International Research Journal of
SCIENCE, TECHNOLOGY, EDUCATION, AND MANAGEMENT
P-ISSN: 2799-063X — E-ISSN: 2799-0648
Volume 4, No. 4 | December 2024

Seismic vulnerability assessment of Palacio del Gobernador using fragility curve

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ABSTRACT

Palacio del Gobernador is a 48-year standing 9-storey building located at Intramuros, Manila. Its location of about 10.4 km from the West Valley Fault makes it vulnerable to seismic activities that are expected to occur at the fault, including the "Big One." This study assessed the seismic vulnerability of the Palacio del Gobernador by generating and analyzing its seismic fragility curves. The researchers generated the digital model of the building using SAP2000. The structural model was then subjected to a Pushover Analysis. Ground motion data of local and foreign earthquakes were collected from DOST-PHIVOLCS and PEER. These were subjected to Response Spectrum Analysis using PRISM in order to generate their response spectra. The results of the two analyses were used in the Capacity Spectrum Method using SAP2000 to generate damage rank frequencies. These values were then used to generate the seismic fragility curves. The values in these curves revealed that, under a 0.4g PGA ground motion, the Palacio del Gobernador has a 49-50% probability of no damage, 18-20% probability of slight damage, 9-11% probability of moderate damage, 6-7% probability of extensive damage, and a 5% probability of total collapse. In particular, the probability of reaching the exceeding extensive damage is under 10%, which is the reference value for 0.4g PGA ground motion based on Section 208.5.3.2 of the NSCP 2015. These findings indicate that the Palacio del Gobernador is resilient against extensive damage when subjected to an earthquake that is comparable to the "Big One" and does not require additional measures to mitigate potential earthquake damage.

ARTICLE INFO

Received : Sept. 25, 2024
Revised : Nov. 14, 2024
Accepted : Dec. 30, 2024

KEYWORDS

Fragility curve, Palacio del Gobernador, Seismic vulnerability assessment, The Big One

Suggested Citation (APA Style 7th Edition):

Anorico, R.B.R., Cutin, N.S.P., De Guzman, A.G.P., Gigante, J.B., Suapero, P.S.M., & Baylon, M.B. (2024). Seismic vulnerability assessment of Palacio del Gobernador using fragility curve. *International Research Journal of Science, Technology, Education, and Management*, 4(4), 1-9. https://doi.org/10.5281/zenodo.14744004

INTRODUCTION

Areas that experience frequent seismic activity, especially those along active fault lines, are at great risk and at the same time pose a threat to the structural soundness of buildings during an earthquake as this tends to result in a loss of life and businesses. Owing to the need for building owners of such regions to be accountable, researchers have employed the use of seismic assessments alongside vulnerability analysis to account for the risk. By doing so, engineers are able to predict the behaviour of a structure during and after an earthquake, resulting in valuable data that can be leveraged for retrofitting and preparedness plans.

The Philippines in general is at risk of experiencing the "Big One" and Metro Manila's West Valley Fault is on higher notice as it has been predicted that it will at one point experience an earthquake (Malicdem, 2017). That earthquake is said to be on a magnitude 7.2, the damage caused would be significant, hence structures in the region need to go a seismic assessment. The National Structural Code of the Philippines set in 2015 has strict laws on the design of buildings as they have to be earthquake resistant. The guidelines are still comprehensive and assist greatly when coupled with more traditional guidance and even more so the latest updates can be easily searched online. However, for structures that have already been built, especially since older codes were used, the buildings may face problems that would require them to seek an assessment.

Seismic fragility curves were developed to assess the performance of structures in an earthquake-prone area. The application of fragility curves is diverse. In summary, fragility curves allow for probabilistic assessment of physical and social structural damage especially, life loss during earthquakes, without building a detailed mathematical model for the entire structure. Also, fragility curves extend the application of the building performance levels summary tables based on the intensity of the earthquake (Chopra, 2020). As noted above, the stochastic character of the dynamics of the seismic impact on structures makes it necessary to apply probabilistic techniques (Kausel, 2017).

The Palacio del Gobernador is a government office building situated in Intramuros, Manila that is 48 years old and has nine floors. Because of its location, it is approximately 10.4 kilometers away from the West Valley Fault. Due to its age and its existence next to a fault line, its seismic vulnerability serves an important purpose in determining if the safety of the residents is ensured and if the government institutions located there are still operational. This manuscript adds to the already existing pool of knowledge by developing fragility curves so as to assess the structural response of the Palacio del Gobernador under the simulated earthquake condition.

Various studies that assessed seismic vulnerability of existing structures used fragility curves. One of these studies was done on the Philippine General Hospital (Baylon et al., 2022), where it was determined that the Spine Building could collapse. Another study was done on the PUP Nutrition and Food Technology Research Building (Almeria et al., 2021). Other local studies include the seismic analysis of PUP Engineering and Science Research Center (Bernarte et al., 2022) and that of the PUP Nutrition and Food Technology Research Building (Almeria et al., 2021).

To summarize, seismic analysis by generating seismic fragility curves proves appropriate in overcoming the difficulties of rigorous non-linear response history analysis. This method is thus adopted in the present seismic analysis of the Palacio del Gobernador.

Through the undertaking of this seismic vulnerability assessment, it is our sincere hope that we are able to provide an insight into the performance of the building in future seismic events under consideration and, in doing so, emphasize the significance of such assessments in seismically active areas such as the Metro Manila region.

OBJECTIVES OF THE STUDY

The primary objective of this research was to investigate the seismic vulnerability of Palacio del Gobernador against an earthquake of equal or stronger magnitude to the Big One earthquake by generating the seismic fragility curves of the building. Using these curves, it is aimed to determine the probabilities that the Palacio del Gobernador exceeds damage ranks at 0.4g peak ground acceleration along the X- and Y-axes in the North-South and East-West directions.

MATERIALS AND METHODS

The outline of research design is given in Fig. 1. This indicates the use of structural plan of Palacio del Gobernador and the raw earthquake data as the sole inputs to a series of processes to arrive at the ultimate results, which are the fragility curves and their interpretation in terms of seismic vulnerability of the building.

Data Collection

The researchers selected 45 events from the Pacific Earthquake Engineering Research Center (PEER) database. For the local earthquakes, the researchers used 45 station recordings obtained from DOST-PHIVOLCS. The selection considered that the magnitude shall not be less than 5.0 Mw. Also, the dates and locations were considered so as to allow greater variability of the earthquake ground motions, thus respecting the stochasticity of earthquake ground motion.

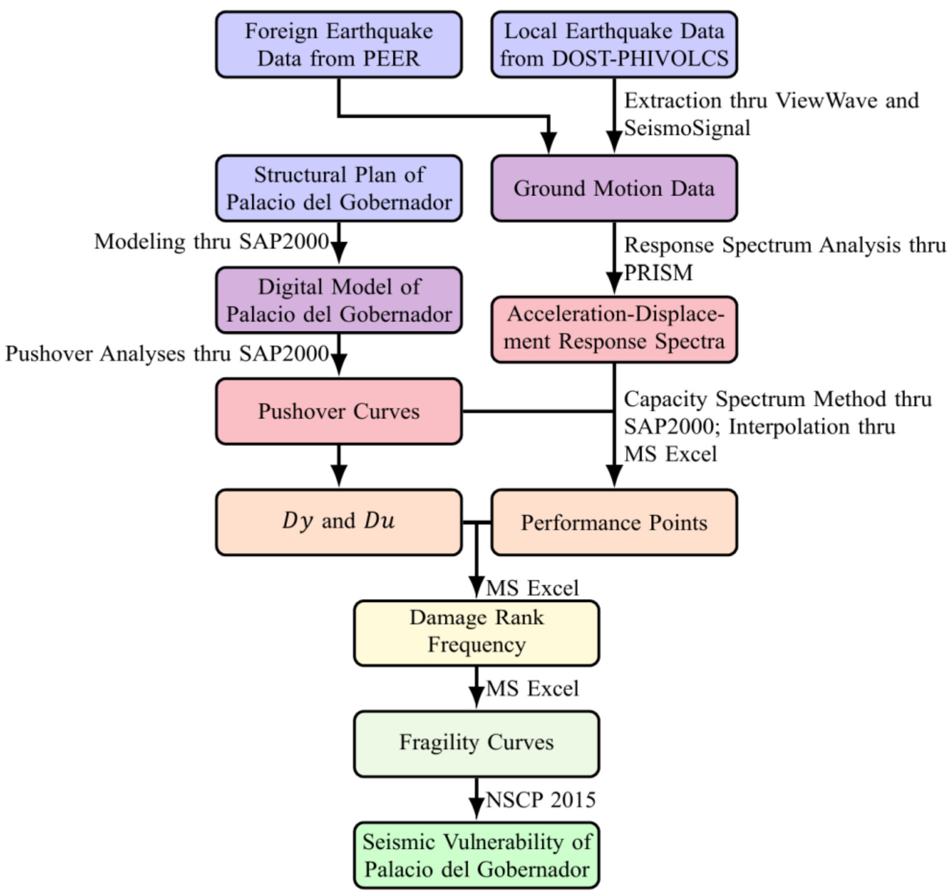

Fig. 1. Research design.

Response Spectrum Analysis

Response spectrum analysis is a prerequisite of the capacity spectrum analysis. While theoretical equations exist for this purpose (Chopra, 2020), using these manually would be impractical especially for a high number of ground motion data. PRISM is a software application that has the feature of generating response spectra, and does so efficiently in terms of time and memory. Hence, the researchers adopted PRISM in response spectrum analysis.

The local earthquake data from DOST-PHIVOLCS were not readable by PRISM. Thus, the ground motion data had to be extracted from them. The software applications ViewWave and SeismoSignal were found useful for this purpose. This extraction was not necessary for the foreign earthquake data as these are already compatible with PRISM.

As different time histories have different peak ground accelerations, these have to be normalized to make different time histories comparable to one another. The target PGAs range from 0.1g to 3.0g with a step of 0.1g. This range is selected in order to have a reliable representative of damage frequencies over which the fragility curves are based. In this response spectrum analysis, only 0.1g was the target PGA upon scaling, while the remaining target PGAs were obtained in the Capacity Spectrum Method. The normalized time history $a_{normalized}(t)$, was obtained using the equation:

$$a_{normalized}(t) = \frac{0.1g}{PGA_{max}}\, a_{actual}(t)$$

where $a_{actual}(t)$ is the actual time history and $PGA_{max} = [a_{actual}(t)]$. This principle is used by PRISM; the target PGA (0.1g in this case) was inputted before PRISM scaled the time history. From the resulting scaled time history, the response spectra were obtained, with the elastic spectra as the spectrum type. The viscous damping ratio was set equal to 5 percent according to Item 2 of Section 208.5.3.2 of the NSCP 2015 (ASEP, 2019).

Structural Modelling

Prior to seismic analyses, a digital model of Palacio del Gobernador had to be generated. SAP2000 has this feature where detailed specifications can be inputted, including the geometry and material properties of the concrete and steel reinforcement. In addition, a three-dimensional image of the model can be displayed, thus allowing for visual inspection for accuracy of the model. Furthermore, SAP2000 has the additional features of conducting Pushover Analysis and Capacity Spectrum Method, which are the succeeding steps of the methodology of the present study. Hence, selecting SAP2000 allows for convenience and compatibility of performing these analytical steps.

Pushover Analysis

The digital model of Palacio del Gobernador was then subjected to linear static load case under dead load. This allowed the generation of the deformed configuration of the building, which would serve as a given for the non-linear static pushover analysis. In this succeeding step, plastic hinges were predetermined at all points that are at 10% of the span length from a joint. Running the pushover analysis finally yields the pushover curves which depict the inter-story deformation as a function of applied base shear.

From the pushover analysis, the yield displacement Dy and the ultimate displacement Du were extracted. These were used as the bases of the definition of the damage states (Vasavada, 2016, as cited in Jambalos et al., 2020) that were used in the generation of fragility curves.

Capacity Spectrum Method

The pushover curves, in conjunction with the response spectra, were used in Capacity Spectrum Method. For each axis of the structure, earthquake, direction, and for selected target PGAs (i.e., from 0.1g to 3.0g with step size of 0.1g), a performance point was generated as a pair of coordinates of base shear and displacement where the pushover curve and the demand spectrum intersects.

To take advantage of numerical analyses, instead of obtaining the performance point for all 30 PGAs directly from the above procedure, only at most ten of them were obtained. The performance points for the remaining PGAs were obtained using linear interpolation. Consideration is made in predicting values that are as accurate as possible by ensuring that the performance point at 0.1g and the performance point at the highest PGA where a performance point exists are recorded, and the number of consecutive PGAs that are to be interpolated did not exceed two. This ensures that the recorded values from SAP2000 are conserved, capturing the behavior of the curve of PGA vs. displacement with no significant errors.

Damage States and Damage Ranks

Using the determined values of Dy and Du, the damage state threshold values were calculated according to the expressions in Table 1.

Table 1. Damage State Threshold Values (Vasavada, 2016, as cited in Jambalos et al., 2020).

Damage States	Spectral Displacements
Slight	$0.7Dy$
Moderate	Dy
Extensive	$Dy + 0.25(Du - Dy)$
Collapse	Du

These damage states are represented by symbols (Table 2). Thus, for example, a spectral displacement that lies below 0.7Dy is said to incur no damage which corresponds to damage rank D, a spectral displacement that lies between 0.7Dy and Dy is said to incur slight damage which corresponds to damage rank A, and so on.

Table 2. Damage Rank (HAZUS, 2003, as cited in Baylon & Marcos, 2018).

Damage Rank	Definition
D	No Damage
C	Slight Damage
B	Moderate Damage
A	Extensive Damage
As	Complete Damage

Given the above definitions, the tables of peak ground acceleration vs. spectral displacement for each earthquake and each direction were transformed into peak ground acceleration vs. damage rank accordingly.

Fragility Curves

The fragility curves depict the probability of exceeding a damage rank given a peak ground acceleration. Among various equations for the cumulative probability of exceedance being used to generate fragility curve, the most commonly used according to Nazri (2018) is given by:

$$Pr = \Phi\left(\frac{\ln X - \lambda}{\xi}\right)$$

where:

Φ = cumulative standard normal distribution function,
X = peak ground acceleration,
λ = mean of $\ln X$, and
ξ = standard deviation of $\ln X$,

as also used by Ibrahim and El-Shami (2011). Thus, the probability of exceedance is log-normally distributed. The mean λ and the standard deviation ξ are evaluated using:

$$\lambda = \frac{\sum f \ln X}{\sum f}$$

and:

$$\xi = \sqrt{\frac{\sum(\ln X - \lambda)^2}{N-1}}$$

respectively. Here, f is the damage rank frequency, and N is the number of values of PGA considered, which, in the present case, is equal to 30.

The probabilities of exceedance at 0.4g PGA were selected. These were compared against 10% as given in Section 208.5.3.2 of the NSCP 2015. This provision is appropriate because 0.4g PGA falls under Intensity VIII (Zera & Nafian, 2017), the intensity of the Big One earthquake.

RESULTS AND DISCUSSION

Pushover Analysis

The pushover analysis revealed that, along the X-axis, the yield displacement is 146.732 mm and the ultimate displacement is 709.232 mm. Along the Y-axis, the yield displacement is 113.787 mm and the ultimate displacement is 994.113 mm. In comparison to the yield and ultimate displacements of structures analyzed, for example, by Baylon & Marcos (2018), Almeria et al. (2021), Atendido et al. (2022), and Bernarte et al. (2022), these are relatively higher in magnitude. This is expected for a taller structure given that the values obtained are roof displacements.

Fragility Curves

The frequency of each damage rank for each PGA, earthquake direction, and axis, were graphed as fragility curves as shown in Fig. 2 and Fig. 3.

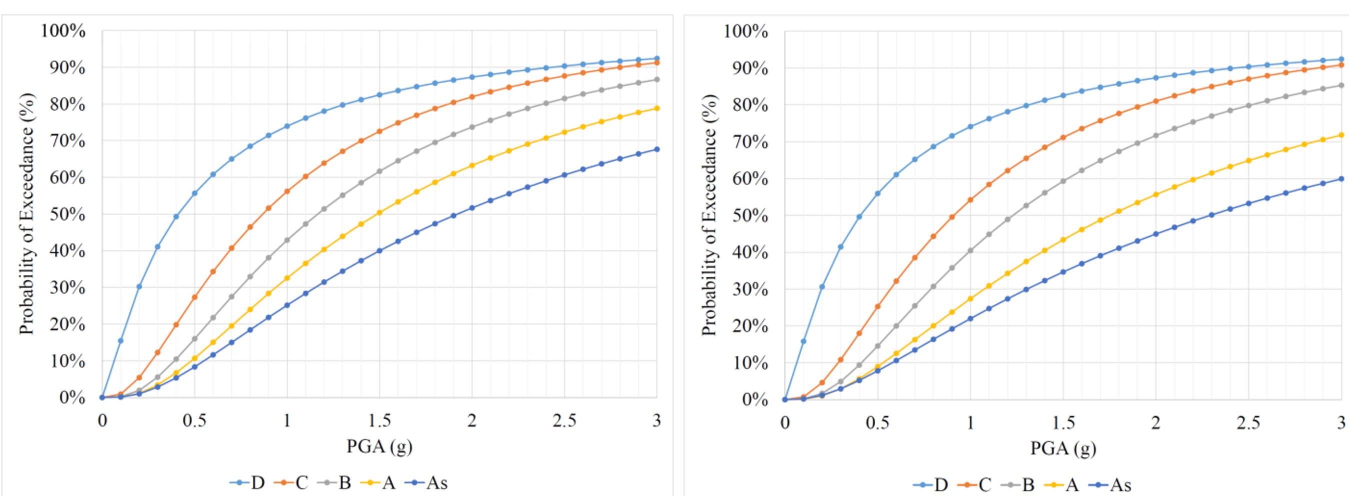

Fig. 2. Seismic fragility curves due to North-South earthquake along X-axis (left) and along Y-axis (right).

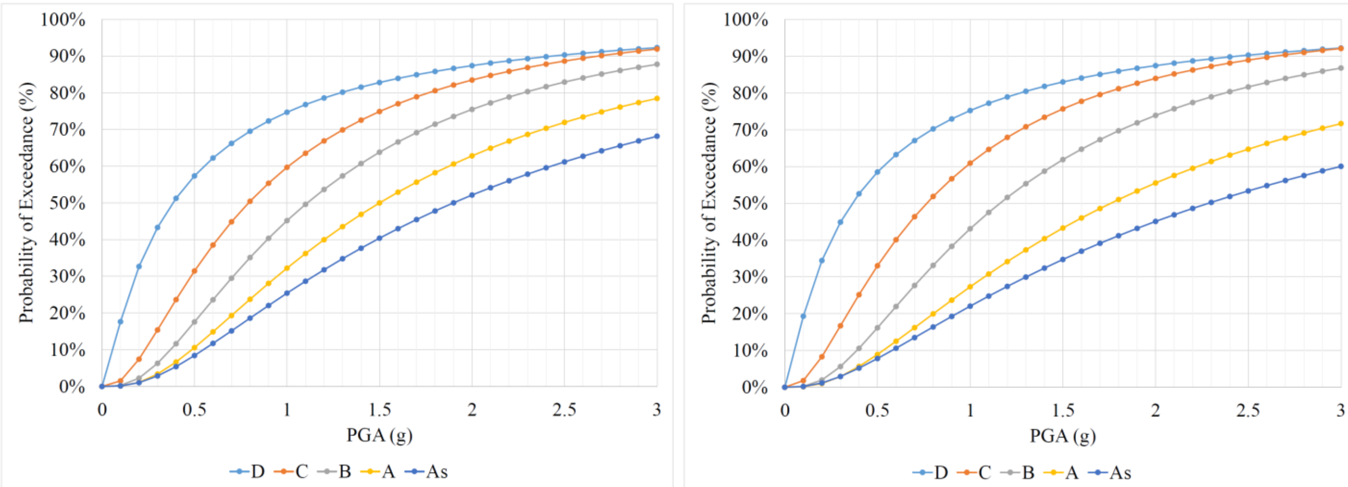

Fig. 3. Seismic fragility curves due to East-West earthquake along X-axis (left) and along Y-axis (right).

For each curve, the probability of exceedance increases monotonically with the increase in PGA. This is an expected behavior owing to being cumulative probability distributions, a behaviour that is also shared by the fragility curves generated by Baylon and Marcos (2018) and in recent papers by Almeria et al. (2021), Atendido et al. (2022), and Bernarte et al. (2022).

As per NSCP 2015 under the seismic provisions, an earthquake of PGA of 0.4g must be attained to expect a moderate to complete damage to buildings. Using the developed seismic fragility curves, the implication is that one can measure the building's performance for a 10% probability of exceedance.

In view of this, the probabilities of exceedance of Palacio del Gobernador at 0.4g PGA were determined from the seismic fragility curves and are summarized in Table 3. The values under extensive and complete damage do not exceed 10%. This indicates that the Palacio del Gobernador does not exceed a probability of 10% obtaining an extensive damage under an earthquake with 0.4g PGA, which satisfies the current seismic design requirement of NSCP 2015 under Section 208.5.3.2.

Table 3. Probability of Exceedance (%) at 0.4g PGA.

		No Damage	Slight Damage	Moderate Damage	Extensive Damage	Complete Damage
North-South	X-Axis	49.2997	19.8474	10.4595	6.7207	5.3602
	Y-Axis	49.5960	17.9928	9.3635	5.6497	5.1885
East-West	X-Axis	51.2372	23.6498	11.6324	6.6374	5.3863
	Y-Axis	52.6014	25.1608	10.5536	5.6375	5.1883

Furthermore, Zera & Nafian (2017) classifies 0.4g PGA as Intensity VIII, which is the expected intensity of the Big One earthquake. Integrating the above results with this, it follows that the Palacio del Gobernador is unlikely to sustain extensive damage under an earthquake that is comparable to the Big One.

The performance-based design of buildings, which is being implemented nowadays, is based on the data gathered from previous time history of ground motion. With the ever-changing climate on earth, one can always update the fragility curves based on the new ground motion data in developing the fragility curves, thus, also updating the "signature" of the building in accordance with the specified provision of the NSCP. In turn, it can be also attributed to the updates of our NSCP in the long run, after amassing greater number of buildings with corresponding fragility curves.

CONCLUSION AND RECOMMENDATION

The study found that the probability of exceedance for Extensive Damage is 7% at X-axis in both directions while, 6% in Y-axis at both directions at 0.4g PGA. These suggest that the structural design of Palacio del Gobernador does not allow 10% of probability of exceeding extensive damage when subjected to ground motion of 0.4g PGA in both directions. Furthermore, as 0.4g PGA equates to an intensity of VIII, the Palacio del Gobernador is unlikely to reach extensive damage during an Intensity VIII earthquake, such as the Big One earthquake. However, the building has a probability of 10% moderate damage under such event. From the results of the analysis, the researchers also found that the measures for improving the capacity of Palacio del Gobernador against severe to collapse damage is not necessary and only measures against moderate damage may be considered.

Specific recommendations for improving the building's resilience are beyond the scope of this paper. Hence, future researchers may consider conducting studies for that purpose.

Another limitation of the present paper is that only the horizontal ground motions were the basis of the generated fragility curves. Thus, future researchers are recommended to include vertical ground motions in the analysis.

Finally, the definitions of the damage ranks were adopted from Vasavada (2016, as cited in Jambalos et al., 2020). Thus, future researchers are advised to be aware of possible changes in the definitions of damage ranks that may emerge in the literature.

REFERENCES

Almeria, C., Barasi, R., Cruz, D. K., Cruza, J., Montifar, J., & Baylon, M. (2021). *Development of seismic fragility curves of the PUP-nutrition and food technology research building* [Undergraduate thesis, Polytechnic University of the Philippines]. https://doi.org/10.13140/RG.2.2.18568.08965.

ASEP. (2019). *National structural code of the Philippines 2015 (7th ed.) Volume I: Buildings, towers, and other vertical structures.*

Atendido, A., Atillano, G., Mabunga, J., & Oliveros, J., (2022). *Development of seismic fragility curves for DPWH building of Doña Rosario elementary school* [Undergraduate thesis, Polytechnic University of the Philippines].

Baylon, M., & Marcos M. (2018). Seismic vulnerability assessment of Adamson University buildings' as-built using fragility curves. *Global Journal of Engineering Research*. https://doi.org/10.17406/GJRE/290899

Baylon, M., Sevilla, M., Cutora, M., Villa, R., Reynes, P., & Montemayor, J. (2022). Development of fragility curves for seismic vulnerability: The case of Philippine General Hospital Spine Building. *International Research Journal of Science, Technology, Education, and Management, 2*(4), 1-11. https://irjstem.com/wp-content/uploads/2023/02/IRJSTEM-V2N4-2022-Paper1.pdf

Bernarte, R., Edralin, L., Lapinig, R., Paguirigan, L., & Perez, D. (2022). *Seismic vulnerability assessment for the PUP Engineering and Science Research Center* [Undergraduate thesis, Polytechnic University of the Philippines].

Chopra, A. K. (2020). *Dynamics of structures: Theory and applications to earthquake engineering* (5th ed.). Pearson Education Limited.

Ibrahim, Y. E., & El-Shami M. M. (2011). Seismic fragility curves for mid-rise reinforcement concrete frames in Kingdom of Saudi Arabia. *The IES Journal Part A Civil & Structural Engineering, 2011*, 1-11. https://doi.org/10.1080/19373260.2011.609325

Jambalos, A.-A., Santos, K., Trillana, R., & Baylon, M. (2020). *Seismic vulnerability assessment of San Agustin church in Intramuros Manila using fragility curves* [Undergraduate thesis, Colegio de San Juan de Letran – Manila]. https://doi.org/10.13140/RG.2.2.14177.5360

Kausel, E. (2017). *Advanced structural dynamics.* Cambridge University Press.

Malicdem, E. (2017). *Barangays and buildings traversed by the valley fault system*. https://doi.org/10.13140/RG.2.2.31921.07526

Meskouris, K., Butenweg, C., Hinzen, K. G., & Höffer, R. (2019). *Structural dynamics with applications in earthquake and wind engineering* (2nd ed.). Springer-Verlag GmbH.

Nazri, F. M. (2018). *Seismic fragility assessment for buildings due to earthquake excitation.* Springer Nature.

Rentschler, J., Klaiber, C., Saldivar-Sali, A., & Shenfeld, E. (2023). *Seismic resilience in Metro Manila: Accessing healthcare after a catastrophic earthquake on the West Valley Fault line*. World Bank Blogs. https://blogs.worldbank.org/sustainablecities/seismic-resilience-metro-manila-accessing-healthcare-after-catastrophic

Zera, T., & Nafian, M. (2017). Comparing two models of mapping the peak ground acceleration (PGA) in Western Java. *International Conference on Science and Technology (ICOSAT 2017)-Promoting Sustainable Agriculture, Food Security, Energy, and Environment Through Science and Technology for Development*, 140-142. Atlantis Press. https://www.researchgate.net/publication/325559647_Comparing_Two_Models_of_Mapping_the_Peak_Ground_Acceleration_PGA_in_Western_Java