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METROPOLITAN MANILA SEISMIC HAZARD MAP USING MIDORIKAWA & HORI SITE AMPLIFICATION MODEL

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ABSTRACT: Since Metropolitan Manila is known to be susceptible to seismic hazards, it is necessary to consider multiple factors in assessing this hazard. Aside from ground motion, the properties of soil which lead to the amplification of seismic waves should be considered. This study aimed to develop a seismic hazard map for Metro Manila considering the soil properties in the area by using Midorikawa & Hori site amplification model. Probabilistic seismic hazard assessment was conducted using earthquake data within 250 km of Metropolitan Manila for 10% and 2% probabilities of exceedance. The site amplification factors were computed using calculated shear wave velocities from SPT-N values. The calculated ground motions were amplified using the site amplification factors considering short-period and mid-period amplifications. The constructed maps of amplified peak ground acceleration (PGA) values showed how soil properties affect the ground motion. It was found that for a short-period amplification, the average PGAs is 0.538 g, and 0.659 g for 10%, and 2% probabilities of exceedance, respectively. While for mid-period amplification, the average PGAs is 0.589 g, and 0.830 g for 10%, and 2% probabilities of exceedance. Using the amplified seismic hazard maps, a better approximation of seismic hazards can be generated for future use.

Keywords: Site amplification, Shear wave velocity, Peak ground acceleration, Probabilistic seismic hazard assessment, Metro Manila

1. INTRODUCTION

Since the Philippines is situated within the Pacific Ring of Fire, the country is considered highly vulnerable to natural hazards such as earthquakes. Typically the damage caused by earthquakes is defined by the magnitude of the event and the distance from the site to the source. However, it is also necessary to consider the varying geological conditions in the area as it also affects the hazards caused by earthquakes [1].

Site amplification refers to the amplification of the earthquake waves as they travel from the source through the soil due to the local geological conditions in the site which is often characterized by shear wave velocity (V_S) [2]. Unlike the studies for liquefaction and slope stability, only a few research in the country have been conducted which consider the effect of site amplification on earthquake hazards due to a general shortage of data for soil profiles and shear wave velocities. Since Metropolitan Manila or Metro Manila is regarded to be susceptible to earthquake hazards and site amplification due to its variable geology [3], it is necessary to include the effects of soil conditions in the evaluation to provide a more accurate representation of ground motion intensities.

In a previous study [4], a reference for site amplification of Metro Manila was developed, however, the site amplification model used in the study is only applicable to strains less than 1% and for periods that are less than or equal to 0.5 seconds. With this, the study aims to develop seismic hazard maps considering site amplification of Metro Manila using a site amplification model [5] that is designed for higher strains and different periods, such as short-period and mid-period amplifications. The developed seismic hazard maps show the amplified peak ground accelerations in the study area for probabilities of exceedance of 10% and 2%. With the development of these amplified hazard maps, a reference and a basis are provided to determine how local site conditions affect ground motion intensities.

2. RESEARCH SIGNIFICANCE

Metro Manila, being the capital of the Philippines, has the densest population in the country and is considered a major contributor to the country’s economy. This shows how important it is for the region to be prepared whenever disaster strikes, especially since its location and soil conditions make it even more vulnerable. By considering site amplification in evaluating hazards, the maps will be able to provide a more accurate representation of seismic hazards for future planning and assessments.

3. METHODOLOGY

The location of the study covers the area of Metro Manila. The region has a total of sixteen (16) cities and one (1) municipality. In this study, a probabilistic seismic hazard assessment (PSHA) was conducted to determine the peak accelerations at bedrock (PA_{rock}) within the study area. The site amplification factors were then identified using the average shear wave velocities (V_{S30}) in Metro Manila and were used to amplify PA_{rock} and obtain the peak accelerations at the ground surface.

3.1 Probabilistic Seismic Hazard Assessment

In conducting PSHA, the equation of the probability theorem [6] is shown in Eq. (1). The equation shows the computation of the probability of exceeding a value of a ground motion parameter, considering the possible magnitudes or locations of an earthquake.

$$\lambda_{y^*} = \sum_{i=1}^{N_S} \sum_{j=1}^{N_M} \sum_{k=1}^{N_R} v_i P\left[Y > y^* \middle| m_j, r_k\right] P\left[M = m_j\right] P\left[R = r_k\right] \quad (1)$$

where:
λ_{y^*} = total mean annual exceedance rate for peak acceleration level y^*;
$N_S =$ total number of potential earthquakes sourcin$n$ the study area;
$N_M =$ total number of magnitude intervals j considered;
$N_R =$ total number of distance intervals k considered;
v_i = average rate of magnitude exceedance for source i;
$P\left[Y > y^* \middle| m_j, r_k\right] =$ probability that a ground motion parameter Y will exceed the peak acceleration level y^* at a specific magnitude interval m_j and a specific distance interval r_k;
$P\left[M = m_j\right]$ = probability that a magnitude M will be included in the magnitude interval m_j;
$P[R = r_k]$ = probability that a distance R will be included in the distance interval r_k.

In this study, the earthquake sources within 250 kilometers (km) of Metro Manila were considered and categorized as either linear sources or areal sources. For linear sources, the probability density function [6] for distance shown in Eq. (2) is used.

$$f_R(r) = \frac{r}{L_f\sqrt{r^2 - {r_{min}}^2}} \quad (2)$$

where:
$f_R(r)$ = probability density function for distance, R;

r = source-to-site distance;
L_f = length of fault;
in = shortest site-to-source distance.

For areal sources, the relation [7] was used as shown in Eq. (3). The area was further divided into square elements. Equation (2) was used to obtain the probability distribution considering the shortest distance from the center of each element to the site.

$$M = 4.532 + 0.887 \log A \quad (3)$$

where:
A = mean rupture area;
M = earthquake surface magnitude when L or $W \leq 100$ km, in moment magnitude otherwise.

The probability distribution for magnitude was computed using the probability density function [6] shown in Eq. (4).

$$f_M(m) = \frac{\beta \exp[-\beta(m - m_0)]}{1 - \exp[-\beta(m_{max} - m_0)]} \quad (4)$$

where:
$f_M(m)$ = probability density function;
m = mean magnitude within the range;
m_0 = minimum magnitude;
m_{max} = maximum magnitude.
$\beta = 2.303b$;
b = seismic constant.

In computing the probability distribution of the ground motion parameter exceedance, the ground motion prediction equations (GMPE) by [8] are shown in Eq. (5), Eq. (6), and Eq. (7) were used for shallow earthquakes. The GMPE by [9] shown in Eq. (8) and Eq. (9) were used for earthquakes generated by subduction zones.

$$\log y = -1.02 + 0.249M_w - \log r - 0.0.00255r \quad (5)$$

$$r = (R^2 + 7.3^2)^{1/2} \quad (6)$$

$$\sigma = 0.26 \quad (7)$$

where:
$y =$ peak horizontal acceleration on seismic bedrock;
M_W = moment magnitude;
r = nearest distance to rupture zone in km.

$$\ln y = 0.2418 + 1.414M_W + C_1 + C_2(10 - M_W)^3 \\ + C_3 \ln(r + 1.7818e^{0.554M_W}) + 0.00670H \\ + 0.3846Z_T \quad (8)$$

$$\sigma = C_4 + C_5 M_W \quad (9)$$

where:
y = spectral acceleration;
C_n = regression coefficients [9];
Z_T = source type indicator.

The value of $P\left[Y > y^* \middle| m_j, r_k\right]$ is computed using the equation by [6] shown in Eq. (10).

$$P\left[Y > y^* \middle| m_j, r_k\right] = 1 - F_Y(y^*) \tag{10}$$

where:
$F_Y(y^*) =$ value of the cumulative distribution function (CDF) of Y at m and r.

The value of $F_Y(y^*)$ is computed using the standard normal variate shown in Eq. (11).

$$z = \frac{\ln y^* - \ln Y}{\sigma} \tag{11}$$

where:
$z =$ Z-score corresponding to the ground motion parameter.

When the values of λ_{y^*} were computed considering the target accelerations from 0.05 g to 1.0 g, the seismic hazard curve was constructed by plotting the accelerations against the mean annual rate of exceedance. By combining the seismic hazard curve with the Poisson model shown in Eq. (12), the peak accelerations at bedrock (PA_{rock}) for probabilities of exceedance of 10% and 2% in 50 years were computed.

$$P[Y_T > y^*] = 1 - e^{-\lambda_{y^*}T} \tag{12}$$

where:
$P[Y_T > y^*] =$ probability of exceedance of y^* in a time period of T.

3.2 Evaluation of Site Amplification

The average shear wave velocities (V_{S30}) and the PA_{rock} were used to quantify the site amplification. To calculate V_{S30}, the SPT-N data or RQD values from the borehole data in Metro Manila were gathered and processed.

For SPT-N values, the model by [10] is used to calculate V_S as shown in Eq. (13). For RQD values, interpolation is done using the table of values by [11] shown in Table 1.

$$V_S = 77.13N^{0.377} \tag{13}$$

where:
$N =$ raw standard penetration resistance.

After computing V_S for each soil layer, the V_{S30} for each site is computed. For soil data with depths greater than 30 meters, the equation by [12] in Eq. (14) was used, otherwise, an extrapolation shown in Eq. (15) was conducted as proposed by [13].

Table 1 Typical values of V_S for a given RQD [11]

RQD (%)	V_S (m/s)
0 < RQD ≤ 50	600
65	760
80	1500
90	2500
100	3400

$$V_{S30} = \frac{\sum_{i=1}^{N} h_i}{\sum_{i=1}^{N} \frac{h_i}{v_i}} \tag{14}$$

$$\log V_{S30} = c_0 + c_1 \log V_{SZ} + c_2 (\log V_{SZ})^2 \tag{15}$$

where:
$h_i =$ thickness of soil layer;
$v_i =$ shear wave velocity at i^{th} layer at the top 30 meters;
$V_{SZ} =$ average shear wave velocity at termination depth;
$c_n =$ regression coefficients [13].

The shear wave velocity map of Metro Manila was then constructed in a mapping software using the computed V_{S30} values. The V_{S30} and PA_{rock} values were used to compute the site amplification factors using the model by [14] shown in Eq. (16).

$$\ln AF = a \ln V_{S30} + b \tag{16}$$

where:
$AF =$ amplification factor;
$a, b =$ regression coefficients in the function of PA_{rock}.

The regression coefficients [5] are computed depending on whether the amplification being considered is short-period amplification or mid-period amplification. Short-period amplification (F_a) covers a period of 0.1 to 0.5 seconds, whose regression coefficients can be computed using Eq. (17) and Eq. (18).

$$a = 0.43{PA_{rock}}^2 + 0.79PA_{rock} - 0.71 \tag{17}$$

$$b = -3.04{PA_{rock}}^2 - 5.40PA_{rock} + 4.98 \tag{18}$$

Mid-period amplification (F_v) covers a period of 0.4 to 2.0 seconds and its regression coefficients can be computed using Eq. (19) and Eq. (20).

$$a = 0.27{PA_{rock}}^2 + 0.07PA_{rock} - 0.72 \tag{19}$$

$$b = -1.51{PA_{rock}}^2 - 0.62PA_{rock} + 4.91 \tag{20}$$

The amplification factors were used to amplify the peak acceleration values computed from the GMPEs, from which new seismic hazard curves were constructed. With this, the amplified peak ground acceleration (PGA) values are computed for 10% and 2% probabilities of exceedance.

4. RESULTS AND DISCUSSION

In this study, earthquake data with a minimum magnitude of 4.0 and spanning from the years 1907 to 2020 were obtained from the Philippine Institute of Volcanology and Seismology (PHIVOLCS). The geotechnical data, on the other hand, were collected from past studies by [5], and [14-18].

4.1 Seismic Hazard Maps

In developing the seismic hazard maps, a geographic information system (GIS) was used similar to [19]. A total of 17 active faults and 1695 earthquake events within 250 km of Metro Manila was considered.

Considering the probabilities of exceedance (POE) of 10% and 2%, the PA_{rock} values in Metro Manila were computed. Table 2 shows a summary of the PA_{rock} values for each city in Metro Manila considering 10% and 2% POE.

Table 2 Average PA_{rock} values in Metro Manila per city and municipality

Location	PA_{rock} (g)	
	10% POE	2% POE
Caloocan	0.390	0.581
Las Piñas	0.430	0.638
Makati	0.451	0.679
Malabon	0.324	0.480
Mandaluyong	0.456	0.687
Manila	0.383	0.571
Marikina	0.442	0.665
Muntinlupa	0.475	0.706
Navotas	0.296	0.437
Parañaque	0.448	0.669
Pasay	0.426	0.637
Pasig	0.443	0.666
Pateros	0.457	0.668
Quezon City	0.436	0.656
San Juan	0.452	0.682
Taguig	0.456	0.685
Valenzuela	0.337	0.500

As seen in Table 2, the average PA_{rock} values in Metro Manila vary from as low as 0.296 g in Navotas and as high as 0.475 g in Muntinlupa for 10% POE. Considering 2% POE, the average PA_{rock} values range from 0.437 g to 0.706 g, which are also in Navotas and Muntinlupa, respectively. Graphical representations of the actual values of PA_{rock} are shown as maps in Fig. 1.

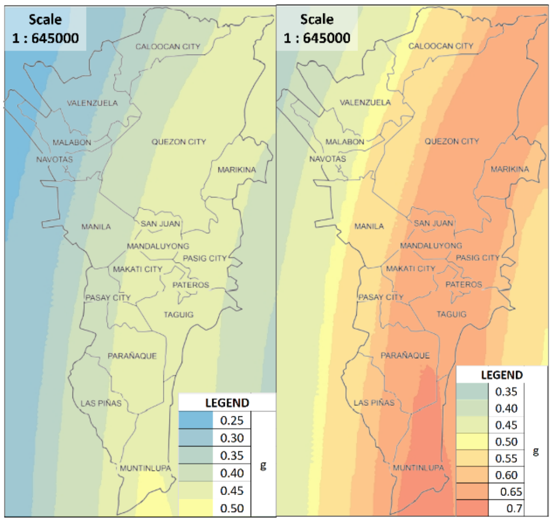

Fig. 1 PA_{rock} in Metro Manila for 10% POE (left) and 2% POE (right)

As shown in the maps, the Muntinlupa area has the highest PA_{rock} values. The contour then spreads outwards, decreasing gradually as the distance from the center increases. The behavior of the contour where the highest PA_{rock} is at the center is due to the presence of the West Valley Fault, which also shows that this fault has the biggest influence on the seismic behavior in Metro Manila. The PA_{rock} values also increase as the probability of exceedance decreases, which shows that large-scale earthquakes are less common than earthquakes on a smaller scale.

4.2 Shear Wave Velocity Map

A total of 1412 borehole data were collected, 1372 of which are within Metro Manila, and 40 are gathered from nearby provinces to complete the interpolation. Relating the number of data used and the area of the study area, a density of 2 borehole data for every square meter was used. Using the different geotechnical data gathered within Metro Manila, the V_{S30} in the study area were computed and mapped. Table 3 shows the summary of V_{S30} in different cities and municipalities in Metro Manila.

Based on Table 3, the average V_{S30} values in Metro Manila range from 206.48 m/s in Manila up to 554.08 m/s in Quezon City. The V_{S30} values describe the stiffness of the soil in each location, which is also attributed to the types of soil present in the area, and their corresponding SPT-N or RQD values. Fig. 2 shows the V_{S30} map of Metro Manila.

Table 3 V_{S30} values within Metro Manila

Location	V_{S30} (m/s)
Caloocan	451.49
Las Piñas	408.35
Makati	380.25
Malabon	260.40
Mandaluyong	546.18
Manila	206.48
Marikina	267.43
Muntinlupa	402.65
Navotas	251.78
Parañaque	498.32
Pasay	244.06
Pasig	401.75
Pateros	299.96
Quezon City	554.08
San Juan	492.20
Taguig	486.59
Valenzuela	452.02

As seen in Fig. 2, the west and east sides of Metro Manila are almost similar with low V_{S30} values, while the center is characterized by high V_{S30} values. The low values on the western side, comprised of Navotas, Malabon, Manila and Pasay, can be attributed to the area being near the coast. The west is also mostly comprised of quarterly alluvial soil where SPT-N values are very low at the surface and are average at deeper layers [15]. Las Piñas and Parañaque are also in the west of Metro Manila, however, the V_{S30} values in the area greatly change as the area considered moves to the right.

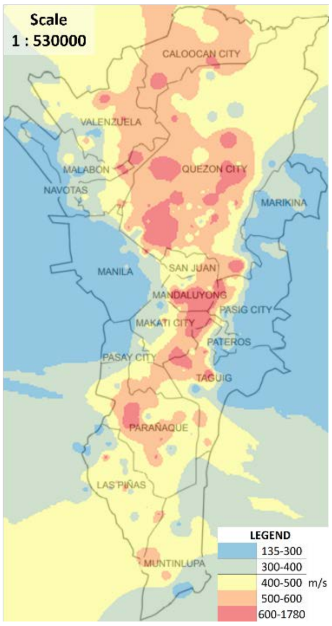

Fig. 2 Map of V_{S30} in Metro Manila

The areas in the eastern part, comprised of Marikina, Pasig, Pateros, and Taguig. have slightly higher V_{S30} values when compared to the west since the areas are far from Manila Bay. However, the soil composition in these areas is similar to the west, with almost the same SPT-N patterns.

The remaining cities in the center, which are Caloocan, Valenzuela, Quezon City, San Juan, Mandaluyong, Makati and Muntinlupa have the highest V_{S30} values. This is due to the tuff and rock formations that are common in the central part of the region [15]. With this, the SPT-N values are generally higher, and refusal can be achieved even in shallow depths.

4.3 Amplified Seismic Hazard Maps

Using the PA_{rock} values mapped in Fig. 1, and the V_{S30} values mapped in Fig. 2, the site amplification factors F_a and F_v were computed. To see the relationship between PA_{rock}, V_{S30}, and the amplification factors F_a and F_v, theoretical values for the first two parameters are used to compute the amplification factors. Table 4 shows the values of F_a and F_v for increasing V_{S30} values, assuming that PA_{rock} is constant.

Table 4 Resulting amplification factors for increasing V_{S30} values

V_{S30} (m/s)	F_a	F_v
150	2.737	3.405
250	2.135	2.399
350	1.813	1.905
450	1.605	1.603
550	1.456	1.397

As seen in Table 4, the values of F_a and F_v decrease as V_{S30} increases. This shows that softer soils cause stronger amplification compared to stiff soils. It can also be observed that considering the amplification factors at the highest and lowest V_{S30}, the value of F_a is 1.88 times smaller, while the value of F_v is 2.43 times smaller. This shows that V_{S30} dependency is stronger for mid-period amplification since the rate of change is greater.

On the other hand, Table 5 shows the values of F_a and F_v for increasing PA_{rock} values, assuming that V_{S30} is constant. As observed, Fa and F_v decrease as PA_{rock} increases. This is due to the nonlinearity of soil behavior [20]. When the ground accelerations are high, the soil response is governed by its high damping ratio, which results in low amplification in the soils. This shows that amplification is greater for earthquakes with low magnitudes at farther distances. Similar to Table 4, Table 5 shows that the mid-period amplification is greater than the short-period amplification.

Table 5 Resulting amplification factors for increasing PA_{rock} values

PA_{rock} (g)	F_a	F_v
0.25	1.813	1.905
0.35	1.627	1.873
0.45	1.445	1.845
0.55	1.269	1.819
0.65	1.104	1.797

Comparing the amplification factors at the highest and lowest PA_{rock} values, it can be seen that F_a became 1.65 times smaller and F_v became 1.06 times smaller. This shows that short-period amplification is more dependent on the change in the PA_{rock} values. After incorporating the amplification factors into the PSHA, the amplified PGAs are computed and mapped.

Shown in Fig. 3 are the maps of amplified PGAs in Metro Manila considering the short-period amplification. Unlike the 10% POE in Fig. 1 where the contour is uniform, the contour in 10% POE in Fig. 3 is more random, with the highest accelerations at the west and east side of the region. Comparing the maps on 2% POE of Fig 1 and Fig 3, it is observed that the areas with the highest PGAs are also the areas with the lowest V_{S30}. This shows that areas with softer soils experience greater amplification. In the 2% POE of Fig 3, it is observed that the contour of the map is more similar to the contour of the non-amplified map in Fig. 1 of the same POE, where the accelerations are higher at the center, and gradually decrease as they move away.

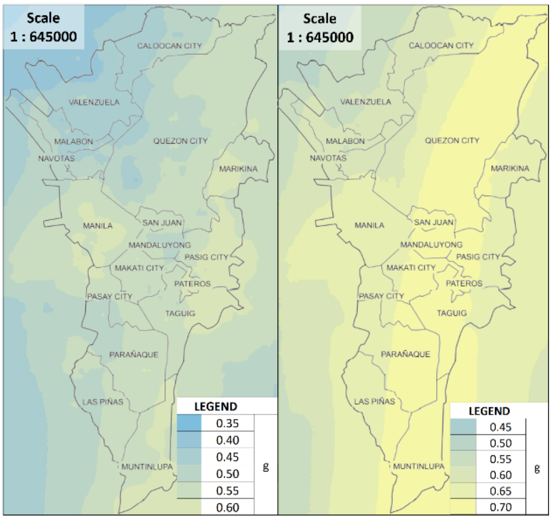

Fig. 3 Map of amplified PGAs in Metro Manila considering short-period amplification for 10% POE (left) and 2% POE (right)

The differences in the contour between the two maps in Fig 3 shows how short-period amplification is more influenced by PA_{rock} as compared to V_{S30} values. Even though some areas are shown to achieve higher PGAs due to the low V_{S30} values, the contour of the map still gradually resembles the contour of the non-amplified ones as the ground motion intensities increase and the POE decreases.

Shown in Fig. 4 are the maps of amplified PGAs in Metro Manila considering mid-period amplification. Unlike the observations in the short-period amplification where the contour tends to resemble the non-amplified maps as the POE decreases, the shape of the contour for the mid-period amplification remains the same, with only the values of the PGA increasing. The maps in Fig. 4 show that the western and eastern parts of the region have the highest GPAs. The main difference observed between the short-period and mid-period amplification is that, for the latter, the areas with the highest PGAs for 10% POE are still the same areas with the highest PGAs for 2% POE. This further shows that mid-period amplification is more dependent on V_{S30} which is constant in a certain area, regardless of the POE considered. A summary of the PGA amplifications is given in Table 6.

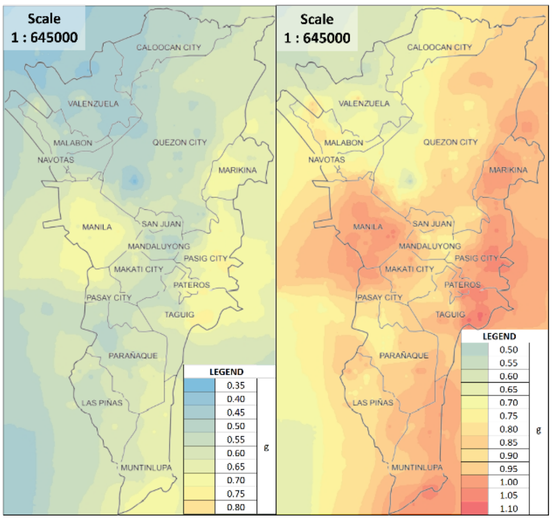

Fig. 4 Map of amplified PGAs in Metro Manila considering mid-period amplification for 10% POE (left) and 2% POE (right)

Table 6 Average of amplified PGA values in Metro Manila

Amplification	PGA (g)	
	10% POE	2% POE
Short-period	0.538	0.659
Mid-period	0.589	0.830

Table 6 summarizes the average PGA in Metro Manila for 10% and 2% POE considering short-period and mid-period amplification. As seen in the table, the average amplified PGAs can range from

0.538 g to 0.830 g depending on the probability of exceedance and period of amplification.

5. CONCLUSION

Due to the susceptibility of Metro Manila to seismic hazards, it is necessary to consider the possible factors, such as local soil conditions, which could intensify the damages from these hazards.

Without considering site amplification, it was observed that the center of Metro Manila has the highest PArock values, which gradually decrease as they move away from the center. On the other hand, the V_{S30} map shows that the eastern and western parts of Metro Manila exhibit low V_{S30} values due to being near a body of water and the presence of quarterly alluvial soils. The central part exhibited the highest V_{S30} values due to the presence of tuff and rock formations in the area.

After obtaining and mapping the amplified PGAs, it was seen that short-period amplification has a stronger dependency on PA_{rock}, while mid-period amplification is more dependent on V_{S30}. For short-period amplification, Metro Manila has an average PGA of 0.538 g and 0.659 g for 10% and 2% POE, respectively. Meanwhile, for mid-period amplification, the region has an average PGA of 0.589 g and 0.830 g for 10% and 2% POE, respectively.

For future studies, it is recommended to explore more methods in performing PSHA such as the use of logic trees, and more GMPEs. It would also be beneficial to use more than one correlation equation for obtaining the V_{S30} to improve the performance of these values.

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