Integrated Framework for Analyzing Seismic Hazard, Exposure, and Vulnerability in Damage and Loss Assessment of Water Network System

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https://doi.org/10.5109/7323314

出版情報：Proceedings of International Exchange and Innovation Conference on Engineering & Sciences (IEICES). 10, pp.545-551, 2024-10-17. International Exchange and Innovation Conference on Engineering & Sciences
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Integrated Framework for Analyzing Seismic Hazard, Exposure, and Vulnerability in Damage and Loss Assessment of Water Network System

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Abstract: *This research presents a methodology for assessing damage and losses in water network systems resulting from seismic events through an integrated analysis of hazard, exposure, and vulnerability. The methodology begins with a thorough seismic hazard analysis, identifying earthquake sources and predicting ground motion characteristics specific to the geographic region of the water network. It then systematically evaluates the exposure of the water pipelines, considering the physical attributes and configurations of its components. The vulnerability assessment component of the study analyzes how the damages to individual pipelines can affect the failure probability of the water network system. An integrated damage and loss assessment model combines hazard, exposure, and vulnerability analyses to estimate potential damage and losses. This research aims to provide water utilities, disaster management authorities, and policymakers with a robust tool for enhancing the resilience of water network systems against seismic threats, ensuring the continuity of water supply services in the aftermath of earthquakes.*

Keywords: Water network system; Seismic hazard analysis; Vulnerability assessment; Monte Carlo simulation

1. INTRODUCTION

The resilience of water network systems (WNS) is foundational to the health, safety, and economic stability of communities around the globe. These systems, known collectively as water lifelines, encompass the entire cycle of water delivery from source extraction through treatment and distribution, to the disposal and treatment of wastewater. In the face of natural disasters, the robustness of these systems is put to the test, with earthquakes presenting a particularly formidable challenge. The seismic vulnerability of WNS not only risks immediate disruption to critical water supplies but also poses long-term public health and economic recovery challenges. Historical seismic events have extensively damaged and impacted these infrastructures, revealing a pressing need for a comprehensive understanding of their vulnerabilities and developing strategies to bolster their resilience. This necessity is amplified in urban areas, where the density of populations and the complexity of infrastructure systems magnify the potential impacts of seismic disruptions. The functionality of WNS is crucial in the aftermath of natural disasters, where access to clean water becomes a primary determinant of public health and recovery efforts.

Seismic events pose a significant threat to the integrity and operational continuity of WNS. Historical and recent earthquakes have demonstrated that the damage to these systems can lead to immediate public health crises and long-term socioeconomic challenges, severely hampering recovery efforts in affected areas. Despite advances in engineering and materials science, the complex interplay of seismic forces and the extensive, often aging, water infrastructure network makes vulnerability and risk assessment a challenging endeavor. The dynamic nature of seismic hazards, combined with the varying conditions of water system components and their distribution, calls for a comprehensive approach to damage and loss assessment that can inform more resilient planning and design. The results of this study can be used to conduct further studies on risk management to reduce the probability for the loss of the occurrence and the impact caused by hazards [1,2].

2. PAST STUDIES ON SEISMIC PERFORMANCE OF WATER NETWORK SYSTEM

The resilience of urban water network systems to seismic events has garnered significant attention in recent decades, given the critical importance of maintaining water supply and sanitation services in the aftermath of earthquakes. A growing body of research has focused on developing methodologies for assessing the vulnerability and enhancing the resilience of these systems against seismic hazards. Early studies by Shinozuka et al. [3] highlighted the need for comprehensive risk assessment frameworks that consider the physical damage to water network components and the resulting service disruptions. These foundational works laid the groundwork for subsequent research in the field, emphasizing the complexity and interdependency of urban water networks.

Advancements in seismic hazard analysis and modeling techniques have significantly contributed to our understanding of the risks posed to water networks during earthquakes. For instance, Hwang et al. [4] developed probabilistic models to assess the vulnerability of water supply systems, incorporating spatial variations in seismic intensity and system-specific characteristics. This approach marked a significant step forward in quantifying potential damages and informed the development of more resilient network designs. Recent research has increasingly focused on integrating geographic information systems (GIS) and computational simulation models to assess and mitigate seismic risks to water networks. For example, O'Rourke et al. [5] utilized GIS-based methodologies to evaluate the seismic performance of water distribution systems, demonstrating the potential of such tools in identifying

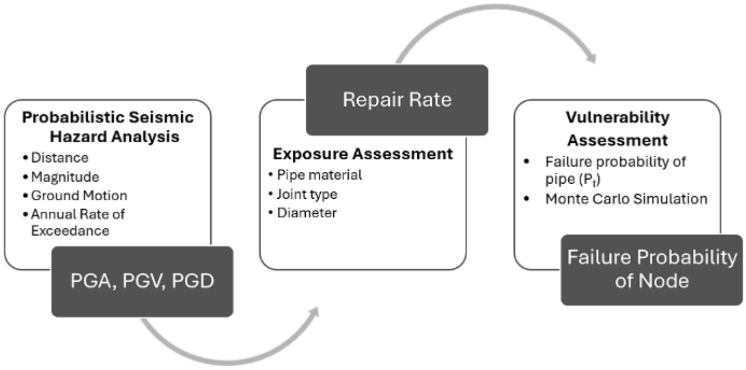

Fig. 1. Framework of hazard, exposure and vulnerability assessment

critical vulnerabilities and prioritizing mitigation efforts. Despite these advances, gaps remain in the comprehensive assessment of earthquake damage and loss for water lifelines. Recent earthquakes have exposed limitations in current modeling approaches, particularly in their ability to account for the dynamic interdependencies within urban infrastructure systems [6]. Moreover, the role of post-earthquake functionality and rapid recovery strategies has become a central focus in recent studies. Maruyama et al. [7] emphasized the importance of resilience metrics in planning for the rapid restoration of water services, proposing a framework that accounts for both physical damage and the socio-economic impacts of service interruptions.

Collectively, these studies underscore the evolving landscape of research on the seismic resilience of water network systems. While significant progress has been made in assessing vulnerabilities and enhancing system robustness [8], the challenge of ensuring the continuity of water services in the face of seismic events remains a critical area of inquiry. The need for innovative, integrated approaches to risk assessment and management is clear, as urban centers worldwide strive to mitigate the impacts of earthquakes on vital water infrastructure. The primary objective of this research is to develop a multidimensional framework for the assessment of earthquake damage and loss in water lifelines. This framework aims to integrate detailed analyses of hazard, exposure, and vulnerability, providing a comprehensive understanding of the risks posed to water systems by seismic events.

3. METHODOLOGY

The methodology of this study is divided into three parts: hazard analysis, exposure assessment and vulnerability assessment (see Fig. 1). The first part uses the Probabilistic Seismic Hazard Analysis (PSHA) to estimate the ground motion in an area covered by a water network system. The analysis involves the calculation of distance, magnitude and ground motion probabilities to predict the peak ground acceleration which can then be converted to peak ground velocity and displacement. These ground motion values are then used to assess the exposure of the pipelines given the seismic hazard wherein the expected damage in the pipes per meter length is quantified using repair rate which varies depending on the pipe material, type of joint and pipe diameter. Using the estimated damages or repair rate on each pipe, the vulnerability of the water network system is assessed by calculating the failure probability. It will start individually per pipe which will be correlated to the node failure probability using Monte Carlo simulation. The succeeding chapters of this study present the detailed methodology for each part.

4. PROBABILISTIC SEISMIC HAZARD ANALYSIS

Probabilistic Seismic Hazard Analysis (PSHA) serves to compute the Peak Ground Acceleration (PGA) for a specific area, using the West Valley Fault as the seismic point of origin. Employing a stochastic approach, this method accommodates the complexities of uncertainties, encompassing factors such as probabilities in distance, magnitude, and ground motion. The results of this analytical process yield a response spectrum, illustrating acceleration values throughout varying temporal intervals. Subsequently, the PGA values are utilized in the construction of a spectral map. This process follows the calculation procedure as discussed by Baker [9]. This paper presents the calculation for Biñan City, Laguna, Philippines as the area of study.

4.1 Distance probability

The initial phase of employing PSHA involves identifying seismic origins. These sources can be categorized as either point, linear, or three-dimensional source zones. Considering the focus of the study on the seismic potential of West Valley Fault, the seismic source is characterized as a linear or fault type. The process of determining distance probability entails evaluating the distance between the fault line and the designated site, also referred to as source-to-site distance [9]. In the QGIS software, the location of the fault line was identified by running a query in the OpenStreetMap (OSM). Given the elongated nature of West Valley Fault rather than being linear, it was segmented into three sections to accurately depict the location of the fault line. Using QGIS, these three sections were further divided into subsegments with each having a length of 500 meters, resulting in a total of 191 segments (see Fig. 2).

After defining the seismic source, the site is represented by grid points spaced at 500 meters which bound the entire city. There is a total of 667 grid points and each of it produced a source-to-site distance to the 190 fault segments which is directly calculated in the QGIS software. In addition, each grid point has its own distance probability distribution and contains a PGA value which was calculated in the succeeding steps. The probability

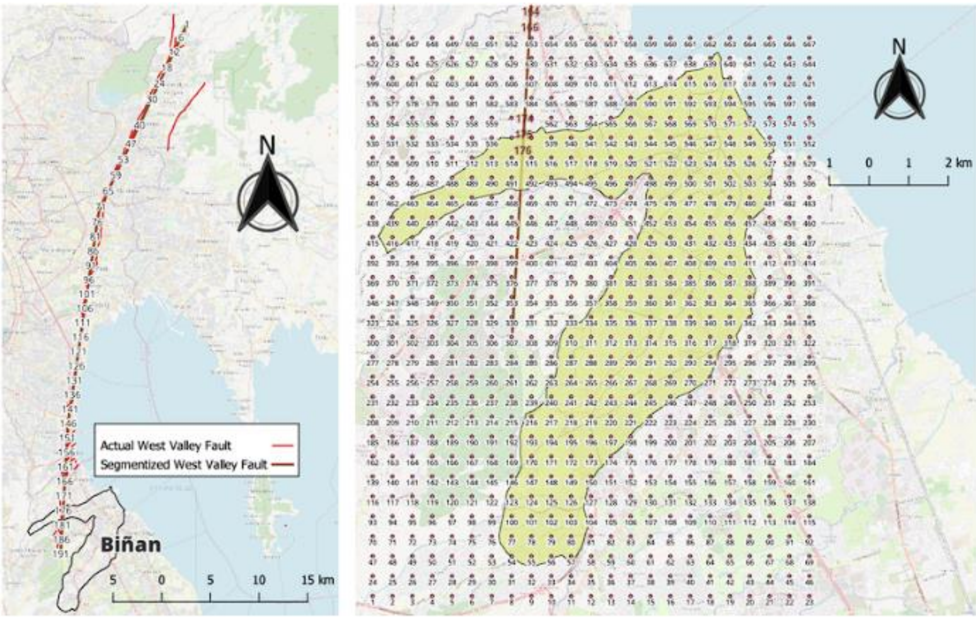

Fig. 2. Linear segments of the fault and grid points of the city

value is taken by counting the number of segments with source-to-site distance falling within the specified range category and getting the normalized value. The result indicates a heightened likelihood of distance probability within the range of less than 20 kilometers, accounting for a cumulative probability of around 40%. A comparable trend of diminishing probability is evident at greater distances for other grid points. Notably, the maximum distance recorded predominantly falls within the 80 to 90-kilometer spectrum. Consequently, seismic incidents originating from the West Valley Fault and occurring beyond the 90-kilometer threshold are improbable.

4.2 Magnitude probability

In this methodology, the raw data of historical earthquakes sourced from PHIVOLCS were filtered to ensure that only the seismic records related to the West Valley Fault are used in this study. This filtering procedure was executed by assuming that only data located within a 50-kilometer distance measured from the linearized fault line, as used in the distance probability, were relevant to the West Valley Fault [10]. Also, only records of M5.2 and above were considered as this is the minimum magnitude considered in engineering interests. This process was done in QGIS by creating a polygon and removing the data situated outside the area of consideration (see Fig. 3).

The filtered earthquake data were then analyzed by using Gutenberg Richter Recurrence Law. Similar to the procedure for distance probability, magnitudes were also grouped into categories using their maximum and minimum values. Each category was assigned an average magnitude derived from the upper and lower bounds. Subsequently, the frequency of filtered seismic records falling within these category limits was documented. These cumulative frequencies and logarithmic representations were then applied following the principles of the Gutenberg-Richter Law. After establishing the recurrence law, the probability density function and magnitude probability for a mean value for each category are calculated. The results indicate the probability distribution of a seismic occurrence

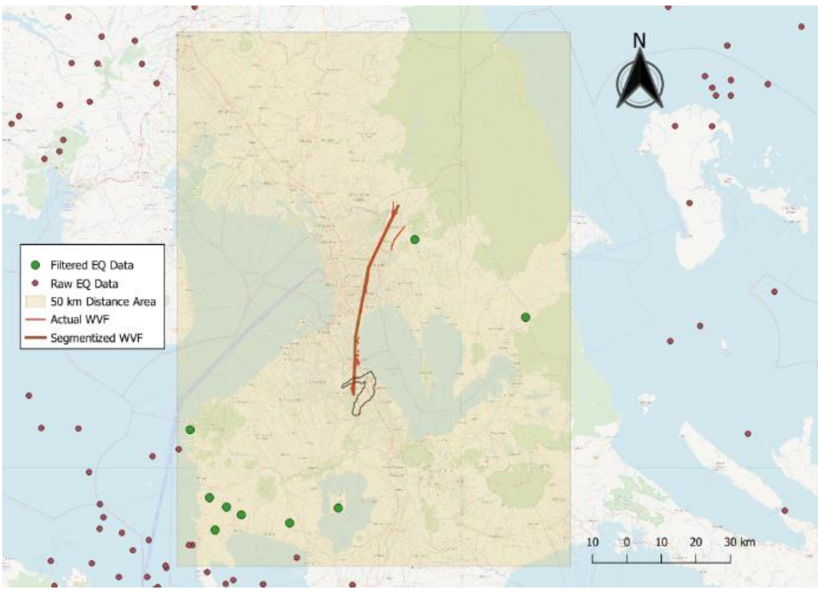

Fig. 3. Filtering of seismic records using QGIS

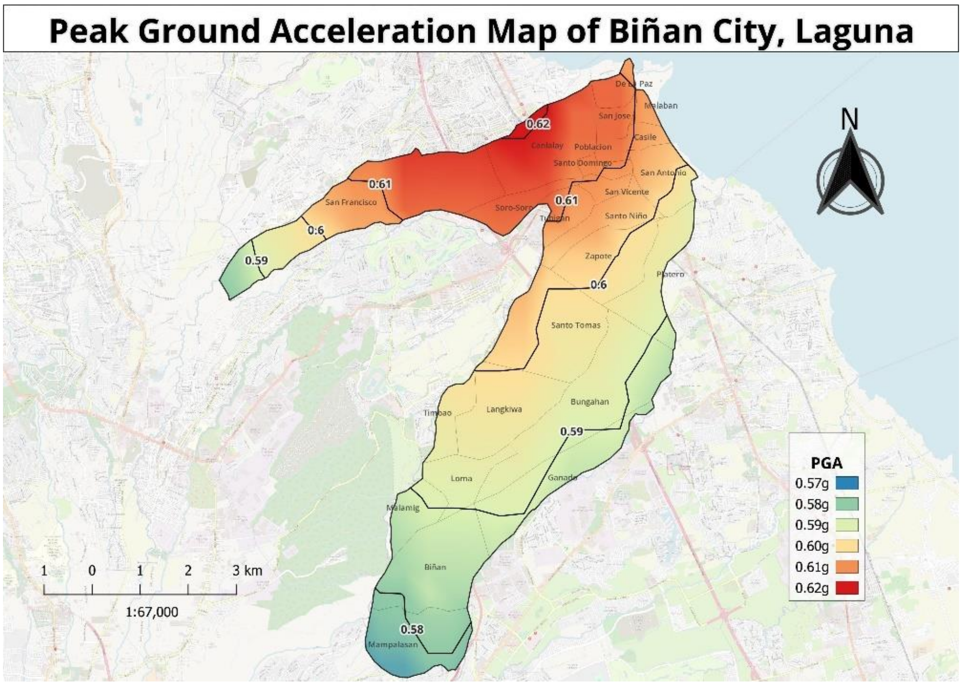

Fig. 4. Seismic hazard map of Biñan City, Laguna, Philippines

encompassing magnitudes ranging from 5.30 to 7.36. Analogous to the recurrence relationship, the results show that higher magnitudes are accompanied by diminished probabilities of happening in contrast to lower magnitudes. The highest probability of 24% materializes at a magnitude of 5.30, while the least likelihood, at 2.5%, is anticipated at a magnitude of 7.36. The mean magnitude values for each category, alongside the categories for distance, were employed in determining the probabilities related to ground motion.

4.3 Ground motion probability

This process involves the range of values calculated established from the distance and magnitude probabilities. Every magnitude interval results in a corresponding ground acceleration value relative to the specified distance range with the use of attenuation model. This study used the model of Youngs et al. [11] which is the same equation used in the Philippine Earthquake Model. The utilized distance values comprised 10-kilometer increments spanning from 0 to 90 kilometers, mirroring the approach employed in distance probability. Conversely, the magnitude values employed were the averages of the magnitude intervals outlined in the magnitude probability.

4.4 Annual rate of exceedance

The methodology of annual rate of exceedance combines all the uncertainties calculated from distance, magnitude and ground motion probabilities. The calculations were done by setting a target PGA of 0.1g to 1.0g. Mathematically, it is the product of the three probabilities.

In this methodology, the ground acceleration value at a specific period was obtained using the function derived from seismic hazard curves. The period used are the same values indicated in the attenuation model from the ground motion probability. Originally, this function allows for the computation of the mean annual rate of exceeding, considering the provided target ground motion values. However, to generate the response spectrum, the values of ground motion assessed at the 2% probability of exceeding within a 50-year timeframe was necessary. In this regard, the Poisson model facilitated the conversion of the 2% exceedance value within the 50-year interval into the corresponding mean annual rate of exceeding. The reciprocal of this rate defines the return period which is 2500 years. Subsequently, with the rate of exceeding established, the ground acceleration per designated timeframe was determined.

4.5 Seismic hazard map

By repeating the same procedure of PSHA for all 667 grid points in the city, each point was stored with acceleration value which is the peak ordinate in the response spectrum. The QGIS software enables the interpolation of acceleration values of the points and spectral map can be established (see Fig. 4). Based on the map, the highest PGA in the city is around 0.63g which is at the northern part. It was also observed that areas near the fault line have higher PGA values. The southern area of the city is predicted to experience an acceleration of 0.57g. Overall, the PGA value of the city ranges from 0.57 to 0.63g which is comparable with the Philippine Earthquake Model.

5. EXPOSURE ASSESSMENT

The exposure of WNS to seismic hazard can be measured in different ways such as pipe strain and ground displacement due to liquefaction [12]. This study focuses on the effects of ground motion to the pipes. In the study of Hou et al. [13], the fragility of buried pipes is calculated based on the empirical formula provided in the guidelines by the American Lifelines Alliance (ALA). In this 2001 Seismic Fragility Formulations for Water Systems, it addresses the susceptibility of underground pipelines to seismic activities, presenting various criteria for failure and suggesting vulnerability models based on historical earthquake data. These models correlate the likelihood of damage with peak ground velocity (PGV) and permanent ground deformations (PGD) taken from the seismic hazard analysis. PGV measures the intense shaking due to seismic waves, whereas PGD assesses changes in the ground such as landslides, liquefaction, settlement, and faults. Additional factors considered include the pipeline's diameter, its age, the year it was laid, and any potential irregularities along its length. The ALA guidelines offer formulas to estimate damages in terms of the rate of repairs expressed in Eq. 1.

$$RR = \max\begin{cases} RR_{PGV} = K_1 \cdot 0.01425 \cdot PGV \\ RR_{PGD} = K_2 \cdot 4.281 \cdot PGD^{0.319} \end{cases} \quad \text{Eq. 1}$$

where RR is the repair rate calculated per 100 meters of pipe length, PGV is in cm/s, PGD is in cm and K_1 and K_2 are adjustment factors depending on different pipe materials indicated in Tables 1 and 2.

Table 1. K_1 constants for repair rate

Material	Joint Type	Soil	Diameter	K_1
Cast iron	Cement	All	Small	1.0
Cast iron	Cement	Corrosive	Small	1.4
Cast iron	Cement	Non-corrosive	Small	0.7
Cast iron	Rubber gasket	All	Small	0.8
Welded Steel	Lap – Arc welded	All	Small	0.6
Welded Steel	Lap – Arc welded	Corrosive	Small	0.9
Welded Steel	Lap – Arc welded	Non-corrosive	Small	0.3
Welded Steel	Lap – Arc welded	All	Large	0.15
Welded Steel	Rubber gasket	All	Small	0.7
Welded Steel	Screwed	All	Small	1.3
Welded Steel	Riveted	All	Small	1.3
Asbestos Cement	Rubber gasket	All	Small	0.5
Asbestos Cement	Cement	All	Small	1.0
Concrete w/ Stl Cyl.	Lap – Arc welded	All	Large	0.7
Concrete w/ Stl Cyl.	Cement	All	Large	1.0
Concrete w/ Stl Cyl.	Rubber gasket	All	Large	0.8
PVC	Rubber gasket	All	Small	0.5
Ductile Iron	Rubber gasket	All	Small	0.5

Table 2. K_2 constants for repair rate

Material	Joint Type	K_2
Cast iron	Cement	1.0
Cast iron	Rubber Gasket	0.8
Cast iron	Mechanical Restrained	0.7
Welded Steel	Arc welded, lap welds (large diameter, non-corrosive)	0.15
Welded Steel	Rubber gasket	0.7
Asbestos Cement	Rubber gasket	0.8
Asbestos Cement	Cement	1.0
Concrete w/ Stl Cyl.	Welded	0.6
Concrete w/ Stl Cyl.	Cement	1.0
Concrete w/ Stl Cyl.	Rubber gasket	0.7
PVC	Rubber gasket	0.8
Ductile Iron	Rubber gasket	0.5

It is important to recognize that while both peak ground velocity (PGV) and peak ground acceleration (PGA) serve as indicators of earthquake intensity, PGV is often deemed a more accurate predictor of structural damage. This preference stems primarily from PGV's proven correlation with damage incidences, positioning it as an effective measure for assessing the potential of seismic movements to inflict harm on structures. In the study of Ordaz et al. [14], the primary reason for PGV's effectiveness in forecasting pipeline damage is its direct association with ground strain, which is the leading cause of pipeline damage due to the propagation of seismic. Furthermore, PGV exhibits sensitivity to longer seismic wave periods in comparison to PGA, thereby offering enhanced predictability through deterministic modeling.

6. VULNERABILITY ASSESSMENT

This phase of the analysis focuses on identifying the probability of a demand node of the WNS being disconnected to a source node. It involves the use of seismic hazard analysis to identify the resulting damages to each pipe which is used to determine the probability of failure. The vulnerability of the WNS is assessed by using the individual exposure of each pipe. The exposure of these individual pipes is quantified as its failure probability with the use of frequency of leaks or breaks per unit length of pipe or referred to earlier as repair rate (RR). This probability is calculated as one minus the probability of not experiencing any breaks along the length of the pipe. In the guidelines provided by ALA [15], the failure probability of buried pipes is assumed to follow an exponential distribution. Using the cumulative distribution function (CDF) of an exponential distribution, the failure probability of each pipe (P_f) is expressed in Eq. 2.

$$P_f = 1 - e^{-RR \cdot L} \quad \text{Eq. 2}$$

where RR is the maximum repair rate between RR_{PGV} and RR_{PGD} taken from the exposure assessment. The failure probability of individual pipes is used to assess the vulnerability of the WNS with the use of Monte Carlo Simulation (MCS). In the study of Fragiadakis et al. [16], the simulation process is used to compute the node-to-node failure probability, which corresponds to the source node going to the demand node or outflow. In each simulation, a uniform random number α_n is generated and assigned for each pipe. The random number and failure probability P_f are used to determine the survivability of each pipe (A_n) as expressed in Eq. 3.

$$A_n = \begin{cases} 1 & if\ 1 - P_f < \alpha_n \\ 0 & otherwise \end{cases} \quad \text{Eq. 3}$$

The expression above simply returns a value of one for each pipe if it fails in that simulation and zero if it survives. Then, all pipes marked with a value of one are removed from the WNS. The new WNS is then used to evaluate if a path exists from source node to demand node. Since some pipes will not be operational, there is a chance that certain demand nodes will be disconnected from a supply node. If a path does not exist, that particular simulation is assigned a value of one. Otherwise, the value is zero. Mathematically, it is expressed in Eq. 4.

$$B_n = \begin{cases} 1 & path\ does\ not\ exist\ from\ source \\ & to\ demand\ node \\ 0 & otherwise \end{cases} \quad \text{Eq. 4}$$

The failure probability of the demand node is calculated using Monte Carlo simulation. It is the number of simulations where a path going to the demand node does not exist divided by the total number of simulations which should be at least 10,000.

$$\overline{P_f} = \frac{\sum_{n=1}^{N} B_n}{N} \quad \text{Eq. 5}$$

where $\overline{P_f}$ is the failure probability of the demand node and N is the total number of simulations. This probability value signifies the chances that a certain demand node will not receive any water supply in an event of seismic hazards. It can then be used by water utilities, disaster management authorities, and policymakers to estimate the losses and enhance resiliency.

7. CONCLUSION

This study presents the results of the seismic hazard analysis and proposes a methodology framework to use the ground motion values in assessing the exposure and vulnerability of water network systems. The methodology begins with a thorough seismic hazard analysis to identify earthquake sources and predict ground motion characteristics specific to the region. The analysis produced a peak ground acceleration map for Biñan City, Laguna which shows that acceleration value ranges from 0.57g to 0.62g. It then systematically evaluates the exposure of water pipelines using repair rate. It considers the physical attributes and configurations of the pipe. The vulnerability assessment component analyzes how damages to individual pipelines can affect the failure probability of the entire system.

In this study, an integrated assessment model combining hazard, exposure, and vulnerability analyses together with other factors such as socio-economic behavior can be done to estimate potential damage and losses. The research aims to equip water utilities, disaster management authorities, and policymakers with a robust tool for enhancing the resilience of water network systems against seismic threats, ensuring the continuity of water supply services post-earthquakes, and facilitating informed restoration and disaster preparedness efforts. Through this comprehensive approach, the study addresses gaps in existing methodologies and offers actionable insights for improving the seismic resilience of water network systems.

The study can be improved by expanding the GIS-based model which can consider other seismic sources other than the West Valley Fault. In addition, the vulnerability of demand nodes can be further used to estimate the economic losses based on the amount of water consumed.

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