VULNERABILITY ASSESSMENT OF SURIGAO METRO WATER DISTRICT UNDER SEISMIC HAZARD

*Sheena I. Better[1] and Lessandro Estelito O. Garciano[2]

[1]De La Salle University-Manila, Philippines

ABSTRACT: Earlier this year, Surigao Del Norte, a province in the Philippines experienced a 6.7 magnitude earthquake. The severe ground movement caused some of the buried pipelines to be pulled-out from their supports. This type of failure occurs when the ground strain during extreme seismic excitation exceeds the strain capacity of the buried pipe. The failure of the pipes resulted in the loss of water that was vital for post-earthquake recovery efforts. In this regard, there is a need to re-assess the vulnerability of the buried pipes of the water network. In this paper, a probabilistic seismic hazard analysis (PSHA) was employed to estimate the seismic hazard within the concession area. Past seismic data that can significantly affect the target structure is used for this purpose. The buried water lifeline system of Surigao Metro Water District (SMWD) was chosen as the target lifeline. An appropriate ground motion prediction equation (GMPE) was used to develop the uniform hazard response spectra for the site. To assess the vulnerability of the pipes three damage states were considered: major, moderate and minor. The probability of major, moderate and minor damage to each pipe was determined using Monte Carlo simulation. Subsequently, fragility curves were obtained.

Keywords: Buried pipelines, PSHA, Damage states, Fragility curve, Monte Carlo simulation

1. INTRODUCTION

Earthquakes are one of the most damaging natural hazards to a built environment. Countries located along the "Pacific Ring of Fire" such as the Philippines experience more earthquakes than any other part of the world. In recent years, there have been three earthquakes in the country that caused damage to lives and property, e.g. Bohol Earthquake in 2013, Batangas Earthquake in 2017 and the Surigao Earthquake in 2017. These earthquakes caused damage to bridges, schools, hospitals and historical structures [1], and power supply system [2]. Aside from potential damage to building and bridges, severe ground movement can trigger damage to buried utility lifelines that can stop the operation of the entire lifeline system. Previous works by Hamada, Shahoo etc. [3-6] discussed the seismic risks of buried water lifelines, as well the behavior of buried water lifelines. The problems posed by the lack of potable water supply for post-seismic recovery operations after a destructive earthquake is, therefore, an important issue. Considering the vulnerability of our buried utility lifelines to extreme environmental events, there has been a change from a passive to a more pro-active stance by various government agencies to study, document, design mitigation measures, and to retrofit structures for the reduction of the effects of these hazards. This paper is a contribution to these efforts. The purpose therefore of this study is to estimate the damage of the buried lifeline network of the Surigao Metro Water District (SMWD) and provide additional information on the effect of seismic ground motion to the buried steel pipes. The main outputs of this research are fragility curves of buried main water pipelines during extreme seismic events that can be used to develop risk management strategies. The paper is organized into the following: first, assessing the site-specific seismic hazard using a probabilistic approach. In this step, the peak ground acceleration (PGA) at bedrock as well as the uniform hazard response spectra at the ground surface is established. Second, the performance criteria as a function of pipe and ground strains due to an earthquake are defined as well as the damage states criteria, i.e. minor, moderate and major damage were calculated. The results are summarized by fragility curves and are developed based on models developed by Koike [7]

2. TARGET AREA

Surigao City is the capital city of Surigao del Norte. It is situated in the northeastern part of Mindanao, Philippines. It has a total land area of 245.3 square kilometers (PSY 2010) with 17 municipalities and 335 barangays. Surigao City has a population of about 140,540 and is composed of three barangays namely: Washington, Taft and San Juan as shown in Fig.1 [8].

Fig.1 Study area (source: www.zamboanga.com)

2.1 Water Network of SMWD

A schematic network diagram is shown in Fig. 2. This figure shows the span and location of the nodes of the lifeline system. It covers the whole city of Surigao with extensions to farther towns and municipalities. The system is composed of 8 different steel pipes. These pipes make up the trunk and distribution lines of the system. Their main function is to circulate water from one point to another. Trunk lines have a diameter of 35 cm to 40 cm that varied in length. Distribution lines have a diameter of 5 cm to 25 cm. Properties of steel pipes are considered on the pipe strain analysis. SMWD have two water sources, several control facilities that include tanks, reservoirs and pumping systems, and demand nodes. These are all connected to the distribution and service lifeline networks.

Fig. 2 SMWD pipe network system

3. METHODOLOGY

3.1 Probabilistic Seismic Hazard Analysis (PSHA)

To estimate the seismic hazard at the site a PSHA was employed in the study as it can capture uncertainties in the estimation of the PGA. The uncertainties include but not limited to the identification of the seismic sources that exposes the area to significant ground motion, uncertainties in the fault parameters, historical data of the seismic events, distribution of the source-to-site distances, epicenter approximations, soil thickness and composition variations, local SPT results and the choice of an appropriate GMPE.

Uniform hazard response spectra for both spectral acceleration and velocity are developed for the estimation of the probability of failure for each pipe diameter and are followed by the probability of damage to each pipe.

3.1.1 Seismic sources identification

Surigao Del Norte is susceptible to frequent earthquakes due to the geologic setting of the province. Three active seismic sources namely Surigao, Central Leyte, and Bohol faults are within the 150 km radius from the target area.

Table 1. Properties of Seismic Sources near SMWD

Fault name	Tectonics	Style	Length (m)
Surigao	Crustal	Strike-slip	153
Central Leyte	Crustal	Strike-slip	116
Bohol	Crustal	Strike-slip	38

Among the three seismic source, the Philippine Fault Zone: Surigao Segment (see Table 1) is the nearest seismic source to the target area and has the higher potential to cause. The 6.7 magnitude earthquake that affected Surigao City last February 10, 2017, is a case in point. According to National Disaster Risk Reduction and Management Council (NDRRMC) site report, 8 persons lost their lives while 249 were injured. More than 10,645 homes were damaged, 555 were totally damaged and 10,090 were partially damaged. The total cost of damage was estimated to be around US$ 14 million [9].

3.1.2 Seismic events modeling

Historical data of the past earthquakes within the 150-km radius were obtained from the Philippines Institute of Volcanology and Seismology (PHIVOLCS) [10]. The records include the date, location, magnitudes, and depths of the seismic events from 1952 to 2014. Only main shocks were considered in the analysis and aftershocks were removed. Moment magnitudes less than 5.2 were removed as these will not trigger damage. Historical surface, body and live wave

magnitudes were converted into moment magnitudes to conform to the GMPE used [11].

3.1.3 Attenuation model and PGA estimation

The Gutenberg-Richter recurrence law was adopted in the study to determine the distribution of the seismic magnitude for each seismic source. It conveys the relationship between the number of earthquakes for each magnitude group interval in comparison to the total number of earthquakes of the target area.

$$\log(\lambda_m) = a - bM \qquad (1)$$

where a and b are constants derived from the regression analysis of the region while M is the earthquake moment magnitude. The probability distribution of the magnitude, $P(M)$ is based on the function shown below [12,15].

$$P\left[M_l \le m \le m_u\right] = \int_{M_l}^{M_u} f_m(m) \approx f_m(\tfrac{m_l+m_u}{2})\,(m_u\text{-}m_l) \qquad (2)$$

The attenuation model of Fukushima and Tanaka (1990) shown below was used to estimate the mean peak horizontal acceleration (*PHA*) for a 10% in 50 years probability (MRI = 475 years), where A is the PHA mean value (in g).

$$\log A = 0.41M - \log(R + 0.03x10^{0.41M}) - 0.0034R + 130 \qquad (3)$$

Total average exceedance rate is determined from Eq. 4.

$$\lambda_{y*} = \sum_{i=1}^{N_s} \sum_{j=1}^{N_m} \sum_{k=1}^{N_r} v_i P\left[Y > y^* \middle| m_j, r_k\right] P\left[M = m_j\right] P[R = r_k] \quad (4)$$

3.2 Uniform Hazard Response Spectra (UHRS)

This UHRS is estimated using McGuire (Sen, 2009) GMPE. The spectral acceleration for the following periods (*T*) 0.1, 0.2, 0.3, 0.5, 1.0, 2.0, 3.0, and 4.0 are calculated using Eq. 5 and Table 2.

$$S_a = b'_1 10^{b_2 M}(R)^{-b_3} \qquad (5)$$

S_a is the spectral acceleration value (in g). Subsequently, spectral acceleration values are converted to spectral velocity, S_v (in/sec)

$$S_V = \frac{P}{2\pi} S_a \qquad (6)$$

3.3 Vulnerability assessment of SMWD network

3.3.1 Damage functions

The damage estimation for this study adapted the models of [16].

Table 2. McGuire's GMPE values

Period (*T*)	*b'₁*	*b₂*	*b₃*	cov, *Sₐ*
0.1	1610	0.233	1.341	0.651
0.2	2510	0.226	1.323	0.577
0.3	1478	0.290	1.416	0.560
0.5	183.2	0.356	1.197	0.591
1.0	6.894	0.399	0.704	0.703
2.0	0.974	0.466	0.675	0.941
3.0	0.497	0.485	0.709	1.007
4.0	0.291	0.520	0.788	1.191

The damage estimation of pipe is divided into three categories such as (*a*) major damage curve wherein the structural reliability of the material considered exceeds the critical or allowable level for the major damage state or ultimate limit state under seismic loading;

$$P[\text{major damage}] = P\left[\varepsilon_{cr}^{maj} - \varepsilon_p < 0\right] \qquad (7)$$

(*b*) moderate damage curve wherein the structural reliability of the material considered exceeds the moderate damage state seismic loading; and

$$P[\text{moderate damage}] = P\left[\varepsilon_{cr}^{mod} - \varepsilon_p < 0\right] \qquad (8)$$

and (c) minor damage wherein the structural reliability of the material exceeds the minor damage state or the serviceability limit state under seismic loading.

$$P[\text{minor damage}] = P\left[\varepsilon_{cr}^{min} - \varepsilon_p < 0\right] \qquad (9)$$

where $\varepsilon_{cr}^{major}, \varepsilon_{cr}^{mod}, \varepsilon_{cr}^{min}$, $_p$ are the critical strains for the different damage states and is the actual pipe strain, respectively. The models above are used to generate fragility curves that express the probability of damage occurrence of material conditioned on the PGA as shown in Fig 3.
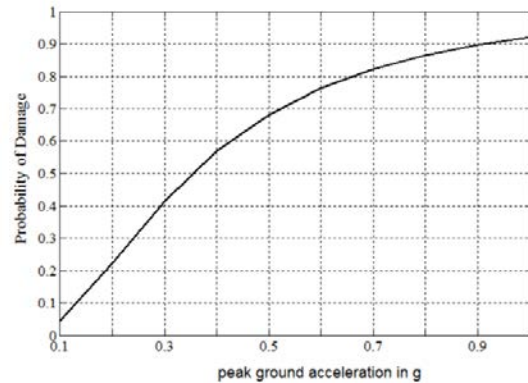

Fig. 3. Sample Fragility Curve

3.4 Pipe and ground strain

The seismic response analysis of buried pipeline is evaluated using ground response displacement (cm) U_h [17] as shown in Eq. 11. The free field displacement of soil particles is based on spectral velocity, a period of the ground surface, the thickness of the ground surface and the distance of the pipeline to the ground.

$$U_h = \frac{2}{\pi^2} S_v T \tag{10}$$

The actual pipe strain is the product of the free field ground strain ε_g and the α_o (see Eq. 11)

$$\varepsilon_p = \boldsymbol{\alpha_o \varepsilon_G} \tag{11}$$

$$\boldsymbol{\varepsilon_G = \frac{2\pi}{L} U_h} \tag{12}$$

The conversion factor α_o is shown in Eq. 13.

$$\boldsymbol{\alpha_o = \frac{1}{1+\left(\frac{2\pi}{\lambda L}\right)^2}} \tag{13}$$

$$\boldsymbol{\lambda = \sqrt{\frac{K}{EA}}} \tag{14}$$

where L is the horizontally traveling wavelength (cm), K is the axial stiffness between the surrounding soil and pipe (N/m), E is the modulus of elasticity (Mpa), A is the pipe cross-sectional area (mm^2).

4. RESULTS AND ANALYSIS

4.1 Probabilistic Seismic Hazard Analysis

The result of PSHA is summarized through the generation of seismic hazard curve and seismic hazard map for the province of Surigao Del Norte where the concession area of SMWD is located. Seismic sources are considered the linear source with distance L, based on the notion that point sources are not capable of generating earthquakes with magnitude 5.8 and above. The mathematical technique of triangulation is used to determine the shortest distance from any point of linear source. The calculated distances are divided by 10 km then normalized to determine their source-to-site distribution.

It can be seen in figure 4 that the likelihood for a seismic event with a moment magnitude of 6.4 to 6.9 to occur with 3 km away is estimated to be around 53% from the site. The annual rate of occurrence is the likelihood of an earthquake with a corresponding magnitude to occur for a year. Values for each seismic source are plotted with the values of a and b (Fig. 5) determined using linear

regression. These are later used in the determination of probability distribution of the earthquake magnitude $P(M)$.
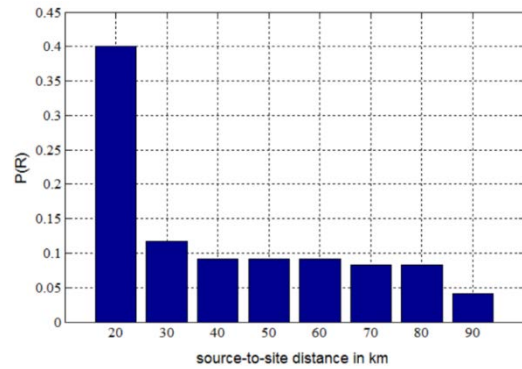

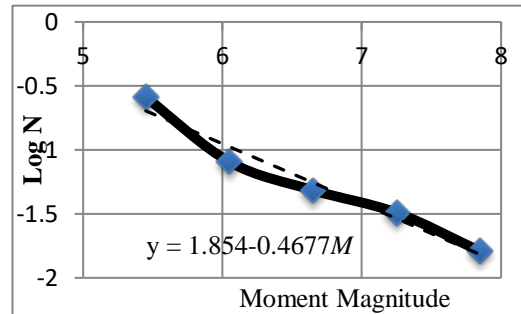Fig. 4. $P(R)$ for 6.4 - 6.9 M_w

y = 1.854-0.4677*M*

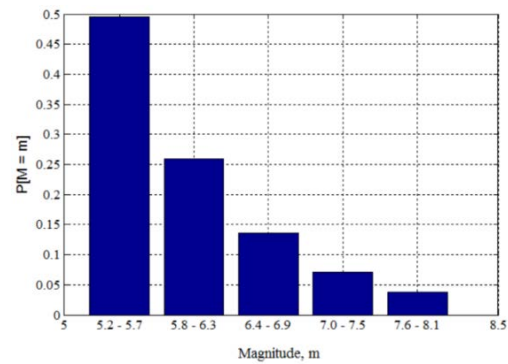Fig. 5. Gutenberg-Richter recurrence plot

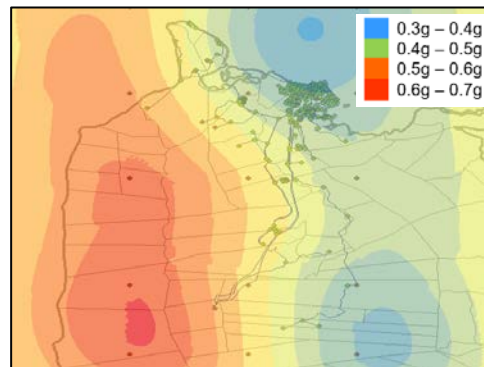Fig 6. Probability of the Magnitude

Fig. 7. Seismic Hazard Map of the area

Figure 6 shows the likelihood of the seismic events with greater magnitudes to have longer return periods than events with smaller magnitude. Earthquakes with a magnitude within 5.2 to 5.7 have a distribution of about 49.6% while earthquake with magnitude 7.6 to 8.1 has a distribution of around 3%. The seismic hazard curve is based on the mean value for all magnitude-distance pairs. The results show that for 0.0021 chance of occurrence for a DBE of 0.7g for PFZ: Surigao Segment. It must be noted that this event is likely to occur within 5km of the fault itself. The acceleration for all points considered is plotted on the map as seen in Figure 7.

4.2 Uniform Hazard Response Spectra

Figure 8 shows the uniform hazard response spectra for Surigao Del Norte. The spectral acceleration at sudden ground motion gradually increases until it reaches its peak movement. It slowly decreases as the period increases.
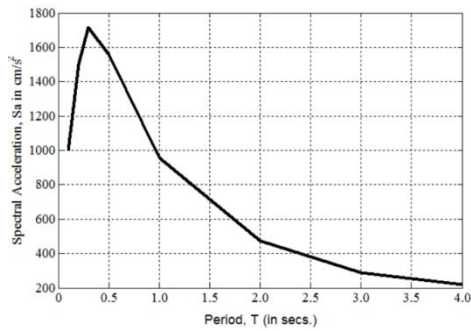

Fig. 8. Uniform Hazard Response Spectra

4.3 Vulnerability Analysis of SMWD

The fragility curves for this study were developed using Monte Carlo Simulation. The succeeding figures show the fragility curves for minor, moderate and major damage states given the pipe diameter of 10 cm.
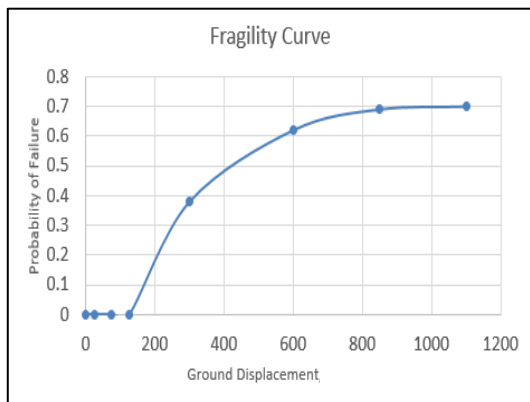

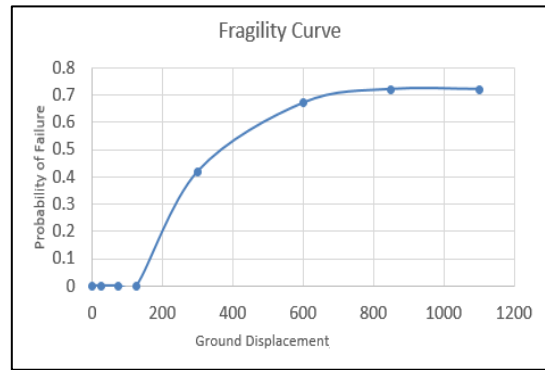Fig. 9. Fragility curve for Major Damage State

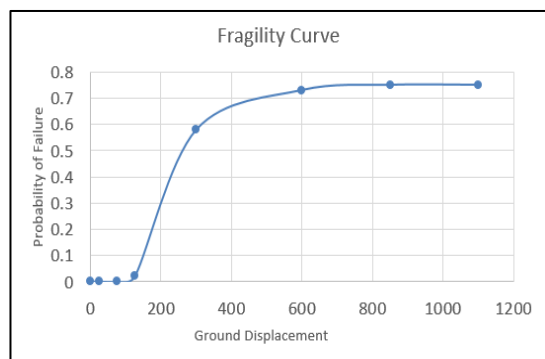Fig. 10. Fragility Curve for Moderate Damage State

Fig. 11. Fragility Curve for Minor Damage State

Figure 12 below shows the summary of the probability of damage for major, moderate and minor damage state of all pipe diameters. The probability of minor damage is higher for all pipe sizes in comparison to major damage state.
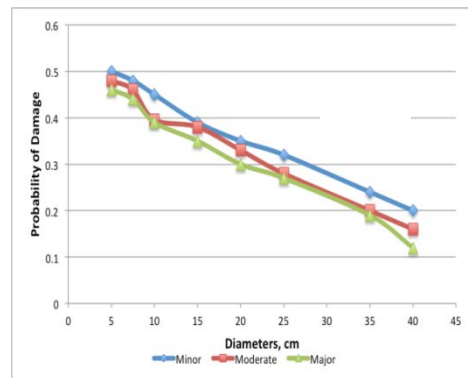

Fig. 12. Damage States for all pipe diameters

5. CONCLUSION

Monte Carlo simulation is used to produce the fragility curves for each damage states. The fragility curves provided for three different damage states showed that the probability of failure for the pipe for the period around 0.1 to 0.5 seconds is around 0 to 10%. Aside from that, it can

be seen that damage probability increases as period increases. It proves that the pipe strain is relative to the ground displacement and period of the seismic event. Major damage state is expected about 70% for longer earthquake periods.

6. ACKNOWLEDGEMENTS

The authors would like to thank Prof. Koike as well as to SMWD and PHIVOLCS for their valuable assistance.

7. REFERENCES

[1] Garciano, L. E., and Taclibon, P. The October 15, 2013, Bohol Island, Philippines earthquake and its damaging effects: An investigative report, Journal of Disaster Factsheets, http://committees.jsce.or.jp/disaster/FS2013-D-0004, Dec. 2013.

[2] Crismundo, M. Panic grips Surigao; Strong aftershocks, water shortage keep quake-affected residents on edge. Manila Bulletin, 2017.

[3] Hamada, M. Critical Urban Infrastructure Handbook, 2014, CRC Press.

[4] Sahoo, S., Manna, B., and Sharma, K. G. Seismic Behaviour of Buried Pipelines: 3D Finite Element Approach, Journal of Earthquakes. Vol. (2014), 2014.

[5] O'Rourke, M. and Ayala, G. Pipeline Damage Due to Wave Propagation. Journal of Geotechnical Engineering, 119 (9), 1993, pp. 1490 - 1498.

[6] Tromans, I. Behavior of Buried Water Supply Pipelines in Earthquake Zones. Doctorate Thesis, Imperial College of Science, Technology, and Medicine, London. 2004.

[7] Koike, T. Seismic Risk Assessment of a Water Supply Lifeline System in Baku. Conference Proceedings. In Proc. Reliability Engineering Conference, Azerbaijan. 2009.

[8] The Philippine Statistical Yearbook (PSY), National Statistical Coordination Board (NSCB), 2010.

[9] NDRRMC (National Disaster Risk Reduction and Management Council). SitRep No. 18 re Effects of Magnitude 6.7 Earthquake in Surigao City, Surigao Del Norte. July 3, 2017, from http://www.ndrrmc.gov.ph.

[10] PHIVOLCS (Philippines Institute of Volcanology and Seismology). Seismicity Map and Catalogue of Surigao Del Norte Earthquakes Magnitude 2.0 and above. 1952-2014.

[11] Giacomo, D., Bondar, I., Storchak, D. A., Engdhal, E.R., Bormann, P., Harrus, J., "ISC-BEM: Global Instrumental Earthquake Catalogue (1900-2009), Physics of the Earth and Planetary Interiors, 2014.in of the Seismological Society of America. 1990.

[12] Kramer, S. Geotechnical Earthquake Engineering. New Jersey: Prentice Hall. 1996.

[13] Fukushima, Y., & Tanaka, T. A new attenuation relationship for peak horizontal acceleration of strong earthquake ground motion in Japan. Bulletin of the Seismological Society of America. 1990.

[14] Thenhaus, P., & Campbell, K. Seismic Hazard Analysis. W. Chen Earthquake Engineering Handbook. 2003.

[15] Sen, T. Fundamental of Seismic Loading on Structure. PSHA. John Wiley & Sons. 2009.

[16] Ogawa, Y. and Koike, T., Structural Design of Buried Pipeline for Severe Earthquakes. Soil Dynamics and Engineering, 2001.

[17] JWWA (Japan Waterworks Association). Seismic Design Guideline for Waterworks Pipeline and Facilities, 1997.