17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

PROBABILISTIC SEISMIC HAZARD ANALYSIS OF THE PHILIPPINES

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Abstract

The Philippines archipelago is seismically active. Most of it is predominantly influenced by convergence between the Eurasian Plate and Philippine Sea Pate, whilst the southern end of the Philippines is also affected by the Molucca Sea Collision Complex. The oblique convergence appears to be primarily accommodated by convergent zones surrounding the archipelago, along Manila-Negros-Sulu-Cotabato Trench system in the west, whereas the west dipping East Luzon Trough-Philippine Trench system accommodates the subduction of the Philippines Sea Pate in the east. Massive crustal deformation is undergoing due to the plate convergence and has created numerous active faults across the country such as the Philippine Fault Zone. Damaging earthquakes regularly occur in the Philippines.

A probabilistic seismic hazard analysis (PSHA) has been carried out for the entire Philippines. The PSHA models the active seismotectonic setting through characterisation of background seismicity and active fault sources. Major active sources include the subduction zones are modelled out to 500km from the Philippines. The ground motion prediction equations (GMPE's) from PEER's Next Generation Attenuation (NGA) West-2 project have been adopted for shallow tectonic sources, while BC Hydro was used for the subduction zones.

The results of the PSHA are compared at selected locations with published seismic hazard zoning mapping for the Philippines, which include the Philippine Earthquake Model (PEM), the zoning map in the National Structural Code of the Philippines (NSCP), the ground motion maps presented in DPWH Guide Specifications – LRFD Bridge Seismic Design Specifications 2013 (BSDS) and the Global Earthquake Model (GEM). The comparisons suggest that the PSHA results from this study are generally comparable to GEM and PEM for 500-year return period. For 1000-year return period, the PSHA results are generally comparable to BSDS and PEM in the northern Philippines while the BSDS and PEM are lower than the PSHA in the central and southern Philippines.

The de-aggregation plots for the central and southern Philippines suggest that a significant contribution to the PGA and 1s spectral acceleration comes from the subduction interface of the Philippine and/or the subducted Molucca Sea Plate. It is inferred that the discrepancy of the PSHA with the published model is due to associating the subduction zones with different GMPE's which was done in the PSHA. This is further investigated in the paper.

Keywords: Seismic hazard; Philippines; Probabilistic Seismic Hazard Analysis

1. Introduction

The Philippines is located in an area of high seismicity and structures within the built environment are designed accordingly. The current seismic National Structural Code of the Philippines (NSCP) [1] originated from the Uniform Building Code developed for California in the United States. In addition to the NSCP, seismic hazard or seismic spectral acceleration maps have also recently been published in DPWH Guide Specifications – LRFD Bridge Seismic Design Specifications 2013 (BSDS) [2] by DPWH and the Philippine Earthquake Model (PEM) by PHIVOLCS [3]. The Global Earthquake Model (GEM) [4], which was created by collating maps computed using national and regional probabilistic seismic hazard models developed by various institutions and projects including PHIVOLCS, also presents the seismic hazard of the Philippines.

In the NSCP, the Philippines is broadly divided into two zones, Zone 2 and Zone 4, which are respectively correspond to Peak Ground Acceleration of 0.2g and 0.4g at 475-year return period. An additional near-fault factor is also applied for the sites which are close to the known active fault to increase the hazard. The BSDS was derived by a probabilistic seismic hazard assessment (PSHA) based on the catalogue of earthquake events recorded between 1907 to 2012, with depth between 0 to 100km, but it is not explicitly stated if active faults were modelled. The PEM was derived using a PSHA, using a catalogue of earthquake events recorded from 1600 to 2015 with modelling of active faults and subduction zone trenches. The PEM model is considered to have been produced by a comprehensive PSHA model but it is not clear how the subduction intraslab earthquake events at deeper level were modelled.

This paper presents a country wide PSHA carried out to determine the seismic hazard based on the latest earthquake information with the modelling of known active faults, subduction interface and intraslab events. The PSHA method combines the knowledge of seismic source zones and their associated earthquake recurrence with appropriate ground motion prediction equations (GMPE's) to produce hazard curves in terms of level of ground motion and an associated annual probability of being exceeded. The Peak Ground Acceleration (PGA) of the major cities, Manila, Cebu and Davao which are located in the northern, central and southern Philippines, were calculated and compared with the published information. De-aggregation plots of these three cities were also produced to examine the major contribution of the seismic sources.

2. Tectonic Setting of the Philippines

The Philippine archipelago is located at the convergence between the Eurasian Plate (also referred as the Sunda Plate) and the Philippine Sea Plate (Figure 1). The oblique convergence appears to be primarily accommodated by convergent zones surrounding the archipelago, mostly characterised by subducting oceanic plates along trench systems. Oceanic lithospheres of the South China Sea, Sulu Sea and Celebes Sea, which all belong to the Eurasian Plate, are consumed along the discontinuous Manila-Negros-Sulu-Cotabato Trench system in the west, whereas the west dipping East Luzon Trough-Philippine Trench system accommodates the subduction of the Philippines Sea Pate in the east [5]. To the south of the Philippines, besides the subduction of the Philippines Sea Plate along the Philippine Trench, arc-arc collision occurs in the Molucca Sea Collision Zone forming a double subduction zone. This is a complex collision process involving the consumption of the Moluccas sea crust entailing the imminent accretion of the Halmahera and Sangihe Arcs [6][7][8].

Where volcanic arcs collide with continent crust, subduction is retarded or disrupted and forms discontinuities within the trench system. In the northern Philippines, the continuity of the Philippine-East Luzon Trench is interrupted and displaced by the Benham Plateau on the Philippine Sea Plate, which is colliding with the eastern Luzon. As such, a transform fault connecting the East Luzon Trench and the Philippine Trench has been formed [9]. In the central Philippines, the North Palawan Block collides with the Philippine archipelago at the Mindoro-Panay region and terminated the subduction between the Manila Trench and Negros Trench. It is suggested that the collision caused the North Palawan Block impingement into the Philippines archipelago to form a suture zone near the Romblon Island Group and western Panay [10]. In the southern Philippines, the Sulu Ridge hits the southwestern portion of the Philippine archipelago between the Sulu and Cotabato trenches. In the central Philippine collision zone, lower seismicity is observed along the boundary of the North Palawan Block and the Philippine Mobile Belt relative to areas to the east (e.g. Philippine Fault Zone and Philippine Trench), north (e.g. Manila Trench) and south (e.g. Negros-Cotabato Trenches). Seismicity in this zone is generally characterised by shallow and low-magnitude earthquakes of strike-slip nature.

Stresses not accommodated in subduction zones or those induced by collision zones, transfer into crustal deformation and led to the development of intraplate faults. The Philippine Fault Zone (PFZ), formed by a series of active faults running across the entire Philippine archipelago, accommodates most of the lateral oblique motions of the subducting Philippine Sea Plate. Other known major active faults discussed in this paper, are the Marikina Valley Fault (in Manila) and Bohol Fault Zone (near Cebu) and Davao Fault System (in Davao).

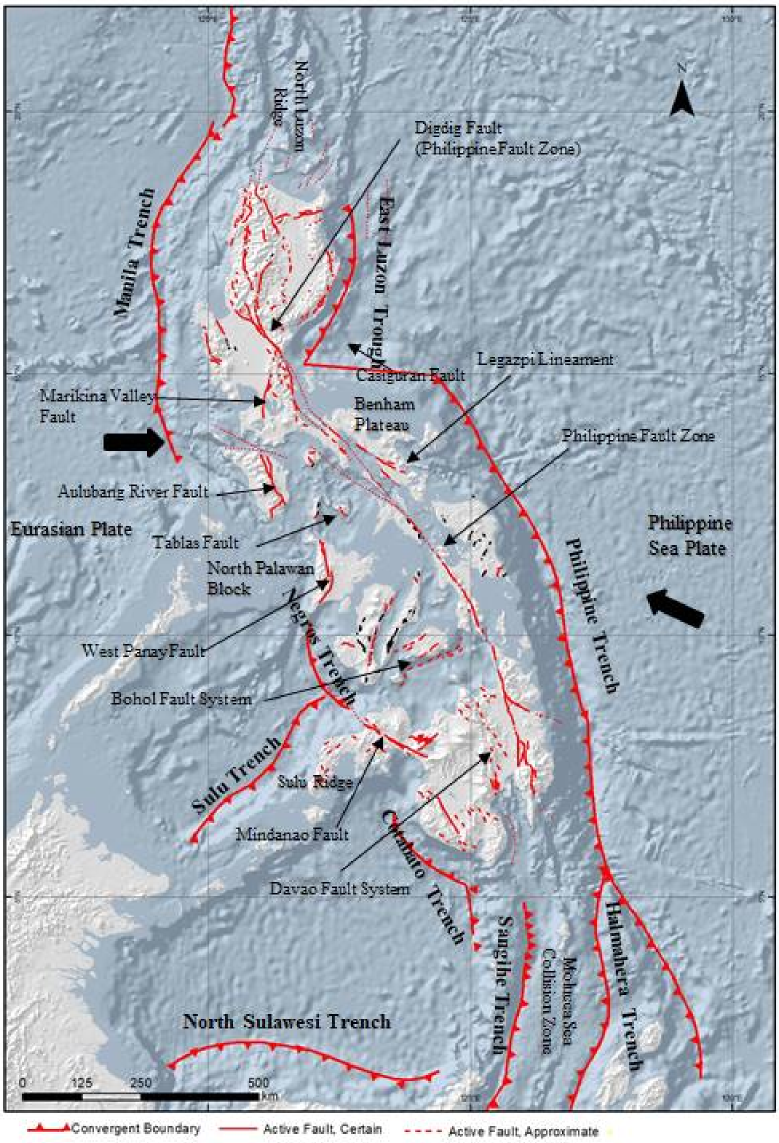


Figure 1 Tectonic Setting of the Philippines

3. Input to the Probabilistic Seismic Hazard Assessment (PSHA)

The PSHA method combines seismic source zoning, earthquake recurrence and the ground motion attenuation to produce "hazard curves" in terms of level of ground motion and an associated annual frequency of being exceeded. It requires the following elements:

- A definition of seismotectonic source zones that define the geographical variation of the earthquake activity.
- A model of earthquake recurrence with respect to earthquake magnitude. There are generally more small (low-magnitude) earthquakes than large (high-magnitude) earthquakes.
- A ground-motion prediction equation (GMPE), or attenuation relationship, which defines what ground motion should be expected at location A due to an earthquake of known magnitude at location B.

The basic methodology adopted is based on that originally proposed by Cornell [11] and includes integration over the aleatory variability of the ground-motion prediction equations. The probabilistic seismic hazard calculations were carried out using the Arup in-house program Oasys SISMIC, which has been verified by Pacific Earthquake Engineering Research Centre [12].

3.1 Earthquake Catalogue

As part of this study, an earthquake catalogue was compiled for the region from instrumental and historical records. The study area extends from latitude 1°N to 23°N and longitude 115°E to 131°E. Historical events before 1900 were compiled from Bautista & Oike [13]. Instrumental records since 1900 were compiled from the International Seismological Centre (ISC) [14], the EHB Bulletin in ISC [15], the ISC-GEM Global Instrumental Earthquake Catalogue [16][17] and earthquake data from PHIVOLCS.

In a PSHA ideally all earthquake events should be statistically independent and foreshocks and aftershocks need to be removed from the catalogue. Gardner & Knopoff [18] have proposed a windowing procedure to remove these events and has been applied. The moment magnitude scale (M_W) was chosen and the body-wave magnitude (m_b), surface-wave magnitude (M_S) values were converted to M_W using Scordilis [19] and Akkar et al. [20]. As the conversion between local magnitude (M_L) and M_W is governed by the instrumentation and tectonic setting which are spatially dependent, there is no unique global conversion. Earthquakes events recorded in M_L were taken as being equivalent to M_W with no conversion applied.

3.2 Seismic Source Zone Model

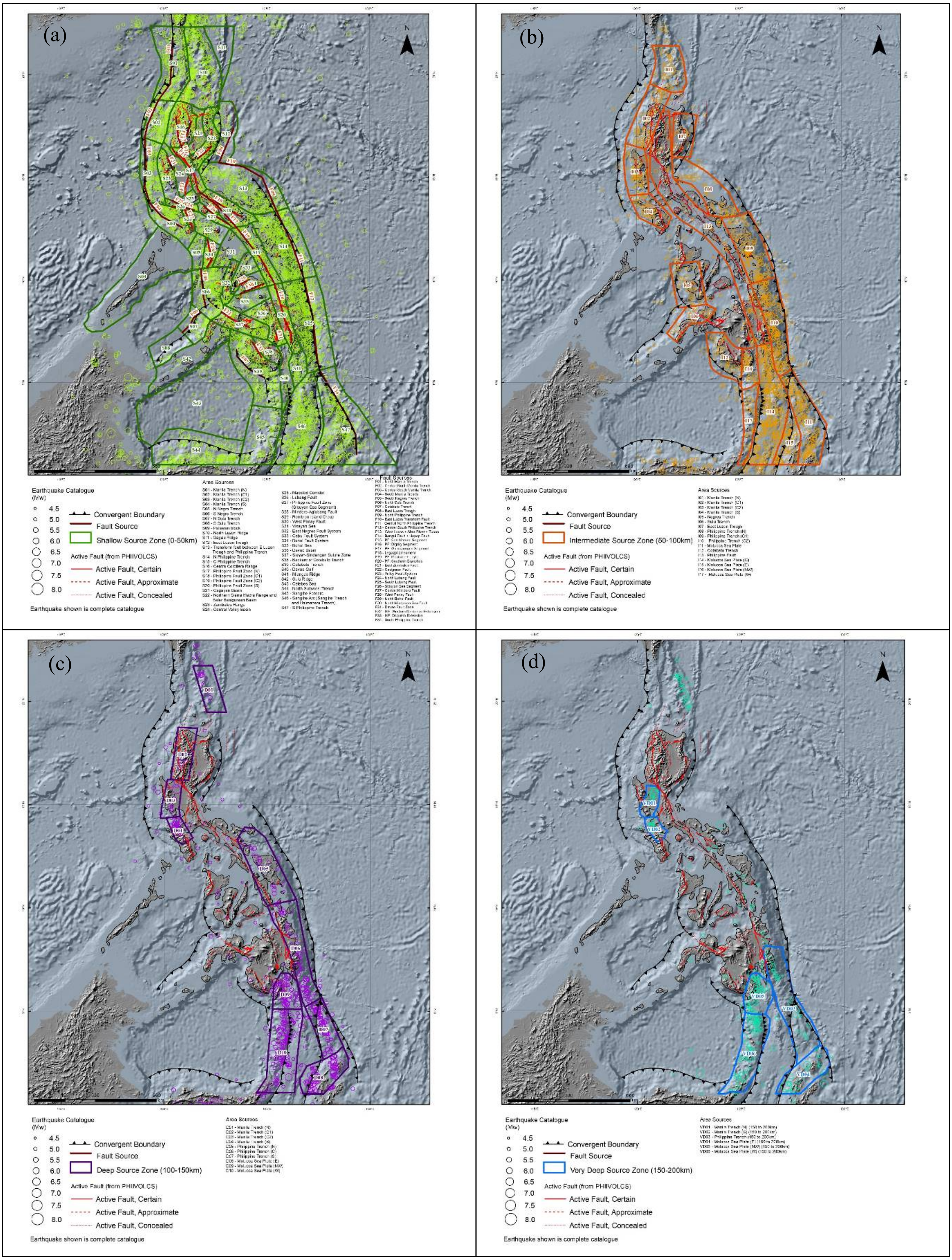
The characterisation of seismotectonic sources is based on the tectonic setting and the spatial distribution of observed seismicity with depth represented by a series of cross-sections throughout the entire study area. The sections show the distribution of seismicity with depth associated with the subduction zone and the increased shallow crustal seismicity associated with active crustal faults. Seismic sources are characterised as follows:

3.2.1 Crustal sources including faults and crustal areal source zones:

The areal source zones capture the crustal seismicity not contributed to any known active fault. There are 47 areal source zones being modelled (Figure 2a). Fault sources model the known major active faults with mapped surface traces published by PHIVLOVS [21] and slip rates characterised in published literature. All the faults, except the PFZ, have been modelled with a depth of 25km as suggested by Galgana et al. [22]. The PFZ is considered to be a deeper structure as suggested by the observed seismicity. Thus, it has been modelled to a depth of 40km. In general, slip rates from literature review were considered, with further adjustment so that the overall recurrence curves match with the observed seismicity.

3.2.2 Subduction zone sources including the interface and intraslab zones.

In subduction zones, the plate interface is typically the locus of plate boundary co-seismic deformation and is the location of the largest earthquakes observed worldwide. Apart from the shallow crust earthquakes, large thrust-fault earthquakes are inferred to occur at the locked interface between the subducting plate and the over-riding plate which are mainly localised at shallow depth. In this PSHA study, the west dipping subducting Philippine Sea Plate (along East Luzon Trough and Philippine Trench) and east-dipping subducting Eurasian Plate (along Manila Trench, Negros Trench, Sulu Trench and Cotabato Trench) are modelled as fault sources. The upper 50km of the subduction plates are modelled as subduction interface events. The Subduction Intraslab areas are characterised by 5 depth zones, an intermediate zone capturing seismicity from 50 to 100km (Figure 2b), a deep zone capturing seismicity from 100 to 150km (Figure 2c) and three very deep zones, 150 to 200km (Figure 2d), 200 to 300km (Figure 2e) and 300 to 500km (Figure 2f). The intraslabs of east dipping of the Eurasian Plate, the west dipping Philippine Sea plate and the fully subducted Molucca Sea Plate are modelled as area source to capture the diffuse earthquake of the seismicity around the subducting slab.


(a)
(b)
(c)
(d)
Earthquake Catalogue
(Mw)
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
Convergent Boundary
Fault Source
Shallow Source Zone (0-50km)
Intermediate Source Zone (50-100km)
Deep Source Zone (100-150km)
Very Deep Source Zone (150-200km)
Active Fault (from PHIVOLCS)
Active Fault, Certain
Active Fault, Approximate
Active Fault, Concealed
Earthquake shown is complete catalogue
Area Sources

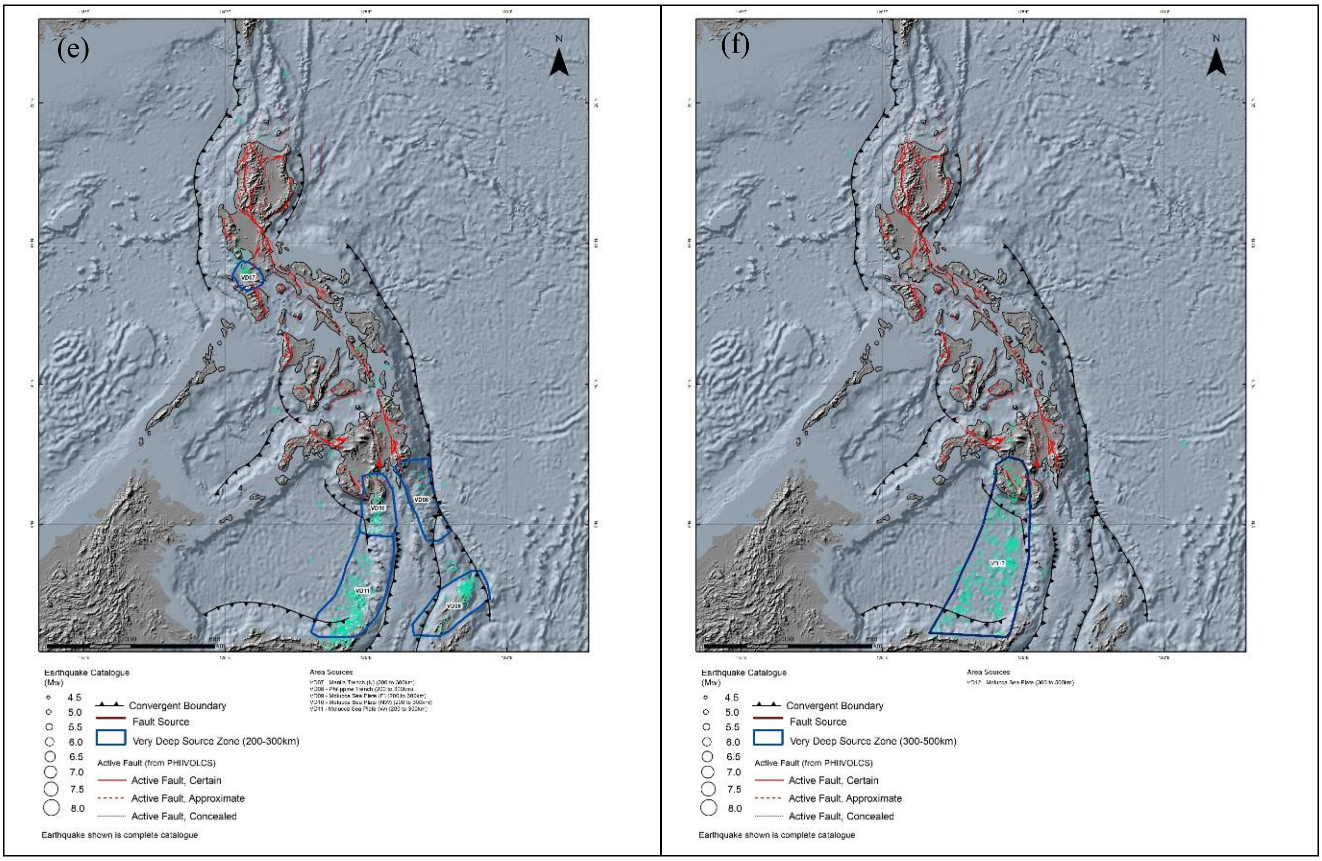


Figure 2 Seismic source zones for the 6 depth ranges used in the PSHA

3.3 Seismic Source Parameters

The rate of occurrence of earthquakes in each area zone is described in terms of magnitude recurrence relationships in the form of the ‘Gutenberg-Richter’ relationship [23]. The a-value (activity rate) and b-value of this relationship has been determined for each source zone through the application of the Weichert [24] maximum likelihood approach applied to the complete part of the earthquake catalogue. The best estimate a-value has been assigned a weighting of unity on the basis of minimal variability observed in a-values for the considered seismotectonic zonation. For the b-values, the variability/uncertainty was assigned to be 10% as lower/upper bound because the standard deviations of the b-values of all the zones roughly range from ~5% to 15%.

Earthquake recurrence curves for fault sources with specified slip rates are based on the procedure recommended by Youngs & Coppersmith [25]. In this procedure, a fault specific earthquake recurrence curve is developed based on the characteristic earthquake. All of the active fault sources are modelled within an associated areal source zone. The areal source zone captures background seismicity which is not attributed explicitly to the fault. The recurrence rate of the earthquakes directly related to the fault source is derived from fault geometry, slip rate and maximum magnitude using the characteristic method [26]. As both sources occupy a similar geographic space there is potential to double count the rate of earthquakes. To address this double counting, the seismic activity of the fault sources are subtracted from their encompassing areal source zone. This maintains the characteristic earthquake recurrence behaviour attributed to the fault source whilst still capturing additional background seismicity determined from the observed earthquake catalogue. The a-value inferred from fault recurrence of the fault sources is subtracted from the a-value in their corresponding areal sources.

Figure 3 shows an example of recurrence plot of a zone for central Philippine Fault Zone. In this fault zone, an areal source was modelled to represent a wider zone of associated seismicity around a mapped and well-defined active fault trace. These zones capture the observed seismicity surrounding an active fault source which is not explicitly generated on the fault surface. 'Gutenberg-Richter' recurrences with three different b-values and maximum magnitude (best estimate, upper and lower bound) are applied to the areal source and the curve fits the observed seismicity. Within this areal source, a fault source (line source) was modelled by mapped surface traces and slip rates characterised in published literature. To avoid double counting, three recurrence curves of "subtraction" are applied so that the overall recurrences curve of the zone matches with the observed seismicity and includes the characteristic events arising from the fault.

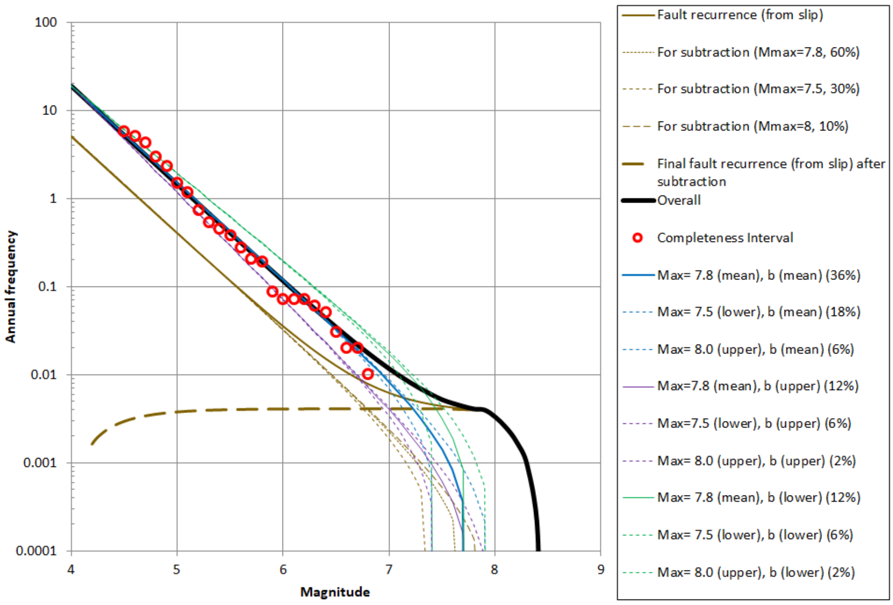


Figure 3 Example of Recurrence Curves

3.4 Limiting Magnitudes

A minimum magnitude of M_W 5.0 has been adopted for this PSHA assessment on the basis that the likelihood of an earthquake of smaller magnitude causing damage to engineered structures can be reasonably discounted. The assigned maximum magnitudes are assessed according to the tectonic setting and observed maximum magnitude which has historically occurred in each zone.

In general, the maximum magnitude [and weighting] of the crustal areal source zones is assigned in accordance to the tectonic setting as follows:

- Forearc: 7.3 [0.3], 7.5 [0.6], 7.8 [0.1].
- Arc/Ridge: 7.6 [0.3], 7.8 [0.6], 8 [0.1].
- Back-Arc/Basin: 7 [0.3], 7.3 [0.6], 7.5 [0.1].
- Offshore: 7.1 [0.3], 7.3 [0.6], 7.5 [0.1].
- Active Crustal Fault: 7.5 [0.3], 7.8 [0.6], 8 [0.1].

The maximum magnitude for the forearc source zone is capped at M_W 7.8. Any observed earthquake $M_W >$ 7.8 within forearc source zone is inferred to be mega-thrust earthquake which are located on the subduction interface and appropriately modelled in the interface fault source. For areal source zones containing a modelled fault source, the maximum magnitude is limited to the background seismicity only.

The maximum magnitude of fault sources has been inferred from Wells & Coppersmith [26] through their correlation between the probable maximum magnitude with fault geometry.

For subduction zones, the maximum magnitude of subduction interface has been inferred from fault geometry. For subduction intraslab, the maximum magnitude adopted is 7.3 [0.3], 7.5 [0.6], 7.8 [0.1].

3.5 Ground Motion Predication Equations (GMPE's)

GMPE's describe the attenuation of earthquake ground motions with distance from the hypocentre. To account for epistemic uncertainty, GMPE's from the Next Generation Attenuation (NGA) West-2 project have been used to model the shallow crustal faulting. NGA West-2 GMPE's adopted include Abrahamson, Silva & Kamai [27], Boore et al. [28], Campbell & Bozorgnia [29] and Chiou & Youngs [30]. Allen et al. [31] compared 173 Philippines earthquake events recorded with some published GMPE's and suggest that Boore & Atkinson [32], Chiou & Youngs [33], Fukushima & Tanaka [34] and Sadigh et al. [35] are good candidates to represent the Philippines setting. As Fukushima & Tanaka [34] only includes PGA and Sadigh et al. [35] has been updated as Chiou & Youngs [30], is only valid for a distance less than 100km, these two GMPE's models were not adopted in this study. Boore & Atkinson [32] and Chiou & Youngs [33] have now been updated as Boore et al. [28] and Chiou & Youngs [30] respectively. Following the recommendations in Allen et al. [31], the updated models of these two GMPE's were weighted 35%, with the other two 15%.

GMPE's by Abrahamson et al. [36] and Zhao et al. [37] were adopted to model the subduction interface and intraslab events. Considering Abrahamson et al. [36] is the most up-to-date GMPE for subduction zones, it was weighted 80% while Zhao et al. [37] was weighted 20%.

4. Results of the PSHA and comparisons with published information

The PSHA calculated uniform hazard response spectra at locations throughout the Philippines and the response spectra of Manila, Cebu and Davao at 500-year return period are presented in Figure 4. The PGA at rock (V_S = 760m/s) are presented and compared with the published ground motions in Table 1 and Table 2 for a limited number of locations. For a 500-year return period, the PSHA results are generally comparable to GEM (approximately -8% to +6%) and within -15% to +40% of PEM.

For a 1000-year return period, the PSHA results are +3 to +20% higher than BSDS for Manila and 25% to 45% higher than BSDS for Cebu and Davao respectively. It appears that the hazards of central and southern Philippine are generally lower as stated in BSDS. The hazard results are 15% to 25% higher than PEM for Manila and Davao, and 25% lower than PEM in Cebu.

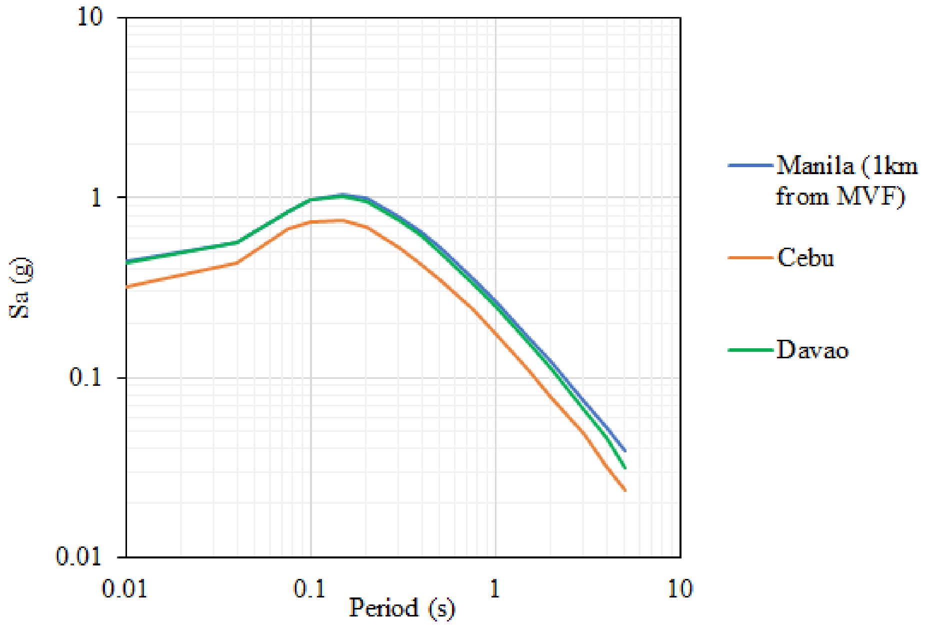


Figure 4 Response spectra of Manila, Cebu and Davao at 500-year return period (V_S = 760m/s)

Table 1 - Comparison of PGA at a 500-year return period

Site	Arup PSHA	PEM	GEM	NSCP
Manila	0.38 to 0.47	0.4	0.35 to 0.5	0.4 (0.6*)
Cebu	0.32	~0.45	0.33	0.4 (0.6*)
Davao	0.43	~0.4	0.45	0.4 (0.6*)

Note: * the highest PGA value by adopting near fault factors stated in NSCP

Table 2 - Comparison of PGA at a 1000-year return period

Site	Arup PSHA	BSDS (2013)	PEM
Manila	0.47 to 0.64	0.6	0.4 to 0.5
Cebu	0.4	0.3	0.5
Davao	0.54	0.3	0.4

5. Discussion

The NSCP broadly presents the seismic hazard as two zones, which would lead to underestimate the hazard when the site is near active faults, and overestimate at distances far from active faults. The underestimation can be rectified by applying the near fault factors as stated in the NSCP.

The PSHA presented in this paper is comparable with GEM, but shows has some discrepancies with BSDS and PEM. The following sections discuss this in more detail.

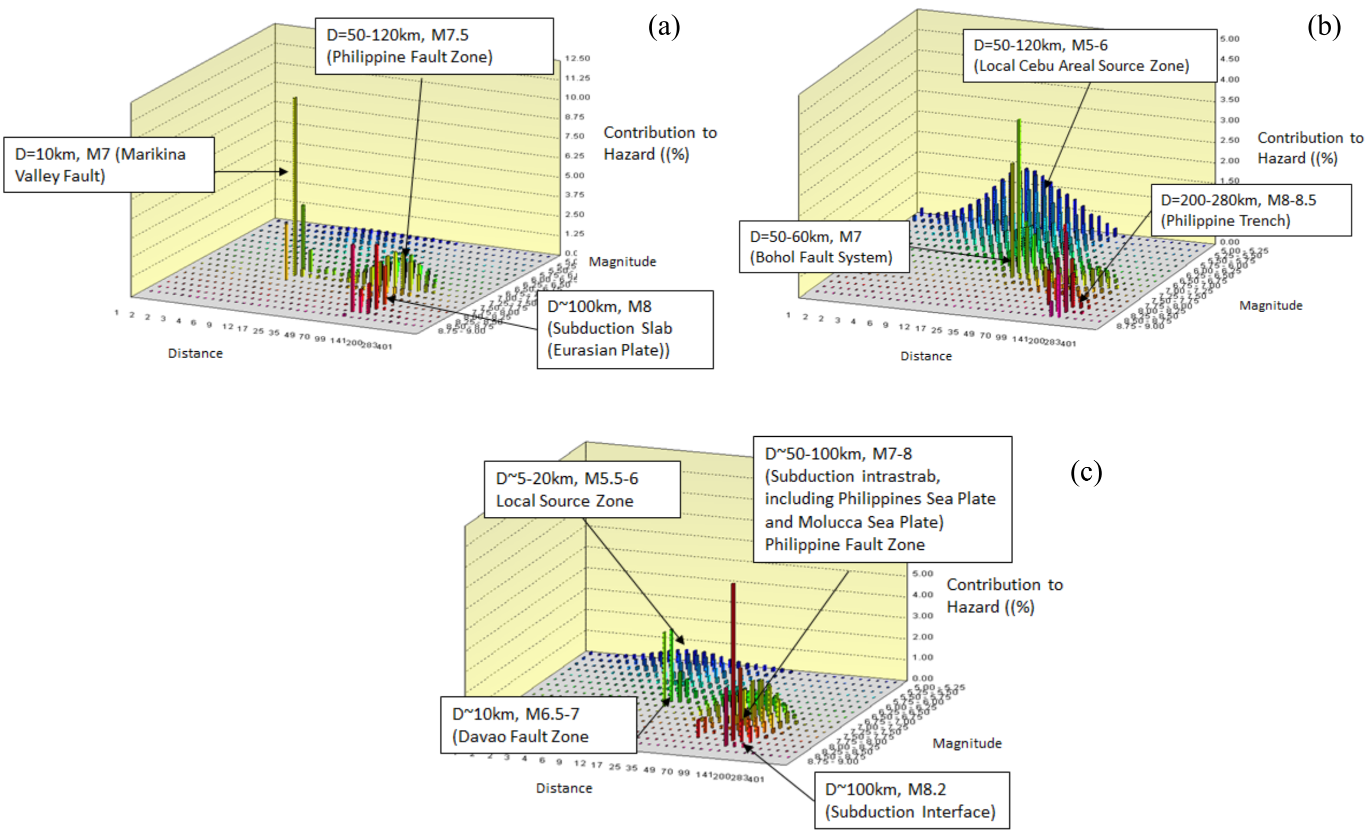


Figure 5 De-aggregation plots of PGA at 500-year return period for Manila, Cebu and Davao

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5.1 Comparison with BSDS

In general, the PGA from the PSHA is higher than that of BSDS for Cebu and Davao but comparable with BSDS for Manila depending on the distance to Marikina Valley Fault.

For Manila, the de-aggregation plot at the location 10km from the fault was presented in Figure 5a. Major contribution to the hazard comes from the Marikina Valley Fault. It follows that the hazard is highly dependent on the distance to the fault. When the active fault is modelled as a line source, the highest hazard would be near the mapped fault lines. The PGA map only shows a single PGA value for the whole of Manila which suggests that faults in BSDS may not have been modelled as line sources.

For Cebu, the de-aggregation plot (Figure 5b) suggests that a certain amount of contribution to the PGA come from North Bohol Fault and the Philippine Trench. A probable reason for the difference may be attributed to the modelling of the North Bohol Fault, which was not discovered until the earthquake of M7.2 which occurred on 15 October 2013. As BSDS was published in 2013, the North Bohol Fault was not likely to have been modelled in BSDS leading to an underestimation of the hazard.

For Davao, the de-aggregation plot (Figure 5c) suggests that significant portion of the contribution to the PGA come from subduction intraslab (Philippine Sea Plate and Molucca Sea Plate) and some contribution from the Philippine Trench and Davao Fault System. If the subduction intraslabs were not modelled, the hazard will be lower. In addition, the Davao Fault System was not presented in the active fault map from PHIVOLCS until their map published in 2018 and it is likely that the Davao Fault System was not included in the BSDS model.

5.2 Comparison with PEM

Generally, the PGA predicted by the PSHA is lower than that of PEM for Cebu, higher than PEM for Davao and comparable with PEM for Manila.

For Cebu, the PSHA model has not modelled the Cebu Fault System explicitly as a line source as the Cebu Fault System was considered only as a potential active fault and consequently its activity is uncertain. In PEM, the Cebu Fault System has been modelled which would lead to a higher hazard.

For Davao, both PEM and the PSHA model included the Davao Fault System. A possible reason of the difference may be due to the modelling of subduction instraslabs and the subduction interface.

5.3 Limitation of the comparison

The seismic hazard calculated from a PSHA model is affected by many factors such as seismic source zone modelling, recurrence parameters, maximum earthquake magnitude and GMPE's, etc. Without full details of the modelling and adopted seismic parameters of the models in BSDS and PEM, this paper can only investigate the implication of the seismic source zones modelling.

6. Summary and Conclusions

A country-wide probabilistic seismic hazard analysis (PSHA) has been completed for the Philippines. The PSHA includes a review of geological and tectonic setting, earthquake catalogue compilation and processing, development of source model, including areal sources and fault sources in different depth ranges and application of the ground motion prediction equations.

The results of Manila, Cebu and Davao were calculated and were compared with the published information from NSCP, PEM, BSDS and GEM all of which presented the seismic hazard of the Philippines. Comparisons with results of the PSHA presented in this paper suggest they are similar to GEM. The NSCP is not sufficiently detailed to capture the seismic hazard in particular if the location is close to an active fault, which will lead to underestimation of the seismic hazard if near fault factors are not applied. In the comparison with PEM and BSDS, the seismic source modelling was investigated by reviewing the de-aggregation plots. It is suggested that modelling a fault source (line source) is important for a location which is close to an active fault. In addition, the deep source zones such as subduction intraslabs cannot be omitted, in particular the site is on the overriding plate and near subduction trench. Reviewing the seismic source zone in 3 dimensions is essential for the countries that lie on complex tectonic settings near to convergent plate boundaries.

There are many components and parameters which affect the results of the PSHA and this paper only studies the potential impact of seismic source zone delineation. The importance of updating the seismic hazard where latest research and study are made available such as updating of relevant GMPE's and discoveries of active faults is also emphasised.

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