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Seismic hazard assessment for public infrastructure in Metro Manila

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ABSTRACT: The Philippines is currently experiencing a stable economic growth, coupled with steady increase in population. With Metro Manila housing the business districts, government offices, schools, and major hospitals, traffic congestion has been a recurring problem due to insufficient transport infrastructures. Several mass transportation systems were approved by the Philippine government for design and construction. However, with the country situated in the Circum-Pacific Belt, Metro Manila is affected by several earthquake generators, most prominent of which is the Valley Fault System. A seismic hazard analysis aimed at contributing to safe and cost-effective design of public infrastructures was carried out and presented in this paper.

1 INTRODUCTION

1.1 *Study area*

Metro Manila, the Philippines' National Capital Region (NCR), is the political, economic, and cultural center of the Philippines. With a total area of approximately 620 km^2, NCR houses several business districts, schools, hospitals, and government offices. A census conducted in 2015 showed that the population in Metro Manila is approximately 12 million which is steadily increasing every year. Metro Manila is thus considered as one of the most densely populated areas in Southeast Asia. With the continuous increase in the population comes the need to alleviate the traffic congestion and travel time in the city. Several mass transportation systems such as MRT, skyways, and subways are given the go-signal by the Philippine government for design and construction.

1.2 *Significance of the study*

Geographically, Metro Manila is located in Luzon Island. It is influenced by several earthquake generators, among which is the Valley Fault System. Paleoseismic studies have shown that the Valley Fault System is active. Trenching across the northern portion of the fault, coupled with Carbon-14 dating, showed that three or four faulting events occurred during the last 1400 years. An estimate of approximately 200 to 400 years has been suggested as a possible recurrence interval for large magnitude earthquakes (Nelson et al, 1995). Many research studies estimated a possible magnitude 7 or more for this fault and considering that no seismic event is known after 17th century, it means that the active phase of the Valley Fault System is approaching.

In order to provide a safe and cost-effective design of a proposed major transport infrastructure in Metro Manila, the geological and geotechnical conditions, as well as the seismicity of the area, must be well understood.

2 GEOLOGY AND SEISMICITY

2.1 *Regional geology*

The underlying formation in Metro Manila is the Pleistocene Guadalupe Formation, known as the Guadalupe Tuff Formation. This consists of the lower member Alat Conglomerate and upper member Diliman Tuff. The Alat Conglomerate is a group of massive poorly sorted round pebbles and small boulders conglomerate and sandstone with medium to thin bedded mudstone or shale, while the Diliman Tuff is a volcanic ejecta with some amount of tuffaceous sandstone, tuffaceous siltstone, and shale. This formation, locally referred to as "adobe", stretches from Quezon City and extends to the Province of Cavite in the south.

2.2 *Tectonic setting and seismicity*

The Philippine Mobile Belt corresponds to the complex boundary between the Eurasian Plate and the Philippine Sea Plate. The Philippine Mobile Belt refers to the portion of the Philippine archipelago bounded to the west by the Manila-Negros-Cotabato-Sulu Trenches and to the east by the East Luzon Trough-Philippine Trench. The active 1200 km long Philippine Fault, as well as many other active seismic sources found within the Philippines, is a physical manifestation of the surrounding tectonic plates' opposing movements.

2.3 *Seismicity*

The Philippines accounts for 3.2% of the world's seismicity. It is situated in the Circum-Pacific Belt a.k.a. "Ring of Fire", where 80% of the world's earthquakes occur. Philippine seismicity is mainly related to plate subduction and in part to strike-slip motions along trans-current faults.

A search of the United States Geological Survey (USGS) earthquake database was conducted for earthquakes with magnitudes of at least 4.0 within 100 km of Metro Manila. There was a total of 442 events since 1900. The list included only 5 strong events between magnitudes 6.0 and 8.0—the strongest of which was a magnitude 7.5 earthquake that occurred in August 20, 1937. This was a shallow 15 km deep earthquake; the epicenter of which is approximately 69.4 km away from the center of Metro Manila. According to the Philippine Institute of Volcanology and Seismology (PHIVOLCS), this was caused by the 19 km wide, 56 km long strike-slip Laguna-Banahaw Fault.

2.4 *Potential earthquake generators*

From the maps produced by PHIVOLCS and Mines and Geosciences Bureau (MGB), the following potential earthquake generators were considered in the seismic hazard analysis:

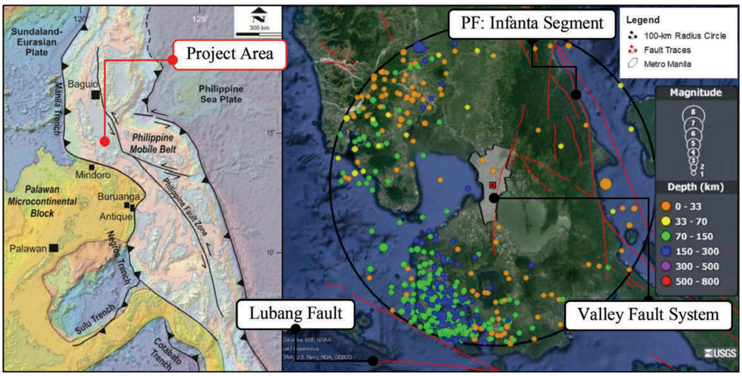

Figure 1. Tectonic Boundaries in the Philippines (Left, Source: Dimalanta and Yumul, 2016) and Distribution of Historical Earthquakes around Metro Manila (Right, Source: USGS)

The Valley Fault System is a system of active faults that cuts through Metro Manila. It consists of the West Valley Fault (WVF) and East Valley Fault (EVF), which can generally be classified as strike-slip faults. West Valley Fault is the nearest active fault in Metro Manila which extends from the southern Sierra Madre to Tagaytay over a distance of 110 km. East Valley Fault, on the other hand, extends over a distance of about 30 km.

Lubang Fault is an active left-lateral strike-slip fault that passes through the Verde Passage between Mindoro and Batangas and continues west towards the Manila Trench. The Lubang Fault is a major branch of the Philippine Fault.

Manila Trench can be traced as a narrow but elongated bathymetric depression that extends from Taiwan to Mindoro. The trench accommodates the eastward oceanic crust subduction of the South China Sea basin beneath the Luzon arc. The trench is associated with an eastward dipping Benioff zone, thrust focal mechanism solutions, and a belt of active volcanoes. Seismic reflection profiles across the 5100 m trench show deformation of the sedimentary fill, which indicate that the trench is active.

The Philippine Fault Zone (PFZ) an active left-lateral strike-slip fault that cuts across the entire Philippine archipelago over a distance about 1200 km. It is the most active earthquake generator in the country and has been the source of several devastating earthquakes. The Infanta segment of the Philippine Fault, in particular, is seismically quiet and can be considered a seismic gap.

3 GEOHAZARDS

3.1 *Liquefaction*

Liquefaction is a phenomenon wherein loose, saturated, cohesionless soil is subjected to cyclic shear stress that results in an increase in pore water pressure and reduction of the effective stress to zero. This results in the fluid behavior and near zero shear resistance of the soil. The liquefaction susceptibility map shown in Figure 2 (Left) shows varying degrees of hazard for different areas of Metro Manila.

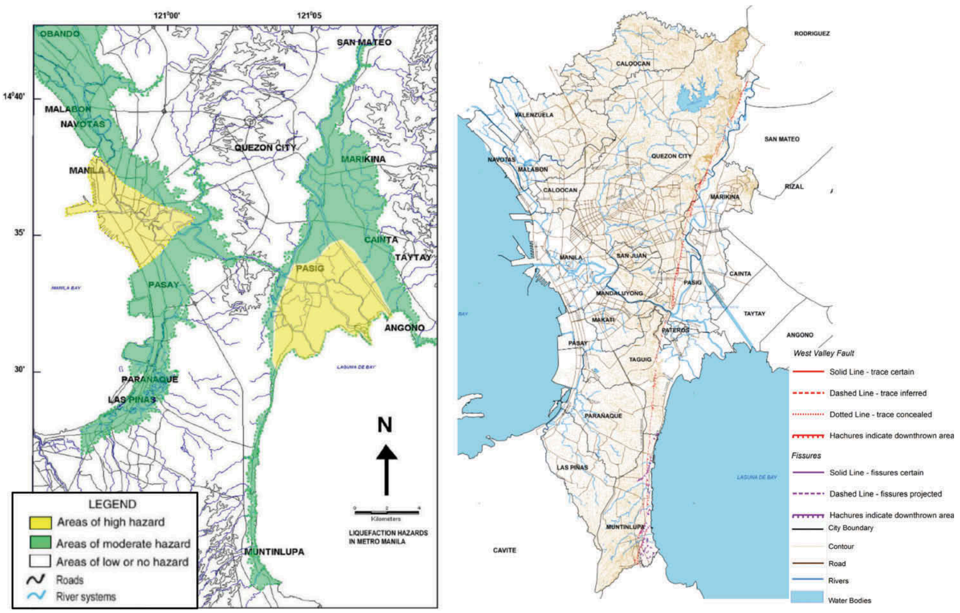

Figure 2. Liquefaction Susceptibility Map of Metro Manila (Left) and Ground Rupture Hazard Map of Metro Manila (Right) (Source: PHIVOLCS)

3.2 *Ground shaking and ground rupture*

Ground shaking is caused by the passage of seismic waves, primarily surface waves near the epicenter of the earthquake. The intensity of the shaking depends on the local geology, duration and intensity of the earthquake, and distance from the epicenter. The Earthquake Impact Reduction Study for Metropolitan Manila (MMEIRS) by Japan International Cooperation Agency (JICA), Metropolitan Manila Development Authority (MMDA), and PHIVOLCS, estimated strong ground shaking (Intensity 8) due to the possible movement of the Valley Fault System.

Fault displacement, on the other hand, can cause surface rupture along the surface trace of an active fault or along a presumed active fault, causing severe damage to structures or other developments located on the fault trace. The ground rupture hazard map of Metro Manila, which shows minor risk for most areas except for those near the West Valley Fault, is shown in Figure 2 (Right).

MMEIRS estimated casualty, both dead and injured, of around 147,100. Several offices, residential, mid-rise and high-rise structures are also expected to be heavily damaged.

4 DYNAMIC PROPERTIES OF ROCKS

Rock dynamic properties provide strength-deformation characteristics that exhibit how the subsurface will behave when subjected to dynamic loads such as earthquakes. In this study, geophysical tests (e.g. Downhole Seismic Test, Cross Hole Seismic Test) were conducted across Metro Manila in order to measure in-situ seismic wave velocities of the Guadalupe Tuff. Dynamic properties can then be determined using empirically-derived equations correlated to the measured velocity of the in-situ seismic waves. Complementary to the in-situ measurements, Ultrasonic Pulse Velocity (UPV) testing was also conducted on rock core samples to measure the intact compressional wave velocity.

4.1 *Compressional/primary wave velocity (VP)*

From the results of the geophysical tests, intact V_P range from 1045 to 4221 m/s, with an average value of 2275 m/s. Statistically speaking, the bandwidth (mean plus-or-minus the standard deviation) of measured intact V_P falls within 2275 ± 565 m/s, with the majority falling within the range 2245 to 2545 m/s. Out of the 385 tested samples, 64 of them fall below the lower limit of the said bandwidth and 24 of them fall above the upper limit.

These values are indicative of rocks that can be classified as mainly sandstone or shales, which characterize the very composition of the Guadalupe Tuff formation. Samples with slow propagation velocities (< 1500 m/s) are indicative of high shale composition, high porosity, high water content, unexposed change in material (layer of non-homogeneity), or some combination of these characteristics. On the other hand, samples with faster propagation velocities are indicative of sandstone. Velocities that exceed 3000 m/s are generally intact, homogenous samples.

4.2 *Shear/secondary wave velocity (V_S)*

A site's soil type is an indicator of how stiff the subsurface is, and how seismic waves amplify and dissipate through its stratification. In effect, knowing the soil type provides information on how high the surface acceleration can be after seismic waves attenuate from source to site through the bedrock.

Among the different dynamic properties, it is generally suitable to use the shear wave velocity of the top 30 m (V_{S30}) to determine which category the site's soil type falls under. The range of V_{S30} values that correspond to each soil type category are tabulated in the National Structural Code of the Philippines (NSCP) 2015 Table 208-2.

From the results of the geophysical tests, the average measured V_{S30} of Metro Manila is determined to be 784 m/s, which just barely falls under soil profile type S_B. This suggests that Metro Manila is generally underlain by soft rocks, which is essentially what the Guadalupe Tuff is composed of. Not only are these findings consistent with the information gathered

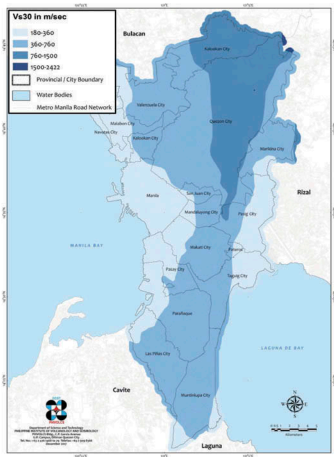

Figure 3. Metro Manila V_{S30} Model (Source: PHIVOLCS)

from sampling, but they are also consistent with the generalized Metro Manila V_{S30} site model published by PHIVOLCS.

5 SEISMIC HAZARD ANALYSIS

Seismic Hazard Analysis (SHA) is the process of quantifying the overall seismic hazard of an area in terms of ground shaking. SHA can be thought of as a means to mitigate other seismic hazards brought about by ground shaking, such as landslides, liquefaction, and subsidence among others.

One of the approaches in performing SHA is the Probabilistic Seismic Hazard Analysis (PSHA). PSHA quantifies seismic hazard at different levels of ground motions, depending on the recurrence interval or return period of the seismic event. PSHA also considers multiple seismic sources simultaneously and accounts for uncertainties related to distance, time, recurrence, and size (magnitude).

In performing PSHA, empirically-formulated attenuation models are utilized to determine the expected surface acceleration by estimating how seismic waves propagate and travel from source to site. Attenuation models are commonly referred to as Ground Motion Prediction Equations (GMPE), and these equations were formulated using globally-acquired earthquake data such as epicenter locations, hypocentral depths, Peak Ground Accelerations (PGA), and magnitudes.

At present, Filipino engineers typically extract seismic design accelerations from the NSCP which utilizes the 1994 national-scale response spectrum. PHIVOLCS also conducted a more-recent national-scale PSHA in 2017 and published an atlas called the Philippine Earthquake Model (PEM). PEM provides the results from the PSHA of the Metro Manila for ground motions with Probabilities of Exceedance (PoE) of 2%, 5%, and 10% in 50 years, while considering actual soil conditions defined by the Metro Manila V_{S30} model. Ground motions with PoE of 2%, 5%, and 10% in 50 years correspond to ground motions with return periods of 2475, 975, and 475 years, respectively. The intent for publishing the PEM is to serve as an update to the code-prescribed design spectrum.

In recent years, the Pacific Earthquake Engineering Research (PEER) Center, with the cooperation of other multi-disciplinary agencies and institutions across the globe, started a multidisciplinary research program that developed complex GMPE's called New Generation Attenuation Relationships (NGAR). It should be noted that PHIVOLCS used NGAR GMPE's in conducting the PSHA for the PEM 2017.

The following NGAR GMPE's were utilized in the PEM 2017 for shallow crustal seismic events: a) Abrahamson, Silva, and Kamai (2014); b) Campbell and Bozorgnia (2014); and c)

Chiou and Youngs (2014). For subduction zones, available GMPE's were developed prior to the PEER's globally-interactive research program. The following GMPE's were utilized in the PEM 2017 for seismic events related to subduction zones: a) Atkinson and Boore (2003); and b) Youngs, et al. (1997).

5.1 *PSHA methodology*

PSHA models are structured to account for both epistemic and aleatory uncertainties using the Total Probability Theorem. This theorem states that the mean annual rate of spectral acceleration exceeding a certain value of acceleration (a), can be obtained by summing the individual probabilities (P) of events that consider a particular uncertainty parameter such as moment magnitude (M, m) and source-to-site distance, for every contributing seismic source (v) within the vicinity. Identifying the exact location of future earthquakes is trivial. As such, it is acceptable to assume that earthquakes occur randomly both in size and location within a particular zone. This assumption can be considered in a Poisson model, where the only parameter is the mean rate of earthquake occurrence. In this model, the probability of the ground shaking, in terms of Sa, exceeding a particular acceleration within a certain time frame (t) is given as:

$$P\ (Sa > a) = 1 - e^{-\lambda at} \tag{1}$$

The PSHA database or "*catalog*" used in this study contains USGS-recorded earthquake events within the study area. Magnitudes are converted first from body wave magnitude (m_b) to M_s:

$$M_s = 10.29 - 3.55m_b + 0.48{m_b}^2 \tag{2}$$

To homogenize the catalog to moment magnitude values, the global regression relationships developed by Das (Das et.al, 2011) can be used to convert Ms to M. Main shocks were then isolated through a process called "declustering", where each record can be identified as either main shock, aftershock, or foreshock using the criteria and time-window algorithm of Gardner and Knopoff (van Stiphout et.al, 2012).

General area seismic sources were delineated based on the clustering of earthquakes in the historical catalog and their assumed seismotectonic boundaries. Each source is tied to the parameters and/or focal mechanism of the earthquake generator bound within the area. These zones were grouped into three depth categories: shallow crust (0 to 50 km deep), mid crust (50 to 100 km deep), and deep crust (100 to 300 km deep). Seismicity of shallow crust area sources is attributed to earthquakes caused by active faults and background earthquakes not associated to any identified active structure. On the other hand, the seismicity from the given subduction zones are attributed to earthquakes generated as subduction interface events. The Philippine Trench, East Luzon Trough, and Manila Trench are the subduction zones that comprise the mid crust and deep crust area sources, whose resulting seismic activities are attributed to the earthquakes generated at the subduction instraslab events. For simplicity, all faults and subduction zones are to be modeled as simple fault sources, wherein rupture surfaces are set to be planar and can be defined by their respective fault trace, average dip angle, and rake angle. The physical properties of subduction zones are based on tsunami hazard studies.

5.1.1 *Recurrence*

The magnitude recurrence relationship for earthquakes can be defined by the Gutenberg-Richter (GR) recurrence law, whose parameters, a and b, correspond to the overall rate of seismic events in the vicinity (a) and the relative ratio of small to large magnitude earthquakes (b), respectively.

$$log(N) = a - bM \tag{3}$$

The activity rate of line sources is then estimated from the moment release rate by a source. The manner in which this moment rate is distributed to constrain the activity rate is defined by a characteristic magnitude frequency distribution (MFD). A characteristic MFD assumes that individual faults and fault segments tend to produce similar magnitude or characteristic

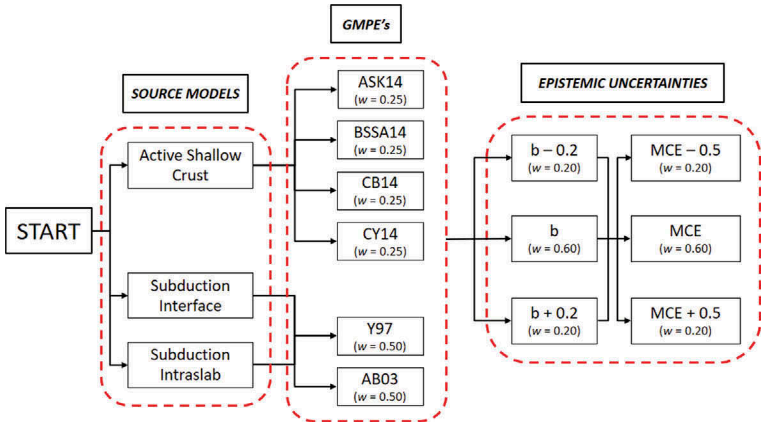

Figure 4. Logic Tree for Horizontal Ground Motions

earthquakes. For some active faults, like the West Valley Fault, there are no historical instrumental seismic data available.

For these kinds of faults, recurrence parameters are identified from paleoseismic studies, whose characteristic magnitude are related to their associated displacement or slip rate. The characteristic model tends to underestimate the hazard contributed by moderate magnitude earthquakes.

5.1.2 *Logic tree*

The following flow chart shows the adopted logic tree for the PSHA calculation. It must be noted that each branching level will apply to all items in the previous branch (the GMPE's will apply to all sources and the variations in b will apply to all combinations of GMPE's and sources).

Note that hypocentral depth distributions are treated as aleatory uncertainties. They were identified separately for each source depending on the observed depth distributions from the earthquake catalog.

5.1.3 *Design accelerations*

Design accelerations to be adopted in seismic analysis can be taken from the response spectra generated from PSHA. In anticipation of the varying code requirements when designing different types of structures, target response spectra shall represent the uniform hazard based on ground motions with 2% and 10% Probabilities of Exceedance (PoE) in 50 years. These ground motions correspond to return periods of 2,475 and 475 years, respectively.

6 RESULTS

According to NSCP 2015 Chapter 208.5.3.2, the ground motion to be considered in seismic analysis should, as a minimum, correspond to one having a return period of 475 years. This level of ground motion has the same hazard level prescribed as the design spectrum prescribed in the NSCP 2015 for typical vertical structures; and is also one of the hazard levels provided in the PEM 2017. As such, this study will quantify the ground shaking hazard for a 475-year ground motion and compare it with both the NSCP 2015 and PEM 2017 response spectra. It should be noted that these response spectra consider rock site conditions (S_B) based on measured V_{S30}.

The following figure shows the generated 5%-damped response spectra from all three studies. Evidently, the PEM 2017 prescribes much lower values than both the code-prescribed and site-specific response spectra, and this is true all for all period values. Comparing this study's response spectrum to what is prescribed in the code, the PGA (represented by the y-intercept or the spectral acceleration at 0th period) does not differ much. Focusing on the shorter period range (up to 0.2 s), spectral accelerations are also very close. It should be noted, however, that rocks or very hard/dense soils tend to resonate with high-frequency seismic waves,

Table 1. Probabilistic peak ground acceleration comparison

Return Period (years)	Probability of Exceedance (POE) in 50 years	Peak Ground Acceleration (g)		
		NSCP 2015	Site Specific PSHA	PEM 2017
475	10%	0.53	0.59	0.40
975	5%	n/a	0.72	0.45
2475	2%	n/a	0.88	0.55

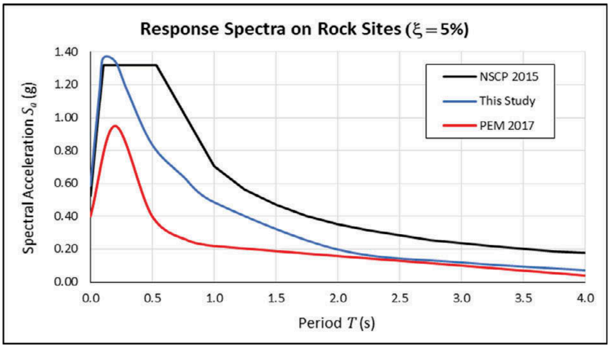

Figure 5. 5%-Damped 475-Year Response Spectra on Rock Sites

and not so much with low-frequency seismic waves. This is the reason the response spectra on rock site are expected to peak somewhere within 0.1 to 0.3 s. However, the NSCP design spectrum plateaus the peak spectral acceleration up to 0.5 s. As a result, the generalization of the code-prescribed spectrum is very much highlighted in this scenario.

7 CONCLUSION

The probabilistic seismic hazard analysis carried out for a proposed major transport infrastructure in Metro Manila yielded higher values of peak ground acceleration for various return periods, compared to the provisions of NSCP 2015 and the Philippine Earthquake Model (PEM) 2017.

It is therefore essential that site-specific seismic hazard analysis is undertaken for essential facilities and critical structures, in order to come up with robust and earthquake-resistant design.

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