

# Proposed seismic hazard maps of Sumatra and Java islands and microzonation study of Jakarta city, Indonesia

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This paper presents the development of spectral hazard maps for Sumatra and Java islands, Indonesia and microzonation study for Jakarta city. The purpose of this study is to propose a revision of the seismic hazard map in Indonesian Seismic Code SNI 03-1726-2002. Some improvements in seismic hazard analysis were implemented in the analysis by considering the recent seismic activities around Java and Sumatra. The seismic hazard analysis was carried out using 3-dimension (3-D) seismic source models (fault source model) using the latest research works regarding the tectonic setting of Sumatra and Java. Two hazard levels were analysed for representing 10% and 2% probability of exceedance (PE) in 50 years ground motions for Sumatra and Java. Peak ground acceleration contour maps for those two hazard levels and two additional macrozonation maps for 10% PE in 50 years were produced during this research. These two additional maps represent short period (0.2s) and long-period (1.0s) spectra values at the bedrock. Microzonation study is performed in order to obtain ground motion parameters such as acceleration, amplification factor and response spectra at the surface of Jakarta. The analyses were carried out using nonlinear approach. The results were used to develop contour of acceleration at the surface of Jakarta. Finally, the design response spectra for structural design purposes are proposed in this study.

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## 1. Introduction

Indonesia has been well known as one of the most seismically active countries in the world. This is due to its location – it is surrounded by three major active tectonic plates of the earth: Eurasian, Indo-Australian, and Philippine plates. Therefore, the construction design in Indonesia should consider these seismic activities. The most effective

way to reduce disasters caused by earthquakes is to estimate the seismic hazard and to implement this information on a seismic code for use in building design and construction so that the structures possess adequate earthquake resistant capacity (Hu 1996).

This paper presents the latest research works regarding macrozonation study for Sumatra and Java islands, Indonesia. The purpose of this study

**Keywords.** Seismic hazard assessment; total probability theorem; macrozonation study; microzonation study.

is to propose a revision of the seismic hazard map in Indonesian Seismic Code SNI 03-1726-2002. The study covers the development of spectral hazard maps of Sumatra and Java islands and microzonation study for assessing the effects of local soil conditions of Jakarta city to the ground motion at the bedrock.

Sumatra and Java islands were selected for this research because most of the population, infrastructure and structure facilities are concentrated in these two islands. Whereas, Jakarta city is selected because this city is the main business and administration centre of Indonesia; hence, it has significant numbers of settlements, high-rise buildings, monumental structures and other critical facilities. Therefore, the risks of this city are relatively higher than other cities in Indonesia.

## 2. Background research

Currently, Indonesia has implemented the Indonesian seismic hazard map into a standard code in designing earthquake resistance structures (SNI 03-1726-2002) as shown in figure 1. The seismic hazard map shows the peak ground acceleration (PGA) contours at bedrock for 10% probability of exceedance (PE) in design time period of 50 years or corresponding to return period of approximately 475 years.

Since the seismic hazard map was published in SNI 03-1726-2002, there are several issues that need to be considered in seismic hazard analysis in order to obtain more reliable results. Issues, such as the recent seismic activities, the latest research works regarding fault characteristics around Java and Sumatra, the improvements of the method in seismic hazard analysis, and the latest provisions in International Building Code 2000 (IBC 2000) should be considered for the future Indonesian Seismic Code.

Several great earthquake occurrences in Indonesia in the last two years necessitate revision of seismic hazard parameters. Some of the great earthquakes are the 2004 Aceh Earthquake ( $M_w$  9.0–9.3) which was followed by tsunami, the 2005 Nias Earthquake ( $M_w$  8.7), and the 2006 Jogja Earthquake ( $M_w$  6.3). These earthquake events must be considered while determining seismic hazard parameters especially maximum credible earthquake magnitude (MCE).

There are two basic approaches used to model geometries of seismic sources in hazard analyses: an area and a fault source. The previous Indonesian seismic hazard map was developed using area sources model. This 2-dimension (2-D) model has some limitations in modelling the fault source geometries. The fault source model or

3-dimension (3-D) model could improve the modelling of seismic sources significantly. This model can represent the geometry of fault source more reliably than the 2-D model. Therefore, this model should be considered for future Indonesian seismic hazard maps.

The recent research works regarding paleoseismology of the Sumatran Subduction Zone (SSZ) and neotectonic of Sumatran Fault Zone (SFZ) conducted by Sieh and Natawidjaja (2000) and Natawidjaja (2002) showed the unique characteristics of SSZ and the fault segmentation of SFZ. These research works also showed that the Sumatran fault is highly segmented. These results could affect the seismic hazard assessment especially in modelling the seismic sources for Sumatra. Therefore, the results of these seismotectonic conditions should be taken into account in developing new seismic hazard maps for Sumatra region.

At this moment, most of seismic designs in Indonesia follow the International Building Code (IBC 2000). This code implements spectral hazard maps for 2% PE in design time period of 50 years (2500 years return period of earthquakes). The maps are based on spectral acceleration rather than peak ground acceleration (PGA), peak ground velocity (PGV), or zone factors. Two spectral hazard maps are used in this provision: short period (0.2 s) and long-period (1.0 s). Since the existing Indonesian seismic hazard map is based on PGA at bedrock for 10% PE in 50 years (475 years return period of earthquakes), the Indonesian spectral hazard maps for 2% PE in 50 years are necessarily to be developed.

Geotechnical factors often exert a major influence on damage patterns and loss of life in earthquake events. In other countries, several attempts have been made to identify their effects on earthquake hazards related to geotechnical factors in the form of maps or inventories. Mapping of seismic hazards at local scales to incorporate the effects of local geotechnical factors is called microzonation.

At this moment, the microzonation study for Jakarta city is not well established yet. On the other hand, Jakarta city is being rapidly developed, with major installations and high-rise structures being constructed at a rapid pace. Therefore, microzonation study for Jakarta city is urgently required in order to mitigate the effects of earthquake hazards in the future.

## 3. Tectonic settings of Sumatra and Java

The identification of seismic sources including all potential seismic sources capable of generating significant ground motion at the site is one of the most



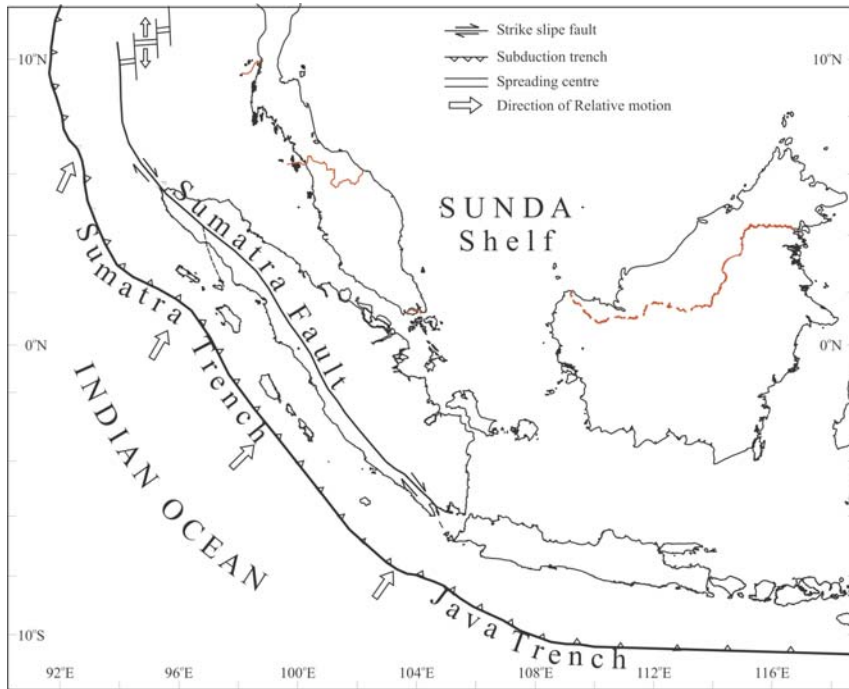


Figure 2. Tectonic setting of Sumatra and Java islands (Huchon and Le Pichon 1984).

important in seismic hazard assessment. Seismic sources are identified on the basis of geological, seismological and geophysical data. The association of geologic structures with historical seismicity may classify their roles within the present tectonic stress regime. In order to differentiate seismic sources, the tectonic features that affected Sumatra and Java regions are divided into three different classifications: subduction zones, transform zones, and diffuse seismicity zones.

### 3.1 Sumatra segment

Generally tectonic features that affected Sumatra island can be divided into two seismic source zones: subduction and transform fault zones. All of those earthquakes that occurred near convergent boundaries where an oceanic plate is being subducted under an island arc or continent are classified as subduction zones. The second classification is transform zone. Transform zone is a terminology for earthquakes that occurred on the boundary between two lithospheric plates that are sliding past one another (transform plate boundary).

Sumatra subduction zone (SSZ) is used to classify all of those earthquakes that occurred near convergent boundaries where the Indo-Australian plate is being subducted under the Eurasian plate (figure 2). SSZ defines one of the most active plate tectonic margins in the world. The Sumatran plate boundary trends northwest; however, the vector of relative plate motion (65 mm/yr) between the Indo-Australian plate and the Eurasian plate

is oriented about  $N10^{\circ}E$  (Huchon and Le Pichon 1984; Prawirodirdjo *et al* 1997; Sieh *et al* 1999). Thus, relative motion between the plates is highly oblique (Rivera *et al* 2002).

Seismicity and focal mechanisms show that the subduction interface is very shallow and dips gradually; down-dip from near horizontal to about  $13^{\circ}$ – $15^{\circ}$  beneath the outer arc ridge. The convergent component on the interface (megathrust) is 40–45 mm/yr (Sieh *et al* 1999). The large megathrust earthquake events in the Sumatra subduction zone in the last two centuries were in the year 1833, with a magnitude of 8.8–9.2; in the year 1861, with a magnitude of 8.3–8.5; in the year 2004, with a magnitude of 9.0–9.3 and in 2005, with a magnitude of 8.7.

The Benioff zone extends the SSZ to depths of the order of 200 km (Newcomb and McCann 1987), and formed dip angle to about  $40^{\circ}$ – $45^{\circ}$ . The largest earthquake around this region occurred on 28 December 1935 at a longitude of  $98.3^{\circ}E$  and latitude of  $0^{\circ}S$  and magnitude,  $M_S$ , of 8.1.

The transform zone of Sumatra is formed due to the oblique convergence of Indo-Australia with Eurasia plates (figure 2). This mechanism results in lateral displacement across the Sumatran fault (Sieh and Natawidjaja 2000). The 1900 km long structure of Sumatran fault accommodates right lateral strike slip associated with the oblique convergence along the plate margin. The slip rates along the fault vary from 6 to 27 mm/year with the slip rate accelerating to the west (Petersen *et al* 2004).

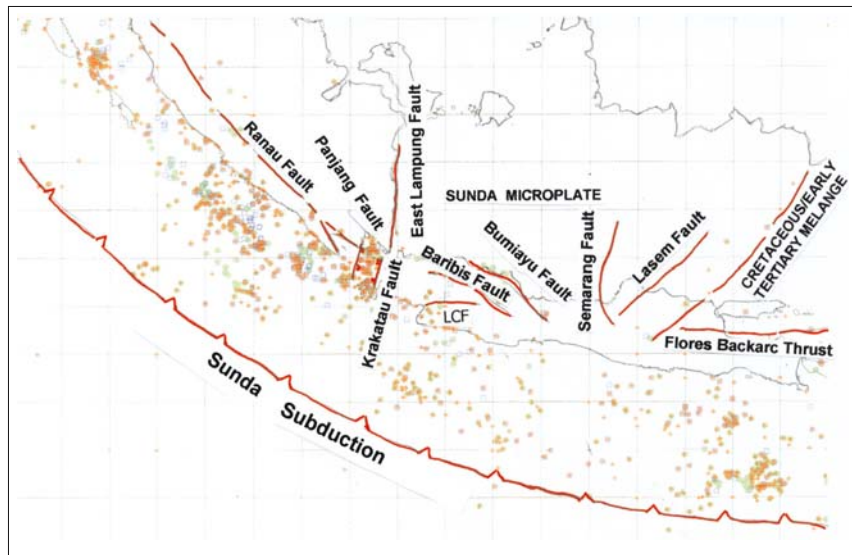


Figure 3. Structures of Java island (LAPI ITB 2007).

All of these earthquakes occurred due to strike slip movement along clearly defined faults in the frontal arc area of Sumatra Fault classified as Sumatra transform zone (STZ). Several large earthquakes have occurred in this zone. These events were included the 1926 Padang Panjang ( $M_S = 6.75$ ), the 1933 Liwa ( $M_S = 7.5$ ), the 1964 Aceh ( $m_b = 6.7$ ) and the 1993 Liwa ( $M_S = 7.2$ ) earthquakes.

### 3.2 Sunda Strait

Sunda Strait is located in the transitional zone between the Sumatra and Java segments of the Sunda Arc and it is one of the most active areas in Indonesia in terms of volcanism, seismicity and vertical motion (figure 2). Extension of the Sunda Strait has formed a structurally bound graben and is the locus of the historic Krakatau volcanic complex. The explosion of the famous Krakatau volcano in 1883 occurred right in the middle of the strait.

### 3.3 Java segment

Firmansjah and Irsyam (1999) classified the seismic source zones of Java island into three: subduction zone, transform zone, and diffuse seismicity. In the subduction zone south of Java, the Java segment of the Sunda Arc extends from Sunda Strait on the west to Bali Basin on the east. Old oceanic crust (150 my) is relatively converging in a direction essentially normal to the arc at the rate of about 6.0 cm/year in the West Java trench and 4.9 cm/year in the East Java trench. The Benioff seismic zone along the Java segment dips approximately  $50^\circ$  and extends to depths of about 600 km

and a gap in seismicity exists in this segment between a depth of 300 and 500 km.

Three major-to-large earthquakes were reported in historical records prior to instrumental recording. These events occurred in 1840, 1867 and 1875. Several large events were also recorded since 1903. The record of historic seismicity along the Java segment indicates that within a period of about 300 years, no great interplate (megathrust) earthquakes have occurred that were similar to the 1833 and 1861 Sumatra events.

Java transform zones occurred on clearly defined shallow crustal faults on Java island such as Sukabumi, Baribis, Lasem, and Semarang faults (figure 3). According to Hamilton (1979), and Newcomb and McCann (1987), no faults of regional extent, similar to the Sumatra fault are present on Java. However, several other workers have reported evidence of recent right lateral strike-slip deformation on Java. Therefore, the geologic evidence for the presence of active intraplate structures on Java is equivocal.

Diffuse seismic zones include all earthquakes that occur in areas where seismicity is not associated with a single fault or fault type. Most of this diffuse seismicity is found in back arc areas of collision zones, like Flores back-arc faulting behind the eastern end of Sunda Arc and western end of Banda Arc (figure 3).

## 4. Earthquake data

Seismic hazard assessment requires as complete a history as possible of earthquakes in or near the region of interest. The earthquake catalogue used

in this study was based on compilation of several catalogues from local and international institutions, such as International Seismological Centre (ISC), National Earthquake Information Center, U.S. Geological Survey (NEIC-USGS), and other catalogues.

The combined catalogue covers an area from 90°E to 125°E longitude and 10°S to 10°N latitude. The minimum magnitude is 5.0 and maximum depth is 200 km. The total number of earthquakes in the combined catalogue is 14119. The starting date for the catalogue is 13 May 1897 and the last event in the catalogue is dated 31 December 2004.

Typical characteristics of earthquake catalogues are as follows:

- the magnitude scales used in the catalogues are not uniform. This is due to the fact that the earthquake events were recorded using more than one type of instrument;
- the earthquake catalogues have contained both the main shock events and the accessory shock events (foreshock and aftershock events). Therefore, the data are not valid to be used when the temporal occurrence of earthquakes are analyzed using Poisson model; and
- the small events are usually incomplete in earthquake catalogues. This is due to the limited sensitivity and coverage of the earth by seismographic networks.

The first problem is solved by choosing a consistent magnitude for seismic hazard assessment (SHA), and then the other magnitude scales are converted to the chosen magnitude scale by using empirical correlation. In this research, a moment magnitude,  $M_w$ , is chosen as a measurement to quantify the size of earthquake. Other types of magnitude in the catalogues were then converted to  $M_w$  by using empirical correlations (Geller 1976; EPRI 1994; Rong 2002; Hendriyawan 2007). The latest empirical correlations proposed by Hendriyawan (2007) were used in this research for converting the other magnitude scales to moment magnitude scale.

The second problem is solved by declustering the catalogue using time and distance windows criteria. The criteria proposed by Gardner and Knopoff (1974) were used in this research because these criteria have considered the time and distance windows for magnitude above 8.0. The algorithm eliminates 9059 accessory shock events. The combined catalogue, after removal of accessory shock events, contains 5060 records or more than 50% of earthquake records have been eliminated in the combined catalogue. Out of 5060 records, 967 records are from the Sumatra faults.

The third problem is solved by performing catalogue completeness analysis. In this study, historical earthquake data that occurred between 1897 and 2004 have been analyzed for completeness using Stepp method (1973). Based on the catalogue completeness analysis of the general southeast Asia regions, the earthquakes within interval  $5.0 \leq M_w < 6.0$  are completely reported only during the most recent 28-year interval or since 1978, interval  $6.0 \leq M_w < 7.0$  are completely reported during the most recent 33-year interval or since 1972, and magnitude more than 7.0 are completely reported over 104-year sample interval (Hendriyawan 2007).

## 5. Seismic source modelling

The link between the database and any modelling methods for deriving hazard levels is a regional seismotectonic model, which should be based on a coherent merging of the regional databases. The procedure should integrate the elements of the seismological, geophysical and geological databases in order to construct a coherent seismotectonic model (or alternative models) consisting of a discrete set of seismogenic structures.

A seismic source zone is defined as a seismically homogenous area, in which every point within the source zone is assumed to have the same probability of being the epicentre of a future earthquake (Erdik *et al* 1982). An ideal delineation of seismic source zones requires a complete comprehension of the geology, tectonics, paleoseismology, historical and instrumental seismicity, and other neotectonic features of the region under study. However, it is not always possible to compile detailed information in all these fields for the majority of the world. Thus, frequently, seismic source zones are determined with two fundamental tools: a seismicity profile and the tectonic regime of the region under consideration.

There are several model seismotectonic sources for Indonesia that have been proposed by previous researchers, such as Firmansjah and Irsyam (1999); Kertapati (1999); and Zhang *et al* (1999). All these models, except the model from Zhang *et al* (1999), were developed to fulfil the requirement for analyzing the seismic hazard of Indonesia. The latest model proposed by Irsyam *et al* (2007) for revision of Indonesian seismic hazard maps was used in this study. The seismic source models are shown in figure 4.

Generally, there are five potential seismogenic sources addressed in this study, which are

- (1) Sumatra subduction faults,
- (2) Sumatran fault,

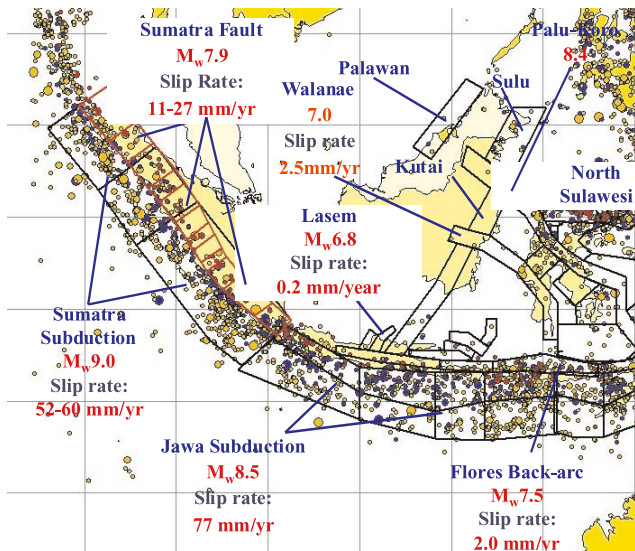


Figure 4. Seismic source model used for development of Indonesian spectral hazard maps (Irsyam *et al* 2007).

- (3) Sunda Arc subduction fault,
- (4) Reverse thrusting faults, and
- (5) Java shallow crustal faults.

According to these seismotectonic features, the seismic source zones around the site region are divided into several seismic zones as seen in figure 4. Based on the focal depth and dip angle, subduction zones were divided into interplate (megathrust) zones and intraplate (benioff) zones. In this study, only seismic source zones within a radius of 500 km from the site are considered. Those outside this radius may not significantly influence the peak ground acceleration.

Characterization of seismicity at a particular site or region is commonly expressed in seismic hazard parameters. Seismic hazard parameters are needed for fully describing earthquake activity within the earth's crust in a certain region. There are three parameters that are most commonly considered in seismic hazard assessment, i.e.,  $a$ - $b$  parameter, recurrence rate, and maximum size of future earthquakes for each source. This is generally accomplished by studying the magnitude–frequency relation using the available data on past earthquakes.

There are two models of magnitude–frequency relation. The first model is the exponential model. Based on this model, the temporal distribution of earthquakes is assumed to follow frequency–magnitude relationship proposed by Gutenberg–Richter (G–R) (1954). The second model is the characteristic model. The characteristic recurrence frequency distribution reconciles the exponential rate of small- and moderate-magnitude

earthquakes with the larger characteristic earthquakes on individual faults.

The simplest method to obtain  $a$ - $b$  value is the least square method (LS). The disadvantage of the LS method is that it cannot be used directly to calculate the mean annual rate of exceedance from combining different completeness catalogues. Usually, this method produces overestimated  $b$  values that cause the rates of large earthquakes to be underestimated. Several researchers such as Dong *et al* (1984), Weichert (1980), Kijko and Sellevoll (1989, 1992) or KS method have proposed alternative methods to obtain  $a$ - $b$  values and to minimize bias. These methods have accounted the relationship between earthquake data and interval time when the catalogues are homogeneous.

When the data on earthquake is sufficient, the knowledge of slip rates on fault can also be converted into expected seismicity (Todorovska and Jordanovski 1994). In fact, both of these sources complement each other and should be considered for better and more reliable estimation of seismicity. The slip rate for all Sumatra and Java seismic source zones are shown in figure 4.

Seismic hazard assessment also requires a parameter of maximum credible earthquake magnitude (MCE). MCE is defined as the maximum earthquake that a fault or fault zone can reasonably be expected to generate (Slemmons and Chung 1982; Kramer 1996). Generally the methods for evaluating  $m_{\max}$  can be divided into two main categories: deterministic and statistic (Kijko and Graham 1998). In this study, the maximum magnitude for each seismic source has been estimated independently by using historical data, geological method, and statistical method. All of these methods are then compared and analyzed to determine an appropriate MCE for each source zone. The MCE for seismic sources of Sumatra and Java are shown in figure 4.

Azlan *et al* (2006) and Irsyam *et al* (2005) have proposed the seismicity parameters for seismic source zones around Sumatra and Java, respectively. Generally, there are three groups of seismic source zone for Sumatra and four groups for Java. These seismic hazard parameters were calculated using three methods: Least Square (LS), Weichert (1980), and Kijko and Sellevoll (1989, 1992). These three methods were used in order to consider the epistemic uncertainties. The seismic hazard parameters are shown in figures 5 and 6.

Based on the analysis, the ranges of  $b$  values are 0.6 to 0.9 for Sumatra and 0.8 to 1.0 for Java. The range of  $b$ -value is normally about 0.65 to 1.00 (Cornell 1968), hence, the low  $b$ -values of Sumatra indicate the characteristics of seismic sources that have the potential to produce high earthquake hazards.

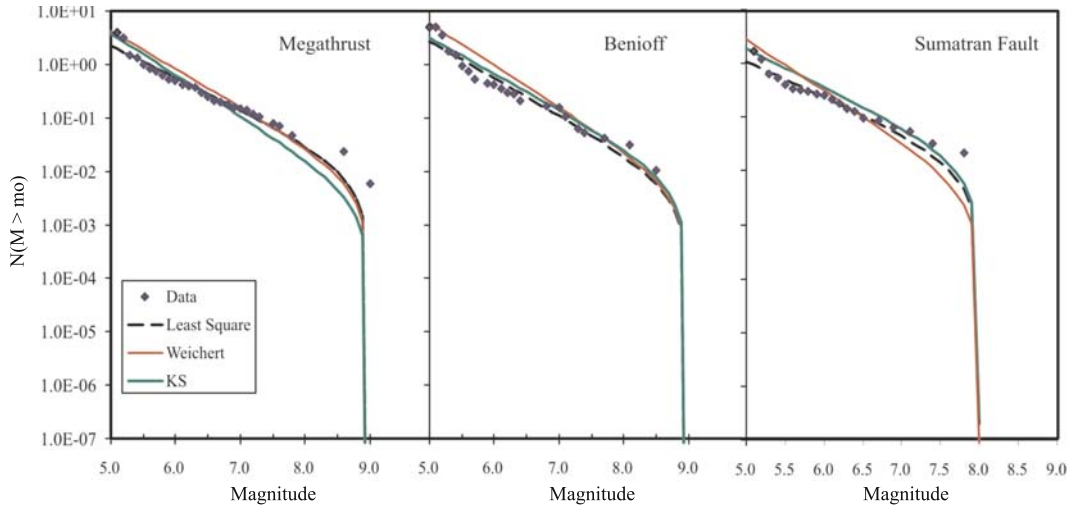


Figure 5. Recurrence relationship models for SSZ and SFZ (Azlan *et al* 2006).

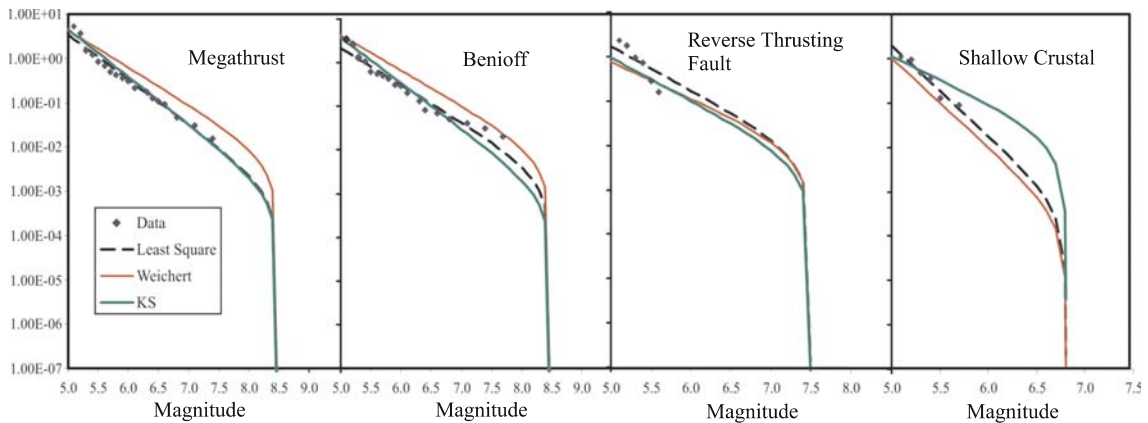


Figure 6. Recurrence relationship models for Java (Irsyam *et al* 2007).

## 6. Attenuation functions

There has been a number of attenuation functions derived in the last two decades. Most of them were derived in a certain region where peak ground acceleration records had been available. Due to insufficient PGA data needed to derive an attenuation function, there is no attenuation function developed particularly for Indonesia region. The only way is to adapt attenuation function derived in other regions, which is similar to Indonesia region tectonically and geologically. It is of importance that the selection was based on earthquake mechanism, which is generally categorized into subduction zone earthquakes and shallow crustal earthquakes.

The attenuation relationships for subduction zone at rock sites developed by Youngs (1997) and that for shallow crustal developed by Boore *et al* (1997) and Sadigh (1997) for extension tectonic region are selected. The selection is based on a

low variability compared to others as a result of the previous study conducted by Firmansjah and Irsyam (2000).

## 7. Logic tree

Epistemic uncertainty is included in the PSHA by explicitly including alternative hypotheses and models. The logic tree allows a formal characterization of uncertainty in the analysis by including alternative interpretations, models, and parameters that are weighted in the analysis according to their probability of being correct. Logic trees (Kulkarni *et al* 1984; Coppersmith and Youngs 1986) are used in this study in order to allow uncertainty in selection of models for attenuation, recurrence rate, and maximum magnitude to be considered.

In this research, the characteristic model and the exponential model were assigned a relative

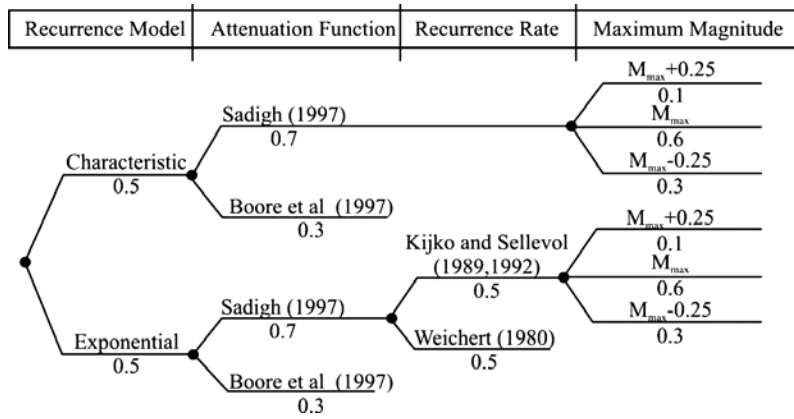


Figure 7. Logic tree used in the analysis.

likelihood of 0.50 each. Attenuation proposed by Sadigh (1997) and Boore *et al* (1997) were assigned 0.7 and 0.3, respectively. The recurrence rates calculated according to the method of Weichert (1980) and that of Kijko and Sellevoll (1989, 1992) were considered equally likely to be correct. At final level, different relative likelihoods were assigned to the maximum magnitude. The logic tree model is shown in figure 7.

## 8. Spectral hazard maps

The spectral hazard maps were developed based on total probability theorem as proposed by Cornell (1968) and Merz and Cornell (1973). This model assumes that the earthquake with magnitude,  $M$ , and the hypocenter distance,  $R$ , as a continuous independent random variable.

Current earthquake design practice for conventional structures is nominally based on the use of 10% or 2% probability of exceedance (PE) in 50 years ground motions (BSSC 1998; Leyendecker *et al* 2000). In order to cover those two design ground motions, the analyses were performed for 10% and 2% PE in design time period of 50 years or correspond to return period of approximately 500 and 2500 years, respectively.

The hazard calculations were performed for several combinations of attenuation functions, seismic hazard parameters, and maximum magnitudes. The result of each analysis is then multiplied by the relative likelihood of its combination of branches in the logic tree. The macrozonation maps at bedrock were developed not only for PGA, but also for 0.2 s (short period) and 1.0 s (long period) as shown in figures 8–11.

Generally, the acceleration values in this study are relatively higher than the PGA maps of Indonesian Seismic Design Code (SNI 03-1726-2002). The increasing of the acceleration values are

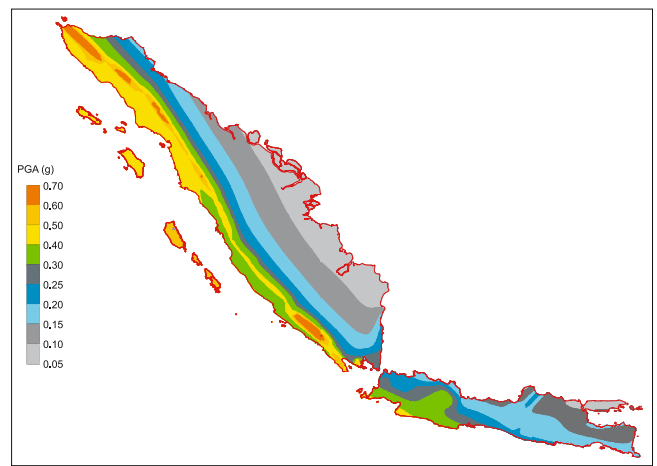


Figure 8. Peak ground acceleration contour maps for 10% PE in 50 years.

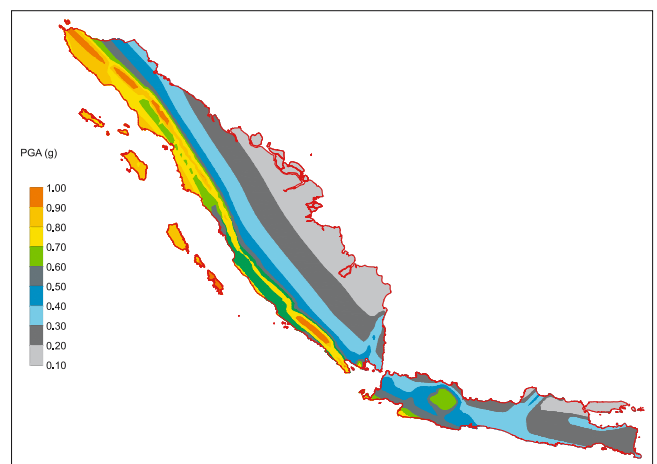


Figure 9. Peak ground acceleration contour maps for 2% PE in 50 years.

affected by a few factors such as the determination of maximum magnitude and the use of 3-D models.

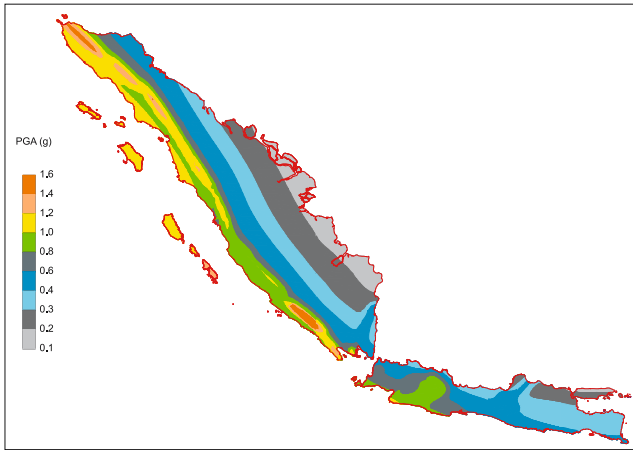


Figure 10. Spectral hazard map for 10% PE in 50 years ( $T = 0.2$  s).

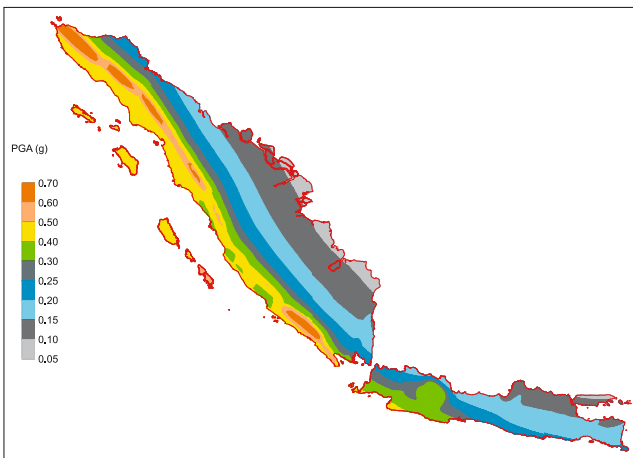


Figure 11. Spectral hazard map for 10% PE in 50 years ( $T = 1.0$  s).

## 9. Deaggregation hazard

For physical interpretation of the results from PSHA and to take certain engineering decisions, it is desirable to have a representative earthquake, which is compatible with the results of the PSHA method (Trifunac 1989). This could be achieved through the deaggregation of the probabilistic seismic hazard (McGuire 1995). Such deaggregation should be carried out for a target annual frequency of exceedance, typically the value selected for determining the design basis ground motion at the site. The results of deaggregation will be used to identify the mean magnitude and distance of earthquakes that control the ground motions at these response spectral frequencies. Figure 12 shows an example of the result of deaggregation hazard for Jakarta.

The deaggregation analysis at a site for hazard level 10% PE in 50 years shows the combinations of magnitude-distance of each of the source zones

(subduction, shallow crustal, and background), which have a major contribution to the PGA values. The result shows that the mean magnitudes of subduction, shallow crustal, and background zones are  $M_w$  8.03,  $M_w$  6.88, and  $M_w$  5.85, respectively and at a distance 212.2, 65.7 and 13.5 km, respectively. This information is used to generate scaled response spectra at bedrock of Jakarta.

There is no representative strong motion data for Indonesia at this moment, therefore time history data for Jakarta city is generated synthetically by modifying the existing time history data using spectral matching analysis. The actual ground motions from worldwide earthquakes were selected based on the similarity of their characteristics such as magnitude, distance and site conditions and then the spectrums were scaled for matching them with the spectrums from deaggregation analysis. The spectrum matching analysis was performed using software EZ-FRISK<sup>TM</sup> from Risk Engineering Inc. This software provides Norm Abrahamson's time-dependent spectral matching method (Abrahamson 1998) that has adopted and modified the procedure proposed by Lilhanand and Tseng (1987, 1988).

## 10. Microzonation study

In microzonation study, ground response analysis was performed using one-dimensional (1-D) shear wave propagation method in order to develop microzonation maps of Jakarta city. 1-D method is based on the assumption that all boundaries are horizontal and that the response of a soil deposit is predominantly caused by shear wave propagating vertically from the underlying bedrock. Although the soil layers are sometimes inclined or bent, they are regarded as horizontal in most cases. Furthermore, the length of a layer is infinite compared to its thickness. It is thus practical to model them as 1-D horizontal layers. Analytical and numerical procedures based on this concept, incorporating linear approximation to nonlinear soil behaviour, have shown reasonable agreements with field observations in a number of cases (Kramer 1996).

The ground response analysis should consider the nonlinearity of soil behaviour to provide reasonable results. There are two approaches to include the effect of nonlinearity of soil material into the analysis: equivalent linear and nonlinear approaches. Equivalent linear models imply that the strain will always return to zero after cyclic loading, and since a linear material has no limiting strength, failure cannot occur. The nonlinear of soil behaviours are approximated by determining the values that are consistent with the level of strain induced in each layer.

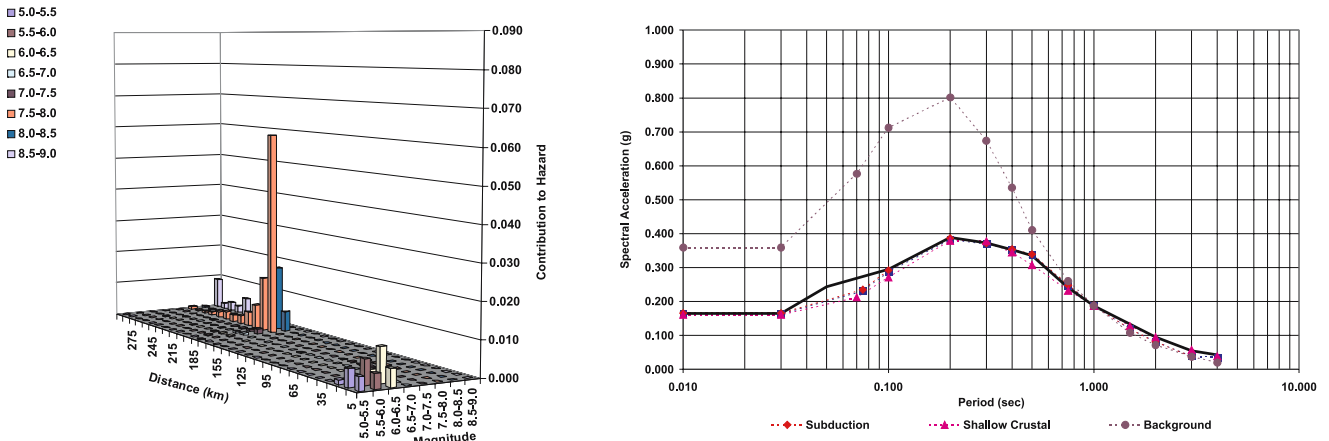


Figure 12. Deaggregation hazard and scaled response spectra at bedrock for Jakarta.

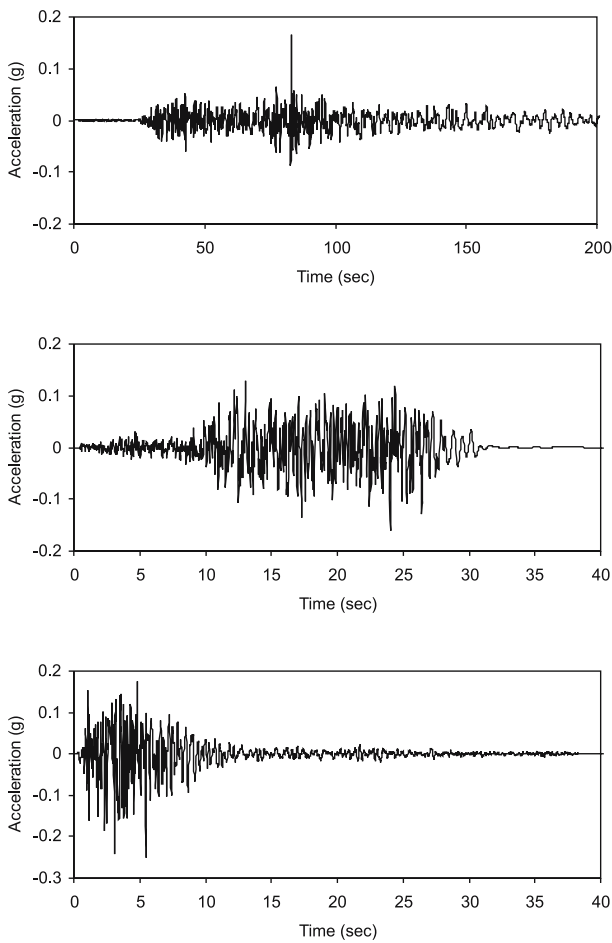


Figure 13. Proposed ground motion used for Jakarta city.

The equivalent linear approach is incapable of representing the changes in soil stiffness that actually occur during the earthquake. It also means that it cannot be used directly for problems involving permanent deformation or failure. An alternative approach is to analyze the actual nonlinear response of a soil deposit using direct numerical

integration in the time domain. The advantages of nonlinear method are (Kramer 1996):

- the stiffness of an actual nonlinear soil changes over the duration of large earthquake, such high amplification levels that occur in equivalent linear approach, will not develop in the field; and
- nonlinear method can be formulated in terms of effective stresses to allow modelling of the generation, redistribution, and eventual dissipation of excess pore pressure during and after earthquake shaking.

In this study, the ground response analyses were performed using nonlinear approach. The analyses were carried out using program NERA (Bardet and Tobita 2001), which stands for Nonlinear Earthquake Response Analysis. This program uses soil model proposed by Iwan (1967) and Mroz (1967) to model nonlinear stress-strain curves of soil.

Shear wave propagation analyses were performed for all existing soil data in Jakarta city to obtain peak acceleration and amplification factors at the surface. The classification of a particular site was determined by referring specifications from 1997 UBC or 2000 IBC. Based on  $V_{S-30}$ , the soil data can be classified as soil class  $S_D$  (medium stiff) or  $S_E$  (soft soil) as shown in figure 14. The results of site response analysis at several points were used to develop design response spectra at the surface.

### 11. Design response spectra

The influence of soil conditions on the ground motion can be translated into the modification of response spectra shapes by using spectral amplification factors. Since the amplification factors are very sensitive to the reference site conditions, the

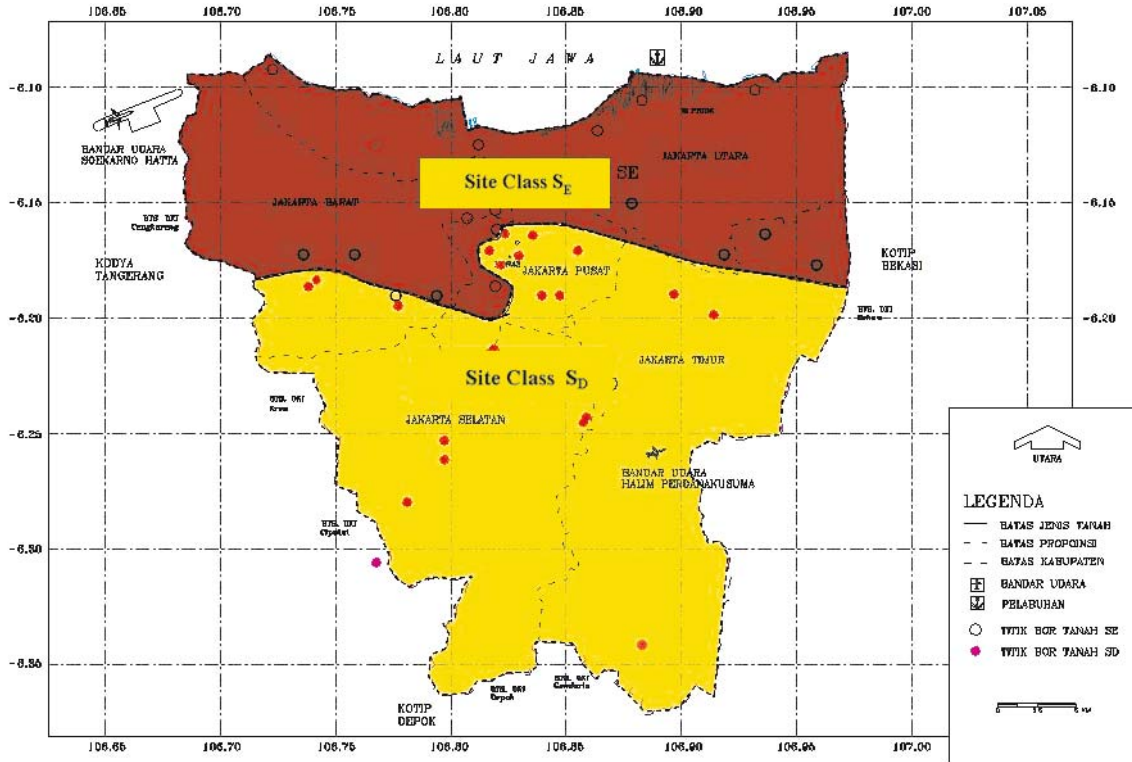


Figure 14. Site classification of Jakarta city in accordance with 1997 UBC.

application of amplification factor must appropriately consider the site conditions corresponding to the reference motion. Therefore, in most building codes or provisions, the influence of local soil conditions is considered by using spectral amplification factors for different soil classes. These amplification factors are used for constructing the design response spectra on a particular site condition (e.g., BSSC 1998; ICBO 1997; and ICC 2000).

The design spectra can also be obtained by averaging and smoothing a set of response spectra at a particular level, such as a *p*th percentile of the spectra from records with similar characteristics such as soil conditions, epicentral distance, magnitude, and source mechanism. An 84 percentile (mean plus one standard deviation) of the spectra is commonly used by engineers, which is approximately mean-plus-one standard deviation of the spectra (Seed et al 1976; Anderson et al 2006).

In this research, design response spectra were developed by applying the methods proposed by 1997 UBC. The amplification factors in those codes were modified based on mean-plus-one standard deviation (84.1 percentile) of the response spectra from the ground response analyses. The results were then compared to the design response spectra from the Indonesian Code SNI 03-1726-2002 as shown in figure 15.

Based on the analyses, the proposed design response spectra are generally higher than spectra

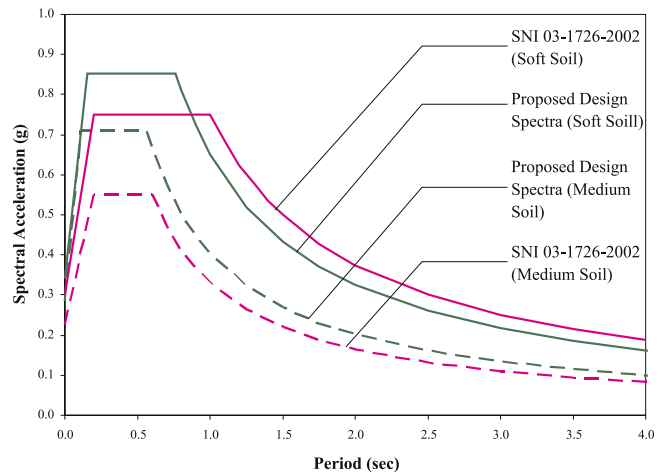


Figure 15. Proposed design response for Jakarta (475 years return period of earthquakes).

envelopes from SNI 03-1726-2002. This is due to the PGA of Jakarta city from this research which is higher than the PGA from Indonesian Code (SNI 03-1726-2002).

### 12. Summary and conclusion

This research has developed Indonesian spectral hazard maps based on probabilistic seismic hazard analysis, which gives not only peak ground acceleration but also short period (0.2 s) and long-period

(1.0 s) spectra values at the bedrock of Sumatra and Java. Two hazard levels were considered in this study to represent 10% and 2% probability of exceedance (PE) in design time period of 50 years or the corresponding to return period of approximately 500 and 2500 years, respectively.

Microzonation study was performed in this research for Jakarta city in order to obtain ground motion parameters such as acceleration, amplification factor and response spectra at the surface of a particular city. Jakarta city was selected in this study because the risks of these areas are relatively higher than other cities in Indonesia.

In this study, the analysis was performed using nonlinear approach in order to consider the actual nonlinear response of a soil deposit. The results of site response analysis at several points were used to develop microzonation maps of Jakarta for 500 years return periods. One microzonation map was produced in this research that can be used as input for seismic design, land use management, and estimation of the potential for liquefaction and landslides.

The design response spectra were proposed in this research for structural design purposes in Jakarta. In this study, the procedures proposed by 1997 UBC and SNI 03-1726-2002 were used as references for developing a smooth or a design spectrum for site categories of  $S_D$  (medium stiff soil) and  $S_E$  (soft soil) in Jakarta. The amplification factors in those codes were modified based on mean-plus-one standard deviation of the response spectra from the ground response analyses. Based on the analyses, the proposed design response spectra are generally higher than spectra envelopes from SNI 03-1726-2002.

## References

- Abrahamson N A 1998 Non-Stationary Spectral Matching Program RSPMATCH; PG&E Internal Report, February.
- Anderson J G, Su F and Zeng Y 2006 Characteristics of ground motion response spectra from recent large earthquakes and their comparison with IEEE standard 693. 2006 SSA Meeting: 100th Anniversary Earthquake Conference, Commemorating the 1906 San Francisco Earthquake, April 18–22, San Francisco.
- Azlan Adnan, Hendriyawan, Aminaton Marto and Masyhur Irsyam 2006 Development of Seismic Hazard Map for Peninsular Malaysia; *Proceeding on Malaysian Science and Technology Congress*, PWTC Kuala Lumpur, Malaysia, 18–26 September.
- Bardet J P and Tobita T 2001 NERA – A Computer Program for Nonlinear Earthquake Site Response Analyses of Layered Soil Deposits; Department of Civil Engineering, University of Southern California.
- Boore D M, Joyner W B and Fumal T E 1997 Equation for Estimating Horizontal Response Spectra and Peak Acceleration from Western North America Earthquakes: A Summary of Recent Work; *Seismol. Res. Lett.* **68**(1) 128–153.
- Building Seismic Safety Council 1998, 1997 Edition NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings, FEMA 302/303. Part 1 (Provisions) and Part 2 (Commentary); Developed for the Federal Emergency Management Agency. Washington DC.
- Coppersmith K J and Youngs R R 1986 Capturing Uncertainty in Probabilistic Seismic Hazard Assessments with Intraplate Tectonic Environments; *Proceeding, 3rd US National Conference on Earthquake Engineering, Charleston, South Carolina* **1** 301–312.
- Cornel C A 1968 Engineering Seismic Risk Analysis; *Bull. Seismol. Soc. Am.* **58**(5) 1583–1606.
- Dong W M, Bao A B and Shah H C 1984 Use of Maximum Entropy Principle in Earthquake Recurrence Relationships; *Bull. Seismol. Soc. Am.* **74**(2) 725–737.
- EPRI 1994 The Earthquake of Stable Continental Regions; Vol. I: Assessment of Large Earthquake Potential. File Report Electric Power Research Institute, Palo Alto, California.
- Erdik M, Doyuran V, Yucemen S, Gulkan P and Akkas N 1982 A Probabilistic Assessment of the Seismic Hazard in Turkey for Long Return Periods; *Proc. 3rd International Earthquake Microzonation Conference*, Seattle, Washington.
- Firmansjah J and Irsyam M 1999 Development of Seismic Hazard Map for Indonesia; *Prosiding Konferensi Nasional Rekayasa Kegempaan di Indonesia*, ITB, Indonesia.
- Firmansjah J and Irsyam M 2000 Development of Attenuation Model and Engineering Practice Level Acceptance, LAPI ITB Report for ARCO Bali North Inc., Terang Sirasun Development.
- Gardner J K and Knopoff L 1974 Is the Sequence of Earthquakes in Southern California, with Aftershocks Removed, Poissonian? *Bull. Seismol. Soc. Am.* **64** 1363–1367.
- Geller R J 1976 Scaling Relations for Earthquake Source Parameters and Magnitudes; *Bull. Seismol. Soc. Am.* **66** 1501–1523.
- Gutenberg B and Richter C F 1954 Seismicity of the Earth; (Princeton, New Jersey: Princeton University Press).
- Hamilton W 1979 Tectonics of the Indonesian region: U.S. Geological Survey Prof. Paper 1078.
- Hendriyawan 2007 Seismic Macrozonation of Peninsular Malaysia and Microzonation of Kuala Lumpur City Center and Putrajaya; Universiti Teknologi Malaysia: PhD. Thesis.
- Hu Y X 1996 Earthquake Engineering, London: E & FN Spon.
- Huchon P and Le Pichon X 1984 Sunda Strait and Central Sumatra Fault; *J. Geol.* **12** 668–672.
- International Code Council 2000 International Building Code 2000. International Code Council. International Conference of Building Officials. Whittier, CA, and others.
- International Council of Building Officials 1997 Uniform Building Code. Whittier, CA.
- International Seismological Centre, On-line Bulletin, <http://www.isc.ac.uk/Bull>, International Seismological Center, Thatcham, United Kingdom.
- Irsyam M, Hoedajanto D, Kertapati E, Boen T, Petersen M D, Dangkoa and Asrurifak M 2007 Usulan Revisi Peta Hazard Kegempaan Wilayah Indonesia. National Conference of Indonesian Society of Civil and Structural; August 21–22, Jakarta, Indonesia.

- Iwan W D 1967 On a class of models for the yielding behavior of continuous and composite systems; *Journal of Applied Mechanics, ASME* **34** 612–617.
- Kertapati E 1999 Probabilistic Estimates of the Seismic Ground Motion Hazard in Indonesia; *Proceeding National Conference of Earthquake Engineering*; Institute of Technology Bandung, Indonesia. p. 1-1~1-16.
- Kijko A and Graham G 1998 Parametric-historic Procedure for Probabilistic Seismic Hazard Analysis Part I: Estimation of Maximum Regional Magnitude  $m_{max}$ ; *Pure Appl. Geophys.* **152** 413–442.
- Kijko A and Sellevol M A 1989 Estimation of Earthquake Hazard Parameters from Incomplete Data Files Part I. Utilization of Extreme and Complete Catalog with Different Threshold Magnitudes; *Bull. Seismol. Soc. Am.* **79(3)** 645–654.
- Kijko A and Sellevol M A 1992 Estimation of Earthquake Hazard Parameters from Incomplete Data Files Part II. Incorporation of Magnitude heterogeneity; *Bull. Seismol. Soc. Am.* **82(1)** 120–134.
- Kramer S L 1996 *Geotechnical Earthquake Engineering*; New Jersey: Prentice-Hall.
- Kulkarni R B, Youngs R R and Coppersmith K J 1984 Assessment of Confidence Intervals for Results of Seismic Hazard Analysis; *Proceeding, 8th World Conference on Earthquake Engineering*, San Francisco: pp. 90–98.
- Lembaga Afiliasi Penelitian Indonesia 2007 Seismic Hazard Assessment for PLTU 3 Banten-Teluk Naga 3x (300–400) MW. Final Report for Rekadaya ElektriKa. Jakarta, Indonesia.
- Leyendecker E V, Hunt R J, Frankel A D and Rukstales K S 2000 Development of Maximum Considered Earthquake Ground Motion Maps; *Earthquake Spectra* **16(1)** 21–40.
- Lilhanand K and Tseng W S 1987 Generation of Synthetic Time Histories Compatible with Multiple-Damping Response Spectra. SmiRT-9. Lausanne, K2/10.
- Lilhanand K and Tseng W S 1988 Development and Application of Realistic Earthquake Time Histories Compatible with Multiple Damping Response Spectra; *9th World Conf. Earth. Engineering*, Tokyo, Japan **2** 819–824.
- McGuire R K 1995 Probabilistic Seismic Hazard Analysis and Design Earthquakes: Closing the Loop; *Bull. Seismol. Soc. Am.* **85** 1275–1284.
- Merz H A and Cornell C A 1973 Aftershocks in Engineering Seismic Risk Analysis. Report R73-25. Massachusetts: Department of Civil Engineering, MIT, Cambridge.
- Mróz Z 1967 On the Description of Anisotropic Work Hardening; *Journal of Mechanics and Physics of Solids* **15** 163–175.
- Natawidjaja D H 2002 Neotectonics of Sumatran Fault and Paleogeodesy of the Sumatran Subduction Zone; Doctor of Philosophy Thesis. California Institute of Technology, Pasadena, California.
- National Earthquake Information Center United States Geological Survey, <http://neic.usgs.gov/neis/epic/epic.html>.
- Newcomb K R and McCann W R 1987 Seismic History and Seismotectonics of The Sunda Arc; *J. Geophys. Res.* **92(B1)** 421–439.
- Petersen M D, Dewey J, Hartzell S, Mueller C, Harmsen S, Frankel A D and Rukstakels 2004 Probabilistic Seismic Hazard Analysis for Sumatra, Indonesia and Across the Malaysian Peninsula; *Tectonophysics.* **390** 141–158.
- Prawirodirdjo L, Bock Y, McCaffrey R, Genrich J, Calais E, Stevens C, Puntodewo S, Subraya C, Rais J, Zwick P and Fauzi 1997 Geodetic Observations of Interseismic Strain Segmentation of the Sumatra Subduction Zone; *Geophys. Res. Letter.* **24** 2601–2604.
- Rivera L, Sieh K, Helmberger D and Natawidjaja D 2002 A Comparative Study of the Sumatran Subduction-Zone Earthquakes of 1935 and 1984; *Bull. Seismol. Soc. Am.* **92(5)** 1721–1736.
- Rong Y 2002 Evaluation of Earthquake Potential in China; University of California Los Angeles: PhD. Thesis.
- Sadigh K, Chang C Y, Egan J A, Makdisi F and Youngs R R 1997 Strong Ground Motion Attenuation Relations for Shallow Crustal Earthquakes Based on Californian Strong Motion Data; *Seismol. Res. Lett.* **68(1)** 190–198.
- Seed H B, Ugas C and Lysmer J 1976 Site-Dependent Spectra for Earthquake-Resistant Design; *Bull. Seismol. Soc. Am.* **66** 221–243.
- Sieh K and Natawidjaja D 2000 Neotectonics of the Sumatran Fault, Indonesia; *J. Geophys. Res.* **105** 28,295–28,326.
- Sieh K, Ward S, Natawidjaja D and Suwargadi W 1999 Crustal Deformation at the Sumatran Subduction Zone Revealed by Coral Rings; *Geophys. Res. Lett.* **26** 3141–3144.
- Slemmons D B and Chung D H 1982 Maximum Credible Earthquake Magnitudes for the Calaveras and Hayward Fault Zone, California; *Proceedings Conference on Earthquake Hazards in the Eastern San Francisco Bay Area. California Division of Mines and Geology, Special Publication* **62** 115–124.
- Standar Nasional Indonesia 2002 Tata Cara Perencanaan Ketahanan Gempa untuk Bangunan Gedung (SNI 03-1726-2002), Badan Standardisasi Nasional.
- Stepp J C 1973 Analysis of the Completeness of the Earthquake Hazard Sample in the Puget Sound Area; NOAA Technical Report, ERL 267-ESL 30. Boulder, CO: 16–28.
- Todorovska M I and Jordanovski L R 1994 A Probabilistic Model for Assessment of the Total Earthquake Losses for a Building; *Proceedings, 10th Europ. Conference Earthquake Engineering*, Aug. 28–Sep. 2, Vienna, Austria, 1017–1022.
- Trifunac M D 1989 Threshold Magnitudes Which Cause Ground Motion Exceeding the Values Expected during the Next 50 Years in a Metropolitan Area; *Geofizika* **6** 1–12.
- Weichert D H 1980 Estimation of the Earthquake Recurrence Parameters for Unequal Observation Periods for Different Magnitudes; *BSSA* **70(4)** 1337–1346.
- Youngs R R, Chiou S J, Silva W J and Humphrey J R 1997 Strong Ground Motion Attenuation Relationship for Subduction Zone Earthquakes; *Seismol. Res. Lett.* **68(1)** 58–73.
- Zhang P, Yang Z, Gupta H K, Bhatia S C and Shedlock K M 1999 Global Seismic Hazard Assessment Program (GSHAP) in Continental Asia; *Annali Di Geofisica.* **42(6)** 1167–1190.