SEISMIC ASSESSMENT OF LRT LINE 1 MONUMENTO TO 5ᵀᴴ AVENUE CARRIAGEWAY PIER USING FRAGILITY CURVE

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Abstract

The susceptibility of the Philippines to an earthquake is high due to its location. It is found in the Pacific ring of fire making most of its structure vulnerable to earthquakes. Especially of those that are near active faults and structure that are considerably decrepit. Manila, being at the center of economic, academic, residential and commercial activities in the Philippines, is at risk due to the West Valley Fault earthquake threat according to MMEIRS. In response to this, a need for seismic assessment of the most essential lifeline structure would be a great hand to national government, community and people within the vicinity. The study is done primarily to assess the integrity of the LRT carriageway between – 5ᵗʰ avenue & Monumento station when subjected to different ground motions. Using SAP 2000 and the data for peak ground acceleration gathered from PHIVOLCS, K-NET, and PEER, two methods of widely used analyses for earthquakes was used to analyze the modelled structure: The Nonlinear Static Analysis (Pushover Analysis) and the Nonlinear Dynamic Analysis (Time History Analysis). The final output shall be a fragility curve which relate a certain percentage of probability of damage with its respective peak ground acceleration. In addition, the fragility curve was then used to apply the concepts of Interval Uncertainty Analysis to express the same output but in terms of certain range. With this results, the researchers will fully understand the behaviour of this lifeline when such catastrophic event takes place.

Keywords: *Fragility curves, pushover analysis, hysteresis, LRT, Seismic assessment, interval uncertainty analysis*

1.0 INTRODUCTION

The specific geographic location of the Philippines makes it vulnerable to a lot of tectonic activities. The country is susceptible to seismic hazards and it is essential for the people to know the threat that it will cause. Due to its vulnerability, there is a need to institutionalize systems and programs that would improve the disaster resilience of local communities (Salaverria, 2015).

Transportation lifelines are not exceptions to this kind of phenomenon. These lifelines are used to transport manpower in businesses and commercial establishment. If affected, the economic breakdown might arise due to losing of millions of pesos. The safety of the citizens and the integrity of the structure of these lifelines are at stake if a more destructive earthquake occurs. Like the 2013 Bohol earthquake that generated a magnitude of 7.2 that had ₱2.25 billion worth of damage to public buildings, roads, bridges, and flood controls. As follows, the need for seismic analysis for these structures emerged. To mitigate the effects of such temblor, retrofitting the structure that might collapse is the best choice (Brizuela, 2015).

To date, it is impossible to predict when an earthquake will strike even with the current technology the world has to offer. But based on historical records, the next West Valley Fault "Big One" might happen within this lifetime. In the last 1,400 years, the West Valley Fault only

moved four times and has an interval of 400 years. The last major earthquake from the West Valley Fault happened in 1658 (Solidum Jr., 2015). Analyzing the records, the West Valley Fault is due in these modern days. Table 1 summarizes seismological data which is vital to determine the level of seismic hazard in the vicinity area.

Table 1: Seismological Data

Model Number	8
Fault Name	West Valley Fault
Tectonics	Crustal
Style	Strike Slip
Magnitude	7.2
Fault Length (km)	67
Fault Width (km)	21
Dip angle	90 degrees
Depth (km)	2
Past earthquake along the fault, Magnitude	August 19, 1658 5.7

Source: Matsuoka & Ikenishi (2004)

The West Valley Fault is approximately 10 kilometers away from the Monumento station of LRT line 1, which will be the focus of this research. This research will study and provide a seismic analysis on the piers of the LRT 1 between the Monumento and 5th Avenue stations. It has been 30 years since the construction of the LRT line 1. Since then, the line has withstood many disasters like the Rizal day bombing, earthquakes, and floods that may cause deterioration to the piers and foundation. Doing research would be essential as the threat of this "Big One" arises.

2.0 REVIEW OF RELATED LITERATURE

2.1 Foreign Studies

Extensive seismic accidents during the past few decades have continued to demonstrate the destructive power of an earthquake, with failures to structures such as bridges, as well as giving rise to great economic losses. Economic losses for bridges very often surpass the cost of damage and should, therefore, be taken into account in selecting seismic design performance objectives (Girard, Légeron, & Roy, 2012). Highway bridge network has a compelling contribution towards the economic welfare of a country and thus earthquake-induced damage to bridge structures can cause potential economic catastrophe to the country (Siddiquee, 2015).Thus, a seismic analysis would be more constructive before the said earthquake will happen.

One of the most popular means in evaluating the seismic performances of existing and newly constructed buildings is by the use of nonlinear static pushover analysis. The expectation is that the pushover analysis will provide adequate information on seismic demands imposed by the design ground motion on the structural system and its components (Govind *et al.,* 2014). Nonlinear static (pushover analysis) is one of four analysis procedures embodied in FEMA 356 / ASCE 41 and commonly used in performance based design approaches. By several researchers (Banerjee & Shinozuka, 2007; Mander, 1999; Mander & Basoz, 1999; Shinozuka *et al*., 2000); it is performed on bridge components to estimate their capacity whereas component demand is calculated from response spectrum analysis. Later, seismic capacity and demand are plotted together against increasing spectral acceleration. Probabilities of reaching any certain damage states are calculated from the intersection between these two plots. Although this method captures the nonlinear response of the structure, lack of ability to consider the hysteresis damping of the structure makes it less attractive.

Nonlinear dynamic time history analysis is considered as the most effective method for fragility analysis and used widely by several researchers (Billah & Alam, 2013; Choi, 2002; Karim & Yamazaki, 2003; Nielson, 2005;

Padgett, 2007). Its ability to capture the dynamic response of structure by considering geometric nonlinearity and material inelasticity allows producing reliable fragility curves. Unlike other methods fragility analyses using nonlinear time history analysis necessitates a large amount of ground motion time history data that also results in high computational costs. This particular study adopted nonlinear time history analysis to generate seismic fragility curves for wall pier bridge type (Siddiquee, 2015).

2.2   Local Studies

It was the Luzon earthquake of July 1990 that researchers started the collaborative study about the seismic hazard analysis in the Philippines. The seismic hazard in the Philippines was evaluated from historical earthquake data using a new computer program called the Seismic Hazard Mapping Program (H-Map). The seismic hazard is given in terms of the expected peak ground acceleration and expected acceleration response spectrum. Regions including Central Luzon which suffered heavy damage during the 16th of July 1990 earthquakes were identified. The design level of seismic force of the Philippines was then compared with those of Japan and is found to be considerably lower. Long period structures are found to be more vulnerable to damage. The collection of strong ground motion records from Philippine earthquakes is necessary for more realistic design levels for the Philippines. From the seismic hazard maps, a seismic zoning map based on the expected maximum accelerations is proposed (Yamazaki, Molas, & Tomatsu, 1992).

Another study conducted due to the collaborative efforts of Japan International Cooperation Agency (JICA), Metropolitan Manila Development Authority (MMDA), and Philippine Institute of Volcanology and Seismology (PHIVOLCS) was the "Study for Earthquake Impact Reduction for Metropolitan

Manila in the Republic of the Philippines (MMEIRS)". This study was done from August of 2002 to March of 2004 and covered the entire Metropolitan Manila, with an area of 636 km^2. This study aims to achieve "A Safer Metropolitan Manila from Earthquake Impact" and proposed its goals and main objectives listed as follows; 1) To develop a national system resistant to earthquake impact, 2) To improve Metropolitan Manila's urban structure resistant to earthquake, 3) To enhance effective risk management system, 4) To increase community resilience, 5) To formulate reconstruction systems, 6) To promote research and technology development for earthquake impact reduction measures (Matsuoka & Ikenishi, 2004).

The study began by analyzing the past historically recorded earthquakes and instrumentally recorded earthquakes, a total of 18 earthquakes were selected as scenario earthquakes, which have potential damaging effects to Metropolitan Manila: also earthquake ground motion, liquefaction potential, slope stability and tsunami height are estimated.

A total of 18 scenario earthquakes were set. Three types of fault length were used for the West Valley Fault (WVF) considering the low continuity in the north and south. Tsunami was evaluated for the movement of Manila Trench and re-occurrence of 1863 earthquake. The empirical formula by Wells and Coppersmith (1994) was used to calculate the earthquake magnitude and fault width from fault length (Matsuoka & Ikenishi, 2004).

Finally three models, namely, Model 08 (West Valley Faults M.7.2), Model 13 (Manila Trench M.7.9) and Model 18 (1863 Manila Bay M.6.5), were selected for detail damage analysis because these earthquake scenarios showed typical and severe damages to Metropolitan Manila. Given the previous models, the MMEIRS study estimated the damage of the potential rupture of West Valley Fault, approximately 40% of the total number of

residential buildings within Metropolitan Manila will collapse or be affected. If a building collapses, it will directly affect a large number of people, since it is estimated to cause 34,000 deaths and 114,000 injuries. Moreover, additional 18,000 deaths are anticipated by the fire spreading after the earthquake catastrophe. This human loss, together with properties and economy losses of Metropolitan Manila will be a national crisis (Matsuoka & Ikenishi, 2004).

2.3   Fragility Curves

Bridges, railway bridges, are one of the most susceptible highway structures when it comes to seismic damages. The method often used in assessing the capability of specific structure to an earthquake is seismic fragility curve (Shinozuka *et al*., 2001). Fragility curve is a conditional probability of a structure of attaining or exceeding a given damage when subjected to seismic loads (Zhong *et al.,* 2010). Basically, it is the most commonly used method for assessing structures under the occurrence of an earthquake, to come up with evaluating seismic risks as well as for decision-making process. Seismic fragility curve analysis has a huge role in seismic risk assessment; yet some fragility models of structures focus on the condition of the structure assuming that it is newly built, yet the service life of the structure has the chance of ignoring the fact that it will face multiple earthquakes during its lifetime (Yan, 2013).The output of fragility curve can be used by researchers, reliability experts, administrators, and design engineers to evaluate and improve the structural and non-structural seismic capability of structures (Requiso, 2013).

There is no particular applicable best method for calculating fragility curves (Shinozuka *et al*., 2000). Different methods such as non-linear static and non-linear dynamic may be used. Both linear and nonlinear are used for structural analysis of structures. In a nonlinear analysis, the behaviour of material beyond a linear elastic limit, nonlinearity are taken into account, this method uses ground motion data to be executed.

The seismic fragility curves assess the vulnerability of a structure for each damage state namely; slight, moderate, extensive and complete damage. The probability of exceeding in percent of a particular damage is plotted with the ground motion intensity which expressed in PGA (Peak Ground Acceleration).

3.0   METHODOLOGY

To develop the seismic fragility curve of the pier in LRT line 1, 5th Avenue to Monumento Station, two nonlinear methods has been adopted, the Nonlinear Static Analysis (Habibullah & Pyle, 1999) and Nonlinear Dynamic Analysis (Karim & Yamazaki, 2001). The mode of failure is shear.

The following are the step by step procedure for the nonlinear static analysis by Habibullah & Pyle (1999):

1. Model the whole system using SAP 2000 (Figure 1) and define the necessary section properties in the usual manner. The graphical interface of the structural computer programs makes this task quick and easy.
2. Locate the pushover hinges on the model by selecting the frame member and assigning them one or more hinge properties. The program includes several built-in default hinge properties that are based on average values from ATC-40 for concrete members and average values from FEMA-273 for steel members.
3. Define the pushover load cases.
4. Run the basic static analysis as well as the static nonlinear pushover analysis.
5. Display the pushover curve.

The sample generated pushover curve (Figure 2) will now provide the yield and maximum displacement of the system. The area under the yield displacement is defined as the Energy at yield (Figure 3). These values were used later on once the nonlinear dynamic analysis has been finished.

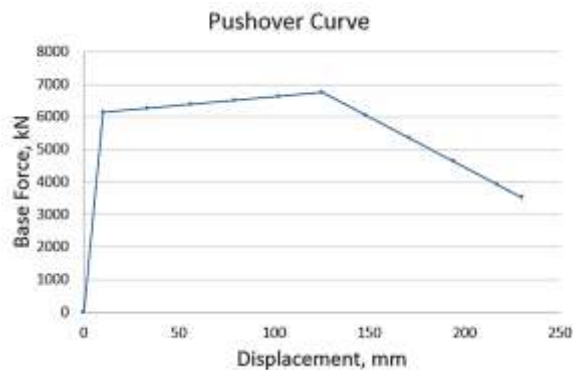Figure 1: SAP2000 model of LRT Line 1 Monumento to 5th Avenue Carriageway Pier

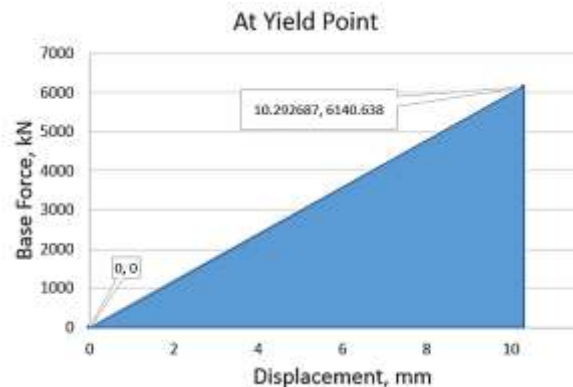Figure 2: Pushover curve of LRT Line 1 Monumento to 5th Avenue Carriageway Pier

Figure 3: Energy at Yield point of LRT Line 1 Monumento to 5th Avenue Carriageway Pier

For the nonlinear dynamic analysis, the researchers will use the selected ground motion data obtained from past historical earthquakes. The steps for this method of analysis by Karim and Yamazaki (2001) are as follows:

1. Select the earthquake ground motion records. These data depends on the availability from the sources, i.e., PHIVOLCS, K-net, and PEER.
2. Normalize PGA of the selected records to different excitation levels.
3. Create the basic computer model of the system using SAP 2000. Input the earthquake ground motion data in the program by defining the time history function.
4. Define the time history load case which is a nonlinear modal function.
5. Run the non-linear dynamic response analysis using the selected records.
6. The program will now display the plot function known as the hysteretic model for the nonlinear dynamic response analysis which will provide the hysteretic energy and the maximum displacements. A sample hysteresis model is shown in Figure 4.
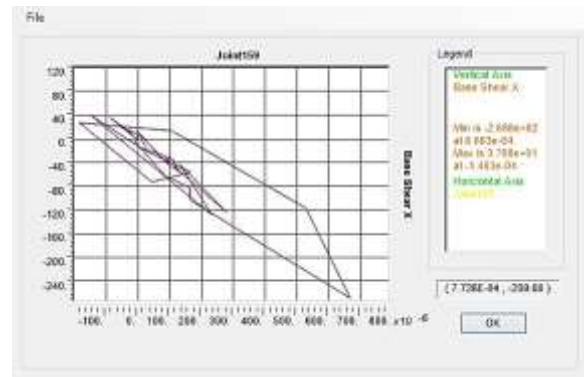

Figure 4: Hysteresis of LRT Line 1 Monumento to 5th Avenue Carriageway Pier under the ground motion of Kobe 1995 earthquake at Kakogawa station, PGA=0.6g. Force in kN, displacement in meters

For the construction of the conventional seismic fragility curve an analytical approach will be adopted to construct the fragility curves of the system (Karim & Yamazaki, 2001). The steps in constructing the seismic fragility curves are as follows:

1. Obtain the ductility factors. The maximum displacement and hysteretic energy obtained from Time history analysis along with the obtained maximum displacement, displacement at yield and yield energy from the pushover analysis were accounted to solve for the ductility factors known as displacement ductility, ultimate ductility and hysteretic energy ductility.

$$\mu_d = \frac{\delta_{\max(dynamic)}}{\delta_y}$$

$$\mu_u = \frac{\delta_{\max(static)}}{\delta_y}$$

$$\mu_h = \frac{E_h}{E_e}$$

where:

$\delta_{\max\ (static)}$= displacement at maximum reaction at the push over curve (static)
$\delta_{\max\ (dynamic)}$= maximum displacement at the hysteresis model (dynamic)
μ_y = yield displacement from the pushover curve (static)
E_h= hysteretic energy, i.e., area under the hysteresis model
E_e= yield energy, i.e., area under the push-over curve (static) but until yield point only

$$I_D = \frac{\mu_d + \beta \cdot \mu_h}{\mu_u}$$

where:

β is the cyclic loading factor taken as 0.15 for bridges.

2. Obtain the damage indices of the structure in each excitation level. 3. Calibrate the damage indices for each damage rank (see Table 2). In this study the researchers will use Table which shows the relationship between the damage index and damage rank. This step will be repeated prior to the other selected ground motion data.

Table 2: Damage Index Relation to Damage Rank

Damage Index I_D	Damage Rank DR	Description
[0.00, 0.14]	D	No Damage
(0.14, 0.40]	C	Slight Damage
(0.40, 0.60]	B	Moderate Damage
(0.60, 1.00]	A	Extensive Damage
(1.00, ∞)	As	Complete Damage

Source: HAZUS, 2003

3. Obtain the number of occurrences of each damage rank in each excitation level and get the damage ratio. In this step the number of occurrence of each damage rank at their respective ground excitation level is counted. A sample table for number of occurrence is shown in Table 3 and the probability of occurrence as shown in Figure 5.

Table 3: Tabulation of Frequencies for the Probability of Occurrence

PGA	D	C	B	A	As
0.2	15	0	0	0	0
0.4	8	7	0	0	0
0.6	5	10	0	0	0
0.8	4	9	2	0	0
1.0	3	8	2	2	0
1.2	3	5	5	2	0
1.4	1	5	5	4	0
1.6	1	5	2	6	1
1.8	1	4	3	5	2
2.0	1	4	1	6	3
SUM	42	57	20	25	6

Figure 5: The Probability of Occurrence

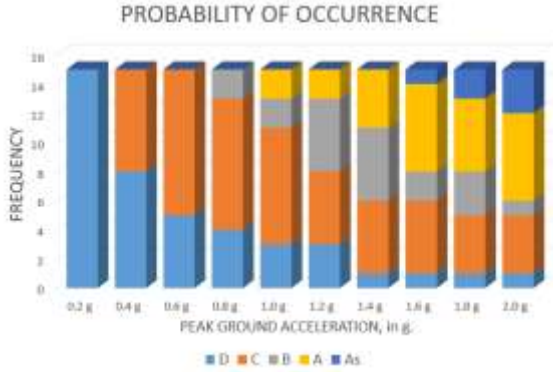Figure 6: Conventional Seismic Fragility Curves of LRT Line 1 Monumento to 5th Avenue Carriageway Pier in X-direction

4. Construct the fragility curves for each damage rank using log normal distribution. Obtain the mean and standard deviation for each damage rank, the cumulative probability (P_R) of exceedance of the damage equal or higher than the damage rank can be computed. Then by plotting acquired cumulative probability with the peak ground acceleration (PGA normalized to different excitation), the fragility curve can now be obtained. See Figure 4 for conventional seismic fragility curves.

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

After getting the mean and standard deviation using maximum likelihood method, the probability of exceedance (P_R) can now be computed. Where $\tilde{\Phi}$ is the standard normal distribution, X is the peak ground acceleration, λ is the mean and ξ is the standard deviation.
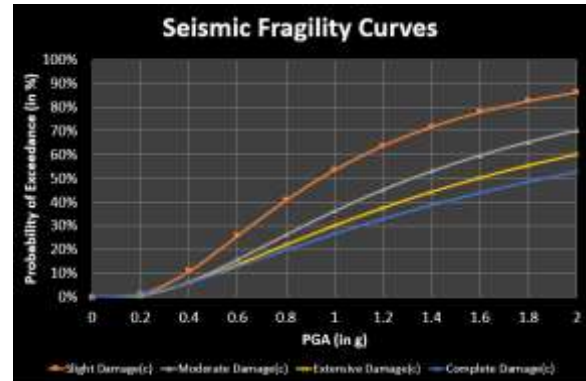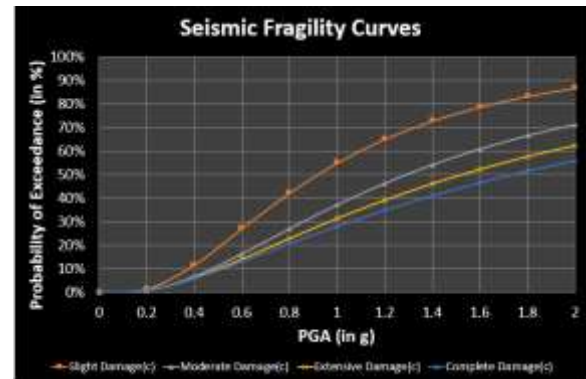

Figure 7: Conventional Seismic Fragility Curves of LRT Line 1 Monumento to 5th Avenue Carriageway Pier in Y-direction

5. For the construction of the unconventional fragility curve using Interval Uncertainty Analysis (IUA). The assumption of the researcher is that all the results of Nonlinear Static Analysis and Nonlinear Dynamic Analysis are in Normal Distribution function. See Figure 8.
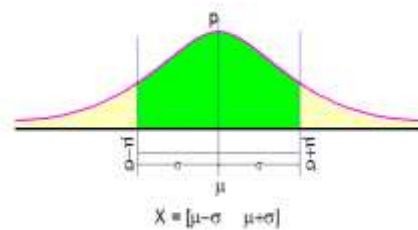

Figure 8: The concept of Interval Uncertainty Analysis (Baylon M. B., 2016)

To get the lower and upper bound, the coefficient of variation is defined as:

$$c.o.v. = \frac{\sigma}{\mu}$$

The value of the coefficient of variation may vary between 1%, 5%, 10%, and 20% depending on the outcome of the fragility curve. There is an optimum c.o.v. in every damage ranks.

$$\tilde{X} = \left[(1-\text{cov})\mu \quad (1+\text{cov})\mu\right]$$

Obtain the ductility factors that are calculated with the use of Interval Arithmetic Operations.

$$\tilde{\mu}_d = \frac{\tilde{\delta}_{\max(dynamic)}}{\tilde{\delta}_y}$$

$$\tilde{\mu}_u = \frac{\tilde{\delta}_{\max(static)}}{\tilde{\delta}_y}$$

$$\tilde{\mu}_h = \frac{\tilde{E}_h}{\tilde{E}_e}$$

$$\tilde{I}_D = \frac{\tilde{\mu}_d + \beta \cdot \tilde{\mu}_h}{\tilde{\mu}_u}$$

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

4.0   RESULTS AND DISCUSSION

The conventional seismic fragility curves (Figures 6 and 7) show the different amount of damages to the pier in LRT Line 1 located between the 5ᵗʰ Avenue to Monumento Station when subjected to different peak ground acceleration with shear being the mode of failure. Lifelines in the Philippines such as the LRT are designed to withstand a peak ground acceleration of 0.4g according to the Department of Public Works and Highways - Bureau of Design (DPWH-BoD). Taking this into

consideration, the probability of exceedance when subjected to 0.4g are as follows: For X-direction, the probability of exceedance are 10.96%, 6.56%, 6.15%, and 6.23% for slight damage (C), moderate damage (B), extensive damage (A), and complete damage (A$_S$) respectively. For Y-direction, the probability of exceedance are 11.62%, 6.66%, 6.18%, and 6.16% for slight damage (C), moderate damage (B), extensive damage (A), and complete damage (A$_S$), respectively. The west valley fault will probably produce a 7.2 magnitude earthquake according to Solidum Jr. (2013).

A 7.2 magnitude earthquake is equivalent to 0.18g-0.34g in PGA (see Table 4). In that case, the probability of exceedance are 1.31% slight damage (C), 0.85% moderate damage (B), 1.03% extensive damage (A), and 1.29% complete damage (A$_S$), and 1.42% slight damage (C), 0.84% moderate damage (B), 0.97% extensive damage (A), and 1.16% complete damage (A$_S$) for X-direction and Y-direction, respectively.

Comparing the probability of exceedance of X and Y Fragility Curves in 0.4g PGA, The Y fragility curve has a higher probability of exceedance than X. The reason is that either the Y-direction is the weak axis of the structure, or the ground motion are more prominent in Y-direction than of that in the X-direction.
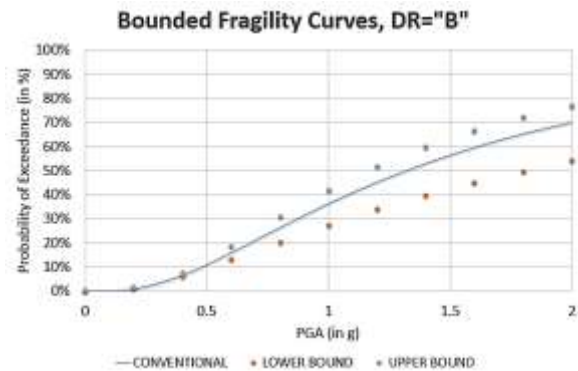

Figure 9: Bounded Seismic Fragility Curve for a Damage Rank of Moderate Damage
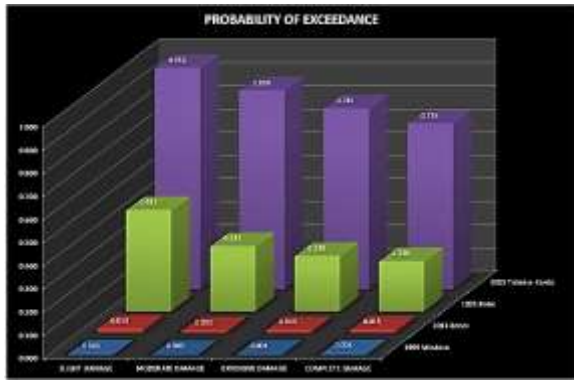
Figure 10: Probability of Exceedance for the X-direction, Ground motion data vs. Damage Rank
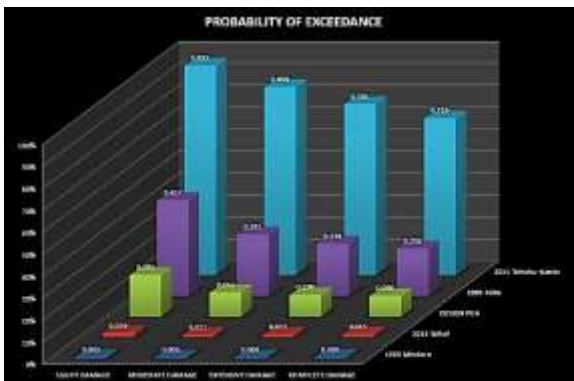

Figure 11: Probability of Exceedance for the Y-direction, Ground motion data vs. Damage Rank

In this study, the researcher was able to provide a seismic fragility curve for both x and y directions of the asset. These seismic fragility curves gives a plot which relates the probability of exceedance of the pier at a certain peak ground acceleration. This plot alone can give an approximation of how damaged the structure will be if a certain intensity of earthquake takes place.

The Figures 10 and 11 are the graphical representation of the probability of exceedance of the structure for a corresponding earthquake's intensity measure, i.e., peak ground acceleration (PGA). The graph shows that there's a significant difference between the Philippines and Japan earthquakes, this only shows that earthquakes like those in Japan will severely damage the structure. To give a more detailed explanation of how the structure will be

damaged when it struck by a certain intensity of earthquake, Table 4 shows the relation of the peak ground acceleration with intensity, this figure also shows the average earthquake effects and the potential damage of the structure due to earthquake.

Table 4: PGA Relation to that of the Instrumental Intensity

Instrumental Intensity	Acceleration (g)	Perceived Shaking	Average earthquake effects	Potential Damage
I	<0.0017	Not felt	Microearthquakes, not felt, or felt rarely by sensitive people. Recorded by seismographs	None
II – III	0.0017–0.014	Weak	Felt slightly by some people. No damage to buildings.	None
IV	0.014–0.039	Light	Often felt by people, but very rarely causes damage. Shaking of indoor objects can be noticeable.	None
V	0.039–0.092	Moderate	Noticeable shaking of indoor objects and rattling noises. Felt by most people in the affected area. Slightly felt outside. Some objects may fall off shelves or be knocked over.	Very Light
VI	0.092–0.18	Strong	Felt by everyone. Casualties range from none to a few.	Light
VII	0.18 –	Very	Felt in wider	Modera

	0.34	strong	areas; up to hundreds of miles/kilometers from the epicenter. Strong to violent shaking in epicentral area. Death toll ranges from one to 25,000.	te
VIII	0.34 – 0.65	Severe	Felt across great distance with major damage mostly limited to 250 km from epicenter. Significant death toll.	Moderate to Heavy
IX	0.65 – 1.24	Violent	Damaging in large areas. Felt in extremely large regions. Death toll in the thousands.	Heavy
X+	> 1.24	Extreme	Permanent changes in ground topography. Death toll can surpass 10,000.	Very Heavy

Source: Murphy & O'Brien (1977)

5.0   CONCLUSION

It is known that Philippine structures were designed to withstand a 0.4g earthquake, referring to Table 3, a 0.4g earthquake can cause a moderate to heavy damage in the structure. Checking the validity of the constructed fragility curve, at 0.4g (PGA) the plot shows a relatively small percentage of probability of exceedance. It is also known thru the use of constructed fragility curve that the structure will have a high percentage of probability of exceedance, that the structure will have an extensive damage at 2.0g (PGA). Which is acceptable since it is only an approximation. Based from the observation of this study, the structure can tolerate an

earthquake that most likely to occur in the Philippines, hence the structure is relatively safe and strong.

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