Seismic hazard analysis for public infrastructure in Metro Manila

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ABSTRACT

Metro Manila is the Philippines' National Capital Region and the nation's political, economic and cultural center. Several transport infrastructure, including the expansion of its current light rail transit (LRT), new elevated highways, and the first subway system, are either under construction or in the detailed engineering design stage. Being situated in tectonically active zone, the seismic design of this major infrastructure is a primary consideration. This paper presents a seismic hazard analysis aimed at contributing to the robust and cost-effective design of public infrastructure. The results of the study are also compared with the provisions of the National Structural Code of the Philippines (2015), and the Philippine Earthquake Model (2017).

Keywords: Metro Manila; Philippines; infrastructure; Seismic Hazard Analysis; Valley Fault System

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 and geologic data have shown that the Valley Fault System is active. Trenching across the northern portion of the fault, coupled with Carbon-14 dating, show 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 Tectonic Setting

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 1200km 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.

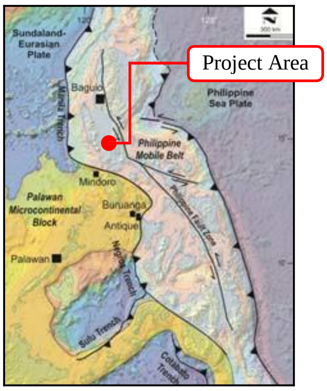

Fig. 1. Tectonic Boundaries in the Philippines (Dimalanta and Yumul, 2016).

2.2 Regional Geology

The underlying formation in Metro Manila is the Pliocene-Pleistocene Guadalupe Formation, known as the Guadalupe Tuff Formation (GTF). 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.

2.3 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 15km 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 19km wide, 56km long strike-slip Laguna-Banahaw Fault.

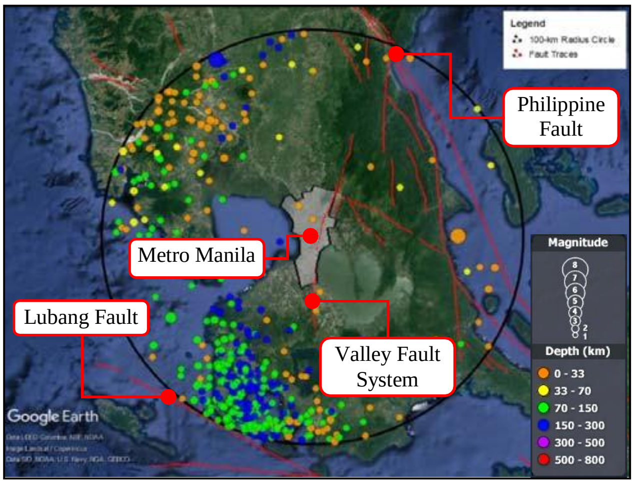

Fig. 2. Distribution of Historical Earthquakes around Metro Manila (United States Geological Survey).

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:

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.

The Philippine Fault (PF) 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.

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 map shown in Figure 3 indicates the varying degrees of liquefaction susceptibility for different areas of Metro Manila.

3.2 Ground Rupture

In the event of an earthquake, the rupture along the surface of an active fault may cause severe damage to structures or other developments around the vicinity of the trace. The ground rupture hazard map of Metro Manila shows minor risk of ground rupture for most areas in Metro Manila except for those near the West Valley Fault. One study estimated the casualty, both dead and injured, to be around 147,100. Several offices, residential, mid-rise and high-rise structures are also expected to be heavily damaged.

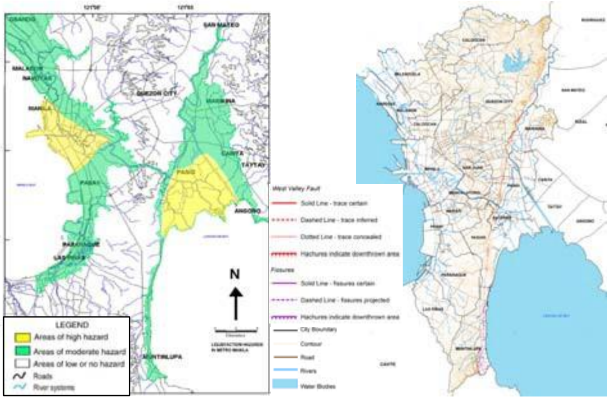

Fig. 3. (Left) Liquefaction Susceptibility Map and (Right) Ground Rupture Hazard Map of Metro Manila (PHIVOLCS).

4 SUBSURFACE CONDITIONS

An area’s site class provides strength-deformation characteristics and, in effect, is an indicator of how the subsurface will behave when subjected to dynamic loads such as earthquakes.

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

Table 1. Site Class Categories (NSCP 2015 Table 208-2).

Soil Profile Type	Soil Profile Name / Generic Description	Average Soil Properties for Top 30 m of Soil Profile		
		Shear Wave Velocity, V_{S30} (m/s)	SPT, N-value	Undrained Shear Strength, S_u (kPa)
S_A	Hard Rock	> 1500		
S_B	Rock	760 to 1500		
S_C	Very Dense Soil and Soft Rock	360 to 760	> 50	> 100
S_D	Stiff Soil Profile	180 to 360	15 to 50	50 to 100
S_E	Soft Soil Profile	< 180	< 15	< 50
S_F	Soil Requiring Site-specific Evaluation			

In this study, geophysical tests (e.g. Downhole Seismic Test, PS Suspension Logging) were conducted across Metro Manila in order to measure in-situ seismic wave velocities of the GTF. Other elastic properties (which can further be used in numerical modeling) can then be determined using empirically-derived equations correlated to the measured velocity of the in-situ seismic waves.

From the results of the geophysical tests, the average measured V_{S30} of northern Metro Manila is determined to be 856.50 m/s, which just barely falls under site class S_B. On the other hand, the average measured V_{S30} of southern Metro Manila is determined to be 675.00 m/s, which is on the higher bound of site class S_C.

These findings suggest that Metro Manila is generally underlain by soft rocks, which is essentially what was expected of the GTF. Not only are these findings consistent with the information gathered from sampling, but they are also consistent with the generalized Metro Manila V_{S30} site model map (left image) published by PHIVOLCS.

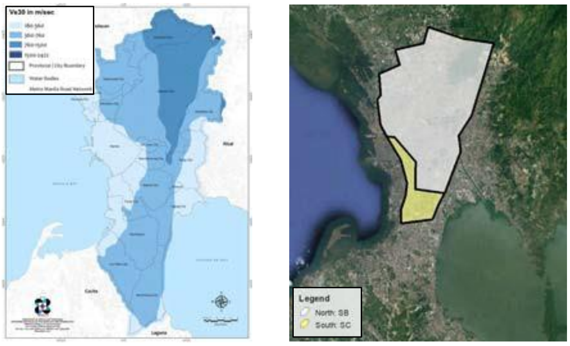

Fig. 4. Metro Manila V_{S30} Map (Left image from PHIVOLCS).

5 SEISMIC HAZARD ANALYSIS

Seismic Hazard Analysis (SHA) is the process of quantifying the overall seismic hazard of an area in terms of acceleration. The probabilistic approach (PSHA) in performing SHA quantifies seismic hazard at different levels of risk depending on the recurrence interval or return period of the design ground motion. PSHA also considers multiple seismic sources simultaneously and accounts for uncertainties related to distance, time, recurrence, and size (magnitude).

In performing SHA, 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 information (e.g. epicenter location, depth, and magnitude). In this study, the New Generation Attenuation West 2 (NGA-West2) GMPE’s developed by the Pacific Earthquake Engineering Research (PEER) Center were used for fault systems, and the BC Hydro GMPE (Abrahamson et al., 2016) was used for subduction zone sources.

At present, Filipino engineers typically extract seismic design accelerations from the NSCP, which utilizes a generalized national-scale response spectrum developed in 1994. Design accelerations for 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 of ground motions with 2%, 5%, and 10% Probabilities of Exceedance (PoE) in 50 years. These ground motions have return periods of 2,475, 975, and 475 years, respectively. In light of this, PHIVOLCS conducted a national-scale PSHA in 2017 and published the Philippine Earthquake Model (PEM)—an atlas of maps containing isolines of equal spectral acceleration.

6 RESULTS

According to NSCP 2015 Chapter 208.5.3.2, the ground motion to be considered in seismic analysis for typical vertical structures should, as a minimum, correspond to one having a return period of 475 years. This return period is one of the hazard levels provided in both the NSCP 2015 and the PEM 2017. As such, the site-specific 475-year seismic hazard generated from this study shall be compared to both the NSCP 2015 and PEM 2017 response spectra.

The following figures show the generated 5%-damped 475-year response spectra of the northern and southern areas of Metro Manila from all three studies.

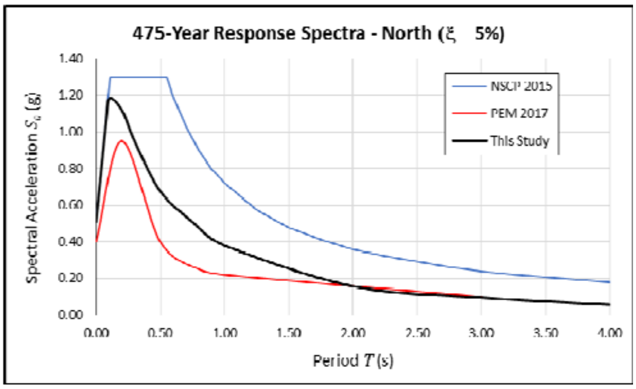

Fig. 5. 5%-Damped 475-Year Response Spectra (Northern Area).

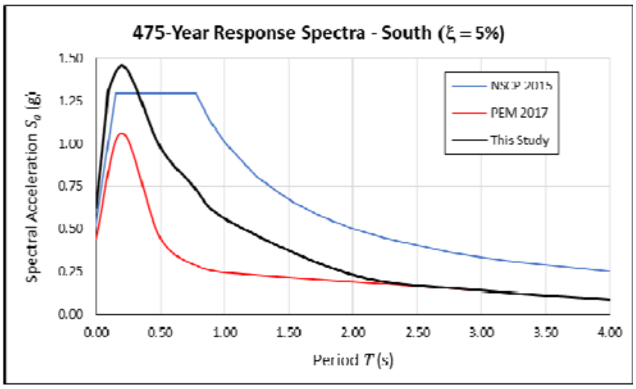

Fig. 6. 5%-Damped 475-Year Response Spectra (Southern Area).

Evidently, the PEM 2017 prescribes much lower values than both the code-prescribed and site-specific response spectra. This is true throughout the whole period domain for both site classes. Comparing this study's response spectra to what is prescribed in the code, the Peak Ground Accelerations (the y-intercept or the spectral acceleration at 0th period) do not differ much. Focusing on the shorter period range (up to 0.2s), spectral accelerations are also very close. It should be noted, however, that rocks or very hard/dense soils (site classes S_B and S_C) tend to resonate with high-frequency seismic waves, and not so much with low-frequency seismic waves. This is the reason the response spectra on site classes S_B and S_C are expected to peak somewhere within 0.1s to 0.3s, and is also the reason why the response spectrum for the southern area of the Metro Manila peaks at a longer period compared to that of its northern counterpart.

As the period increases past the shorter period range, the spectral accelerations of the code-prescribed response spectra plateaus and becomes much higher than the other response spectra thereafter (near-source effects play a significant role in this finding). As a result, the generalization of the code-prescribed spectrum is very much highlighted in this scenario.

When designing for specific infrastructures within the Metro, this study's site-specific response spectra can be used as long as near-source effects are accounted for prior to analysis.

7 CONCLUSION

The probabilistic seismic hazard analysis of Metro Manila carried out in this study 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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