array. By integration of the (5) we obtain

$$\rho(r,\omega) = Jo\left(\frac{\omega r}{c(\omega)}\right) \quad (6)$$

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

$$\rho(r,\omega) = \frac{1}{2\pi} \int_0^{2\pi} \frac{Re[S_{CX}(\omega,r,\theta]}{\sqrt{S_C(\omega).S_X(\omega,r,\theta)}} d\theta \quad (7)$$

where $S_c(\omega)$ and $S_x(\omega,r,\theta)$ are the power densities of the microtremor at sites C and X respectively, and $S_{CX}(\omega,r,\theta)$ is the cross spectrum between ground motions at these two sites. Thus the SPAC coefficients may be obtained by averaging the normalized coherence function defined as the spectrum between points C and X in the direction $\theta$. From the SPAC coefficient $\rho(r,\omega)$, the phase velocity is calculated for every frequency from the Bessel function argument of (6), and the velocity model can be inverted**.**

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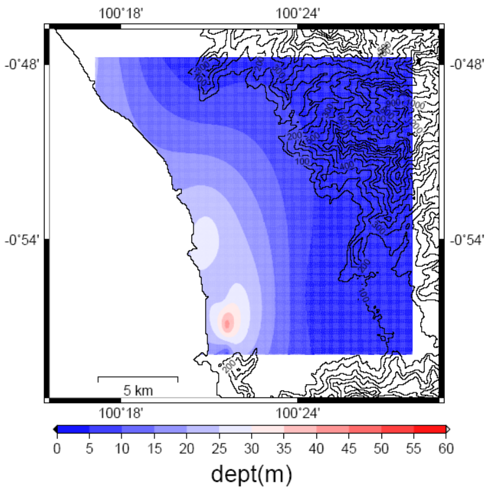


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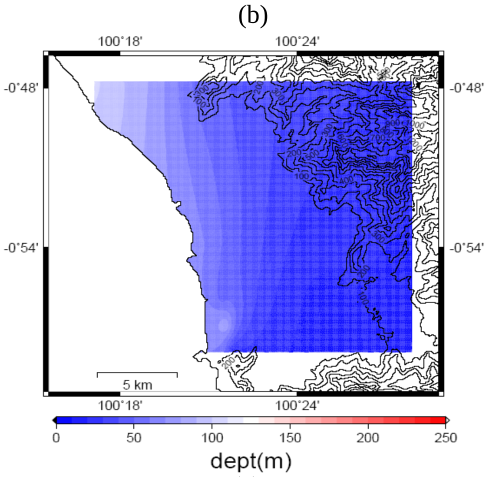


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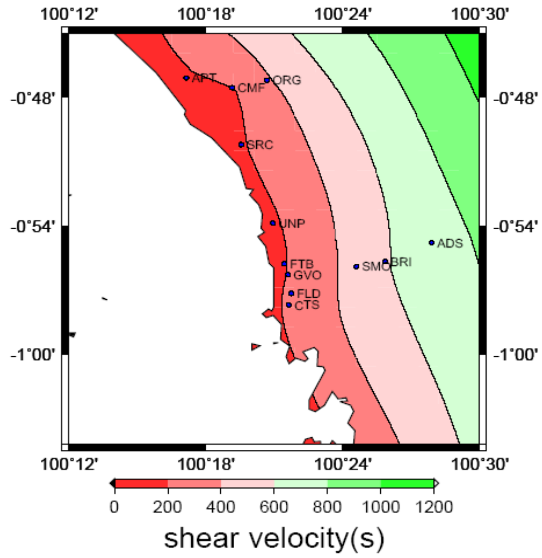


(d)

**Fig.4** Observation sites, soil profile and distribution of average shear wave velocity, (a) Array observation sites, (b) layer 1 (Vs < 400m/s) and (c) layer 2 (Vs >400m/s), (d) Distribution of $V_{s30}$ (m/sec).

## 5 SHAKING CHARACTERISTICS BY QUESTIONNAIRE SURVEY

### 5.1 Survey Outline

Seismic intensity has been used to quantify the severity of the ground shaking based on the observed or felt effect in a limited area [7]. The method was originally developed by [15] and has been widely applied to the development of seismic macro or micro zoning maps in Japan since 1970. The method has also been applied in India and Indonesia by Honda in 2005. It has been useful for estimating seismic shaking in a limited area and for determining intensity distributions over local areas [7]. The original questionnaire sheet was written in Japanese; however, it was translated into Indonesian, for its application to Aceh. The questionnaire has 35 items that cover recognition of shaking, location, shaking duration, possibility of movement, structural damage, swinging of hanging objects, and 27 other items.

For the 2009 Padang earthquake, some sentences were modified to make it more relevant for local people while not changing the original topics covered by the questionnaire. People living near the observation points were interviewed using the questionnaire [15]. The questionnaire survey was conducted from December 24 to 31, 2010, three months after the main shock. The survey was carried out in all districts of Padang by distributing and completing 500 questionnaires through a direct interview process with residents of the city. The interviewers explained each item of the questionnaire to residents, discussed the responses given, and documented the answers on the standard answer sheets.

### 5.2 Estimation of JMA Intensity

The calculation of the seismic intensity determined by the questionnaire is described as:

$$IQ \quad = \frac{1}{N_e}\sum_{i}^{n_q} \beta_i(m_i) \tag{8}$$

where $m_i$ is chosen by a respondent for the $i$th question (e.g., $i$=12 and $m_{12}$=12), $\beta_i(m_i)$ is a seismic coefficient, $n_q$ is the number of effective questions of each questionnaire and $N_e$ is the number of responses from all questions. To obtain the JMA intensity ($I_{JMA}$), the result from (8) is inserted into ( 9) [16].

$$I_{JMA=2.958\,x\,(I_Q-1.456)^{0.547}} \tag{9}$$

Finally, to obtain the JMA intensity ($I_{JMA}$) for each district, the calculation for each questionnaire is averaged as follows.

$$I_{JMA} = \frac{1}{N}\sum_{i=1}^{N} I_{JMA(i)} \tag{10}$$

where $N$ is number of questionnaires in one location, and $I_{JMA(i)}$ is the seismic intensity for each questionnaire.

The results of the questionnaire survey conducted to estimate the shaking intensity distribution in Padang during the earthquake are summarized in mapped. The results of the questionnaire survey conducted to estimate the shaking intensity distribution in Padang during the earthquake are in mapped. The seismic intensity ($I_{JMA}$) for the suburbs and downtown were lower 5 ($5^-$) and upper 5 ($5^+$) respectively (**Fig.5**). A JMA seismic intensity, $I_{JMA}$, value of $5^-$ corresponds to 4.5< $I_{JMA}$ <5.0 and $5^+$ equates to 5.0< $I_{JMA}$ <5.5. A value of $5^+$ corresponds to very strong ground motion where many people are considerably frightened and find it difficult to move. Non-engineered structures sometimes collapse, walls crack, and gravestones and stone lanterns overturn. A value of $5^-$ corresponds to strong ground motion. Many people are frightened and feel the need to hold on to something stable. Occasionally, less earthquake-resistant buildings suffer damage to walls, and windows may break and fall. The distribution of various intensity values came from differences in the subsurface structural conditions of each district.

### 5.3 SHAKING CHARACTERISTICS

By comparing the results of the 500 questionnaires of the seismic intensity survey with microtremor observations (110 single-site observations and numerous other 12-site array observations), we found a correlation, in which the subsurface area or site is seen to correspond to the soft soil condition (which we here define as $V_{s30}$<400 m/s) that exceeds the predominant period. This area corresponds to the thick alluvium in the coastal area of Padang. The thickness of the alluvium gradually decreases in a landward direction from the coast.

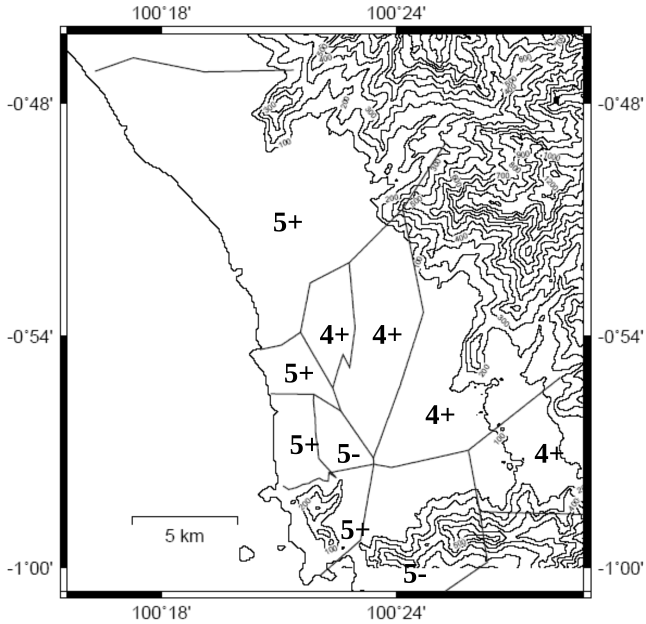


**Fig.5** Distribution of seismic intensity at every districts.

As a result, greater seismic intensities are observed in the coastal area and the value decreases from coastal to mountain areas. Important information from respondents' answers were collated. The area was divided in two by considering subsurface structure condition: shear velocities $V_{s30}$<400 m/s, corresponding to soft soil (area 1), and $V_{s30}$>400 m/s, corresponding to the engineering bedrock conditions (area 2). The structural type, the age of building, and the number of floors in each of the two areas were found to be generally the same. However, the shaking duration was significantly different.

In area 1, 96% of respondents said that the duration of shaking was longer than 2minutes, but in area 2, only 39% of respondents felt the duration of shaking to be longer than 2 minutes. These observations support the existence of a thick alluvial layer that caused the prolonged shaking that most people living in the coastal area felt during the earthquake.

## 6 CONCLUSIONS

Our survey conducted in Padang consisted of (1) microtremor observations (single and 12-channel arrays) made before and after the earthquake of September 30, 2009, and (2) a questionnaire survey of 500 people in the Padang area. The central part of the city, consisting of the four districts, P. Utara, P. Barat, P. Selatan and P. Timur, experienced greater seismic intensities (5+) compared with other areas (districts) of Padang.

According to microtremor observations, downtown Padang is underlain by soft soil conditions ($V_{s30}$<400 m/s). Consistent results concerning the soil condition were found based on predominant period observations and the questionnaire survey. In both cases, the coastal area was determined to have a soft soil conditions ($V_{s30}$<400 m/s), a longer predominant period, and a greater seismic intensity.

Padang has a thick alluvial layer in the coastal area (with a predominant period between 2.0 and 4.2 s) that thins toward the mountains (with a predominant period less than 2.0 s). The subsurface geology also changes slowly from soft soil in the coastal area to rocky conditions in the mountains. The seismic intensity decreases from the coastal area (5+) to mountains ( 4+).

These results provide critical information for making shaking maps, updating hazard maps, and developing disaster prevention countermeasures in Padang.

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