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SEISMIC RELIABILITY ANALYSIS OF LIFELINE: A CASE STUDY ON THE WATER NETWORK SYSTEM OF BIÑAN CITY, LAGUNA

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ABSTRACT: Lifelines are essential networks and it is vital for these network systems to remain properly functional during or after destructive earthquakes. In the Philippine geographical context, the West Valley Fault which traverses Metro Manila is a seismic threat capable of producing a maximum magnitude of 7.2. In this study, the reliability of Laguna Water network system was assessed under earthquake loads due to West Valley Fault. Probabilistic seismic hazard analysis (PSHA) was utilized to estimate the seismic hazard of the network area. Recorded earthquake history from the Philippine Institute of Volcanology and Seismology was used as part of the seismic analysis. The analysis estimated the ground motion values by using a similar Ground Motion Prediction Equation (GMPE) used in the latest Philippine Earthquake Model (PEM). Seismic hazard analysis shows that the earthquake hazards for the site are peak ground accelerations of 0.52g and 0.62g for return periods of 500 and 2500 years respectively. Using the ground motion intensity, ground strain value was attained ranging from 0.02% to 0.16% at scales of 0.1g to 1.0g. Monte Carlo simulation was used to determine the probability of damage. Using the unscaled peak ground acceleration, the probability of minor damage ranges from 15% to 19%. Given a 2500-year return period, seismic hazard analysis resulted to a peak ground acceleration of 0.62g which has a 20% probability for pipes to experience minor damage. Subsequently, the entire network system has a 1% probability of minor damage given the same return period of seismic hazard.

Keywords: Water pipelines, PSHA, Reliability, Monte Carlo simulation

1. INTRODUCTION

Earthquake is a natural hazard which is one of the most destructive occurrences. Numerous destructive magnitudes of this hazard happened in different countries which resulted in damages in structures most especially in built environments. As such, earthquake indirectly causes death toll through the collapse of buildings and secondary hazards such as water scarcity and fire. In the 1995 Kobe earthquake in Japan, a fire occurred in an area of about 1 square kilometer due to natural gas release and electricity sparks [1]. As such, earthquake leads to damage not just on structures but also in buried lifelines. Other than lifeline central facilities, transmission components such as pipelines should also be assessed since the system spatially extends over a wide area of distances and could be subjected to different seismic loading despite being under the same earthquake hazard [2]. The risk analysis of lifelines involves seismic hazard estimation as input data and damage, reliability, restoration and mitigation as output data [3]. Previous studies analyzed the probability of damage of water network subjected to seismic loading under different sources of the earthquake [4]-[5].

The Philippines is located at the Ring of Fire where numerous occurrences of earthquake happened. In the past five years, there were two major earthquakes that hit the country. In 2013, a M7.2 earthquake hit the areas of Bohol and Cebu City which resulted to a death toll and injuries of 227 and 996 individuals, respectively [6]. Meanwhile, a M6.7 earthquake in 2017 affected 11 towns in Surigao which resulted in water scarcity due to busted pipelines [7]. As such, one of the seismic events being prepared is due to the West Valley Fault which traverses Metro Manila and neighboring provinces. The said fault can produce a magnitude of 6.0 with a peak of up to 7.2 [8].

Given the risk imposed by the West Valley Fault, the purpose of this paper is to assess the system reliability of water network of Laguna Water. This process involves Probabilistic Seismic Hazard Analysis (PSHA) to determine the ground motion in terms of peak ground acceleration (PGA) [9]. The PGA values are related to pipe strain values for the load parameter [10]. Then, the probability of damage of each component is obtained using Monte Carlo simulation. Subsequently, the probability of damage of each component is used to calculate the system reliability [11].

2. SITE INFORMATION

Biñan City is a municipality in the province of Laguna located in the Southern Luzon of Philippines. The city is 34 kilometers south of Manila, the capital of the country, and it is a firstclass city in terms of income classification. The city has a population of approximately 334,000 having a density of 1,000 individuals per square kilometer [12]. In addition, situated in the city are two world-class industrial parks. Geographically, Biñan City is being traversed by West Valley Fault in three (3) of its barangays. In the Philippine Earthquake Model (PEM) released by Philippine Institute of Volcanology and Seismology (PHIVOLCS), the city falls within the PGA of 0.4g and 0.5g for a return period of 500 years as shown in Fig. 1 [13].

Fig. 1 PGA map for the 500-year return period

2.1 Water Network of Biñan City

Laguna Water is the provider of water services in Biñan City together with other two municipalities nearby. Figure 2 shows the map of the water network provided by Laguna Water. The water network data includes coordinates, length, sizes and material of the pipes. The network is composed of steel pipes with arc-welded joints with 9 different diameter sizes ranging from 50 to 500 millimeters. These sizes are classified as main and distribution lines. In this study, the assessment focuses on the main pipes which were assumed to have a diameter of at least 150 millimeters.

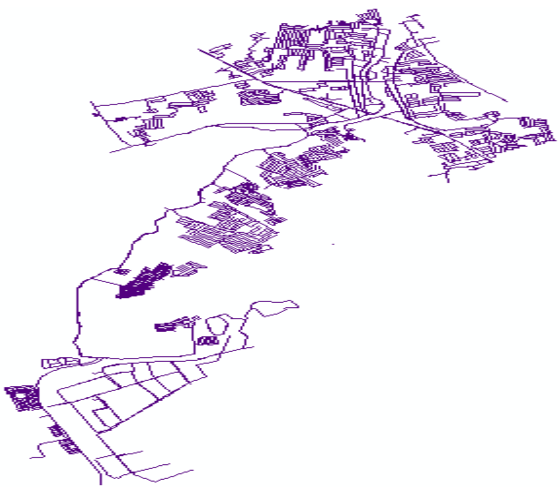

Fig. 2 Biñan City water network system

3. PROBABILISTIC SEISMIC HAZARD ANALYSIS (PSHA)

Seismic hazard analysis is used to estimate the PGA at the site with West Valley Fault as the seismic source. The stochastic approach considers uncertainties particularly distance, magnitude and ground motion probabilities [9]. The outputs in this analysis are Uniform Hazard Response Spectra (UHRS) which shows the acceleration values at different periods. As such, the PGA values are used to generate a spectral map.

3.1 Distance Probability

The seismic source considered in the research is only West Valley Fault. Since the fault is not linear and extends for about 95 kilometers, it is linearized into three segments. Table 1 shows the length of each segment and the number of 500-meter strips for source-to-site distances. Meanwhile, the site is the area covered by the water network system. As such, it is represented as grid point spaced at 500 meters. Assuming that earthquake could occur anywhere within the fault line, there are 190 source-to-site distances for each grid points.

Table 1 Fault segment details

Segment	Connecting Points	Distance (km)	No. of Strips
1	1 and 2	26.5	53
2	2 and 3	27.5	55
3	3 and 4	41	82
		95	190

Figure 2 shows the distance probability distribution, clustered into 10-kilometer groups, out of the 190 strips of the West Valley Fault. It is evident that the probability of an earthquake occurring within a 20-kilometer radius is 42%. Moreover, the likelihood decreases at larger distances wherein 90 kilometers is the largest distance possible.

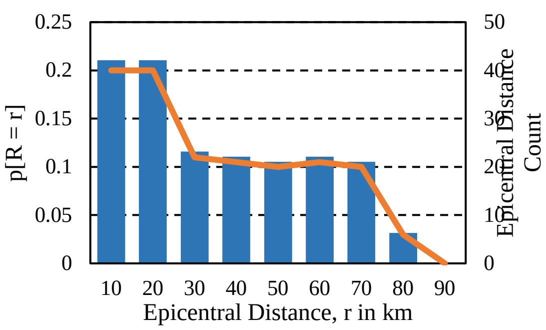

Fig. 3 Distance probability distribution

3.2 Magnitude Probability

The seismic data used are based on the historical earthquake data from PHIVOLCS recorded from 1900 to 2015 [14]. The analysis used moment magnitudes of engineering interest only having a value of M5.2 and above [13], [15]. Seismic data was also filtered based on coordinates which are located within 50 kilometers from the fault line as shown in Table 2. The relationship between the seismic events and magnitudes was established through bounded Gutenberg-Richter Recurrence Law as represented by Eq. (1).

Table 2 West Valley Fault seismic data

Lat.	Long.	Depth, (km)	Mw			Mw
			Ml	Mb	Ms	
14.50	121.50	33	0	0	7.5	7.47
14.20	120.60	60	0	0	6.8	6.77
14.00	121.00	50	0	0	5.7	5.89
13.96	120.87	49	0	5	0	5.24
13.98	120.74	4	0	5.1	0	5.30
14.70	121.20	22	0	4.9	0	5.18
13.94	120.67	21	0	5.3	0	5.44
14.00	120.70	33	0	4.9	0	5.18
14.02	120.65	5	4.7	5.7	5.1	5.81

$$\log \boldsymbol{\lambda_m} = \boldsymbol{a} - \boldsymbol{bm} \quad (1)$$

where $\boldsymbol{\lambda_m}$ is the mean annual rate of exceeding magnitude *m*, and $\boldsymbol{a}$ and $\boldsymbol{b}$ are constants from recurrence function.

The probability of distribution of a magnitude, $\boldsymbol{P}[\boldsymbol{M}]$ in a given interval is expresses as,

$$\boldsymbol{P}[\boldsymbol{m_l} < \boldsymbol{m} < \boldsymbol{m_u}] = [\boldsymbol{f_M}(\boldsymbol{m})](\boldsymbol{m_u} - \boldsymbol{m_l}) \quad (2)$$

where $\boldsymbol{m_l}$ and $\boldsymbol{m_u}$ are lower and upper limits of magnitude respectively, and $\boldsymbol{f_M}(\boldsymbol{m})$ is the magnitude probability density function.

Figure 4 shows the magnitude distribution function magnitudes M5.30 up to M7.36.

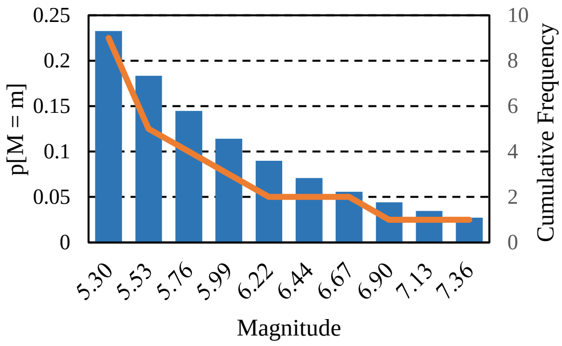

Fig. 4 Magnitude Probability Distribution

3.3 Ground Motion Probability and Mean Annual Rate of Exceedance

In this process, the ground motion values are estimated and compared to obtain the rate of exceeding target ground motions from 0.1g to 1.0g. The values of rate of exceedance are used to calculate the PGA at return periods of 500 and 2500 years.

3.3.1 Ground motion prediction equation (GMPE)

The GMPE used to estimate the motion values is based on the similar model used by PHIVOLCS in the generation of PEM. The attenuation model by Youngs, Chiou, Silva and Humphrey [17] predicts the PGA, $\boldsymbol{ln\,y}$ generated by subduction zone earthquakes and represented by the expression,

$$\begin{aligned}\ln \boldsymbol{y} &= -\mathbf{0.6687} + \mathbf{1.438}\boldsymbol{M_w} + \boldsymbol{C_1} \\ &+\boldsymbol{C_2}(\mathbf{10} - \boldsymbol{M_w})^{\mathbf{3}} + \boldsymbol{C_3}\ln[\boldsymbol{r} + \mathbf{1.097}\boldsymbol{e}^{0.617\boldsymbol{M_w}})] \\ &+\mathbf{0.00648}\boldsymbol{H} + \mathbf{0.3643}\boldsymbol{Z_T}\end{aligned} \quad (3)$$

where $\boldsymbol{M_w}$ is the moment magnitude, $\boldsymbol{r}$ is the source-to-site distance, $\boldsymbol{H}$ is the focal depth, $\boldsymbol{Z_T} = \mathbf{0}$ for interface earthquake $= \mathbf{1}$ for interslaan b earthquake, and $\boldsymbol{C}$ are constants from Table 3.

Table 3 Constants for attenuation model

Period	C1	C2	C3	C4	C5
0	0.00	0.00	-2.329	1.45	-0.1
0.075	2.4	-0.0019	-2.697	1.45	-0.1
0.1	2.516	-0.0019	-2.697	1.45	-0.1
0.2	1.549	-0.0019	-2.464	1.45	-0.1
0.3	0.793	-0.0020	-2.327	1.45	-0.1
0.4	0.144	-0.0020	-2.230	1.45	-0.1
0.5	-0.438	-0.0035	-2.140	1.45	-0.1
0.75	-1.704	-0.0048	-1.952	1.45	-0.1
1.0	-2.870	-0.0066	-1.785	1.45	-0.1
1.5	-5.101	-0.0114	-1.470	1.5	-0.1
2.0	-6.433	-0.0164	-1.290	1.55	-0.1
3.0	-6.672	-0.0221	-1.347	1.65	-0.1
4.0	-7.618	-0.0235	-1.272	1.65	-0.1

3.3.2 Mean annual rate of exceedance

This process involves the combination of the three calculated probabilities wherein seismic hazard curves are generated. The annual rate of exceedance of ground motion, $\boldsymbol{\lambda_{y^*}}$ is expressed as,

$$\begin{aligned}\boldsymbol{\lambda_{y^*}} &= \sum_{\boldsymbol{i=1}}^{\boldsymbol{N_S}} \sum_{\boldsymbol{i=1}}^{\boldsymbol{N_M}} \sum_{\boldsymbol{i=1}}^{\boldsymbol{N_R}} \boldsymbol{\lambda_m P}[\boldsymbol{Y} > \boldsymbol{y}^*] \\ &\boldsymbol{P}[\boldsymbol{M} = \boldsymbol{m_j}]\boldsymbol{P}[\boldsymbol{R} = \boldsymbol{r_k}]\end{aligned} \quad (4)$$

where $P[Y > y^*]$ is the ground motion probability, $P[M = m_j]$ is the magnitude probability, and $P[R = r_k]$ is the distance probability.

3.4 Uniform Hazard Response Spectrum (UHRS)

The UHRS was generated by evaluating the corresponding PGA of a certain return period. As such, 2% and 10% exceedance in 50 years are used which are also equivalent to 2500 and 500 years respectively. Figure 5 presents the calculated PGA at both return periods from 0 to 4.0 seconds. The PGA values of 0.62g and 0.52g occur at 0.1 seconds for 2% and 10% exceedance, respectively.

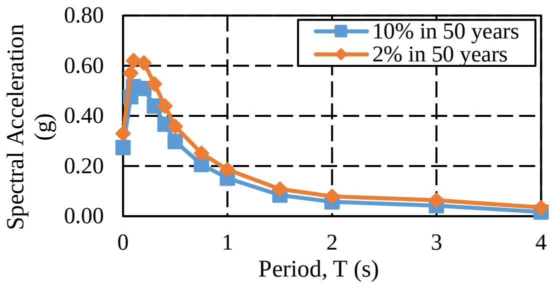

Fig. 5 Uniform hazard response spectrum

3.4.1 Spectral Map

By taking the PGA at 2500 years of all grid points of the water network area, a seismic map of Biñan City was generated. As shown in Fig. 6, PGA values range from 0.56g to 0.62g depending on the location. Areas closer to the West Valley Fault produced higher ground motion values.

4. PIPE STRAIN ESTIMATION

Shinozuka and Koike [10] established a model on the relationship between seismic ground motion, particularly spectral velocity, and pipe strain gave the site condition and details of the pipe. As such, the computed PGA values are converted to velocity using the model for Level 2 ground motion in Japan as shown in Eq. (5) [17]. This level of ground motion is similar to an event with a return period of 2500 years.

$$S_v = \frac{S_a}{0.2} S_v' \tag{5}$$

where S_v is the spectral velocity, S_a is the spectral acceleration, and S_v' is the response spectral velocity for Level 2 ground motion.

The spectral velocity is related to ground response displacement $U_h(x)$ and ground strain ε_G

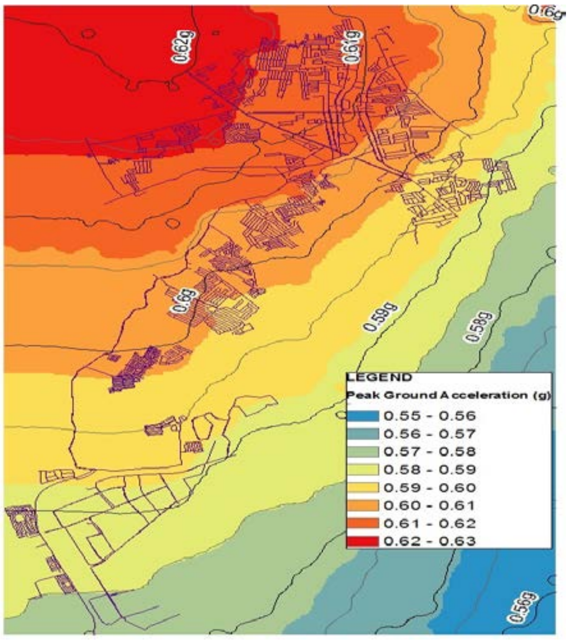

Fig. 6 Spectral maps at 2500-year return period

which are both dependent on side conditions. These site conditions are patterned on the constants used in the PEM [13]. The expressions are represented as,

$$U_h(x) = \frac{2}{\pi^2} S_v T_G K_{h1} \cos\left(\frac{\pi x}{2H}\right) \tag{6}$$

$$\varepsilon_G = \frac{\pi U_h(x)}{L} \tag{7}$$

where T_G is the typical period of grthe ound surface, K_{h1} is the seismic intensity for underground structures, x is the pipe depth, H is the ground layer thickness, and L is the wavelength.

The ground strain is then translated to pipe strain ε_p by multiplying to a conversion factor α_1 which is based on the material properties of the pipe. It can be expressed as,

$$\varepsilon_p = \alpha_1 \varepsilon_G \tag{8}$$

$$\alpha_1 = \frac{1}{1 + \left(\frac{2\pi}{\lambda_1 \times L'}\right)^2} \tag{9}$$

$$\lambda_1 = \sqrt{\frac{K_{g1}}{EA}} \tag{10}$$

where L' is the apparent wavelength, K_{g1} is the axial stiffness between surrounding soil and pipe, E is the elasticity modulus of pipe, and A is the cross-sectional area of pipe.
the

5. RELIABILITY ANALYSIS OF PIPELINE

5.1 Monte Carlo Simulation

The simulation generated 10,000 random samples given the mean and standard deviation from PGA. The capacity of the pipe is based on theoretical values for the critical strain of steel pipes with arc-welded joints upon reaching buckling strain [18]. The performance function is expressed as,

$$\boldsymbol{P(damage)} = [\boldsymbol{\varepsilon_{cr} - \varepsilon_p < 0}] \tag{11}$$

where $\boldsymbol{P(damage)}$ is the probability of damage and $\boldsymbol{\varepsilon_{cr}}$ is the critical strain of pipe.

Figure 7 shows the plot of the Monte Carlo simulation. It shows that some samples passed the critical strain for minor damage which indicates that the joints are vulnerable to leaking. Moreover, no sample exceeded the moderate critical strain.

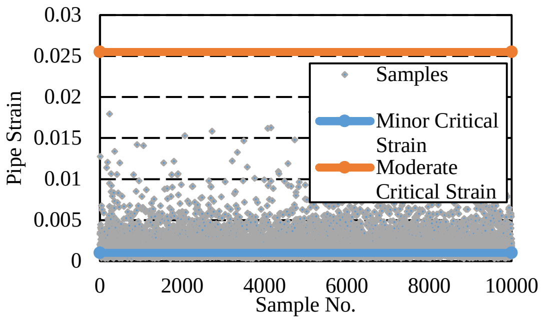

Fig. 7 Monte Carlo simulation

5.2 Component Reliability

Based on the PGA for a 2500-year return period, the damage probability for each pipe diameter from 150 to 500 millimeters is established as shown in Fig. 8.

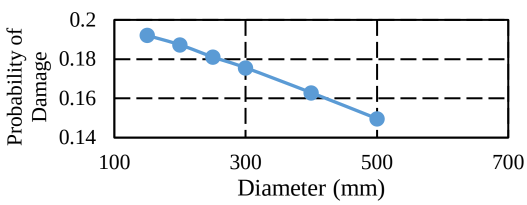

Fig. 8 Damage probability of pipe diameters

Figure 8 shows that pipes of larger diameter produced a lower probability of damage compared to smaller pipe diameter. However, the difference between the maximum and minimum diameters is only 5%.

The probability of damage of a single pipe depending on the scale of PGA from 0.1g to 1.0g is shown in Fig. 9. It is evident that a PGA of 0.62g for a return period of 2500 years will produce a 20% probability for a pipe to experience minor damage. In addition, by evaluating the graph function, a 100% chance of damage will occur at a PGA of 2.33g.

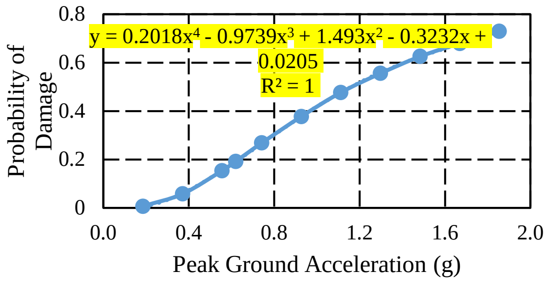

Fig. 9 Fragility curve for minor damage state

5.3 System Reliability

The expression used to calculate the system reliability of the entire water network considers the component reliability of each pipe [11]. It is the union of the probabilities of tie-sets. A tie-set is a series of pipes from the source node to the distribution node. The probability of damage of each tie-set is permitted by taking the product of probabilities of each component. The equation is expressed as,

$$\boldsymbol{P[C(damage)]} = \boldsymbol{P}\left[\bigcup_{i=1}^{NT} \boldsymbol{T_k(damage)}\right] \tag{12}$$

$$\boldsymbol{P[T_k(damage)]} = \prod_{i=1}^{TL_k} \boldsymbol{P(damage)} \tag{13}$$

where $\boldsymbol{P[C(damage)]}$ is the probability of damage of the system, $\boldsymbol{P[T_k(damage)]}$ is the probability of damage of a tie-set, $\boldsymbol{NT}$ is the number of tie-sets, and $\boldsymbol{TL_k}$ is the number of links in a set.

Since system probability of damage was taken as the product of component probabilities, tie-sets with less number of links resulted to a higher probability value. The plot of the fragility curve for system reliability is shown in Fig. 10. Based on the PGA of 0.62g from PSHA, the system has 1% probability of damage. As such, through the graph function, the system has a 100% chance of damage given a PGA of 2.58g which is close to 2.33g value from component reliability.

6. CONCLUSIONS

Based on the PSHA conducted in the area covered by the water network, seismic activity has a 42% probability of occurring within 0 to 20 kilometers from anywhere within the West Valley Fault to the site. Based on the PSHA conducted in the area covered by the water network, seismic activity has a 42% probability of occurring at a distance of 0 to 20 kilometers from anywhere within the West Valley Fault to the site. In addition, UHRS was generated for return periods of 500 and 2500 years wherein it is concluded that the earthquake hazards for the site are PGAs of 0.52g and 0.62g respectively. Subsequently, the spectral map was established for the site area.

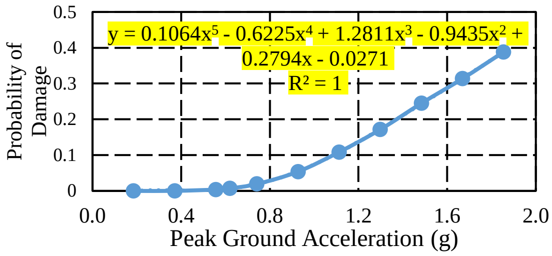

Fig. 10 System fragility curve

In the Monte Carlo simulation, all samples did not exceed the moderate damage state limit. Therefore, the water network system will only experience minor damage state at the event of seismic activity. Using the unscaled PGA, the probability of minor damage ranges from 15% to 20% at an increasing diameter of the pipe. As such, the chance of a pipeline to be surely damaged will occur at a PGA of 2.33g. As a system, the governing probability of damage came from tie-sets of least number of links and smallest diameters. Therefore, there is 1% that the entire water network system would experience minor damage.

7. ACKNOWLEDGMENTS

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