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Development of fragility curves for seismic vulnerability assessment: The case of Philippine General Hospital spine building

Michael B. Baylon[1], Maria Emilia P. Sevilla[2], Miller DL. Cutora[3], Rikki Mae S. Villa[4], Princess Mherlene P. Reynes[5], Jhona May V. Montemayor[6]
[1]*USHER Technologies Incorporated, Philippines*`
[2,3,4,5,6]*Pamantasan ng Lungsod ng Maynila, Philippines*
Corresponding email: ikingbalon@gmail.com

ABSTRACT

The Philippine General Hospital (PGH) is a tertiary hospital in Ermita, Manila, that was founded on August 17, 1907. It adheres to the philosophy of providing all Filipinos with internationally competitive, cost-effective, compassionate, and accessible health care. It was recently one of the COVID-19 facilities. The PGH sits 9.2 kilometers east of the West Valley Fault, making it more vulnerable to 'The Big One,' a 7.2 magnitude earthquake. Until present, no research has been done to examine the PGH's seismic susceptibility in the case of a large-magnitude earthquake. In keeping with this, the study intended to analyze the seismic susceptibility of the Spine Building, one of PGH's oldest structures. It focused on constructing fragility curves to assess if the building could sustain a 0.4g peak ground acceleration (PGA) earthquake with a maximum likelihood of exceedance of 10%, as required by the Philippine National Structural Code (NSCP) for Seismic Zone 4 sites. The study employed 12 worldwide and 12 local earthquakes from the Incorporated Research Institutions for Seismology, with PGA excitation levels ranging from 0.1g to 3.0g (with a 0.1g gap) (IRIS). The structural model of the PGH Spine Building was created using SAP2000, which was subsequently utilized to perform Pushover Analysis using the Capacity Spectrum Method (CSM). The PGH Spine Building might collapse with 0.538g PGA, which corresponds to Intensity VIII, according to the results of the developed fragility curves, producing significant structural shaking. Furthermore, for 0.4g PGA, the calculated highest likelihood of exceedance in the 'collapse damage' condition was 5.24 percent, with no results above 10%, implying that the PGH Spine Building complies with the NSCP seismic requirement for structures located in Seismic Zone 4. As a result, an adequate retrofitting strategy is not required for the PGH Spine Building.

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INTRODUCTION

Philippine General Hospital, officially known as the University of the Philippines-Philippines General Hospital, is a general hospital devoted to providing all Filipinos, particularly the poor and underprivileged, with internationally competitive, cost-effective, compassionate, and accessible health care (PGH, 2021). PGH has been classified as one of the country's COVID-19 referral sites in light of the COVID-19 pandemic. While treating other patients, the hospital allocated 130 beds for COVID-19 patients (Llaneta, 2020).

A study to examine the seismic susceptibility of the Philippine General Hospital (PGH) in the case of a large-magnitude earthquake has never been conducted. Given that the Philippines is an archipelago, its distinctive geographic location - between two main tectonic plates and within the Pacific Ring of Fire - makes it among the top three countries in terms of population exposure and susceptibility risk (Bollenttino, Alcanya, Enriquez, & Vinck, 2018). Furthermore, the Philippines contains several active faults that make it more prone to earthquakes and volcanic eruptions.

The research employed Pushover Analysis and the Capacity Spectrum Method (CSM) to generate fragility curves for the x and y axes of the PGH Spine Building. To that end, the CSM only examined ground motion data from previous earthquakes in the horizontal (East-West) and vertical (North-South) directions. As a result, information about the earthquakes was collected from the Incorporated Research Institutions for Seismology (IRIS). The magnitude and severity of the 12 international earthquakes (from Japan, Taiwan, Indonesia, Thailand, India, Nepal, and China) and 12 local earthquakes are shown individually in Tables 1 and 2.

Table 1. Information of Selected International Earthquakes

Location	Magnitude	Date
Tohoku, Japan	9.1	March 11, 2011
Western Coast of North Sumatra	9.0	December 26, 2004
Japan's Northern Coast	8.3	November 15, 2006
Kathmandu, Nepal	7.9	April 25, 2015
Taipei, Taiwan	7.7	September 20, 1999
Gujarat, India	7.7	January 26, 2001
Miyagi, Japan	7.0	March 20, 2021
Awaji Island, Japan	6.8	January 16, 1995
Near West Coast of Honshu, Japan	6.6	October 23, 2004
Hualien, Taiwan	6.4	February 6, 2018
Tainan, Taiwan	6.4	February 5, 2016
Mae Lao District, Thailand	6.1	May 11, 2004

Table 2. Information of Selected Local Earthquakes

Location	Magnitude	Date
Palimbang, Sultan Kudarat	7.5	March 5, 2002
Zambales, Luzon	7.3	December 11, 1999
Mati, Davao Oriental	7.3	May 17, 1992
Bohol, Central Visayas	7.1	October 15, 2013
Baco, Mindoro	7.0	November 14, 1994
Panay, Western Visayas	7.0	June 14, 1990
Sarangani, Davao Occidental	6.9	April 28, 2017
Matanao, Davao del Sur	6.8	December 15, 2019
Bohol, Central Visayas	6.7	February 8, 1990
Cotabato, Maguindanao	6.6	October 29, 2019
Masbate, Bicol Region	6.6	August 18, 2020
Baguio City, Luzon	6.5	July 17, 1990

The study's goal was to assess the PGH Spine Building's sensitivity to seismic activity. The specific goals of this study included modeling the as-built plan of the PGH Spine Building, obtaining yield displacement and ultimate displacement from pushover curves, identifying performance points from the intersection of the capacity curve and response spectrum, developing seismic fragility curves that assess the 10% likelihood of exceeding under various damage states, such as minor, moderate, extensive, and collapse, and assessing the study's findings.

METHODOLOGY

The study's purpose was to see how susceptible the PGH Spine Building would be in the event of a large earthquake in the future. As a result, new parameters were developed to construct the fragility curves utilizing analytical techniques such as Pushover Analysis (Nonlinear Static Analysis) and the Capacity Spectrum Method (CSM). Figure 1 also displays the study design, which included the procedures utilized to generate fragility curves.

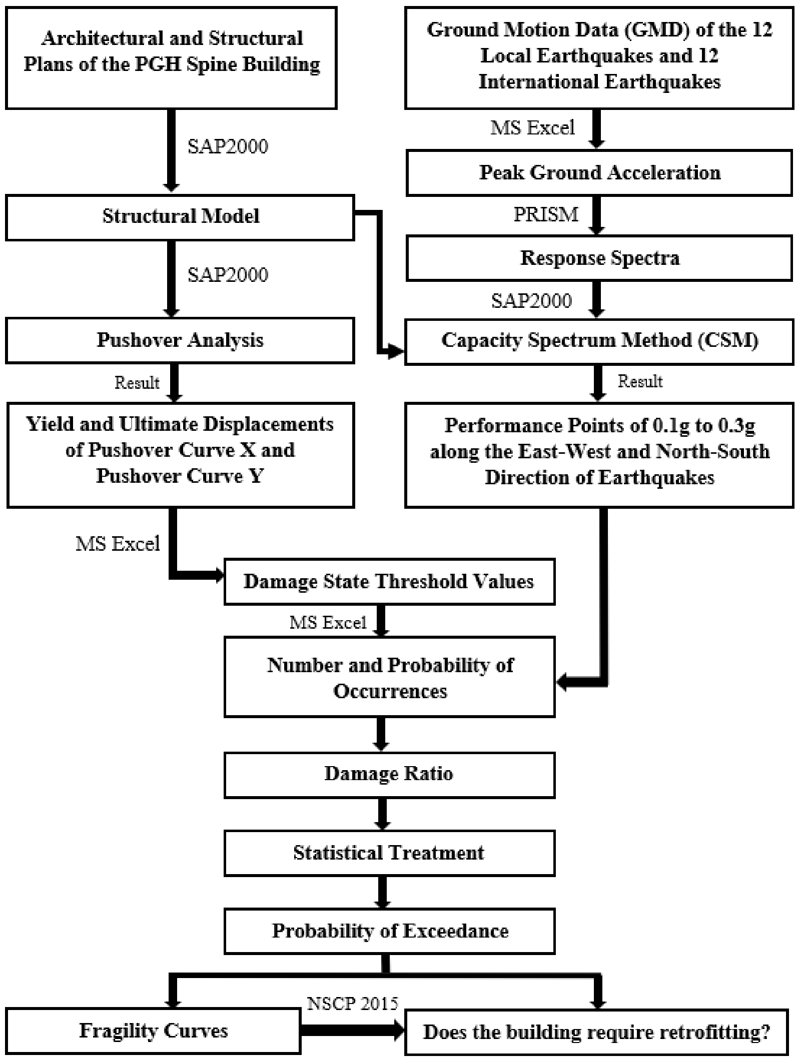

Fig. 1. Research Design in Developing Fragility Curves

Capacity Spectrum Method

The Capacity Spectrum Method (CSM) is a performance-based seismic assessment that evaluates a structure's seismic capacity. According to Wang and Pujol (2014), the most common use of CSM is to estimate the inelastic reaction of an existing structure to an earthquake in order to evaluate its performance and condition. The ATC-40 was used to construct the Capacity Spectrum Method (CSM), which was based on the equivalent linearization approach (Applied Technology Council, 1996). As a consequence, a capacity spectrum consisting of a demand curve and a capacity curve will be formed. The critical performance point in the seismic analysis of the structure is where these two curves intersect. CSM was carried out using the following methods in particular:

1. Select Ground Motion Data (GMD) from IRIS Earthquake Browser.
2. Obtain the Normalized Peak Ground Acceleration (PGA). The Equation (1), formulated by Baylon et al. (2018), was employed to determine the normalized PGAs.

$$PGA_{Nomalized} = (GMD)(\frac{PGA_{Excitation}}{PGA_{Maximum}}) \quad (1)$$

Where:
GMD = ground motion data
$PGA_{Excitation}$ = excitation level of PGA (i.e., ranging from 0.1g to 3.0g with an interval of 0.1g)
$PGA_{Maximum}$ = absolute maximum ground motion data

3. Convert Normalized PGA into Response Spectra through PRISM.
4. Define Response Spectrum functions.
5. Define new load case of the Capacity Spectrum Method (CSM).
6. Set the load cases required to run for Capacity Spectrum Method.

Developing of Seismic Fragility Curves

The yield displacement and ultimate displacement of the Pushover Analysis and the performance points of the Capacity Spectrum Method (CSM) would result in the seismic fragility curves of the PGH Spine Building. The following were the detailed step-by-step process in developing these fragility curves that were adapted by the analytical approach of Shinozuka (2000):

1. Compute the damage state threshold using Table 3 to determine the range of spectral displacement of each damage state.

Table 3. Damage State Threshold Values (Adapted from source: Vasavada & Petel in Baylon et al., 2021)

Damage State	Description	Threshold Values
D	No Damage	$0 < d_{pp} \leq 0.7d_y$
C	Slight Damage	$0.7d_y < d_{pp} \leq d_y$
B	Moderate Damage	$d_y < d_{pp} \leq [d_y + 0.25(d_u - d_y)]$
A	Extensive Damage	$[d_y + 0.25(d_u - d_y)] < d_{pp} \leq d_u$
As	Collapse Damage	$d_{pp} > d_u$

Where:
d_{pp} = displacement of the performance points; d_y = yield displacement; d_u = ultimate displacement.

2. Evaluate the damage state of all the displacement of the performance points of the Capacity Curve and Response Spectra.
3. Determined the number of occurrences of each damage state at each excitation level of peak ground acceleration (PGA).

4. Compute the probability of occurrence, in which the number of occurrences of each damage state at different PGA excitation levels was divided by the total number of occurrences of each damage state.
5. Calculate the damage ratio by getting the cumulative sum of the probability of occurrence.
6. Utilize the natural logarithmic (ln) of PGA to clearly visualize and validate the seismic curves of the damage ratio. The mean and standard deviation for each damage state was obtained by employing Equation (2) and Equation (3).

$$\lambda = \frac{\sum x}{N} \quad (2)$$

$$\xi = \frac{\sqrt{\sum (x-\lambda)^2}}{N-1} \quad (3)$$

Where:
x = individual ground motion data obtained; N = sample size of ground motion data obtained;
λ = mean ground motion data obtained from Equation (2)

7. Compute the probability of exceedance (P_r) using Equation (4) formulated by Shinozuka in Baylon et al. (2021).

$$Pr = \Phi \left[\frac{\{ln(X) - \lambda\}}{\xi}\right] \quad (4)$$

Where:
Φ = standard normal distribution; X = peak ground acceleration; λ = mean of the ground motion data;
ξ = standard deviation.

8. Plot the probability of exceedance against the peak ground acceleration (PGA) excitation level (i.e., 0.1g to 3.0g) to develop the seismic fragility curves in the x and y axes of the PGH Spine Building due to East-West and North-South directions of earthquakes.

RESULTS AND DISCUSSION

Following the site visit, the structural modelling of the PGH Spine Building was developed utilizing the as-built blueprints, both architectural and structural. Following that, the Pushover Analysis and Capacity Spectrum Method (CSM) were used. These two analyses produced seismic fragility curves for the PGH Spine Building.

Using SAP2000, the structural model was created in compliance with the architectural and structural designs. In accordance with this, Figure 2 depicts the final structural model in isometric perspective. The model depicted the various structural parts of the PGH Spine Building, with the research focusing solely on the structure's beams, girders, and columns. Aside from that, the foundation now has pinned hinge joint restrictions.

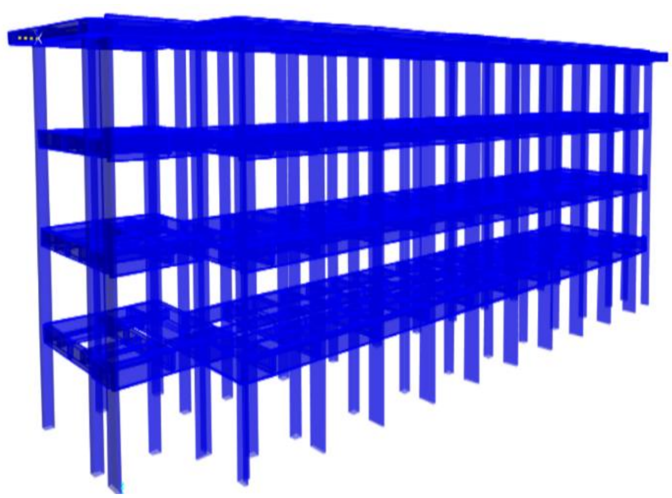

Fig. 2. Isometric View of Structural Model of PGH Spine Building

Figure 3 shows the Pushover Curve in the x-direction of the PGH Spine Building. It could also be observed that the yield displacement (d_y) appeared to be the point where the change of slope took place, which was explicitly at 14.915 mm of displacement under 1047.394 kN. In addition, it was found out that the ultimate displacement (d_u) of the Pushover Curve in the x-direction was at 522.164 mm under the maximum base shear force of 5022.896 kN.

Figure 4 illustrates the Pushover Curve in the y-direction of the PGH Spine Building. It could be observed that an 11.697 mm of displacement at a base shear force of 1068.634 kN is the point where the change in slope took place, thus pertained to yield displacement (d_y). In addition, it could also be observed that a displacement of 447.422 mm at a maximum base shear force of 4224.747 kN is ultimate displacement (d_u).

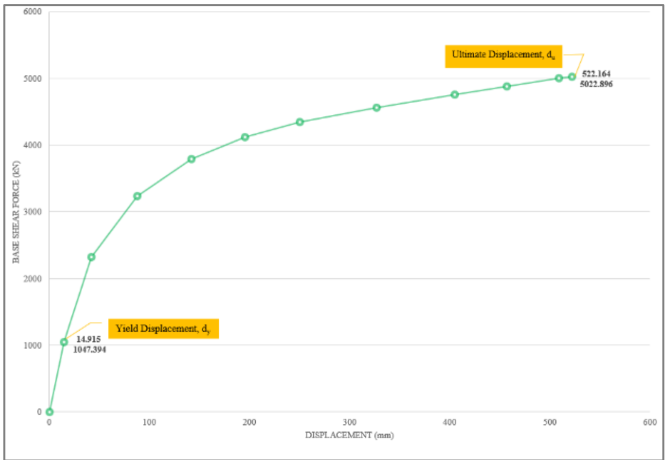

Fig. 3. Pushover Curve in X-Direction of PGH Spine Building

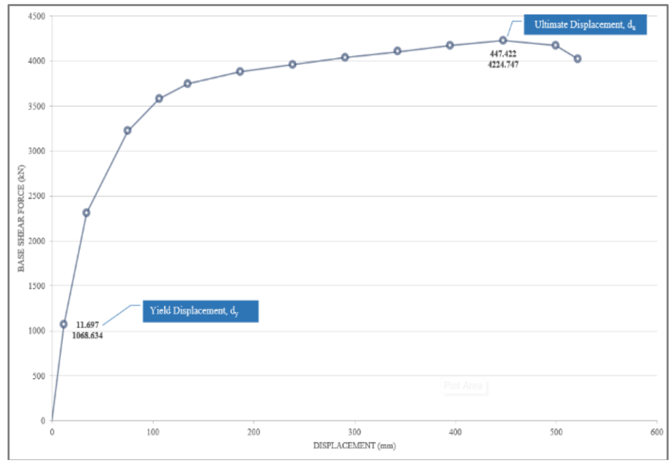

Fig. 4. Pushover Curve in Y-Direction of PGH Spine Building

Figure 5 displays the capacity curve of the building in the x-direction, while Figure 6 presents the capacity curve in the y-direction. The pushover curves were translated into capacity curves wherein the displacement from pushover curve was converted into the spectral displacement of the capacity curve. Meanwhile, the base shear force from the pushover curve was also transformed into the spectral acceleration of the capacity curve.

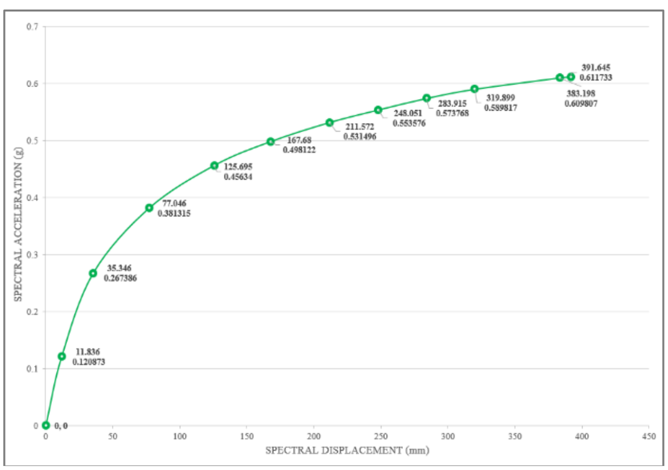

Fig. 5. Capacity Curve in X-Direction of PGH Spine Building

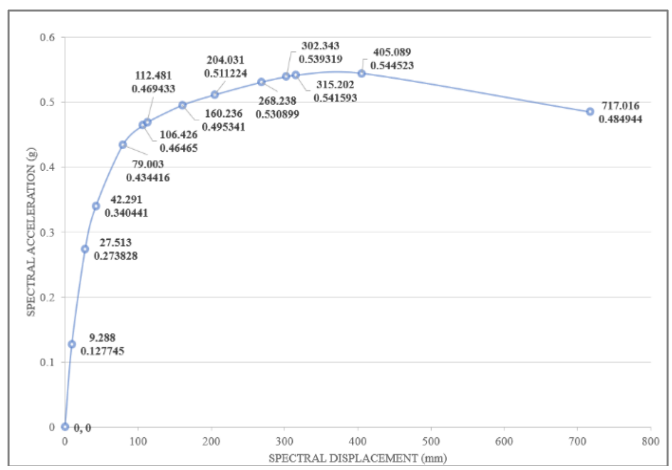

Fig. 6. Capacity Curve in Y-Direction of PGH Spine Building

The damage state threshold values were obtained using the yield displacement (d_y) and ultimate displacements (d_u) displayed in Pushover Curves in x and y directions. The threshold values were calculated using Table 3, and then applied for both x and y axes, as summarized in Tables 4 and 5.

Table 4. Summary of the Calculation of Threshold Values in X-Axis of the PGH Spine Building

DS	Solution	Threshold Values (mm)
D	$0 < dpp \leq 0.7(14.915)$	$0.000 < dpp \leq 10.441$
C	$0.7(14.915) < dpp \leq 14.915$	$10.441 < dpp \leq 14.915$
B	$14.915 < dpp \leq [14.915 + 0.25(522.164 - 14.915)]$	$14.915 < dpp \leq 141.727$
A	$[14.915 + 0.25(522.164 - 14.915)] < dpp \leq 522.164$	$141.727 < dpp \leq 522.164$
As	$dpp > 522.164$	$dpp > 522.164$

Table 5. Summary of the Calculation of Threshold Values in Y-Axis of the PGH Spine Building

DS	Solution	Threshold Values (mm)
D	$0 < dpp \leq 0.7(11.697)$	$0.000 < dpp \leq 8.188$
C	$0.7(11.697) < dpp \leq 11.697$	$8.188 < dpp \leq 11.697$
B	$11.697 < dpp \leq [11.697 + 0.25(447.422 - 11.697)]$	$11.697 < dpp \leq 120.628$
A	$[11.697 + 0.25(447.422 - 11.697)] < dpp \leq 447.422$	$120.628 < dpp \leq 447.422$
As	$dpp > 447.422$	$dpp > 447.422$

Seismic Fragility Curves

Under peak ground accelerations (PGAs) ranging from 0.1g to 3.0g, the seismic fragility curves would assess the likelihood of reaching or surpassing each damage condition - minor, moderate, extensive, and collapse. As shown in the pictures below, the Pr of each damage condition (slight, moderate, substantial, and collapse damage) was plotted in a single graph to allow for clear interpretation. The damage condition "D" or "No Damage" must not be included in the fragility curves in practice. Furthermore, the seismic fragility curves in the x and y axes of the PGH Spine Building in the East-West and North-South earthquake directions were analyzed, taking into account the four (4) damage states.

As shown in Figure 7, the x-axis of the PGH Spine Building was expected to be damaged at the maximum peak ground accelerations (PGAs) that reached the 10% probability of exceedance: at most 0.258g for 'slight damage,' at most 0.538g for 'moderate damage,' at most 0.570g for 'extensive damage,' and at most 0.583g for 'collapse damage. As a result, damage to the building in the x-axis would occur at 0.258g PGA until total damage occurred at 0.583g PGA of a probable large-magnitude earthquake.

The fragility curves in Figure 8 illustrate the maximum peak ground acceleration (PGA) at which the building reached a 10% probability of exceedance for the following damage states: 'slight damage' at most 0.303g,'moderate damage' at most 0.546g, 'extensive damage' at most 0.566g, and 'collapse damage' at most 0.587g, when measured along the y-axis of the PGH Spine Building. According to this, the y-axis building would sustain mild damage at 0.303g PGA and total damage at 0.587g PGA.

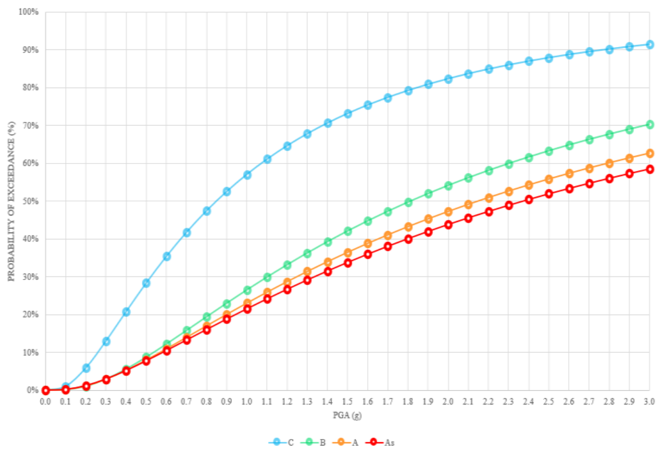

Fig. 7. Seismic Fragility Curves in X-Axis of the PGH Spine Building along the East-West Direction of Earthquakes

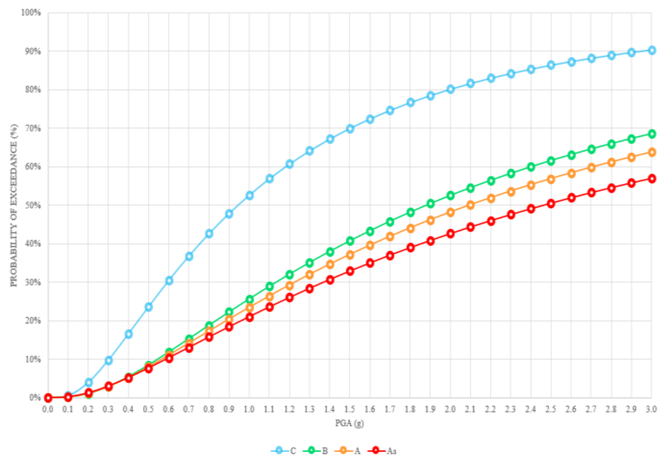

Fig. 8 Seismic Fragility Curves in Y-Axis of the PGH Spine Building along the East-West Direction of Earthquakes

Furthermore, seismic fragility curves in the x-axis in the North-South direction of the earthquakes were created, as shown in Figure 9. These fragility curves were used to determine the PGH Spine Building's ability to endure a 10% likelihood of exceeding. With this, it was shown from the curves that the x-axis of the PGH Spine Building considered the following maximum peak ground acceleration (PGA) of the possible earthquake, such as: at most 0.275g for 'slight damage', at most 0.536g for 'moderate damage', at most 0.569g for 'extensive damage', and at most 0.589g for 'collapse damage'. Based on these findings, it was determined that the specified structure could withstand an earthquake with PGA ranging from 0.275g to 0.589g.

Figure 10 also shows the seismic fragility curves of the PGH Spine Building in the y-axis according to the North-South orientation. The developed fragility curves demonstrated the maximum peak ground acceleration (PGA) that the building could withstand with a 10% probability of exceeding, such as'slight damage' at most 0.306g,'moderate damage' at most 0.538g, 'extensive damage' at most 0.573, and 'collapse damage' at most 0.587g. As a result, the building's y-axis could withstand PGAs weighing from 0.306g to 0.587g.

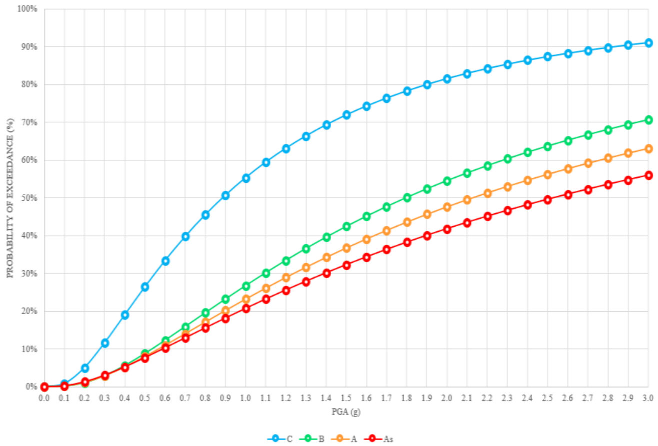

Fig. 9. Seismic Fragility Curves in X-Axis of the PGH Spine Building along the North-South Direction of Earthquakes

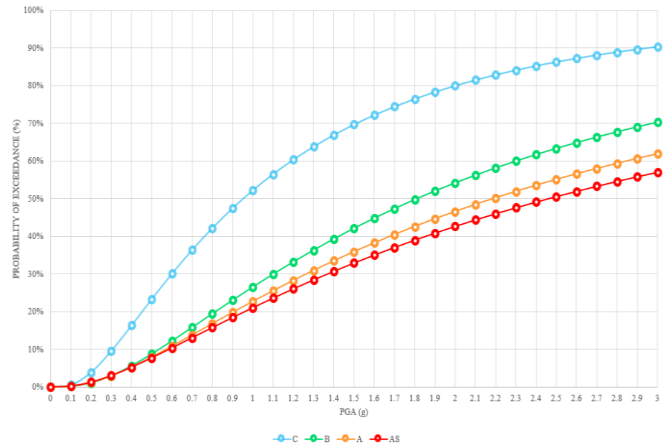

Fig. 10. Seismic Fragility Curves in Y-Axis of the PGH Spine Building along the North-South Direction of Earthquakes

The Philippine General Hospital (PGH), along with the rest of the country save for Palawan (excluding Busuanga), Sulu, and Tawi-Tawi, is required to have no more than a 10% chance of collapsing in 50 years with a peak ground acceleration (PGA) of 0.4g.

The study investigated the Probability of Exceedance (Pr) of the 'collapse damage (As)' state when the x and y axes of the PGH Spine Building were subjected to an earthquake with 0.4g PGA, taking into account the seismic requirements specified by the National Structural Code of the Philippines (NSCP) and the Structural Engineers Association of California (SEAOC). According to the results shown in Table 6, the PGH Spine Building had a probability

Furthermore, the building could survive an earthquake of 0.4g PGA, meeting the NSCP criterion for structures in Seismic Zone 4. As a result, the PGH Spine Building was declared safe when subjected to seismic activity, because only base shear force was the mode of collapse.

Table 6. Probability of Exceedance of PGH Spine Building in X and Y Axes along East-West and North-South Direction of 0.4 PGA Earthquake

	East-West (E-W) Direction of Earthquakes				North-South (N-S) Direction of Earthquakes			
	C	B	A	As	C	B	A	As
X-Axis	20.74%	5.52%	5.20%	5.20%	19.03%	5.55%	5.21%	5.24%
Y-Axis	16.66%	5.41%	5.22%	5.22%	16.33%	5.52%	5.20%	5.22%

CONCLUSION AND RECOMMENDATION

Conclusion

The least/critical peak ground acceleration for each damage condition was calculated using Table 7. The PGH Spine Building would sustain ‘slight damage (C)' if confronted to a 0.258g PGA earthquake. However, a'moderate damage (B)' to the building would result at a 0.536g PGA earthquake. Meanwhile, the building would sustain 'severe damage (A)' in the event of an earthquake with a PGA of no more than 0.566g. Finally, the building would sustain 'collapse damage (As)' during a PGA of no more than 0.583g. As a result, it was determined that the PGH Spine Building could only sustain a maximum of 0.583g PGA, which is greater than the 0.4g minimum standard of the Philippine National Structural Code (NSCP). Furthermore, if the expected seismic activity exceeds 0.583g PGA, the structure will be fully destroyed and ruled unsafe. The damage level of 0.583g PGA equates to Intensity VIII or'severe' shaking.

Furthermore, Table 7 shows that the PGH Spine Building's y-axis had a larger peak ground acceleration. The reason for this is that either the building's y-axis is regarded stronger, or ground motion data are more noticeable and experienced in the x-axis than in the y-axis. Given this, the structural components of the PGH Spine Building's x-axis were deemed more important.

Table 7. Maximum Peak Ground Acceleration (PGA) at 10% Probability of Exceedance of Each Damage State

Direction	X-Axis				Y-Axis			
	C	B	A	As	C	B	A	As
East-West	0.258g	0.538g	0.570g	0.583g	0.303g	0.546g	0.566g	0.587g
North-South	0.257g	0.536g	0.569g	0.589g	0.306g	0.538g	0.573g	0.587g

Furthermore, the produced fragility curves determined that the greatest Probability of Exceedance (Pr) at 0.4g PGA under the 'collapse damage (As)' condition was 5.24 percent, with no values above 10%. PGH Spine Building therefore met the criterion for constructions located in Seismic Zone 4. As a result of this seismic requirement, the PGH Spine Building did not require an adequate retrofitting strategy.

Recommendations

The researchers recommend the following to future researchers:

- The study is only limited to the data indicated in the structural plans of the building; therefore, it is recommended to perform validation tests, such as Rebound Hammer Test, Penetration Resistance Test, and Rapid Visual Inspection to determine the current properties and strength of the structure.
- Since the study only focused on a particular building in Philippine General Hospital (PGH), the Spine Building, broadening the project structure scope is recommended for more applications and significance. Investigating more buildings and structures inside the PGH vicinity could also expand the scope of the future study.
- Furthermore, future researchers could study other structures such as schools, residential buildings, industrial buildings, dams, bridges, and others to compare the fragility curves of these structures as they have distinct usage.

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