Probabilistic Seismic Hazard Assessment for Central Manila in Philippines

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Abstract

A probabilistic seismic hazard assessment has been carried out for the central Manila in Philippines. A review of the geological and tectonic setting and earthquake catalogue with 500km surrounding the central Manila is performed in this paper. The dominant seismic source contributing to the hazard within the study is the Marikina Valley Fault System. Other known active seismic sources affecting the study area include the Manila Trench plate interface to the west, the East Luzon Trough plate interface to the north-east, and the Philippine Fault Zone to the east. Other seismogenic structures include the Lubang Fault and Mindoro-Aglubang Fault. The attenuation relationships are selected from the recent developed Next Generation Attenuation Relationships for shallow crustal earthquakes and the well developed subduction attenuation relationships.

The calculated bedrock horizontal peak ground acceleration (PGA) and response spectra for 50%, 10% and 2% chance of being exceeded in the next 50 years (equivalent to 72, 475 and 2,475 years return period) of the study area will be presented. The result response spectrum of 475 years return period will be compared with the recommended design response spectrum in National Structural Code of the Philippines, NSCP (2001).

Keywords: seismic, Manila, design, acceleration, response, spectrum

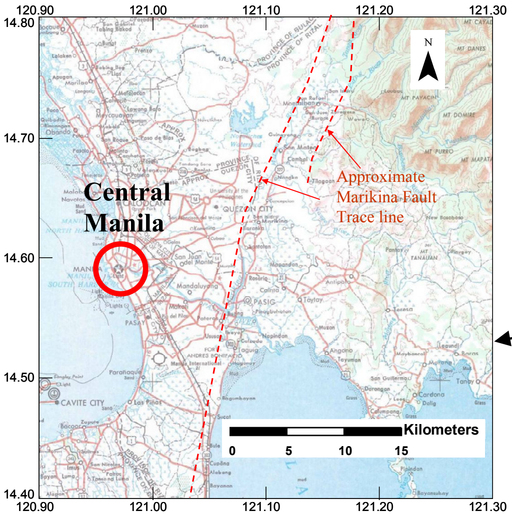
1 INTRODUCTION

Philippines is located in an area of high seismicity. The current seismic National Structural Code of the Philippines, NSCP (2001) is originated from the Uniform Building Code developed for California in the United States.

This paper presents a study of probabilistic seismic hazard assessment for the central and Manila in Philippines and the results are compared with the NSCP (2001).

2 REGIONAL TECTONICS AND GEOLOGY OF HONG KONG

A review of the geological and tectonic setting for 500km surrounding the study area was performed in this report and the probabilistic hazard assessment was based upon these geological interpretations. The location of central Manila is shown in Figure 1.



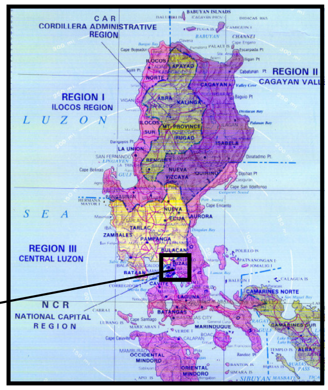


Fig. 1 Central Manila, Philippines

(Base map extract from NAMRIA Map Sheet 1:250000 PCGS2511)

The dominant seismic source contributing to the hazard within the study are the West Marikina and East Marikina Fault of the Marikina Valley Fault System (see Figure 2). Other known active seismic sources affecting the study area include the Manila Trench plate interface to the west, the East Luzon Trough plate interface to the northeast, and the Philippine Fault Zone to the east. Other seismogenic structures include the Lubang Fault and Mindoro-Aglubang Fault (see Figure 3).

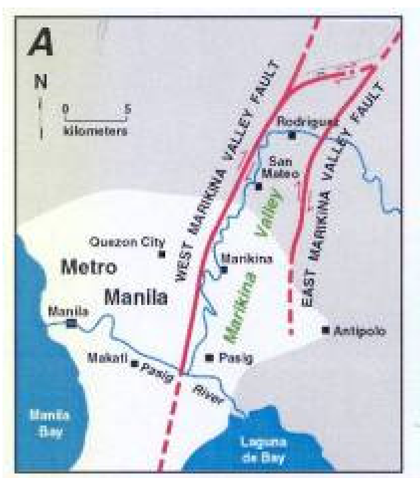


Fig. 2 The Marikina Valley Fault System

(From Nelson and others, 1995)

Fig. 3 Map of Active Faults and Trenches in Luzon

(Extract from PHIVOLCS, 2000)

3 SEISMIC HAZARD ASSESSMENT

3.1 *Seismic Hazard Assessment Methodology*

The probabilistic seismic hazard assessment (PSHA) methodology, e.g. Cornell (1968), McGuire (1993), has been applied using Oasys SISMIC, the in-house PSHA program of Arup. The PSHA methodology used the following steps:

i. Potential seismic sources were defined on the basis of regional geology and seismicity.
ii. Seismicity parameters defining the rate of earthquake activity were derived for each of the potential seismic sources.
iii. Ground motion attenuation relationships, considered to be appropriate for the region, have been defined.
iv. The annual frequencies of various levels of specified ground motion levels being exceeded have been derived by first determining the likelihood that each ground motion will be exceeded if an earthquake of a certain magnitude at a certain distance occurs. By multiplying this likelihood with the annual frequency of such an event occurring in any of the source zones, the annual frequency of the ground motion occurring is derived. By summing the results from all relevant earthquake distances and magnitudes the overall annual frequency is established.

3.2 *Earthquake Catalogue*

Due to active motion of the plates on both sides of the Philippine archipelago numerous earthquakes are generated, making the Philippines an area of marked seismic hazard. Numerous and often large earthquakes have been recorded in the country in the past history. Earthquake data instrumentally and macroseismically measured have been obtained from PHIVOLCS. Instrumental earthquake data for the study area were obtained from PHIVOLCS. The data comprised earthquakes since 1907 greater than magnitude 4.0 within the study area bounded by Latitudes 10°N and 20°N and the Longitudes 116°E and 126°E. This study area has been defined for encompasses of the events which can affect the hazard level at the Central and northern Manila Area (Figure 4).

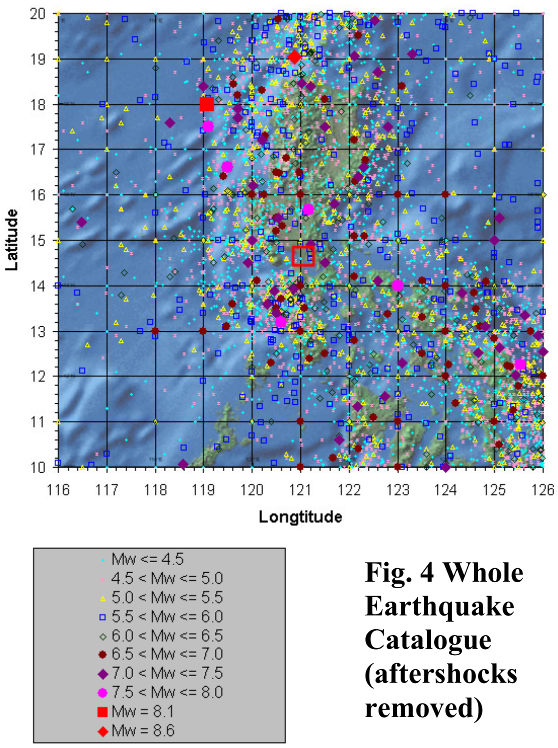


Fig. 4 Whole Earthquake Catalogue (aftershocks removed)

In order to ensure the PHIVOLCS earthquake data is complete, other worldwide earthquake catalogue for events from 1964 to 2008 have been compiled from the IRIS database. The IRIS database includes several catalogues, such as the International Seismological Centre (ISC) and the National Earthquake Information Centre (NEIC). The IRIS Preferred catalogue uses the list of events considered to be the most accurate for that time period. In cases of conflicting information from the different sources, the entries from the more complete and reliable catalogue has been retained. Aftershocks are earthquake events which are usually connected with a parent event which is often large, whilst foreshocks precede such events. This method has been adopted to remove the aftershocks in this study. It is important to carry out such de-clustering of earthquakes to avoid the over-estimation of the recurrence rate of earthquakes, especially the large magnitude earthquake which can associate with hundreds of aftershocks.

3.3 *Catalogue Completeness*

The statistical completeness of the catalogue has been assessed. Figure 5 shows the magnitude recurrence relationship for earthquakes in the whole study area in the conventional form proposed by Gutenberg and Richter (1956) as follow:

$$\mathrm{Log}_{10}\, N = a - bM$$

where N is the annual number of earthquakes greater than magnitude M and a and b are parameters for annual number of earthquakes.

In this form, the annual number (expressed as a log to the base 10) of earthquakes greater than magnitude M is plotted as a function of that magnitude. If a data set is complete the annual number of earthquakes greater than each magnitude will be similar for a range of time periods (assuming there are no temporal trends in the level of seismicity). Figure 5 shows that the annual number of earthquakes from 1907 to 2008 contains fewer earthquakes below magnitude 7.0 than the data between 1964 and 2008. Although it appears the there is considerably scatter above magnitude 7.5, the historical published records suggested that they are complete above magnitude 7.5, since the data between 1907 and 2008 and the data between 1964 and 2008 become converged. A complete set of data includes records for all the events that occurred above a certain magnitude over a considered time period. The following data sets have been considered as complete for the corrected earthquake catalogue:

1907 – 2008: $M_W \geq 7.5$
1964 – 2008: $M_W \geq 5.0$
1993 – 2008: $M_W \geq 4.5$

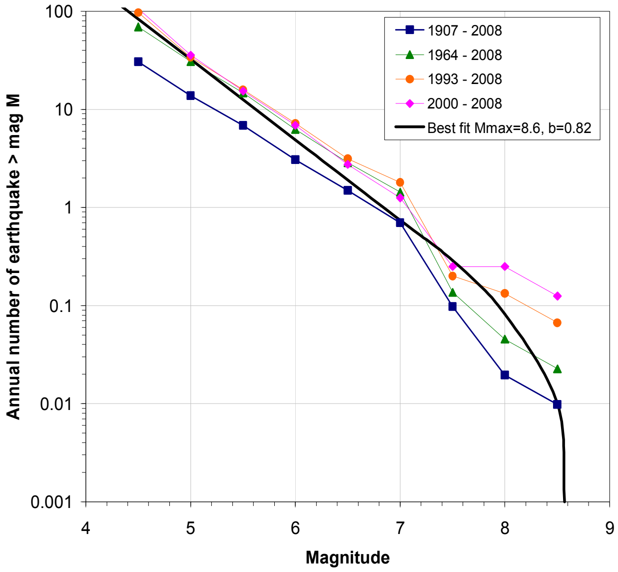


Fig. 5 Magnitude Recurrence Plot for the Whole Study Area

3.4 *Seismic Source Model*

Seismic sources identified and characterised for the evaluation of earthquake hazard include crustal sources including faults and crustal areal source zones and subduction zone sources. The characterisation of seismic sources is based on the tectonic setting and the spatial distribution of observed seismicity presented in Sections 2 and 3.2, respectively.

The known active structures in the vicinity of the site selection area include the subduction zones (Manila Trench, Philippine Trench, and East Luzon Trench), faults (Philippine fault, and the Marikina Valley Fault), and areal source zones capturing the crustal seismicity not attributed to faults. For example the Lubang Faults and Mindoro-Aglubang Fault to the southwest are more distant from the site and their seismic activity can be considered generally as areal sources of diffused seismicity.
Six source models have been defined in this study as follow:

- **Source Model 1 – Shallow Crust (Focal Depth ≤ 50km)**

A total of 14 shallow source zones have been defined in according to their distribution of seismicity and regional geological and tectonic setting as described in Sections 2 and 3.2. These areal source zones represent parts of the region that can be characterised as having similar tectonic and seismological characteristics. The source zone map for source model 1 is presented in Figure 6.

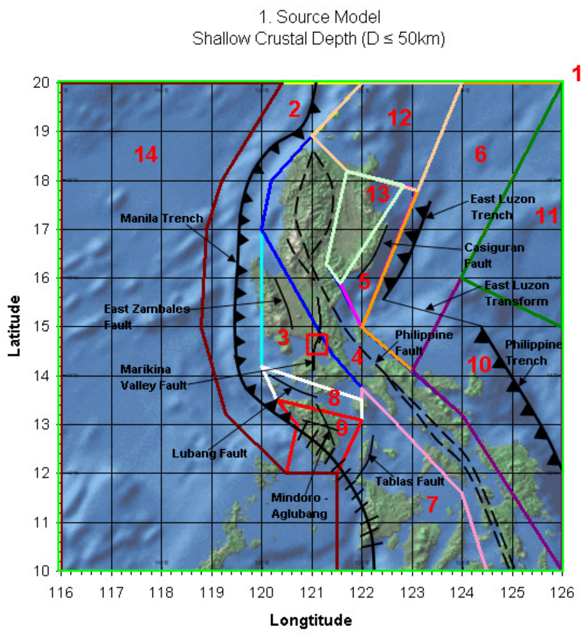


Fig. 6 Source Model 1 – Shallow Crust (Focal Depth ≤ 50km)

- **Source Model 2 and Model 3 – Intra-slab (Mid Crust and Deep Crust)**

Offshore to the west of Luzon is the Manila Trench, a deep ocean trough that represents the surface expression of the eastward-dipping subduction zone (Figure 3). The east-ward dipping Eurasian Plate extends to a depth of about 200km below southern Luzon (Hayes and Lewis, 1984). The closest approach of the Manila trench to the study area is about 200 km along the section of the trench with the highest seismicity. On the eastern side of the Philippine island arc, the Philippine Sea Plate is subducted westward under the Eurasian Plate/Philippine Islands Plate. Subduction occurs both south of Luzon along the Philippine Trench and near northern Luzon along the East Luzon Trough. The upper 50km of the Manila trench, East Luzon Trench and Philippine Trench sub-duction has diffuse seismicity and is thus represented as an area source in the shallow crustal seismicity Source Model 1.

The middle (50km – 100km) and lower (100km – 300km) sections of the subduction zones have been model as diffuse area sources represented as a series of intra-slab fault surfaces which generally strike north-south direction and a dip angle increasing with depth. In this way the intra-slab zones of the subduction plates can be directly repre-sented by a fault with an estimated activity rate based on associated areas of seismicity represented in Figures 7 and 8. However, the middle section of East Luzon Trench and middle and lower sections of Philippine Trench are modelled as area sources for sim-plicity and they are more distance from the concession area.

- **Source Model 4 and Model 5 – Interface (Manila Trench Plate and East Luzon Trench Plate)**

In subduction zones, the plate interface is typically the locus of plate boundary coseis-mic deformation and is the location of the largest earthquakes observed worldwide. Apart from the shallow crust earthquakes, large thrust-fault earthquake are inferred to occur at the locked interface between the subducting plate and the over-riding plate. In the PSHA model, it is reasonable to model the large earthquake events above $M_w > 7.5$ by a fault model with minimum recorded earthquakes of about 7.0. The association of a Quaternary volcanic arc on Luzon Island, moderate to high levels of seismicity extending to depths of more than 200 kilometres, and the observed deformation in the young sediments in the Luzon Trough are all considered to be the results of active subduction at the Manila Trench (Hamburger et al, 1983). The slip rate on the Manila Trench based on historical seismicity is estimated to be 30-65 mm/year (Acharya, 1980 and Rantucci, 1994); however the slip of the fault may also be taken up by creep or aseismic movement. Based on the seismic activity rate and data from subduction zones worldwide, a more realistic estimate of the slip rate may be 10 to 25 mm/year. A weighting method is used to define different slip rates of 5mm/year (15%), 10mm/year (35%) and 25 (50%) for Manila Trench Interface.

Subduction in the East Luzon Trough is offset from the Philippine Trench along an east-west trending transform fault at 15.0 ^{0}N latitude. This transform defines the southernmost extent of the subducted Philippine Sea Plate to the northeast of Manila. The slip rate on the East Luzon Trench based on historical seismicity is estimated to be 70 to 85 mm/year (Barrier et al., 1991). However, based on the seismic activity rate and worldwide data, a more realistic estimate of the slip rate may be 10 to 35 mm/year. This is consistent with the low rate of large earthquakes from 1907 as shown on Figure 5. A weighting method is used to define different slip rates of 10mm/year (25%), 20mm/year (50%) and 35 (25%) for East Luzon Trench Interface.

Based on the characterisation of potential maximum rupture dimensions and the seismicity data, the maximum magnitude of interface earthquakes are estimated to be in the range of M_w 7.5 to M_w 9.0. Based on the worldwide data, the maximum depth of the seismogenic portion of the plate interface typically is about 20km, although the maximum depth may reach 50 km. In the PSHA model, the associated seismic activity of earthquakes of less than M_w 7.5 from the fault model shall be subtracted to avoid double counting of the seismicity of the shallow crustal earthquakes.

- **Source Model 6 – Marikina Valley Fault System (MVFS)**

The MVFS has a length of about 150 km and has been modelled as a vertical strike slip fault seismic source (Figure 2). Recent paleoseismic studies on the MVFS document multiple ruptures on independent segments of both the West Marikina Valley Fault (WMVF) and the East Marikina Valley Fault (EMVF). The WMVF and EMVF, both accommodate slip from the oblique convergence of the tectonic plate convergence and are Paleoseismological trenching study by PHIVOLCS (1997) and Nelson et al., (2000) assess the potential recent activity of the Marikina fault. Nelson et al. (2000) states that each of 3 to 4 earthquake events logged in the trench would have had a 1 to 2m horizontal rupture offset over the past 1200 to 1400 years. The studies also provide geomorphological evidence of offset alluvial fans and streams. Considering the findings of these studies a series of possible slip rates can be computed (Table 1) and a distribution of probabilities assigned to those rates can be made. In this PSHA model, a weighting method is used to define different slip rates of 1mm/year (10%), 2mm/year (30%), 3mm/year (40%), 4mm/year (10%) and 10mm/year (10%) for Marikina Fault. To avoid double counting in the source model, the seismic activity of the MVFS is subtracted from the shallow earthquakes in the areal source.

Combinations have a specified weighting. This is usually set to one but can be set to a lower value. The weighting represents the likelihood that the Combination exists. It is postulated that a fault system near the site they can be included in a Combination with a suitable weighting. The results of each Combination are added to the results of the other Combinations to give the total overall seismic hazard expressed in terms of the annual rate at which the specified hazard value is exceeded.

Table 1: Summary of Potential Slip Rates of Marikina Fault calculated from observed Paleoseismic features.

Feature	Sites	Displacement (m)	Time (yrs)	Slip (mm/yr)
Trench Offsets - min event, min displacement	3	1	1400	**2**
Trench Offsets - min events, max displacement	3	2	1400	**4**
Trench Offsets - max	4	1	1400	**3**
Trench Offsets - max displacement	4	2	1400	**6**
Offset Stream (unknown # events) - Holocene	1	200	10000	**20**
Offset Stream (unknown # events) - 100,000	1	200	100000	**2**
Offset Stream (unknown # events) - Quaternary	1	200	1800000	**0.1**
Offset Alluvial Fan (unknown # events) - Holocene	1	35	10000	**4**

- **Source Model 7 – Philippine Fault**

The dominate structural feature on Luzon Island is the Philippine Fault Zone (PFZ), a major active strike slip fault that has many geomorphic features characteristic of active faults, including closed depressions along fault scarps, offset streams, and sag ponds (Allen, 1962). The Philippine fault near Luzon Island has ruptured in at least two, and probably three large earthquakes ($M_s > 7.0$) during the past 60 years, including the M_s 7.8 July 1990 earthquake. This brief historical record indicates that rupture length and maximum displacements may typically exceed 75 kilometres and 3 meters, respectively, for individual earthquakes. The slip rate on the Philippine fault based on historical seismicity is estimated to be 68 mm/year (Acharya, 1980). Based on the 6.2 meters of measured displacement in the July 1990 earthquake, a more realistic estimate of the slip rate may be 15 to 30 mm/year (Newhall et al., 1990).

In this PSHA model, a weighting method is used to define different slip rates of 10mm/year (40%), 19mm/year (55%) and 26mm/year (5%) for Philippine Fault. Earthquakes with magnitudes as large as M 7.8 have been attributed to the Philippine fault (Acharya, 1980). A linear fault model is assumed in the PSHA model and a maximum M_w 8.0 is used to limit the fault rupture which is believed to be reasonable. It is important to subtract the seismic activity of shallow earthquakes to avoid double counting of the seismicity.

3.5 *Seismic Source Parameters*

For this study an overall activity was calculated for the entire earthquake database area taking into account completeness and using the methodology proposed by Weichert (1980). This method gave a b value of 0.82 and an activity of about 30 earthquakes per year having a magnitude greater than 5, as shown in Figure 5. In the calculation an individual mean "b" value has been used for each seismic zones and summarised in Table 2. A weight factor has been adopted for a range of "b" value between 0.6 and 1.0 for each seismic zones. Table 3 shows the mean activities "a" derived for each seismic source zone per annual for simplicity. It is considered some of the b values are quite low which may be caused by the incomplete earthquake catalogue at particular zones, however, a higher b-value is adopted as a more reasonable estimate.

A minimum magnitude of 5.0M_W has been assigned for the seismic hazard assessment. This is because the likelihood of an earthquake of smaller magnitude causing damage to engineered structures can be discounted. In areas of high seismicity, such as the Philippines, there is a maximum magnitude event of 8.6 M_w has occurred during the historical catalogue. Alternatively, Kanamori (1997) suggested an empirical relationship to estimate the maximum credible earthquakes from subduction sources, based on the size of the potential source area. Furthermore, Wells and Coppersmith (1995) have derived an empirical relationship which relates surface rupture length to earthquake magnitude for continental earthquakes. The maximum credible earthquake magnitude is summarised in Table 4.

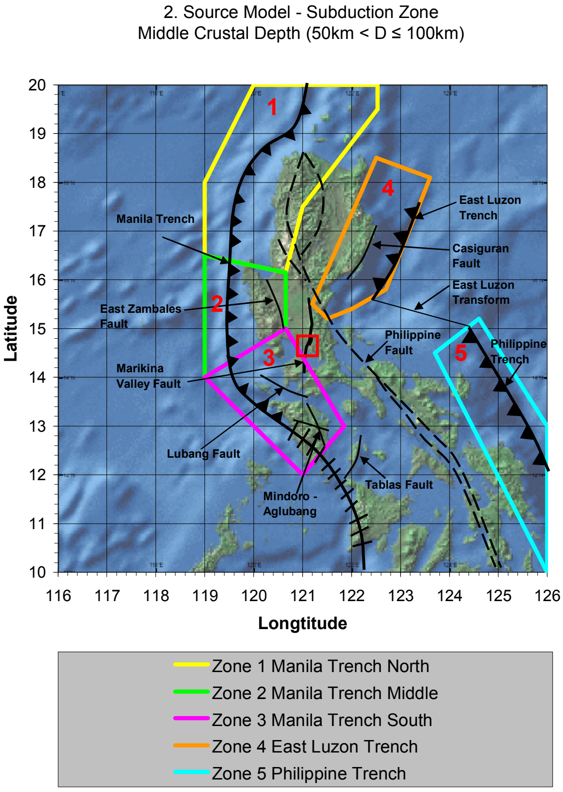


Fig. 7 Source Model 2 – Intra-slab (Mid Crust)

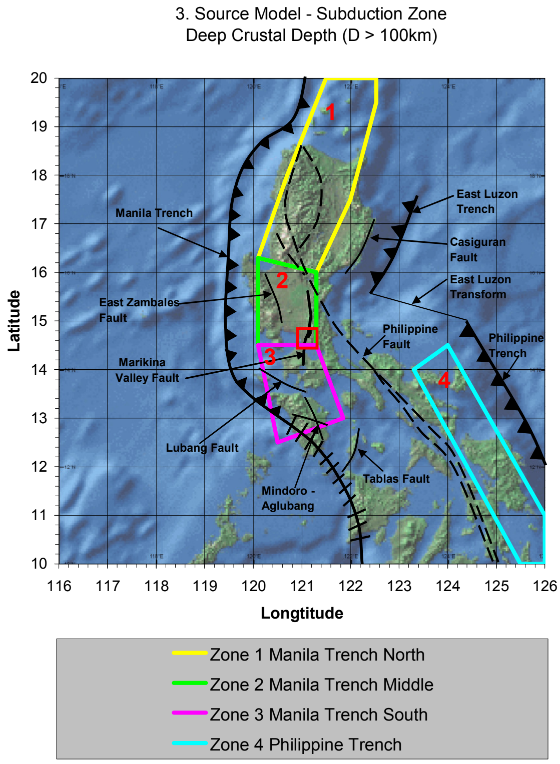


Fig. 8 Source Model 3 – Intra-slab (Deep Crust)

Table 2 : b value for Each Seismic Zones

Source Model	Zone	Area Name	Best Estimated b – value Weichert (1980)	Assumed b - value	
				Mean (60%)	s.d. (40%)
Whole (all depth)	1	Whole	0.82	-	-
Shallow Crust ($D \leq 50$ km)	2	Manila Trench	0.83	0.80	± 0.05
	3	Manila Block	0.69	0.70	± 0.1
	4	Philippine Fault Zone	0.76	0.75	± 0.05
	5	Casiguran Fault	0.75	0.70	± 0.1
	6	East Luzon Trench	0.73	0.75	± 0.05
	7	Panay	0.88	0.85	± 0.05
	8	Lubang Fault	0.56	0.70	± 0.1
	9	Mindoro	0.71	0.70	± 0.1
	10	Philippine Trench	0.70	0.70	± 0.1
	11	Philippine Offshore East	0.55	0.70	± 0.1
	12	Philippine Offshore North	0.82	0.80	± 0.05
	13	Northeastern Philippines	0.92	0.70	± 0.1
	14	Philippine Offshore West	0.68	0.70	± 0.1

Source Model	Zone	Area Name	Best Estimated b – value Weichert (1980)	Assumed b - value	
				Mean (60%)	s.d. (40%)
Med Crust (50 km < D ≤ 100 km)	1	Manila Trench (north portion)	1.11	0.90	± 0.1
	2	Manila Trench (central portion)	1.1	0.90	± 0.1
	3	Manila Trench (south portion)	0.71	0.70	± 0.1
	4	East Luzon Trench	0.92	0.90	± 0.1
	5	Philippine Trench	0.91	0.90	± 0.1
Deep Crust (D > 100 km)	1	Manila Trench (north portion)	0.75	0.75	± 0.05
	2	Manila Trench (central portion)	0.94	0.70	± 0.1
	3	Manila Trench (south portion)	0.87	0.90	± 0.1
	4	Philippine Trench	1.45	0.90	± 0.1

Table 3 : Magnitude - Recurrence Data

Source Model	Zone	Area Name	Area (km^2)	Mean Activity, a_{mean}
Whole (all depth)	1	Whole	1,184,528	5.61
Shallow Crust (D ≤ 50 km)	2	Manila Trench	103,143	4.80
	3	Manila Block	33,144	3.24 (3.40)
	4	Philippine Fault Zone	125,405	4.38
	5	Casiguran Fault	16,697	3.59
	6	East Luzon Trench	108,416	3.74
	7	Panay	84,752	4.52
	8	Lubang Fault	11,231	4.34 (3.30)
	9	Mindoro	18,481	3.27
	10	Philippine Trench	109,953	4.11
	11	Philippine Offshore East	59,896	2.15 (3.00)
	12	Philippine Offshore North	49,695	4.23
	13	Northeastern Philippines	19,548	4.17
	14	Philippine Offshore West	444,167	3.84
Med Crust (50 km < D ≤ 100 km)	1	Manila Trench (north portion)	99,206	5.52 (4.50)
	2	Manila Trench (central portion)	36,283	5.25 (4.30)
	3	Manila Trench (south portion)	49,170	3.41
	4	East Luzon Trench	44,908	4.15 (3.90)
	5	Philippine Trench	58,798	4.56
Deep Crust (D > 100 km)	1	Manila Trench (north portion)	60,844	3.15
	2	Manila Trench (central portion)	23,653	4.18 (2.98)
	3	Manila Trench (south portion)	28,347	4.48 (4.70)
	4	Philippine Trench	48,907	6.86 (4.00)

Table 4: Maximum Credible Earthquake Magnitude

Source	Maximum Credible Earthquake (M_w)
Plate Interface	
Manila Trench Interface (north)	8.5
Manila Trench Interface (central)	8.7
Manila Trench Interface (south)	8.0
East Luzon Trough Interface	8.4
Intra-slab	
Manila Trench Intra-slab	8.0 ± 0.5
East Luzon Trough Intra-slab	8.0 ± 0.5

Source	Maximum Credible Earthquake (M_w)
Shallow Crust	
Manila Trench	8.0 ± 0.5
Manila Block	7.5 ± 0.5
Philippine Fault Zone	8.0 ± 0.5
Casiguran Fault	8.0 ± 0.5
East Luzon Trench	8.0 ± 0.5
Panay	7.5 ± 0.5
Lubang Fault	8.0 ± 0.5
Mindoro	8.0 ± 0.5
Philippine Trench	8.0 ± 0.5
Philippine Offshore East	7.5 ± 0.5
Philippine Offshore North	7.5 ± 0.5
Northeastern Philippines	7.5 ± 0.5
Philippine Offshore West	7.5 ± 0.5
West Marikina Fault	7.7
East Marikina Fault	6.75

The focal depth is the depth from ground level to the hypocentre of an earthquake. The majority of earthquakes in the study area were found to occur within 50km of the ground surface, except for those associated with subduction processes. Based on the earthquake data collated in the catalogues (for magnitude M_W 4.5 since 1964) the focal depth ranges for each zone in the source model have been assigned the certain weight factors as presented in Table 5.

Table 5: Focal Depth Distribution

Areas	Depth in km and (Weight in %)				
Area sources and Manila / East Luzon Trench ≤50km	5 (25)	15 (20)	25 (20)	35 (20)	45 (15)
Manila / East Luzon Trench 50-100km	60 (55)	75 (30)	90 (15)	-	-
Manila / East Luzon Trench >100km	125 (55)	175 (30)	250 (15)	-	-
Marikina Valley Fault	10 (35)	15 (45)	15 (15)	15 (5)	-
Philippine Fault	10 (35)	15 (45)	15 (15)	15 (5)	-

3.6 *Attenuation Relationships*

Attenuation relationships for horizontal ground motions at a range of spectral periods have been used in this study. The following relationships have been selected: Boore and Atkinson (2007); Campbell and Bozorgnia (2007), Atkinson and Boore (2003) and Youngs et al., (1997). The first two are the recent developed next generation of attenuation (NGA) relationships derived in Western North America for shallow crustal faulting whilst the last two represents data for earthquakes generated in subduction zones for both interface and intra-slab earthquake events. The former two relationships have been used with equal weights to model the shallow crustal faulting. For intra-slab events, an equal weighting is used for both Atkinson and Boore (2003) and Youngs et al., (1997) but for interface events only Atkinson and Boore (2003) is used for simplicity. The bedrock condition with shear wave velocity greater than 760m/s is used in this study. It is noted that Youngs et al., (1997) often gives high values of ground motion for distant events, however, this should not be a problem with the level of seismic activity in Luzon.

3.7 *Logic Tree*

A logic tree has been developed for this and it shows the various values and weights given to parameters to capture the influence of epistemic uncertainty. These are discussed below.

- Allowance for variation in the b-value and maximum magnitude M has been incorporated in the seismic model by assigning weights of 60% to the pair of mean values of b and M and 20% to the pair of mean ± SD (Standard Deviation) b and M values, respectively as given in Table 2 and Table 4 for Arup zonation.
- For modelling simplicity all zones have been assigned activity rates equal to the mean value given in Table 3 for Arup zonation model, except some zones have extremely low and high b-value. In this circumstance, an adjusted activity rate is assigned to this zone to match the earthquake magnitude 5-6 in the complete earthquake catalogue since 1964.
- Equal weights were assigned to the Boore and Atkinson (2007) and Campbell and Bozorgnia (2007) attenuation relationships for shallow source zones and equal weight to Youngs et al. (1997) and Atkinson and Boore (2003) for the intra-slab subduction zones. Atkinson and Boore (2003) is only used for the interface events for simplicity.
- The depth distributions are formally treated as logic tree branches in the hazard calculations, however they represent aleatory variability, rather than epistemic uncertainty.

3.8 *Seismic Hazard Assessment Results*

The calculations to determine the seismic ground motions at 72, 475, 2475 years return period were carried out using the *Oasys* SISMIC program. The calculated hazard levels for central Manila, in terms of horizontal response spectral acceleration (for 5% damping) on rock, at three probabilities of 50%, 10% and 2% being exceeded in the next 50 years, are shown in Fig. 9. The attenuation models are based on the latest NGA models developed for the Western North America (WNA) with high seismicity. It is noted that the NGA models can give 30% lower spectral accelerations than the previous attenuation models developed for WNA. However, it is considered that the latest NGA models are the most up-to-date and appropriate attenuation relationships to represent the shallow active crust conditions, especially for high period structures.

The NSCP seismic code defines the seismic zone factor for the study area to be 0.40g and it also states that the Marikina Fault is classified as Seismic Source Type A which is capable of producing large magnitude events and that have a high rate of seismic activity. A near-source factor of 1.20 shall be adopted when the active fault (Type A) distance is less than or equal to 5km which increases the seismic hazard to be 0.48g. The design PGA is similar to the PGA obtained from this study. However, the second corner period of the NSCP design spectrum appears to be conservative for rock site.

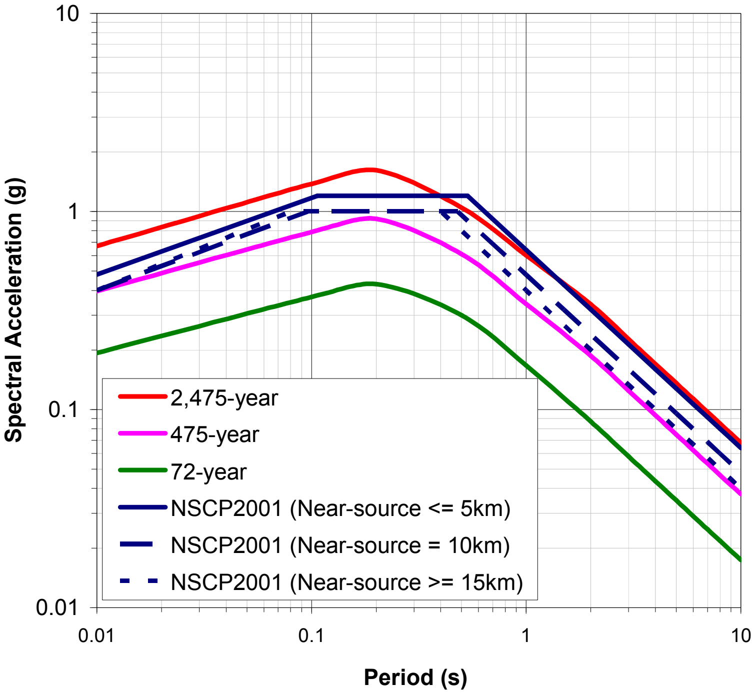


Fig. 9 Uniform Hazard Response Spectra for bedrock horizontal motion

6 CONCLUSIONS

A probabilistic seismic hazard assessment has been carried out for the Central Manila, Philippines. The principle conclusions resulting from this study are follows:

- The main tectonic features affecting the seismic hazard are the Marikina Valley Fault system, Philippine Fault and the Manila Trench; formed by subduction of the Eurasian Plate under the Philippine Island arc.
- An earthquake catalogue has been developed based on data from PHIVOLCS and IRIS for the period between 1907 and 2008. After-shocks have been removed from the catalogue; the magnitudes have been converted to moment magnitude based on the available published equations (EPRI, 1994; Heaton et al., 1986) and the completeness of the catalogue assessed. It was shown that the observed seismicity closely resembles the geological and tectonic structures.
- A minimum magnitude of M_W 5.0 has been assigned for the seismic hazard assessment. This is because the likelihood of an earthquake of smaller magnitude causing damage to engineered structures can be discounted.
- The maximum magnitude, M_{max} of the earthquake for active faults is assessed based on their possible rupture length. The hazard calculations for Central Manila as would be expected to be dominated by the Marikina Fault System.
- The attenuation relationships are selected from the recent developed Next Generation Attenuation Relationships for shallow crustal earthquakes and the appropriate subduction attenuation relationships. The probabilistic assessment is based on various values and weights given to parameters to capture the influence of epistemic uncertainty by way of a logic tree method.
- The calculated peak ground acceleration (PGA) with a 475 year return period (10% chance of being exceeded in 50 years) of Central Manila is about 0.4g which agreed well with the design PGA between 0.40g and 0.48g recommended in the National Structural Code of the Philippines, NSCP (2001) with the near-source factor.

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