DEVELOPMENT OF PROBABILISTIC SEISMIC HAZARD MAP OF PENANG ISLAND, MALAYSIA

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Evaluation of peak ground accelerations (PGAs) for Penang Island, Malaysia, was performed using probabilistic seismic hazard analysis. The PGA results were obtained using the model of Young *et al*. for moment magnitudes (M_w) lower than 8.0 and the model of Petersen *et al.* for M_w larger than 8.0. Amplification factors from bedrock to the surface were obtained by ground motion analysis using the SHAKE program and ground motion data collected at a nearby station. The results are PGA maps of Penang Island reflecting the 40%, 10%, 5%, and 2% probabilities of occurrences within 50 years.

Keywords : *Seismic Hazard Map, PSHA, PGA, Penang Island, Malaysia*

1. Introduction

Penang Island is located in the northwest of Peninsular Malaysia. The capital city of the island is Georgetown; this is a historic city with notable buildings built over 500 years of colonial reign (Fig.1, in circle). Georgetown is one of the principal ports connecting the East and West through the Straits of Malacca and the city was named a UNESCO World Heritage Site on 7th July 2008. Almost two-thirds of Penang Island is hillside and forest. However, because of rapid development and modernization, the hillsides are used for housing development, roads built to connect the east and west of the island and dam to provide water supply.

This paper focus on the probability of seismic hazards in Penang Island. The Island is located in a region of low seismicity with low-to-moderate seismic activity, depending on the distance from the reporting site to the epicenter (Fig. 1). However, recently, a number of earthquakes affected the island, including the Great Sumatran-Andaman earthquake of 2004, which generated a tsunami as well as severe shaking on high ground. The Malaysia Meteorological Agency and mass media reported swaying of tall buildings in Georgetown itself.

Peak ground acceleration data for bedrock can be determined using probabilistic seismic hazard analysis (PSHA) and suitable empirical attenuation relationships and historical data for nearby locations. This mathematical approach can predict the potential for earthquakes. Assessment of ground responses during an earthquake, under ideal conditions, is based on the assumption that such responses are based on upward propagation of stress waves from the bedrock. Factors affecting ground responses include soil conditions and geologic features such as the depth of soil, the bedding planes of soils overlying bedrock, changes in soil types, and faults crossing soil deposits.

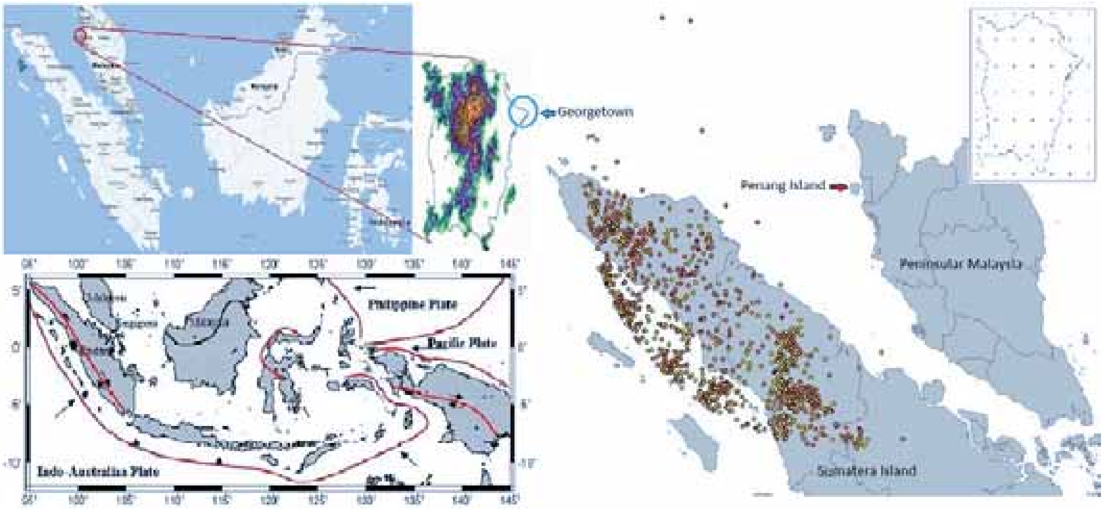

Fig.1. (Left) Location of Penang Island and subduction zones surrounding the island. (Right) Epicentral locations of historical earthquake data used in PSHA analysis; a total of 49 grid points are located on Penang Island (insert).

2. Probabilistic Seismic Hazard Analysis (PSHA)

PSHA is a mathematical method that can quantify uncertainties in the extent of shaking and can be used to understand site behavior during an earthquake. PSHA can map the distribution of future shaking using historical earthquake data from a particular area. In PSHA, the basic steps include identifying all earthquake sources that are capable of producing damaging ground motions, characterizing these earthquakes and the distributions of source-to-site distances associated with potential earthquakes, predicting the distribution of ground motion intensity as a function of these magnitudes and distances, and, finally, combining all uncertainties using a total probability approach.

(1) Identifying earthquake sources and distances

The island has 25 km^2 of land area and relevant earthquake events occur within 600 km of the island (Fig.1, right). Past records showed that the island experienced tremors and tsunamis created by large earthquakes up to 450 km from the island. As most large earthquakes in Sumatra are located about 600 km from the island, all historical records of earthquakes of magnitude 4.0 or more within the 600 km radius were collected for analysis. The target area of this study was the area from 100.261 E to 100.346 E in longitude and 5.483 N to 5.253 N in latitude, and was divided into 49 grids.

(2) Earthquake catalogs and magnitudes

Estimations of the probability of earthquake occurrences are based on historical data; these are some of the important inputs if predictions are to be made. However, such data are scarce. Data were acquired from the US Geological Survey and the Indonesia Meteorology Agency (BMG). The data include historical records on earthquakes including dates, locations, magnitudes, and depths; from 1871 to 2011. Baker[1] considers that if individual faults are not identifiable then earthquake sources can be described regionally. For Malaysia, many uncertainties on fault parameters are evident, so for this paper, areal source model are adopted that employs only historical earthquake data. All records are converted to moment magnitudes[2].

3. Development of Attenuation Models and Estimation of PGA on Bedrock

(1) Attenuation models suitable for Penang Island

Quantification of ground motion is important to understand the behavior of any site during an earthquake.

Attenuation models are used to predict the probability distribution of ground-shaking intensity, as a function of variables including earthquake magnitude, distance from the site, the faulting mechanism, and near-surface site conditions. In the present study, four attenuation relationships were chosen for analysis. The equations used outputs of the attenuation relationships derived by Megawati *et al.*[3], Young *et al.*[4], Petersen *et al.*[5], and Atkinson and Boore[6]. These four equations are widely used in PSHA and allow analysis of subduction zone earthquakes of $M_w > 5.0$ at distances ranging from 10 to 1,500 km to be analyzed depending on the assumptions made and rock types.

Using the dataset of the Malaysian Meteorological Agency[7], records were retrieved from the interval May 2004 to July 2007. This interval contained data on 15 interplate earthquake events of $M_w \geq 5.0$ and of shallow hypocentral depth, thus $h_{hypo} \leq 40$ km. The dataset used had initially been analyzed by Sherliza *et al.*[7] and was then reduced because of distance constraints on all four attenuation relationships.

The magnitudes chosen for analysis were M_w = 6.3, M_w = 6.7, and M_w = 8.6. Although Gutenberg and Richter[8] suggested that choice of more magnitudes might be appropriate, the limited number of recorded PGAs caused us to choose only three. The dataset[7] revealed that the minimum PGA value was 0.3 gal (March 6, 2007; M_w = 6.3) and the maximum 20 gal (March 28, 2005; M_w = 8.6). Fig. 2(a) shows the four attenuation relationships for M_w = 6.3. It may be noted that the attenuation model of Young *et al.*[4] fitted the data well; Malaysia's records fell within the predictive range.

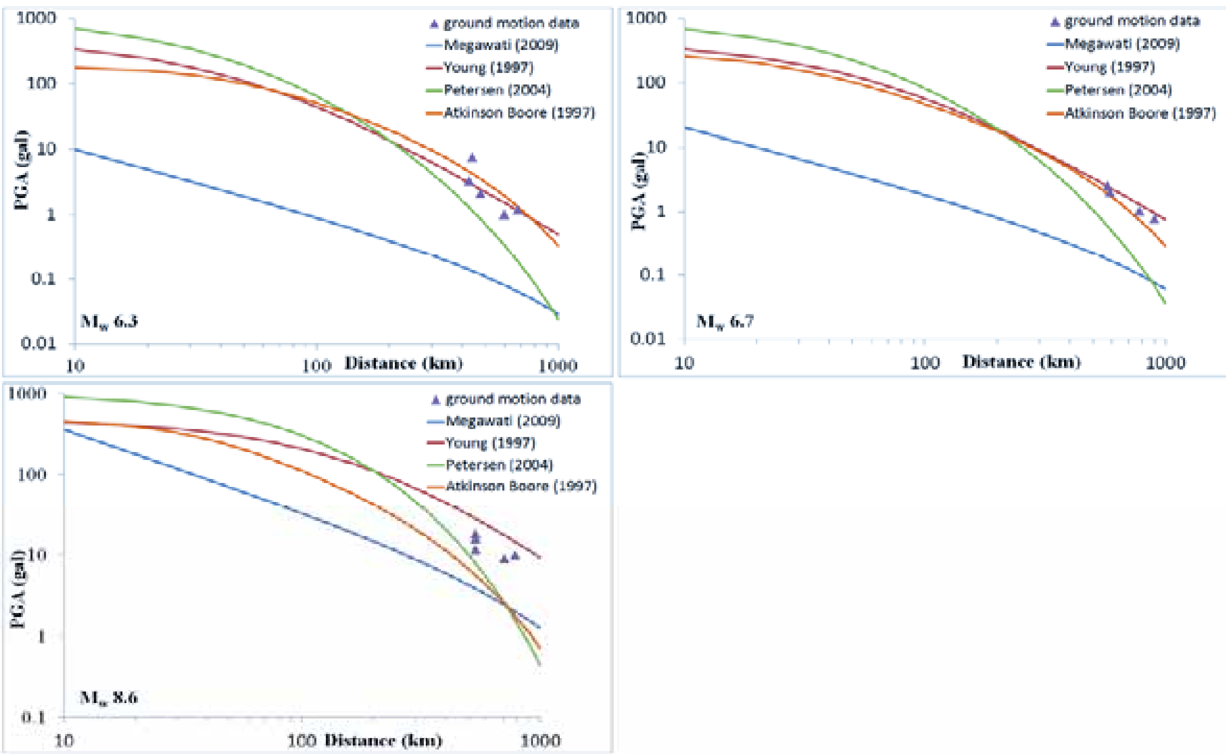

Fig. 2. Comparison of estimated and recorded PGA values of the magnitude of earthquake moment, Mw = 6.3 (top left); Mw = 6.7 (top right); Mw = 8.6 (bottom left).

In Fig. 2(b), the attenuation models of Young *et al.*[4] and Atkinson and Boore[6] predicted values very close to the Malaysian dataset for M_w = 6.7 events and, in Fig. 2(c), the attenuation model of Petersen *et al.*[5] predicted a value that fitted closely to those of the dataset for M_w = 8.6 events. The reason why most attenuation models do not accurately represent or closely fit datasets is because the ranges of distance and maximum earthquake magnitude are considerably less than the optimum values for these models, except in the attenuation model of Megawati *et al*[3].

In Fig.2, it can be seen that the attenuation models of Young *et al.*[4], Atkinson and Boore [6], and Petersen *et al* [5], estimated PGA values very well. Most observed or recorded PGA values were predicted by the models. However, for earthquakes of magnitude of less than 8.0, the model of Young *et al.*[4] should be used; the model considers the depth of the earthquake, h_{hypo}, and the distance, R_{hypo}. For earthquakes of M_w of over 8.0, Fig.2(c) shows that the attenuation model of Petersen *et al.*[5] fits recorded data well, but the model remains unsuitable because the attenuation relationship is based on an earthquake of maximum M_w 8.2.

The attenuation model of Young *et al.*[4] was built via regression analysis of recorded ground motions from interplate earthquakes in Alaska, Chile, Cascadia, Japan, Mexico, Peru, and the Solomon Islands. The relationships identified are valid for earthquakes of $M_w \geq 5.0$ occurring 10 to 500 km distant, and these are shown in Eq.1 with Y_{YOUNGS} in units of *g*. Penang Island is located on granite bedrock, and the equation thus considers the rock conditions:

$$\ln Y_{YOUNGS} = 0.2418 + 1.414 M_w + C_1 + C_2 (10 - M_w)^3 + C_3 \ln(R + 1.7818\ e^{0.554M}) + 0.00607H + 0.3846 Z_T \quad (1)$$

with a standard deviation $\varepsilon = C_4 + C_5 M_w$; C_1 and $C_2 = 0$; $C_3 = -2.552$, $C_4 = 1.45$; and $C_5 = -0.1$, H is the focal depth (in km) and Z_T is the source type (0; this is an interpolate event).

For earthquakes of M_w more than 8.0, the model of Petersen *et al.*[5] is recommended, as shown in Eq.2. This attenuation model was built using data on Sumatran earthquakes; these are relevant to Penang Island. The earthquake distance should be over 200 km. The attenuation model of Young *et al.*[4] is initially applied, but is then modified. R is the distance and Y_{YOUNGS} is equal to the figure calculated using Eq.1; with standard deviation calculated in Y_{YOUNGS}:

$$\ln Y_{PETERSEN} = \ln Y_{YOUNGS} + [-0.0038 * (R - 200)] \quad (2)$$

(2) Peak ground acceleration (PGA) on bedrock

Using the total probability approach, a hazard map for Penang Island was constructed. Eq.3 was used to calculate total probability:

$$\nu = \sum_{i=1}^{N} \nu_{M_{\min}} \int\int P(Y > y \mid m, r) f_{M_i}(m) f_{R_i}(r)\, dm\, dr \quad (3)$$

Where $P(Y>y|m,r)$ is a term from the ground motion attenuation model, and $f_M(m)$ and $f_R(r)$ are probability density functions of magnitudes and distances; these are ultimately integrated. Such integration sums the conditional probabilities of overestimation associated with all possible magnitudes and distances. Fig. 3 shows a PSHA map of the Penang Island bedrock area developed using Eq. 3. The map shows the probabilities of seismic occurrences at the 40%, 10%, 5%, and 2% levels, over 50 years. Figure 3 shows that, in terms of a 40% probability of an event in 50 years (thus, in a 98-year return period), the highest PGA for Penang bedrock is 56.45 gal and the lowest 49.55 gal. For a 10% probability of an event in 50 years (thus, in a 475-year return period), the highest PGA value is 101.92 gal and the lowest 85.06 gal. For a 5% probability of an event in 50

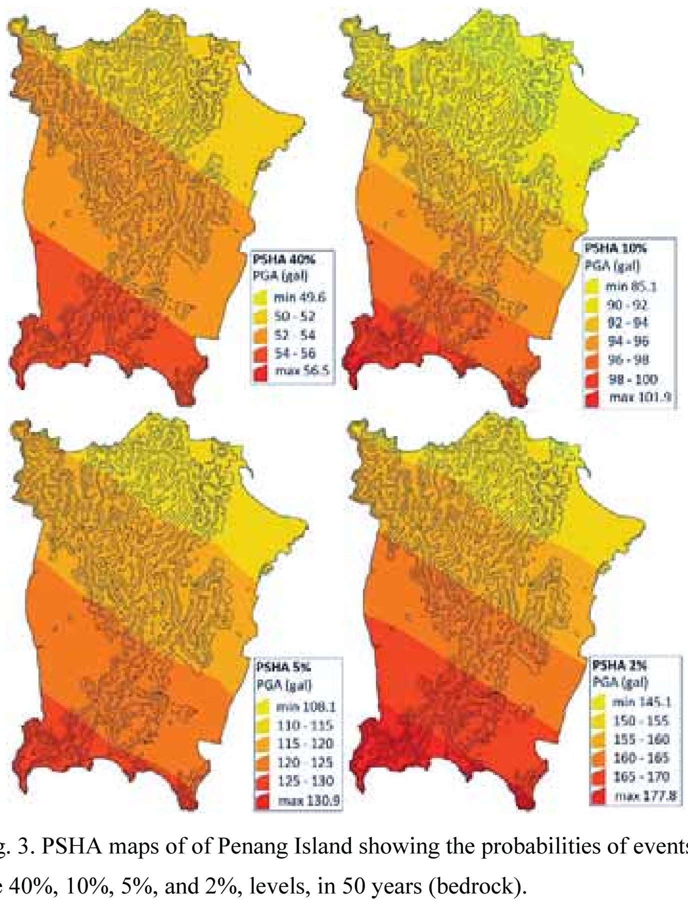

Fig. 3. PSHA maps of of Penang Island showing the probabilities of events at the 40%, 10%, 5%, and 2%, levels, in 50 years (bedrock).

years (a 975-year return period),the highest PGA value is 130.91 gal and the lowest 108.06 gal. For a 2% probability of an event in 50 years (a 2,500-year return period), the highest PGA value is 177.82 gal and the lowest 145.09 gal.

4. Ground Motion Analysis

To develop a surface PGA map, ground response analysis was used to determine surface ground motion at a specific site. For purposes of simplification, this paper simply uses the data to determine ground motion; the responses are not described. Ground response analysis can determine surface motion influenced by the soil layer beneath the surface[9]. Factors affecting the ground response include shear wave velocity, density and layer thickness. The depths of soil deposits and bedrock play important roles in determining the amplification of waves from bedrock to the surface. To analyze ground motion, soil profiles are required and a record of ground motion should be used. This study adopted the 1-D analysis method, so the effect of ground surface irregularity is not considered.

(1) Input of ground motion

In this study, ground motion triggered by a nearby earthquake was analyzed. Ground motion data were collected from the seismic station of the Malaysian Meteorological Agency located in Serdang, Kulim, Kedah (Lat. 5.29, Long. 100.65). The distance from Penang Island to this station is about 50 km and the station is on the top of a mountain; the station is thus assumed to be on bedrock. The input ground motion used was imparted by an earthquake of M_w 8.6 that occurred on 28 March 2005 in Pulau Bangkaru, Indonesia (Lat. 2.09, Long. 97.11). Sherliza *et al.*[7] have made the corrections needed before ground motion data can be used in analysis. Fig. 4 shows the ground motion record that was analyzed.

(2) Soil profile

Penang Island soil profiles were collected from local consultants engaged in several projects on Penang Island. The soil profiles were collected during site investigations. Standard Penetration Tests (SPTs) were performed for each borehole; N numbers were recorded; and soil samples were taken. The test sites were Batu Ferringhi and Tanjung Bungah. A total of 24 records of soil profiles was available, layer types were determined and shear-wave velocities calculated. An example of a borehole is shown in Fig. 5. This borehole was located in Batu Ferringhi 52 m from the shore. Bedrock (granite) was met at 12.6 m. Most boreholes reached bedrock at 10 m if on hilltops and at 15-20 m otherwise.

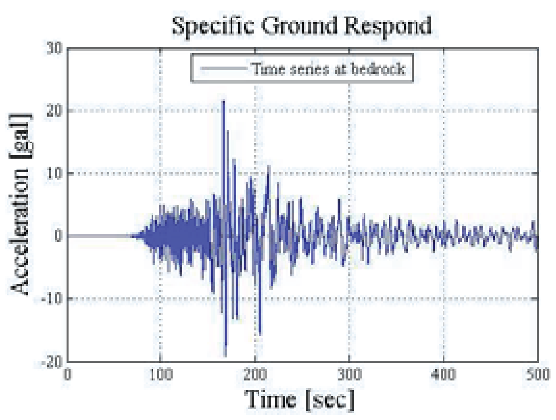

Fig. 4. The earthquake record, in the N-S direction, recorded on 28 March 2005 in Indonesia (Lat. 2.09, Long. 97.11),

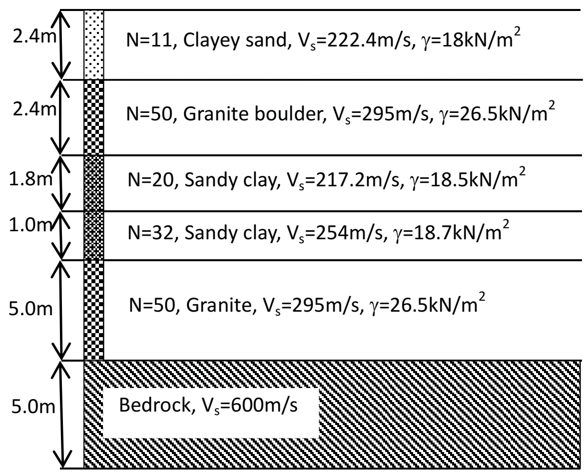

Fig. 5. The Borelog for borehole BH5, Batu Ferringhi.

(3) Analytical procedures for predicting ground responses within soil deposits

Prediction of ground responses involves several steps. First, the characteristics of motion likely to develop in rock formations underlying the site must be explored. Maximum acceleration, the predominant period, and effective duration, are the important parameters. An empirical relationship between these parameters and the distance from the fault to the site is determined[9]. Next, using soil profile information (the N-numbers) from the SPT, the dynamic properties of each soil layer are determined. In this study, a damping factor of 5% was applied to all soil types. Many ways of relating shear-wave velocity and SPT N-number are available and, in this study, the Japanese Highway Bridge Design Code was adapted; this is in general use in Japan[10] and the defined relationship between N-number and shear-wave characteristics is easy to adopt. Such analysis yielded results similar to those obtained by seismic refraction analysis performed in past experience. Eqs. 3 and 4 show the relationships between shear-wave velocity and N-numbers for sandy and clayey soils:

$$V_s = 80N^{1/3}, (m/s) \text{ for sand} \tag{3}$$

$$V_s = 100N^{1/3}, (m/s) \text{ for clay} \tag{4}$$

Next, by reference to soil parameters (unit weight, shear-wave velocity, and the depth of each layer), computation was used to determine the responses of the soil deposits to base-rock motion. The SHAKE program computes responses by viewing soil as a series of layers homogeneous in terms of viscoelastic properties to an infinite horizontal extent, that are subjected to vertically travelling shear waves. The software outputs continuous solutions to wave equations adapted to deal with transient motions using the Fast Fourier Transform algorithm[9]. Taking one borehole (BH5) in Batu Ferringhi as example, the ground response is as shown in Fig. 6 (left). The blue line represents the time series for bedrock and the red line that for the surface. The differences between the peaks of each point on these time series are amplification factors for the site. The amplification factor for BH5 is shown in Fig. 6 (right). For this borehole, the amplification factor was set at 1.7 to estimate PGA on the surface, with reference to the highest possible amplification that could occur in the borehole.

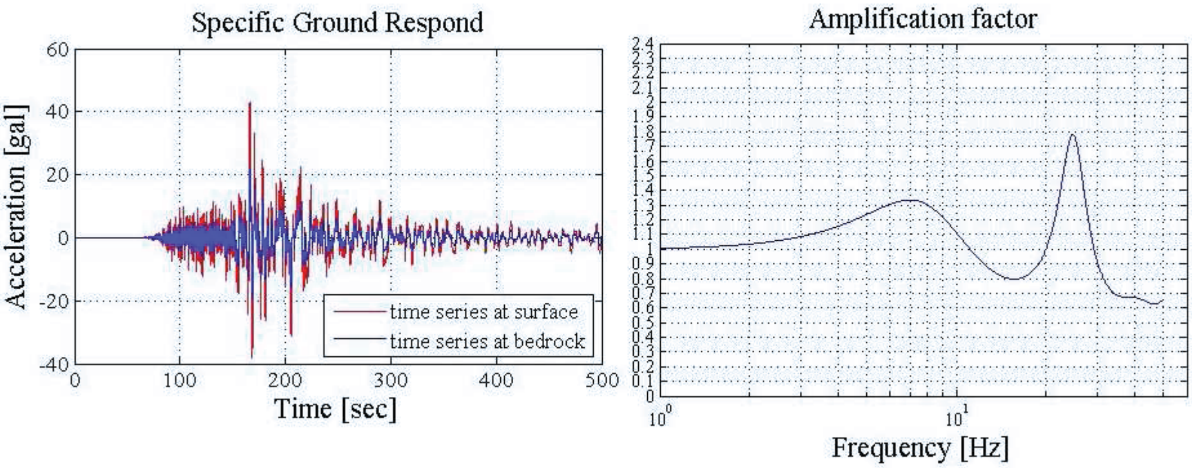

Fig. 6. Left: Ground motion for borehole BH5, Batu Feringhi, Penang. Right: Amplification for borehole BH5, Batu Feringhi, Penang.

5. Peak Ground Analysis Map for Penang Island

From PSHA analysis, each location on the contour line was amplified using the SHAKE program. The idea was that the soil layers at the tops of hills in Penang Island were the same and amplification was considered to be the same as the bedrock PSHA values when heights were higher than the heights of available records.

A map was made. Fig. 7 shows that for a 40% probability of an event in 50 years (a 98-year return period), the highest value of PGA was 110 gal and the lowest 46.4 gal. For a 10% probability of an event in 50 years (a 475-year return period), the highest value of PGA was 200 gal and the lowest 135 gal. For a 5% probability of an event in 50 years (a 975-year return period), the highest value of PGA was 255 gal and the lowest 168.8 gal. For a 2% probability of an event in 50 years (a 2,500-year return period), the highest PGA value was 340 gal and the lowest 255 gal.

In Fig.7, the distributions of peak ground accelerations are highly concentrated in the lowlands, especially near the coast. This is because amplifications on lowlands are higher than on hillsides. The values are relatively small if compared to those of regions of higher seismicity but effects will still be felt on Penang Island if seismic activity occurs within a 600 km radius. The blue circle in Fig.7 represents the Georgetown area. Since the area is located on a lowland, it can be seen that for all probability of occurrences, the PGAs prediction for Georgetown area are at the maximum value. This shows there is effect on seismicity on the historical city. Although it is not as large as what other historical cities in the world anticipated, there are still some risk in case bigger earthquake happen in the future. Since the amplification was obtained by 1-D analysis which cannot take into account the complex shape of the hill, we will investigate the 3-D effect in future analysis. Further investigation should focus on what would happen if an earthquake coincided with heavy rainfall, which is the main cause of landslides on the Island.

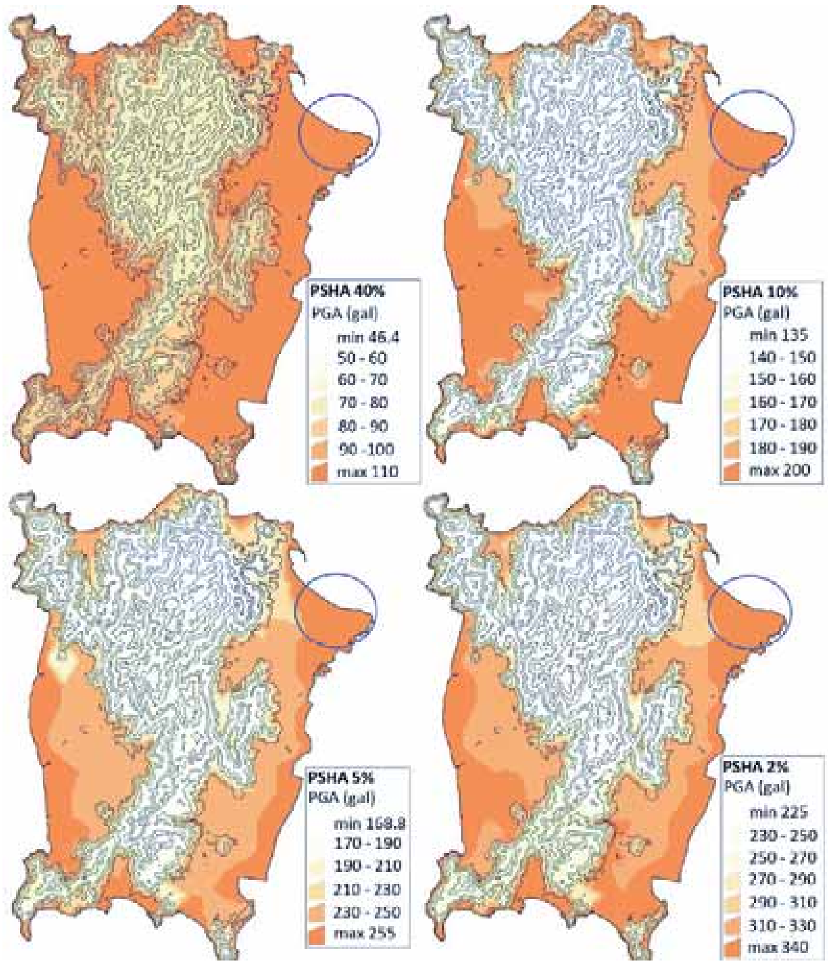

Fig. 7. PGA maps for 40%, 10%, 5%, and 2% probabilities of an event in 50 years (ground).

6. Conclusions

Peak ground accelerations for Penang Island were mapped based on 40%, 10%, 5%, and 2% probabilities of events in 50 years (98-, 475-, 975-, and 2,500-year return periods, respectively). The implications are less than those in highly seismic regions. Lowland areas are at higher risk; they contain softer soils that amplify earthquake motion more than do the soil types of higher ground. This is because the soil layer are shallow, and the bedrock (granite) is located at shallow depths (high level) on the tops of hills, yielding lower amplification factors, which in turn yield lower PGA values.

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