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SEISMIC HAZARD ASSESSMENT FOR PENINSULAR MALAYSIA USING GUMBEL DISTRIBUTION METHOD

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Abstract. This paper presents the preliminary study on seismic hazard assessment which involved developing macrozonation map for two hazard levels, i.e. 10% and 2% probabilities of exceedance in 50 years for bedrock of Peninsular Malaysia. The analysis was performed using statistic theory of extreme values from Gumbel. The analysis covered the earthquake data processing (such as choosing a consistent magnitude to be used in the analysis and identifying main shock events), and selection of appropriate attenuation relationship. Results showed that the Peak Ground Acceleration (PGA) across the Peninsular Malaysia range between 10 and 25 gal for 10% probability of exceedance, and between 15 and 35 gal for 2% probability of exceedance in 50 years hazard levels. These values were lower by about 50 to 65% than those obtained from deterministic analysis.

Keywords: Seismic hazard assessment, macrozonation map, attenuation relationship, Gumbel's Method

Abstrak. Kertas kerja ini mengemukakan kajian awal terhadap penghitungan bencana gempa bumi bagi Semenanjung Malaysia yang mana melibatkan pembinaan peta pengezonan makro bagi dua tahap bencana, iaitu 10% dan 20% kebarangkalian terlampaunya dalam tempoh 50 tahun di batuan dasar bagi Semenanjung Malaysia. Analisis ini dilakukan dengan menggunakan kaedah statistik bagi nilai yang melampaui daripada Gumbel. Analisis ini juga meliputi pemprosesan data gempa bumi (seperti pemilihan magnitud yang konsisten untuk digunakan di dalam analisis dan mengenalpasti peristiwa-peristiwa kejutan utama) dan pemilihan fungsi atenuasi yang sesuai. Analisis menunjukkan bahawa puncak pecutan bumi (PGA) sepanjang Semenanjung Malaysia berkadar di antara 10 gal dan 25 gal bagi kebarangkalian dilampauinya 10%, dan di antara 15 gal dan 35 gal bagi kebarangkalian dilampauinya 2% dalam tahap bencana 50 tahun. Keputusan ini adalah lebih rendah sebanyak 50% hingga 65% berbanding analisis kebolehtentuan.

Kata kunci: Penghitungan bencana gempa, pengezonan makro, hubungan atenuasi, kaedah Gumbel

1.0 INTRODUCTION

Seismic hazard assessment for Malaysia has never been done previously, due to the fact that Malaysian earthquake event in history is not so profound and the nearest distance of earthquake epicenter from Malaysia is approximately 350 km. Generally,

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earthquake can cause significant damages within 100-200 km radius from the epicenter. At further distance, amplitudes of incoming seismic shear waves are generally small [1]. However, the "Bowl of Jelly" phenomenon, as what had happened to Mexico City in 1984 has to be considered more seriously. The phenomenon has shown that even though an earthquake occurred at a far distance, it can have a significant effect due to long period component of the shear waves.

Although Peninsular Malaysia is located in the stable Sunda Shelf with low to medium seismic activity level, tremors due to Sumatra earthquakes had been reported several times. For instance, there were two large earthquakes near Sumatra which occurred at the end of 2002 (M_w = 7.4) and early 2003 (M_w = 5.8). Although no casualties or damages were reported due to those earthquakes, the tremors caused panic to several cities in Peninsula Malaysia which included Penang and Kuala Lumpur. Cracks on buildings in Penang due to the earthquake on 2nd November, 2002, have also been reported.

Our previous study [2] regarding the effects of those two earthquakes had shown that the peak accelerations at bedrock increase about 2 to 5 times at the surface, due to the effect of local soil condition. The effects of those earthquakes to building depend on the natural frequency of the building. According to the data analysis, the maximum effect of the motion will occur on 1 to 10- storey buildings in Penang and Kuala Lumpur.

Based on the above facts, seismic hazard assessment for Malaysia is essential in order to mitigate the effects of potential large earthquake that may occur in the future. One major measure in mitigating the earthquake hazard is to design and build structures using appropriate engineering practices, so that these structures exhibit sufficient resistant against earthquake [3].

This paper presents a preliminary study regarding seismic hazard assessment for Peninsular Malaysia. The study is carried out to develop macrozonation map for Peninsular Malaysia. The analysis was performed using statistical theory of extreme values developed by Gumbel and the results were compared with the macrozonation map obtained deterministically from the previous study.

2.0 EARTHQUAKE DATA

2.1 Data Collection

The analysis of seismic hazard assessment requires data recorded from earthquake events that occurred around at site of interest and observed for a specific time interval. In this research, the data recorded from the earthquake events occurred around Peninsular Malaysia region were obtained from several sources, i.e. U.S. Geological Survey (USGS), the International Seismological Center (ISC), the earthquake events catalogue published by Pacheco and Sykes [4], and the Malaysian Meteorological Service catalogue.

The combined catalogue covers an area from 90°E to 125°E longitude and from 15°S to 15°N latitude. The minimum moment magnitude (M_w) is 5.0 and maximum focal depth is 200 km. The total number of earthquakes in the working file is 12149. The catalogue covers the range of events between 27 February, 1903 and 30 December, 2000. The location of earthquake epicenter during that period of observation is shown in Figure 1.

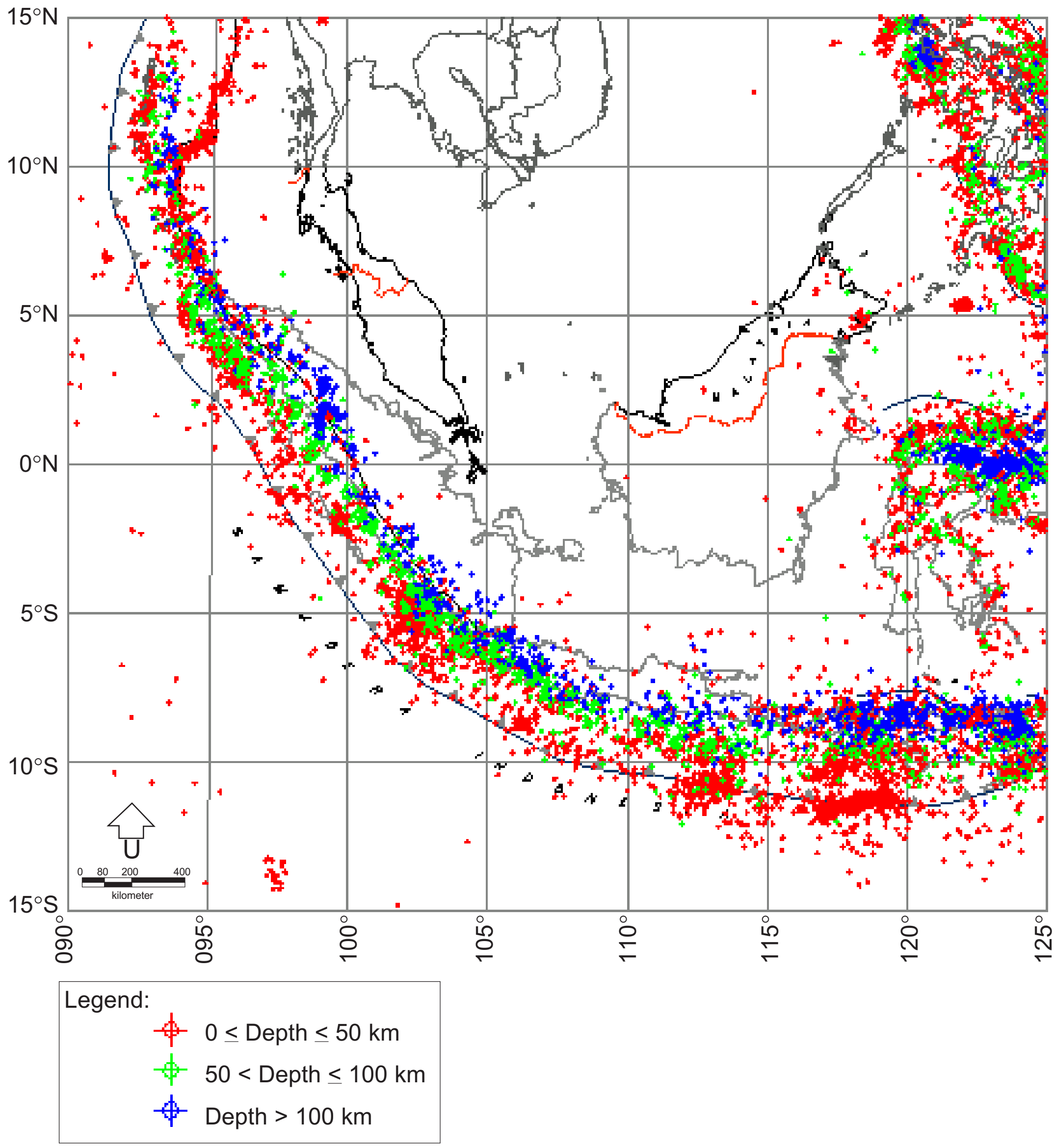

Figure 1 Historical earthquakes around Peninsular Malaysia (*Mw* > 5.0)

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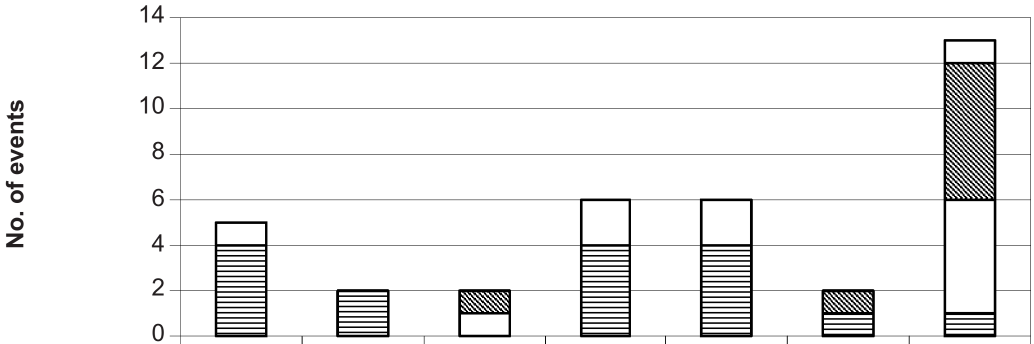
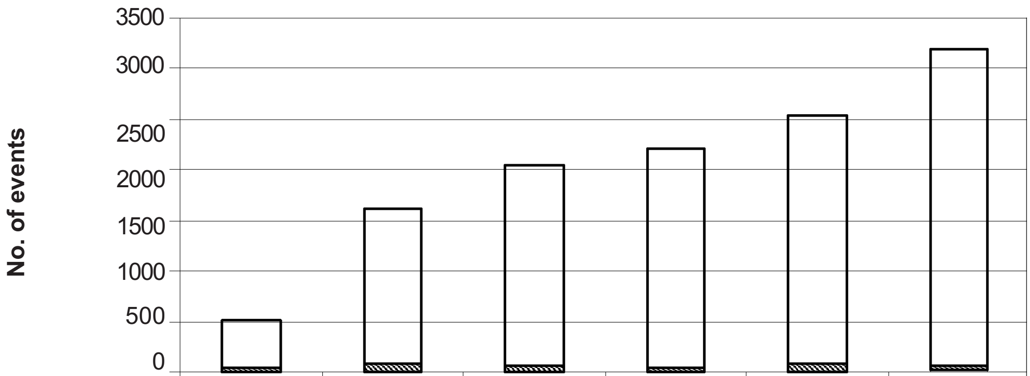
Figures 2 and 3 show three groups of interval magnitude, M_w, i.e. $5 \le M_w < 6$; $6 \le M_w < 7$; and $M_w \ge 7$. These figures show that large earthquakes ($M_w \ge 7$) were recorded along the time interval of observation. The fluctuation in the number of



	1900-1910	1911-1920	1921-1930	1931-1940	1941-1950	1951-1960	1961-1970
□ 5 < *Mw* < 6							1
▧ 6 < *Mw* < 7			1			1	6
□ 7 < *Mw* < 8	1		1	2	2		5
⊟ *Mw* > 8	4	2		4	4	1	1

Time interval (year)

Figure 2 Distribution of three groups interval magnitude between 1900 and 1970



	1971-1975	1976-1980	1981-1985	1986-1990	1991-1995	1996-2000
□ 5 < *Mw* < 6	459	1538	1990	2153	2460	3144
▧ 6 < *Mw* < 7	42	78	56	43	66	44
□ 7 < *Mw* < 8	4	8	2	3	7	10
□ *Mw* > 8		2	1	2		1

Time interval (year)

Figure 3 Distribution of three groups interval magnitude between 1971 and 2000

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moment magnitude of more than 7.0 reported per decade shows no trend in the 100-year sample period from 1900 through 2000. Therefore, it can be assumed that these large earthquakes have been completely reported during the past 100 years. The figures also indicate that the record of earthquake data increases significantly since 1971. Moreover, earthquake data recorded from 1971 to 2000 contributes to about 99% of all the data used in this study. The majority of earthquakes during that interval fall within the range of magnitude between 5 and 7.

All data was processed using statistic principles before being used in the seismic risk assessment. The procedures were performed in order to minimise bias or systematic error, and obtain reliable results. The procedures include the following steps:

(i) Selection on the measurement of earthquake size
(ii) Analysis of main and dependent events

2.2 Selection on the Measurement of Earthquake Size

Earthquake data from the above institutions is recorded using various magnitude scales. Three magnitude values are provided in the data file, i.e. M_S, m_b and M_L. Therefore, selection of measurement that will be used in the seismic hazard assessment is needed. In this study, the moment magnitude, M_w, is chosen to quantify earthquake size because unlike other magnitude scales, this scale is not subjected to saturation [5]. This magnitude scale is based on the seismic moment, a direct measure of the factors that produce rupture along the fault.

There are several relationships used to convert the magnitude scale to other magnitude scale proposed by several researchers such as Geller [6], Electric Power Research Institute [7] and Rong [8]. In this study, the relationships between m_b, M_S, and M_w, have been obtained using the regression analysis. The relationship between m_b and M_w was developed based on 375 data and the correlation between M_S and M_w was obtained based on 249 data. The data was collected from the earlier time of year 1900 until the later time of year 2000.

Based on the regression analysis, the relationship between m_b and M_w is:

$$M_w = 0.528 \cdot m_b^2 - 4.685 \cdot m_b + 15.519; 4 \leq m_b \leq 7 \quad (1a)$$

$$\sigma m_b = 0.24 \quad (1b)$$

Whereas the relationship between M_s and M_W is:

$$M_w = 0.123 \cdot M_S - 0.646 \cdot M_S + 5.644; 3 \leq M_S \leq 8 \quad (2a)$$

$$\sigma M_S = 0.15 \quad (2b)$$

Other formula for correlating m_b to M_w is shown in Figure 4. The relationship between M_w and m_b was also compared to the relationship proposed by Heaton [9]. It can be seen in Figure 4 that empirical correlation from Heaton is relatively smaller than the result from Equation (1a) for magnitude $m_b < 5.5$, and slightly larger than

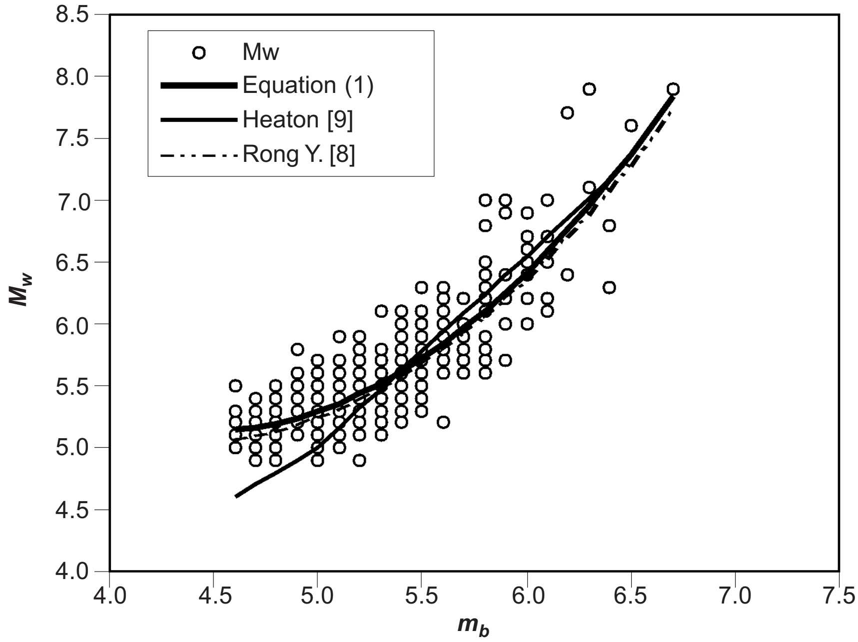

Figure 4 The relationship between m_b and M_w

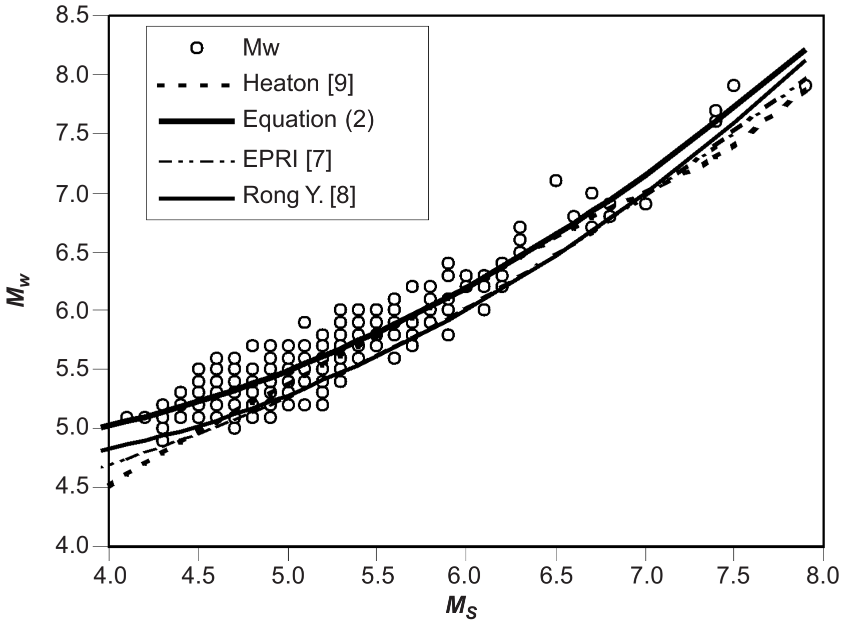

Figure 5 The relationship between M_S and M_w

Equation (1a) for magnitude $m_b > 5.5$. It should be noted that Heaton's chart did not give any information regarding the relationship between m_b and M_w for $m_b > 6.5$. This is because of Heaton's consideration that body wave magnitude will saturate on magnitude above 6.5.

Figure 5 depicts the other formula for correlating M_S with M_w. It can be seen from the figure that the empirical correlations from EPRI [7] and Heaton [9] are relatively smaller than the results from Equation (1b) for all ranges of magnitude. It is also found that the empirical correlation proposed by EPRI [7] is relatively smaller than the one proposed by Heaton [9] for $M_S < 7.5$ and relatively higher for $M_S > 7.5$.

2.3 Main and Accessory Shock Events

Generally, temporal occurrence of earthquake can be divided into Poisson and non-Poissonian model. The Poisson model provides a simple framework for evaluating probabilities of events that follow a Poisson process, whilst the non-Poisson model is based on Elastic Rebound Theory.

The events that follow a Poisson process occur randomly and independently regarding the time, size, or location of any preceding event [10]. The non-Poisson model assumes that the occurrences of earthquakes on a particular fault or fault segment are dependent of past seismicity. Thus, the occurrences of earthquake should depend on the times, sizes, and locations of preceding events. The physical essence of this model is elastic rebound theory.

According to Cornell and Winterstein [11], the Poisson model is useful for practical seismic risk analysis except, when the seismic hazard is dominated by a single source for which the time interval since the previous significant event is greater than the average interevent time, and when the source displays strong characteristic-time behaviour.

In this study, temporal occurrences of earthquake are assumed to follow a Poisson process. Therefore, earthquake events have to be separated between main shock and accessory shocks such as foreshock and aftershock. Usually, earthquake catalogues do not separate between main and accessory shock events [12]. In this case, main shock events should be separated with its accessory shock events (foreshocks and aftershocks) in order to obtain Poissonian earthquake data or independent earthquake events. Several empirical criteria have been proposed by many researchers for several years to identify the main events, such as Gardner and Knopoff [13], Arabasz and Robinson [14], and Uhrhammer [15]. These criteria are used to identify an earthquake sequence that is associated with fault rupture and developed based on the temporal and spatial windows around the largest events of an earthquake. Only events located in a zone approximately parallel to the fault rupture or surrounding the main events are considered as potential foreshocks or aftershocks. An earthquake can be identified as dependent events if they are flagged by the empirical criteria.

In this study, time and distance windows criteria proposed by Gardner and Knopoff [13] were used to identify main events. Time and distance criteria proposed by Gardner and Knopoff [13] can be seen in Figure 6. The algorithm eliminates about 50% of accessory shock events. The combined catalogue, after removal of accessory shock events, contains 6121 records.

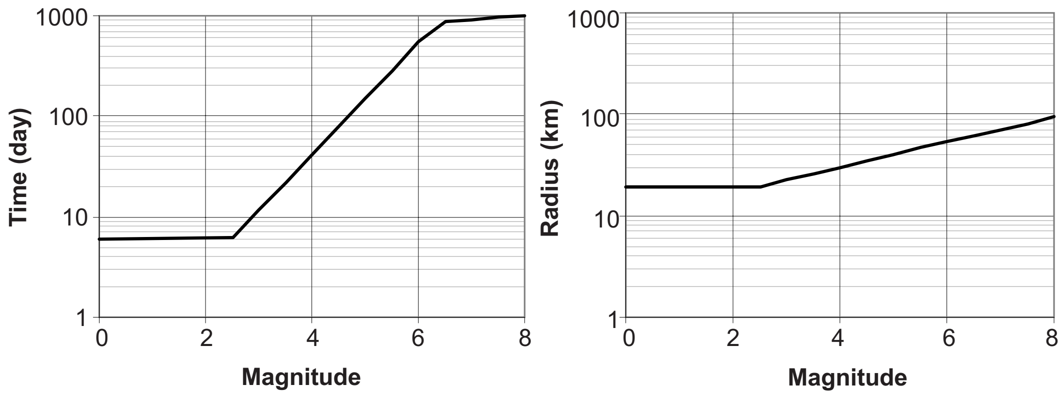

Figure 6 Time and distance windows

3.0 SEISMIC HAZARD ASSESSMENT

3.1 Gumbel Method

The seismic risk analysis may utilise the total probability theorem that relates with the extreme values. This method which is known as Gumbel Distribution can be used to determine the peak ground acceleration for various return periods. The effect of each events to any point of interest can be determined by using the attenuation function, with the assumption that each earthquake event is independent of the point of interest.

The earthquake distribution based on Gumbel distribution can be written as follows:

$$G(M) = \exp\left(-\alpha \cdot e^{(-\beta M)}\right), \quad M \geq 0 \tag{3}$$

Where, α is the mean annual number of earthquake events, β is the parameter that expressed the relation between earthquake distribution with earthquake magnitude, and M is the earthquake magnitude or intensity.

Equation (3) can be simplified as linear relationship as follows:

$$\ln\left(-\ln G(M)\right) = \ln(\alpha) - \beta M \tag{4}$$

The above equation is identical with a linear equation:

$$y = A + Bx \tag{5}$$

Where $y = \ln(-\ln G(M))$, $\alpha = e^A$, $\beta = -B$ and x = magnitude or intensity.

The least square method can be applied to Equation (5) to obtain the values of A and B. The relationship between the return period of earthquake, T, and acceleration, a, can be expressed as follows:

$$a = \frac{\ln(T \cdot \alpha)}{\beta} \tag{6}$$

3.2 Attenuation Relationship

One of the critical factors in seismic analysis is selecting appropriate attenuation relationship. This formula, also known as ground motion relation, is a simple mathematical model that relates a ground motion parameter (i.e. spectral acceleration, velocity and displacement) to earthquake source parameter (i.e. magnitude, source to site distance, mechanism) and local site condition [16].

The most common method to obtain the above relationship is by using empirical method based on historical earthquake data. The relationships between earthquake source parameters and ground motion parameters are obtained statistically using several methods such as single or multiple regression analysis. This method requires a lot of data in order to obtain statistically reliable results. Therefore, empirical method can only be developed in location where the strong motion recordings are abundant, such as in Western North America and Japan.

Since no attenuation relationship has been derived directly for Malaysia due to inadequate ground motion records to develop attenuation formula, several attenuation functions from other countries are adopted. There are a number of attenuation relationships derived in the last two decades since the records of ground motions are readily available. In general, they can be categorised according to tectonic environments (i.e. subduction zone and shallow crustal earthquakes) and site conditions. There are several attenuation relationships derived for subduction zone earthquake, which are commonly used such as by Youngs *et al*. [17]. Whereas attenuation relationships developed by Campbell [16] and Sadigh *et al*. [18], are frequently used to estimate ground motion for shallow crustal or transform zone earthquakes.

In this study, attenuation proposed by Youngs *et al*. [17] was used to estimate the ground motion for subduction earthquake events whilst Campbell [16] relation was used to transform earthquake events. Since Youngs's attenuation was not developed for long distance earthquake, modified equation proposed by Petersen *et al*. [19] was applied in this research. On the other hand, Campbell's attenuation has been developed for a distance of more than 500 km; hence, it is assumed that this equation is applicable to be used for Peninsular Malaysia. These two attenuations are described briefly in the following sections.

3.2.1 Youngs's Attenuation Relationship

This relationship considers two types of subduction zone earthquakes, i.e. interface earthquakes and intraslab earthquakes. Subduction zone interface earthquakes are shallow angle thrust events that occur at the interface between the subducting and overriding plates, while intraslab events occur within subducting oceanic plate and are typically high angle; normal faulting events responding to downdip tension in the subducting plate. Attenuation relations for rock is given as:

$$\ln(y) = 0.2418 + 1.414M - 2.552 \cdot \ln\left(r_{\mathrm{rup}} + 1.7818 \cdot e^{0.554M}\right) + 0.00607 \cdot H + 0.3846 \cdot Z_t \tag{7a}$$

Where, y is the PGA in g's, M is the moment magnitude, r is the source to site distance and Z_t is the type of earthquake mechanism. This formula is valid to be applied only for epicenter distance less than 200 km.

Petersen *et al*. [19] have modified this attenuation in order to calculate PGA for epicenter distances beyond 200 km. Data from IRIS DMC and Singapore Network were used to identify the characteristics of ground shaking at large distances. The modification of the Youngs *et al.* [17] equation for peak ground acceleration for distances beyond 200 km is given as follows:

$$\ln y_{\mathrm{modified}}(M,x) = \ln y_{\mathrm{young}}(M,x) + \left[-0.0038 \cdot (x-200)\right] \tag{7b}$$

Where y is the peak horizontal ground motion in units of g, M is the moment magnitude, and x is the distance in kilometers.

3.2.2 Campbell's Attenuation Relationship

This attenuation relationship was derived using a hybrid method to develop ground motion relations for eastern North America (ENA), for rock sites. Attenuation relationship for rock is given as follows:

$$\ln Y = c_1 + c_2 M_W + c_3 (8.5 - M_W)^2 + c_4 \ln\left[f_1(M_W, r_{rup})\right] + f_2(r_{\mathrm{rup}}) + (c_9 + C_{10} M_W) r_{\mathrm{rup}} \tag{8a}$$

$$f_1(M_W, r_{\mathrm{rup}}) = \sqrt{r_{\mathrm{rup}}{}^2 + \left[c_5 \exp(c_6 M_W)\right]^2} \tag{8b}$$

$$f_2\left(r_{\text{rup}}\right)=\begin{cases}0 & r_{\text{rup}}\le r_1\\ c_7\left(\ln r_{\text{rup}}-\ln r_1\right) & r_1\le r_{\text{rup}}, r_2\\ c7\left(\ln r_{\text{rup}}-\ln r_1\right)+c_8\left(\ln r_{\text{rup}}-\ln r_2\right) & r_{\text{rup}}\ge r_2\end{cases} \quad (8c)$$

$$\sigma \ln Y=\begin{cases}c_{11}+c_{12}M_W; & for\ M_W<M_1\\ c_{13}; & for\ M_W\ge M_1\end{cases} \quad (8d)$$

Where Y is the geometric mean of the two horizontal components of PGA or PSA in g, M_w is the moment magnitude, r_{rup} is the closest distance to fault rupture in km, r_1 = 70 km, and r_2 = 130 km, M_1 = 7.16 and C_1 to C_{13} are the coefficients used for Campbell's attenuation relationship.

3.3 Seismic Sources

Malaysia is located relatively close to the boundary between Eurasian Plate in the northern side and Australian Plate in the southern side. Due to this location, the tectonic features that affect Peninsular Malaysia can be generally divided into two classifications, namely the subduction and transform zones.

3.3.1 Subduction Zone

All of those earthquakes that occurred near convergent boundaries where Indo-Australian plate is being subducted under Eurasian plate are classified into this zone. The Indo-Australian plate is sliding approximately northward beneath Sumatra and Java, where the direction of convergence is N20°E and the overall rate convergence is 7.7 cm/year [20]. Generally, this subduction zone can be divided into three segments, i.e. Sumatra Segment, Sunda Strait Segment, and Java Segment. The Sumatra subduction zone is a very active feature. The largest thrust-fault earthquakes in the Sumatra subduction zone in the last two centuries were in the year of 1833, with the magnitude of 8.8-9.2, in the year of 1861, with the magnitude of 8.3-8.5, on 26th December, 2004, with the magnitude of 9.0, and recently, 28th March, 2005, with the magnitude of 8.7.

3.3.2 Transform Zone

All of those earthquakes occurred due to strike slip movement along clearly defined fault in the frontal arc area such as Sumatra Fault are classified as transform fault. The Sumatra fault is about 1900 km long structure that accommodates right lateral strike slip associated with the oblique convergence along the plate margin. Several

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large earthquakes have occurred in this zone. These events 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.

In this study, the estimations of ground motion parameters (peak ground acceleration) were calculated separately between earthquake events from subduction zone and transform zone. In order to simplify the separation process, seismic sources around Peninsular Malaysia were divided into several seismic zones, as shown in Figure 7. Cross sections of every seismic source of earthquake events with distance versus depth can be seen in Figure 8.

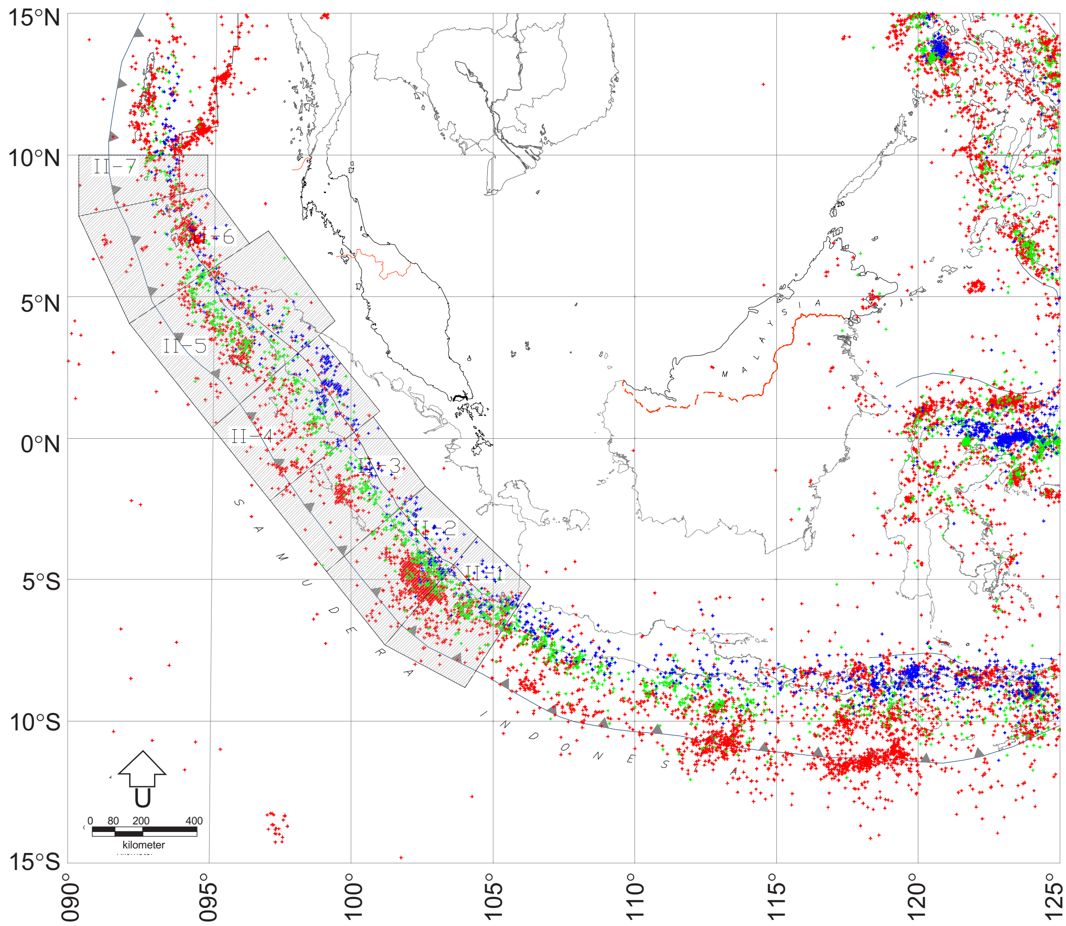

Figure 7 Seismic source zones around Peninsular Malaysia

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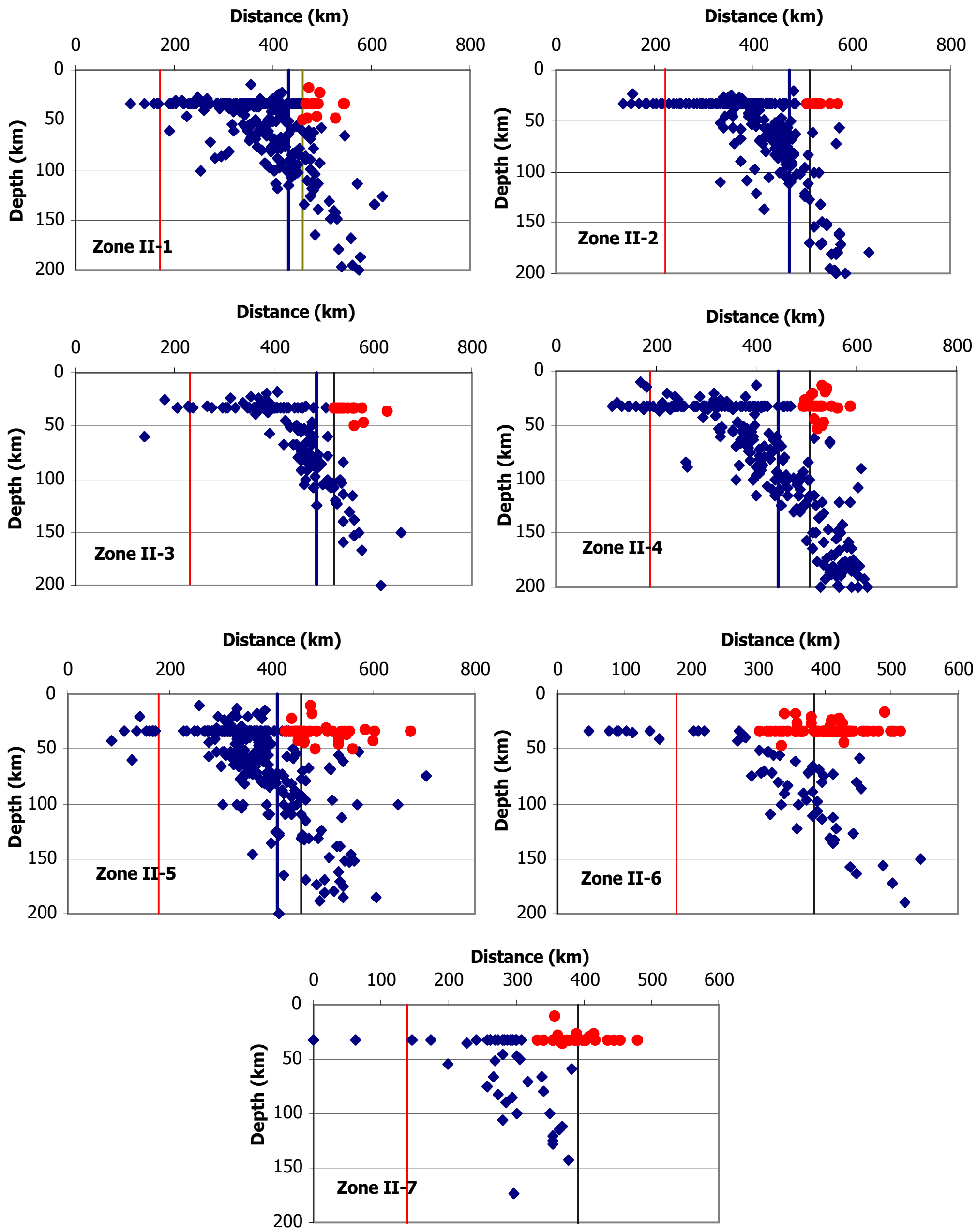

Figure 8 Hypocentral profiles

4.0 RESULTS OF ANALYSIS AND DISCUSSION

The contour maps of Peak Ground Acceleration (PGA) at 10% and 2% probabilities of exceedance in 50 years for bedrock of Peninsular Malaysia can be seen in Figures 9 and 10. The PGA across Peninsular Malaysia is in the range between 10 and 25 gals for 10% probability of exceedance in 50 years hazard levels or 500-year return period of earthquake, and between 15 and 35 gals for 2% in 50-year hazard levels or 2500-year return period of earthquake. The hazard levels show the trend of contour increases constantly from the southwest to the northern side of Peninsular Malaysia.

These values are about 50 to 65% lower than the result from deterministic analysis that has been accomplished in the previous study. As shown in Figure 11, the result of deterministic analysis has divided the PGA map of Peninsular into two zones, i.e. the zone for range between 30 and 50 gals on the east side of Peninsular Malaysia and the zone between 50 and 70 gals on the west side.

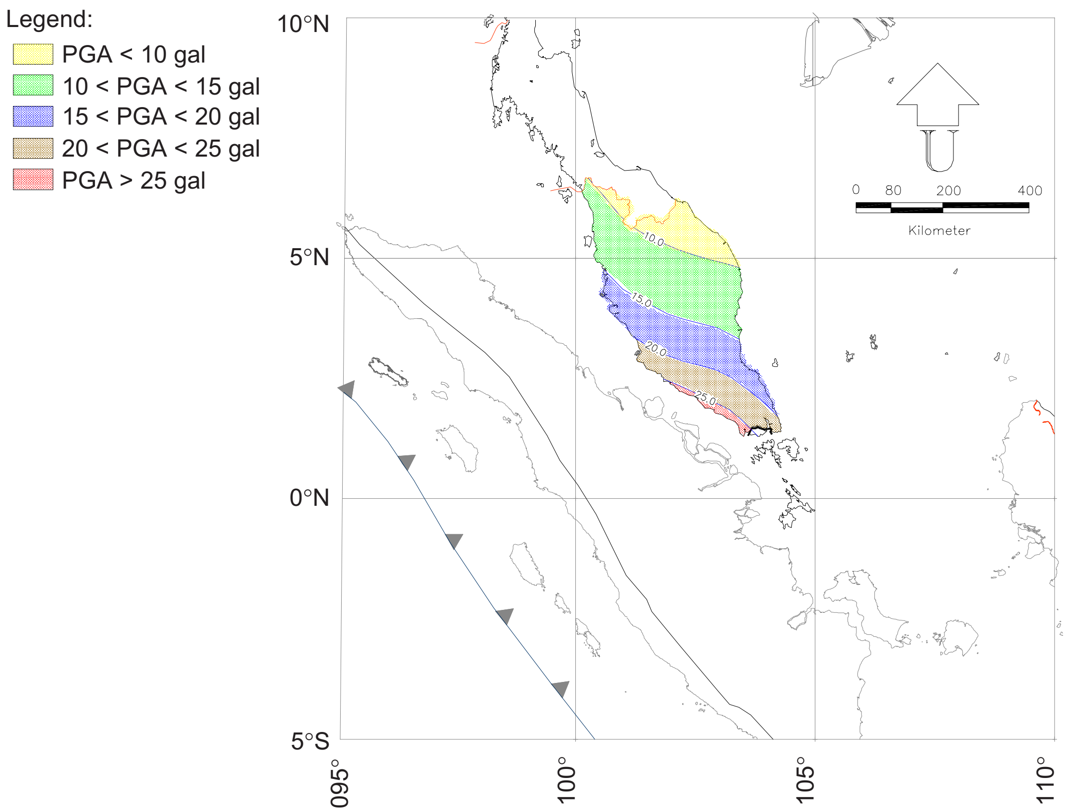

Figure 9 PGA with 10% probability of exceedance in 50 years

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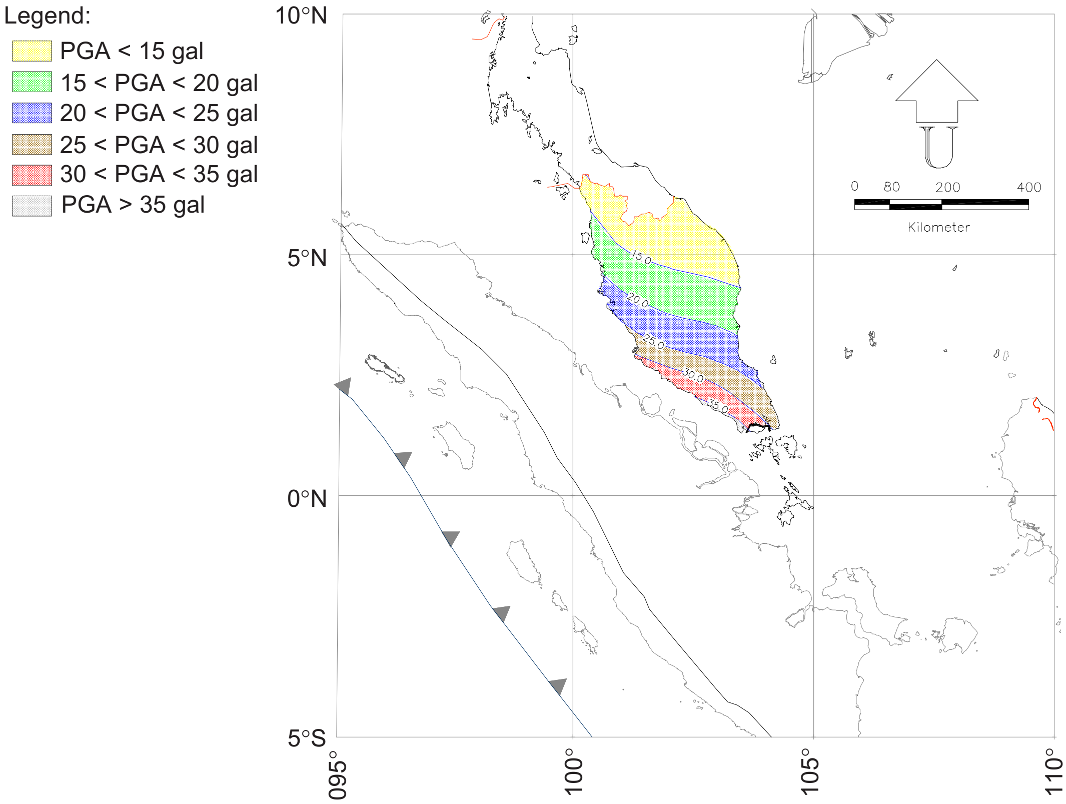

Figure 10 PGA with 2% probability of exceedance in 50 years

It should be noted that deterministic analysis is based on worst-case scenario of earthquake expected in a region and it covers the estimation of maximum magnitude that probably occurred in that region. This method, however, does not provide information on the level of shaking that might be expected during a finite period of time (such as the useful lifetime of a particular structure or facility), producing a big (and perhaps unrealistic) result, and not accounting the effects of uncertainties in the various steps required to compute the resulting ground motion characteristics [10]. In contrast, Gumbel's method is based on historical earthquake and it depends on the completeness of earthquake catalogues. For instance in this study, 100-year historical earthquake records were used to estimate 500 years return period of earthquake. This method has considered the level of shaking that might be expected during a finite period of time.

A more comprehensive method to assess ground motion level is the Probabilistic Seismic Hazard Assessment (PSHA) as developed by Cornell [21]. This method explicitly considers the uncertainties of the size, location and rate of occurrence of earthquake and the variation of ground motion characteristics with the size and location of earthquake in the evaluation of seismic risk. This method could model

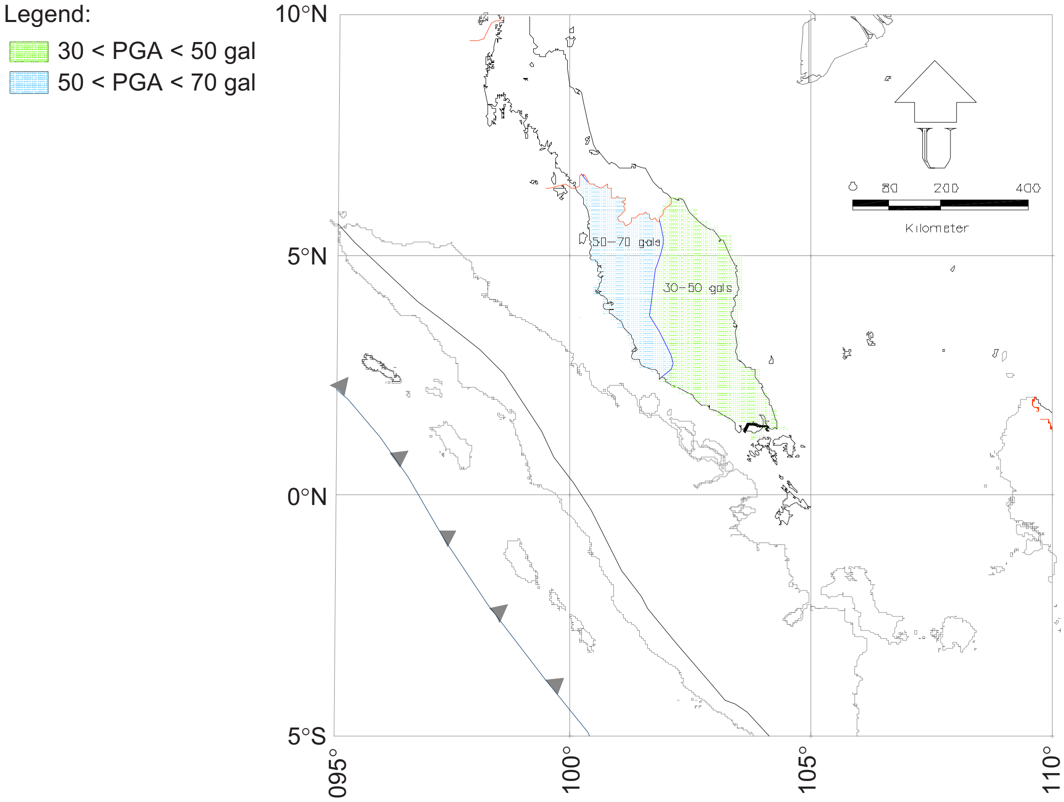

Figure 11 PGA contour based on deterministic method

the earthquake mechanism better than Gumbel's method because it could cover many uncertainties factor of earthquake process. However, at this moment, PSHA method is still being studied in depth.

5.0 SUMMARY AND CONCLUSION

Macrozonation map for Peninsular Malaysia has been developed in this preliminary study using statistic theory of extreme values from Gumbel. The analysis was carried out for two hazard levels, i.e. 10% and 2% probability of exceedance in 50 years for bedrock of Peninsular Malaysia. Based on the analysis, the PGA across Peninsular Malaysia present a range between 10 gal and 25 gal for 10% probability of exceedance in 50 years hazard levels or 500 year return period of earthquake and between 15 gal and 35 gal for 2% in 50 year hazard levels or 2500 year return period of earthquake.

These results have been compared with macrozonation map that was obtained deterministically from the previous study. The difference between those two methods showed that the results of Gumbel's method were lower by about 50 to 65% than the results obtained from deterministic analysis.

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