Framework for Seismic Damage and Renewal Cost Analysis of Buried Water Pipelines

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Abstract: Buried water pipelines suffer extensive damages when subjected to earthquake loading. Probable seismic damage of buried pipelines is typically estimated based on empirical analyses, where the effects of corrosion deterioration are often neglected. Corrosion-induced deterioration weakens the pipeline resistance capacity, which in turn significantly reduces the seismic reliability of water distribution systems (WDS). Improved seismic damage estimation of buried water pipelines needs to consider the effect of corrosion on their seismic performance to assist with the development of an effective and efficient renewal strategy. Hence, the first part of this study improves a current US guideline on seismic repair rate (RR) estimation, based on the observed effects of corrosion on pipeline damages during a recent earthquake (2014 Napa earthquake). Then, a renewal strategy is proposed that addresses the vulnerability of pipelines from the topological viewpoint in addition to the condition index and failure impact index commonly used in practice decisions. In addition, water distribution networks are often large and complex, which leads to considerable computational time and cost for seismic risk assessment. In this study, a computationally efficient methodology named SeismoPi is developed using Python-based open-source libraries for estimating the seismic damage of buried pipelines. The methodology is capable of performing scenario-based seismic damage analysis of complex buried water networks, identifying critical segments and system connectivity, and estimating the renewal cost. The method presents the interactive outputs on maps so that decision makers can easily visualize the results and identify the riskiest segments that need to be rehabilitated. SeismoPi assists decision makers in developing WDS renewable strategies that account for the effects of corrosion deterioration on their seismic performance. Applications of the proposed framework are demonstrated on a few small- to large-sized water distribution systems. **DOI: 10.1061/(ASCE)PS.1949-1204.0000487.** *© 2020 American Society of Civil Engineers.*

Introduction

Seismic Damage to Water Pipelines and Fragility

Water pipelines are mostly buried underground and carry large amounts of water to various consumers through complex distribution systems (Farahmandfar et al. 2016). Water distribution systems (WDS) are usually designed to last for a long period of time, and it is expected that water pipelines will experience various natural hazards (e.g., earthquake) and human-induced hazards (e.g., damage due to ground construction) throughout their life cycle (Fragiadakis and Christodoulou 2014; Choi et al. 2017). Among the types of hazards that may be experienced by WDS, earthquakes are the most damaging and may result in substantial functionality loss to water systems (Karamlou and Bocchini 2017; Choi et al. 2017; Nair et al. 2018; Asadi et al. 2019). Failure in water pipelines may lead to water depressurization in the network and consequently hampers the firefighting capability of WDS (Ariman and Muleski 1981; Mazumder et al. 2020), which can result in severe socioeconomic consequences (Karamlou and Bocchini 2017).

Buried pipelines have sustained large amounts of damage in past earthquakes and resulted in huge economic losses (Ariman and Muleski 1981; Pudasaini and Shahandashti 2018; Nair et al. 2018). A majority of old water pipelines in North America are made of cast iron (CI), and 82% of CI pipes are more than 50 years old (Folkman 2018). Past earthquake records revealed that CI pipelines had experienced higher damage rates (ALA 2001; O'Rourke and Ayala 1993; O'Rourke and Deyoe 2004). For example, the American Lifeline Alliance (ALA 2001) analyzed pipeline damage data of 12 earthquakes and reported that CI, ductile iron (DI), and asbestos pipelines experience a repair rate of 0.00195, 0.00103, and 0.00075 (as a function of peak ground velocity), respectively.

Significant parts of existing water pipelines in many utilities of the US are made of CI pipes that are still in service after their expected lifetime. For instance, about one-third of Los Angeles, California, water pipelines are more than 80 years old, with the oldest one being in service for more than 130 years (Poston et al. 2014; Kim 2018) whereas the typical life of a CI pipe is between 80 and 100 years (Margevicius and Haddad 2002). Older pipelines are likely to have considerable deterioration (Kirmeyer et al. 1994; Rajani and McDonald 1995; Seica and Packer 2004). Deterioration due to aging plays a key role in the high seismic damage observed in older CI and other metallic pipelines (Robert et al. 2016; Mazumder et al. 2019). Failure often takes place in the metallic pipe as stress concentration occurs due to the formation

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of corrosion pits on the pipeline wall (Ji et al. 2017; Zohra et al. 2012).

The American Society of Civil Engineers' 2017 Infrastructure Report Card awarded a grade of D (Poor) to water infrastructure (ASCE 2017). A huge amount of capital investment is necessary to rehabilitate the most urgent and critical water mains. Utilities often apply a risk-reduction approach to rehabilitate critical assets in which they need to identify the riskiest segments of WDS. Because a significant number of water utilities are relying on age-old metallic pipelines, seismic performance of existing WDS needs to be assessed properly to avoid catastrophic consequences, especially in regions of high seismicity. When assessing the seismic performance of water pipelines, the effect of aging and deterioration needs to be modeled properly because the pipelines are designed for a longer lifetime (Biondini and Frangopol 2017).

Methods for seismic fragility estimation of buried pipelines can be classified into empirical, analytical, expert-based, and hybrid methods (Tsinidis et al. 2019). Most seismic fragilities of buried pipelines are often developed from damage data observed after past earthquakes. Expected seismic damage of a pipeline is typically estimated as repair rate (RR) per unit length of pipe (O'Rourke and Ayala 1993; Eidinger 1998; ALA 2001). Empirically developed fragility curves for buried pipelines suffer from the lack of a sufficient amount of data set (Mazumder et al. 2020). Most of the empirically developed fragility curves are suitable for segmented pipelines because a significant portion of damaged data is from the most common type of existing pipelines (e.g., CI) in practice (Nair et al. 2018).

Although there are a number of fragility curves developed for buried pipelines (e.g., O'Rourke and Ayala 1993; Eidinger 1998; O'Rourke and Jeon 1999; Isoyama et al. 2000; ALA 2001; O'Rourke and Deyoe 2004), the American Lifeline Alliance (ALA) 2001 fragility model (ALA 2001) is the most commonly used in current literature. This is because the ALA 2001 model was derived from a larger empirical data set compared with other studies (Nair et al. 2018). Nair et al. (2018) and Mazumder et al. (2020) have given details of empirical fragility relations developed in various studies. ALA 2001 fragility curves incorporate correction factors for pipe material, joint type, diameter size, and soil corrosiveness. Similarly, Isoyama et al. (2000) suggested a modification of the repair rate by multiplying with a correction factor estimated based on pipe diameter, material, topology, and liquefaction. However, one of the major drawbacks of the ALA 2001 guideline and other studies is that they do not consider the effect of deterioration and previous break records in pipeline seismic performance evaluation (Christodoulou and Fragiadakis 2014).

A damage database of past earthquakes is evidence that deteriorated pipelines are susceptible to experiencing a relatively higher number of damages than newer pipelines (O'Rourke and Deyoe 2004). Wang (1990) found that newer pipelines experienced a lesser amount of damages than older pipelines after the 1987 Whitter Narrows earthquake. A similar increasing trend of pipe breaks was found for older ductile iron pipelines after the Loma Prieta earthquake (Eidinger 1998). Recently, Eidinger (2015) found a strong correlation between corrosion and the lower seismic performance of pipelines. Hence, it is important to account for the effect of deterioration in the pipeline when estimating probable seismic damage.

Fragiadakis and Christodoulou (2014) extended the ALA 2001 guideline to evaluate seismic performance by incorporating the effect of previous nonseismic breaks of a pipeline. The modification was done by incorporating the ratio of pipeline's survival curves at damaged and undamaged states. Recently Mazumder et al. (2020) proposed a modification of the ALA 2001 guideline to consider the effect of corrosion deterioration by accounting for the time-variant stress change on buried CI pipelines. The physics-based model proposed by Robert et al. (2016) was considered in their study to estimate stress on the buried pipeline. However, the model is suitable only if detailed data associated with the stress calculation model are available. Eidinger (2015) provided useful insight into the seismic performance assessment of corroded pipelines after analyzing a damage data set of the 2014 Napa Valley earthquake. That author investigated the relationship between soil resistivity and repair rates for unprotected metal water pipelines (e.g., cast iron and ductile iron) and proposed an updated ALA 2001 fragility model for estimating seismic damage of buried water pipelines.

Seismic Analysis of Network

Because an earthquake can severely damage buried water pipelines, reliable seismic damage estimation and pipeline failure prediction in the aftermath of an earthquake are key challenges in pipeline engineering (De Risi et al. 2018). The performance of WDS during an earthquake is also highly interdependent with other infrastructures (e.g., power and road systems) and essential services (e.g., medical facilities). For instance, failure in water pipelines may lead to disruption in essential services (e.g., firefighting system and health care) immediately after an earthquake (Nair et al. 2018). Therefore, seismic response analysis of water distribution networks has received increasing attention from policymakers.

In case of an earthquake, utility managers are often more interested in knowing what will happen to system connectivity rather than individual components. Mechanical connectivity/integrity of a system after an earthquake can be identified using a connectivity approach. Connectivity is a measure of the likelihood that the nodes in a system are physically connected to at least a water source (Wagner et al. 1988). Graph analysis of water networks has made it possible to identify connectivity and critical components in the system before and after an earthquake. WDS are typically large, composed of hundreds of nodes and pipelines, as well as multiple water sources. Seismic damage assessment, consequent network performance, and renewal cost analysis are often regarded as very difficult and time-consuming tasks. Some studies have used topological measures such as betweenness centrality to evaluate the performance of WDS (e.g., Yazdani et al. 2011; Gutiérrez-Pérez et al. 2013; Shuang et al. 2015, 2016; Zarghami et al. 2018, among others).

The seismic risk to water and other infrastructures is often estimated using a scenario-based approach (Adachi and Ellingwood 2009). Adachi and Ellingwood (2008, 2009) evaluated the dependency of the serviceability of WDS on power availability under scenario-based seismic hazard. Those authors emphasized the a dvantages of scenario-based seismic analysis for distributed civil infrastructures. Scenario-based seismic analysis overcomes some practical difficulties in seismic hazard analysis (Chang and Shinozuka 2004; Salman and Li 2018). The output of scenario-based seismic analysis can be interpreted easily by decision makers because annual and negligible probabilities are avoided (Adachi and Ellingwood 2009). Other studies focused on developing frameworks for pipeline rehabilitation planning to reduce seismic risk (e.g., Pudasaini and Shahandashti 2018; Tee et al. 2014; Khan and Tee 2016). Although most of the studies on seismic risk analysis quantify probable damage to water pipelines, studies focusing on postearthquake renewal actions are rare.

Water Network Analysis Tools

Water networks are typically large and complex. As such, seismic performance evaluation of complex and large size networks require

Table 1. Water network analysis tools

Name of tool	Description	Advantages/limitation	References
HAZUS-MH	The GIS-based tool estimates the damage of infrastructures in terms of social and economic values.	Useful for identifying immediate impact assessment. Does not estimate system performance.	FEMA (2012)
WNTR	A Python-based tool developed to perform hydraulic simulation, seismic damage, and resilience analysis of water networks.	A comprehensive tool developed by USEPA and Sandia National Laboratories. WNTR is an EPANET-oriented Python tool capable of performing pressure-driven hydraulic simulation of WDS under disruptive scenarios. This tool does not conduct simulations to compare and analyze diverse restoration strategies for damaged network.	Klise et al. (2017)
MAEviz	Open source tool developed by Mid-America Earthquake Center for performing earthquake risk evaluation infrastructures.	Performs seismic impact assessment but does not include restoration measures or simulation of system performance.	Navarro et al. (2008)
INCORE version 1.0	Open-source multihazard assessment, response, and planning tool for performing risk-based community resilience planning. This tool is developed based on ERGO (previously known as MAEviz)	Second version of IN-CORE module is still under development. Future version will include a comprehensive earthquake assessment based on Python platform.	Gardoni et al. (2018)
GIRAFFE	Computer model that quantifies the damage in social infrastructures in terms of societal and economic value	Assumption of smooth hydraulic functionality under disaster scenario may result in an unrealistic hydraulic condition.	Shi et al. (2006)
REVAS.NET	Estimate system reliability against seismic damage to simulate the detailed postearthquake restoration process.	This model quantifies factors that affect seismic performance based on Isoyama et al. (2000) that ignored correction factor for corrosion.	Yoo et al. (2015)
SeismoPi	This is the tool developed in this paper. It is a Python-based open-source tool that performs scenario-based seismic damage analysis, identifies the critical components and estimates renewal cost of buried pipeline network.	This tool quantifies the probable seismic damage of buried pipelines considering the effect of corrosion deterioration on pipeline walls and estimate subsequent renewal cost of WDS. The input data structure is very simple and easy to prepare. Comma-separated value files that contain the characteristics of the network components are used as the input files. It does not require the user to perform hydraulic analysis and identifies the critical segment of the pipeline network using complex network theory.	

higher computational time and cost. Several tools have been developed by researchers to quantify seismic damage to pipeline networks. Table 1 presents a comparison among various tools available in the literature. However, these tools suffered from a number of limitations, as discussed in Table 1. Some major drawbacks of these tools are that they do not identify critical segments of the complex systems, do not explicitly quantify the effect of corrosion in seismic performance, do not model maintenance strategies, and some may require large computation time.

In this study, a Python-based open-source interactive methodology named SeismoPi Seismic Damage Assessment Tools for Buried Pipelines is developed for estimating seismic damage of buried pipelines. Unlike the other tools, SeismoPi explicitly accounts for the effect of corrosion deterioration in seismic performance of pipeline and supports the development of renewal strategies by decision makers. Also, it does not require hydraulic analysis and complex input files for water networks. This methodology is capable of performing scenario-based seismic damage analysis, identifying critical segments, evaluating system connectivity, and estimating the renewal cost of complex buried water networks. The tool utilizes complex network theory to determine the role of pipeline segments in the system connectivity of WDS. SeismoPi (2020) presents the interactive output on OpenStreetMap so that decision makers can easily visualize the network and identify the riskiest segments that need to be rehabilitated. The program utilizes a number of Python libraries (e.g., Matplotlib, Networkx, Pandas, and Numpy) and is time-efficient for analyzing large networks.

SeismoPi has been made available online. The water network in SeismoPi is modeled as an undirected graph built through a simple structured data input file (e.g., comma-separated values). The generation of the graph model of a WDS is very simple, and stepwise procedures are available in the Github repository.

Research Methodology

A comprehensive seismic damage estimation and renewal analysis framework for buried water distribution systems is presented in this section. The WDS is modeled as a complex graph to estimate the seismic damage and develop maintenance strategies. Analyzing water networks is extremely challenging because they are often composed of a large number of nodes and links. The methodology developed in this study, SeismoPi, utilizes a number of Python libraries that are capable of processing large data and solving complex problems within a considerably short period. Fig. 1 presents the workflow of the proposed framework.

The framework starts with the water network model represented by a graph. In the graph model, the demand nodes and water tanks are defined by the vertices and pipelines defined by the edges of the graph. Important characteristics of an earthquake (e.g., magnitude, focal depth, and location of the epicenter) are assumed to model the impacts of a scenario earthquake. Ground-motion prediction equations (GMPEs) as a function of distance to the epicenter, magnitude, and depth of the earthquake are used for determining the seismic intensities [e.g., peak ground acceleration (PGA) and peak ground velocity (PGV)] at the network site. The RR for the pipelines is estimated as a function of PGV intensity because wave propagation damage usually covers a large area of a distributed network.

The ALA model provides pipeline seismic RR as a function of intensity and fragility of pipelines as a Poisson distribution. In this study, the ALA RR is modified based on the effect of corrosion observed by Eidinger (2015) after the Napa earthquake in 2014. The correction factor (C) is estimated based on the pipe age, material type, and surrounded soil electrical resistivity that accounts for the effect of corrosion. Then, the correction factor is used to estimate the modified RR of each pipeline and the subsequent probability of exceedance of failure limit states. Two types of failure

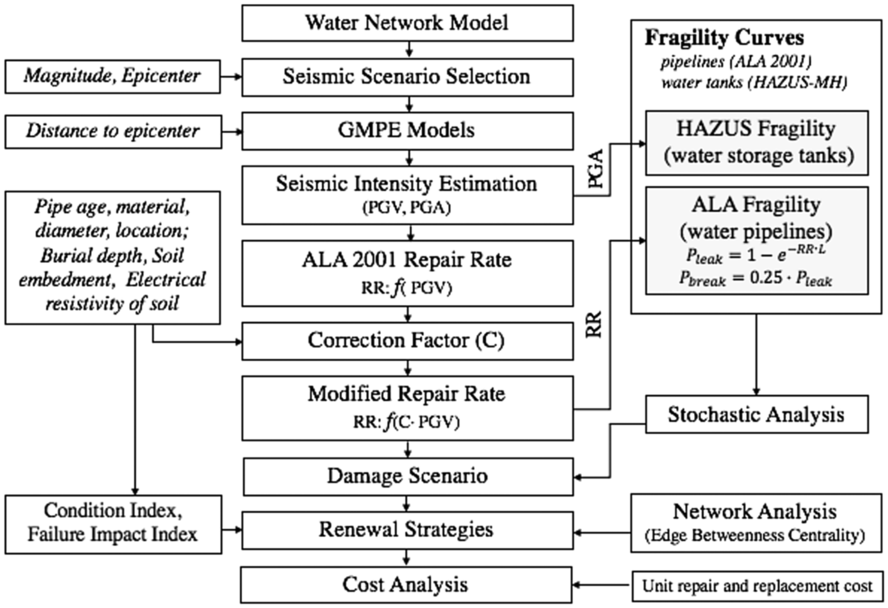


Fig. 1. Framework of seismic damage and cost analysis.

limit states (e.g., leak and break) are considered for developing the damage scenarios of pipelines. On the other hand, PGA intensity is used to determine the probability of failure of water tanks.

HAZUS seismic fragility curves for the aboveground water storage tanks are used for determining the probability of exceedance of various limit states. The damage states of the components are derived based on the seismic intensity and a stochastically generated random number for each component. The physical condition index of an underground pipeline is estimated as a function of pipe age. The failure impact index that determines the degree of impact due to the failure of the pipeline is estimated based on pipe location, pipe size, burial depth, and embedment soil factors. Edge betweenness centrality is used as a measure of the criticality of a component in the WDS. Renewal action is determined for the damaged pipelines based on the pipe physical condition index, failure impact index, and edge betweenness centrality. Once the renewal strategies are set for the damaged pipelines, the renewal cost is determined for the damaged WDS utilizing condition index and the criticality of a component.

The different parts of the proposed framework are discussed in detail in the following sections.

Seismic Intensity Estimation

Scenario-based seismic risk evaluation requires the evaluation of seismic intensity at a site given an earthquake with specified characteristics (e.g., magnitude). The seismic intensity at a site is estimated by utilizing ground-motion prediction equations (also referred to as attenuation laws) for which earthquake characteristics (e.g., magnitude, epicenter location, and depth) are required. GMPEs are often developed by analyzing ground-motion records of a particular earthquake and are typically applicable for specific geologic conditions. The GMPEs proposed by Kawashima et al. (1984) and Yu and Jin (2008) are used for estimating PGA ($\mathrm{cm/s^2}$) and PGV (cm/s) intensities, respectively, as expressed by Eqs. (1) and (2)

$$\mathrm{PGA} = 403.8 \times 10^{0.265M}(R+30)^{-1.218} \tag{1}$$

$$\mathrm{PGV} = 10^{-0.848+0.775M+1.834\log(R+17)} \tag{2}$$

where M = magnitude of an earthquake; and R = distance from epicenter (km).

Fragility Analysis

This study uses pipeline fragility curves estimated based on the ALA (2001) guideline. The ALA 2001 guideline is a widely used concept for determining the seismic performance of buried pipelines. However, one of the major drawbacks of using the ALA 2001 method is that it does not account for corrosion effects (Fragiadakis and Christodoulou 2014; Christodoulou and Fragiadakis 2014; Mazumder et al. 2020). The guideline defined pipeline damage as a function of RR per unit length of the pipeline. RR is estimated as a function of either PGV (in./s) or permanent ground deformation [PGD (in.)]. Equations for RR estimation based on PGV and PGD are expressed as follows:

$$\mathrm{RR} = \begin{cases} k_1 \times (0.00187) \times \mathrm{PGV} \\ k_2 \times (1.06) \times \mathrm{PGD}^{0.319} \end{cases} \tag{3}$$

where RR = repair rate per 304.8 m (1,000 ft); and k_1 and k_2 = correction factors for pipe material, size, joint, and soil type given in ALA (2001). This study proposes to modify the ALA 2001 RR by including the factor for corrosion (k_C) observed by Eidinger (2015), as follows:

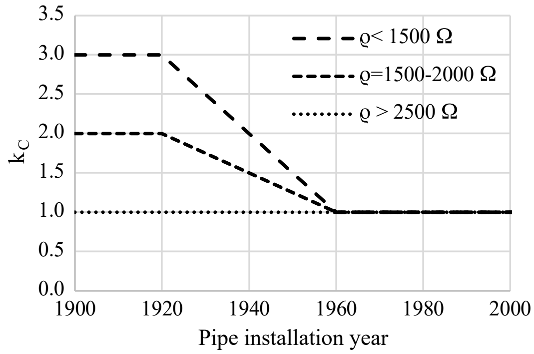
$$\mathrm{RR} = \underbrace{k_1 \times k_C \times}_{C} 0.00187 \times \mathrm{PGV} = C \times 0.00187 \times \mathrm{PGV} \tag{4}$$

where RR = repair rate per 304.8 m (1,000 ft); PGV = peak ground velocity (in./s); k_1 and k_C = ALA fragility modification factors for ground shaking and corrosion, respectively, as shown in Fig. 2(a); and C = combined correction factor ($C = k_1 \cdot k_C$). The value of k_C depends on pipe age and surrounding soil electrical resistivity. Soil corrosivity and soil resistivity are inversely correlated, and hence, soil resistivity provides useful information of corrosive soil environment and probable deterioration of metallic pipelines (Vandelinder 1984).

Napa earthquake struck the city of Napa, California, on August 24, 2014. About 163 instances of repair work were performed

Pipe Material	k_1	k_C
Asbestos	1.0	1.0
Cast Iron	1.0	1.0 ~ 3.0
Ductile Iron	0.5	1.5
PVC	0.5	1.0
Steel	0.7	1.0

(a)



(b)

Fig. 2. (a) Fragility modifier; and (b) corrosion modification factor (k_C) for cast-iron pipe.

within 15 days after the earthquake (Eidinger 2015). Eidinger (2015) investigated the reason behind the higher RR due to ground shaking. The study reveals that the study area is highly corrosive, and a good correlation was obtained between RR and electrical resistivity (ρ) as a measure of Ω-cm for CI pipelines. Fig. 2(b) provides the relationship between corrosion modification factor (k_C) and age of CI pipelines. This study recommended upgrading the seismic fragility model of the pipeline by accounting for the effects of corrosion on pipeline material.

The failure probability of pipeline (P_f) in the ALA 2001 guideline is estimated assuming a Poisson distribution

$$P_f = 1 - e^{-\text{RR}\times L} \tag{5}$$

where RR = modified RR from Eq. (4); and L = length of a pipe. The fragility function can be rewritten as follows:

$$P_f = 1 - e^{-0.00187\cdot\overbrace{C\cdot \text{PGV}\cdot L}^{\Theta}} = 1 - e^{-0.00187\cdot\Theta} \tag{6}$$

where Θ = control intensity equal to $C \cdot \text{PGV} \cdot L$. Two types of failure modes (leak and break) typically happen due to seismic wave propagations (Nair et al. 2018). The HAZUS manual suggested that about 80% and 20% of seismic damages are leaks and breaks, respectively (FEMA 2012). Yoo et al. (2015) assumed the ALA failure probability [as expressed by Eq. (5)] as the probability of break of a pipeline and assumed that the probability of leakage is five times higher than the probability of break of a pipeline due to seismic wave propagation. However, such an assumption may lead to an overestimation of the risk of pipelines. In this study, the failure probability of leakage is considered the same as the ALA failure probability and is assumed to be four times higher than the probability of break ($P_{\text{leak}}/P_{\text{break}} = 4.0$), expressed as follows:

$$P_{\text{leak}} = 1 - e^{-0.00187\cdot\Theta} \tag{7}$$

$$P_{\text{break}} = 0.25 \times P_{\text{leak}} \tag{8}$$

The seismic failure probability of water storage tanks can be estimated from the fragility curves given in HAZUS. This study considered fragility curves for water storage tanks given by FEMA (2012). Figs. 3(a and b) illustrate the fragility curves for pipelines and tanks, respectively.

Damage and Cost Analysis

The damage scenario of WDS can be developed stochastically for a particular earthquake based on the estimated intensities and fragility curves given in Fig. 4(a). The expected damage state for a component is formed based on the control axis value on the fragility curve (e.g., Θ for the pipeline and PGV for water tanks) and a random number generated from a uniform distribution $U[0,1]$ (Klise et al. 2017). For instance, the damage state for a particular pipeline is assigned where the intersection of the x-axis (Θ) and y-axis ($U[0,1]$) falls, as shown in Fig. 4(a). The expected total repair and replacement cost is estimated for each scenario earthquake based on the simulated damage states from the stochastic analysis. The cost estimation is required to consider the renewal policy set by

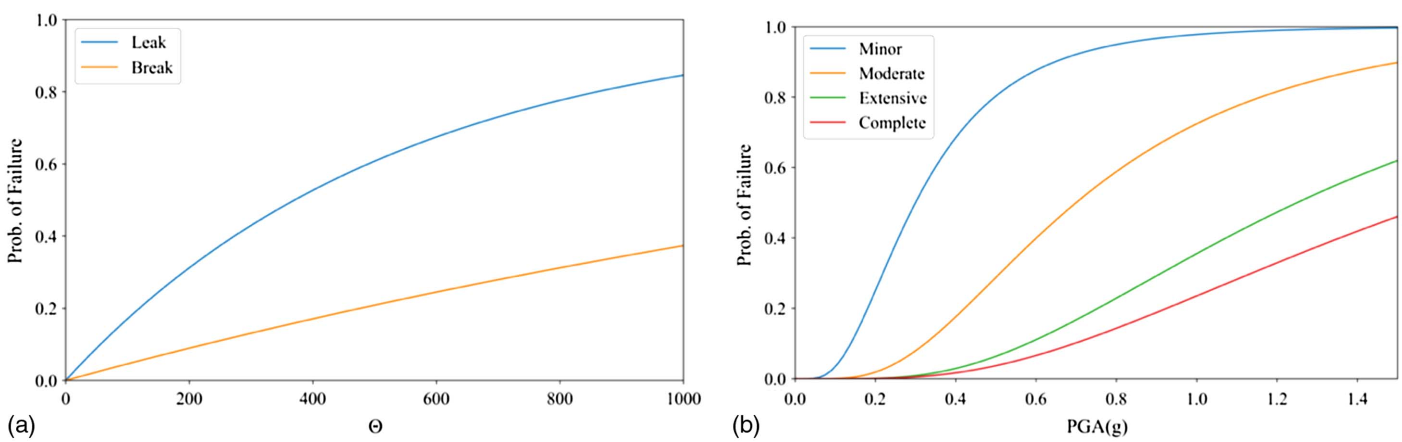


Fig. 3. Fragility curves for (a) pipelines; and (b) on-ground anchored steel storage tanks in HAZUS. (Data from FEMA 2012.)

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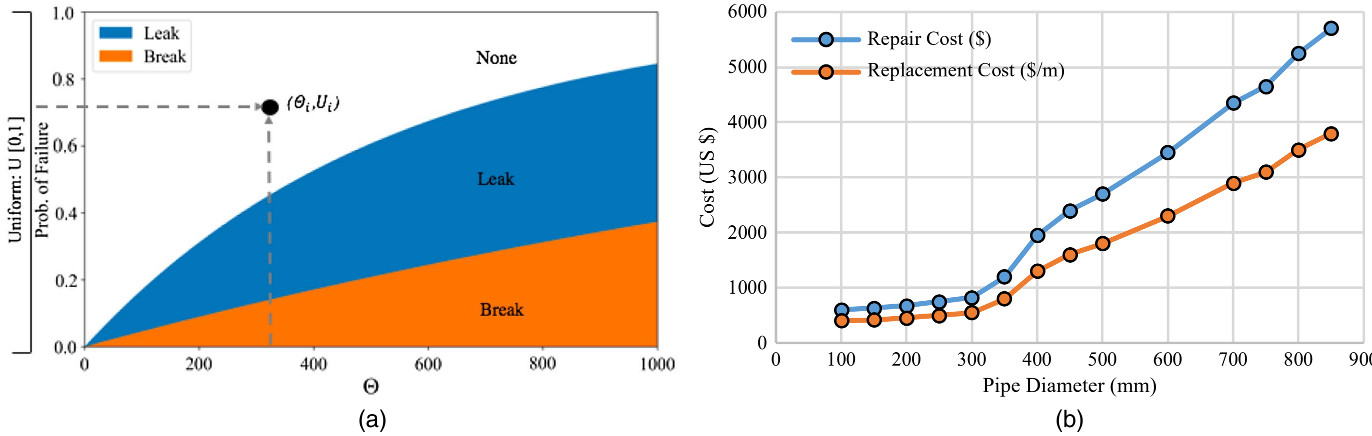

Fig. 4. (a) Stochastic damage scenario development for pipe i; and (b) average single leak/break repair cost and pipe replacement cost for unit length.

the water utility. Renewal cost includes the amount of excavation, transportation, pipe preparation, cutting of the section that contains a defect, welding of sleeves, and quality control test, among others (Jahangiri and Shakib 2018). To estimate the renewal cost, the average replacement cost per unit length and repair cost for a single leak/damage are adapted from previous studies (Choi et al. 2017; Jahangiri and Shakib 2018), as shown in Fig. 4(b).

Because water pipelines are buried assets, maintaining water assets of any size is expensive (Margevicius and Haddad 2002). As expressed previously, the expected total cost is estimated based on the renewal policy set by the utility. A simple renewal policy can be implemented by using the condition index of damaged pipelines, degree of impact due to the pipe failure, and network topology (McDonald and Zhao 2001; Halfawy et al. 2008; Khan and Tee 2016; Fu et al. 2017; Wang et al. 2017; Giustolisi et al. 2019). In this study, a simple pipeline renewal approach is set by combining the underground pipe physical condition index (C_I), degree of impact due to the failure, and the importance of a component based on pipe edge betweenness centrality. The pipeline renewal actions are grouped into two classes: replacement and repair.

The purpose of the condition index is to understand the current structural condition of the pipeline. There are a number of nondestructive testing techniques available for determining the physical condition of pipelines (e.g., closed-circuit television or laser scan). However, condition inspection is often not possible by the utility because it is time-consuming, expensive, and disruptive to other infrastructures (Mazumder et al. 2018). Hence, the underground water pipeline's physical condition index (C_I) is estimated using the regression model provided by Newton and Vanier (2006)

$$C_I = 0.0003T^2 - 0.0003T + 1 \tag{9}$$

where C_I = condition index; and T = pipeline age (years).

In addition to the physical condition of the pipeline, it is also necessary to determine the degree of impact of the failure of a pipeline to prioritize renewal actions. McDonald and Zhao (2001) proposed six factors (i.e., location, soil environment, pipe size, burial depth, functionality of pipe, and seismicity level) for determining the degree of impact for a sewer pipeline failure. In this study, the degree of impact due to the failure of a water pipeline is assessed by modifying the approach proposed by McDonald and Zhao (2001). Because this study measures the seismic intensity and physical damage of pipelines due to a scenario earthquake, function and seismic factors are omitted. A weighted impact rating equation is proposed as follows:

$$I_I = 0.2f_l + 0.267(f_s + f_z + f_d) \tag{10}$$

where I_I = failure impact index; f_l = location factor; f_s = soil factor; f_z = size factor; and f_d = depth factor. The failure impact index I_I ranges from 1.0 to 3.0, representing low to high impact. The impact rating for various attributes of these factors is assigned based on the previous literature (McDonald and Zhao 2001; Shahata and Zayed 2016), as indicated in Table 2. Each factor is classified into three qualitative classes (low, medium, and high). Quantitative factor values are assigned as 1.0, 1.5, and 3.0 for low, medium, and high impact, respectively.

As indicated in Table 2, the consequence due to the failure of a pipeline in a commercial zone is relatively higher than the impact due to the failure of a pipeline in a park area or residential area. Failure impact can be extended depending on the pipe–soil interaction. The consequence due to the large water pipe failure is expected to be higher than the consequence due to the failure of smaller water pipes. The cost of replacement and repair increases with the burial depth because more excavation is required (McDonald and Zhao 2001; Shahata and Zayed 2016).

Edge betweenness centrality (EBC) measures the component's importance in a system by identifying the number of times a component (vertex or edge) serves as media of the shortest path in a complex WDS (Barthélemy 2011). Also, the edge betweenness

Table 2. Impact rating

Factor	Impact rating
Location factor, f_l	High, 3.0: Commercial area, high traffic zone Low, 1.0: Park, agricultural area Medium, 1.5: Residential area, other
Soil embedment factor, f_s	High, 3.0: Silt and sands Low, 1.0: Medium to high plasticity clay Medium, 1.5: Other soil type, average soil condition
Size (diameter) factor, f_z	High, 3.0: > 900 mm Medium, 1.5:300–900 mm Low, 1.0: ≤ 300 mm
Depth factor, f_d	High, 3.0: > 5 m Medium, 1.5:3.0–5.0 m Low, 1.0: < 3.0 m

Source: Data from McDonald and Zhao (2001); Shahata and Zayed (2016).

of pipes provides useful information to capture the emerging hydraulic behavior of the network without performing the hydraulic analysis (Fu et al. 2017; Giustolisi et al. 2019). The EBC is measured by the following expression (Brandes 2008; Giustolisi et al. 2019):

$$\mathrm{EBC}(l) = \sum_{\substack{s \neq u \in V \\ l \in E}} \frac{\tau_{s,u}(l)}{\tau_{s,u}} \tag{11}$$

where $\mathrm{EBC}(l)$ = edge betweenness centrality of edge l; $\tau_{s,u}(l)$ = number of connecting shortest paths from node s to node u that pass through the edge l; $\tau_{s,u}$ = total number of shortest paths from node s to node u; and V and E = set of nodes and edges in the graph, respectively. The true edge betweenness for an undirected graph can be expressed as follows (Brandes 2008):

$$\mathrm{EBC}^{*}(l) = \frac{2}{(n-1)(n-2)} \mathrm{EBC}(l) \tag{12}$$

where n = number of nodes in the graph. Failure frequency of a component is likely to be higher in a WDS if the component has higher EBC (Boeing 2017; Wang et al. 2017).

The compromise ranking method is used to determine the renewal action (RA) by combining the condition index (C_I), failure impact index (I_I), and EBC measures (Opricovic and Tzeng 2004). In order to combine these indicators, the values of C_I, I_I, and EBC are normalized on a scale of [0,1]. The criteria for the seismic renewal of damaged pipelines are assigned as follows:

$$\mathrm{RA} = \begin{cases} \text{repair}, & C_I \times \omega_c + I_I \times \omega_i + \mathrm{EBC} \times \omega_b < R_t \\ \text{replacement}, & C_I \times \omega_c + I_I \times \omega_i + \mathrm{EBC} \times \omega_b \geq R_t \end{cases} \tag{13}$$

where RA = renewal action; ω_c, ω_i, and ω_b = weights of C_I, I_I, and EBC, respectively, with $\sum \omega_i = 1.0$; and R_t = replacement threshold.

Weights and renewal threshold will be set by utility depending on their budget, resources, and rehabilitation policy. Once the renewal actions are set for damaged pipelines, the renewal cost of each pipeline can be estimated by identifying the number of damages (breaks and leakages) for repairable pipelines and the length of the segment that needs to be replaced. The number of breaks and leaks for a damaged pipe segment is determined by the following expression:

$$n_{d_i} = \mathrm{RR}_i \times L_i \tag{14}$$

where n_{d_i} = number of damages (leaks or breaks); RR_i = repair rate; and L_i = length of p ip eline i. The average value of intensities at both ends of a pipe section was taken as the intensity of a pipeline. It is considered that the number of repairs in a damaged (breaks or leaks) pipe segment is at least 1. It is also assumed that the whole pipeline will be replaced wherever replacement is necessary for the maintenance. The total renewal cost of a network is estimated as follows:

$$C_{\text{net}} = \sum_{i}^{n_{rp}} \alpha_1 \times C_{\text{repair}} \times n_{d_i} + \sum_{j}^{n_{rr}} \alpha_2 \times C_{\text{replace}} \times L_j \tag{15}$$

where C_{net} = total expected renewal cost of a WDS after a seismic event; C_{repair} and C_{replace} = cost required to repair one single damage and replace a pipe segment per unit length, respectively; n_{rp} and n_{rr} = number of pipelines to be repaired and number of pipelines to be replaced, respectively; and α_1 and α_2 = unit cost adjustment factors that depend on location. Utilities will determine the factor based on the variation of unit price expressed in Fig. 4(b). Average repair cost for a break and replacement costs for the pipelines are adapted in this study, as given in Fig. 4(b).

System Connectivity

Determining the system connectivity of WDS immediately after an earthquake is critical to developing an appropriate renewal strategy to ensure that the network performance can bounce back to its pre-earthquake condition. The number of components that are disconnected from the source is identified by removing the damaged components from the water network. Renewal tasks should be set optimally so that the WDS will regain its connectivity with the lowest downtime (Vugrin et al. 2014). The topological metric (e.g., edge betweenness) provides information about how the failure of an individual component contributes to the system connectivity loss. EBC is used to determine the renewal actions and strengthen the network to avoid future failures. Renewal tasks are prioritized based on system connectivity map in a way that repairing a minimum number of pipelines establishes a higher level of connectivity between isolated parts and water sources.

Case Studies

In order to illustrate the proposed method, three networks are analyzed. The first network is a relatively simpler and small-size WDS and was chosen to illustrate the proposed method easily. The second network is a moderate-size WDS studied by other researchers. The third network is a large-size WDS servicing a densely populated megacity and is relatively newer compared with the other two networks. SeismoPi was applied to estimate scenario-based seismic damage and consequent renewal cost of these WDS. Various Python libraries (e.g., Numpy, Pandas, and Networkx) are used to analyze these networks, and the outcomes are mapped into OpenStreetMap.

Case Study I: Rancho Solano Zone III Water Distribution System

The Rancho Solano Water Network Zone III located in the city of Fairfield, California, is taken from the ASCE Task Committee on Research database repository of the University of Kentucky (Hernandez et al. 2016). This WDS consists of 112 junctions (nodes), 126 pipes (edges), and 2 elevated water tanks (source). The network is spread over more than 4 km^2 area of land with 20.41 km of water pipelines. The WDS is modeled as an undirected graph using Networkx Python tool, as shown in Fig. 5(a). The nodes and sources are defined by the vertices, and distribution lines are defined by the edges of the network graph. Two types of pipelines (cast iron and ductile) and two types of vertices (demand nodes and tanks) are assumed in the network, as shown in Fig. 5(b). Also, diameter ranges of 16–24 in. (400–600 mm) were considered in this case study.

A seismic scenario is generated for estimating the damage to the WDS. An earthquake with M_W 7.0 and an epicentral depth of 10 km was assumed to have an epicenter at 122°4′12″ W; 38° 16′12″N. The location of the epicenter is marked with a star in the following figures wherever relevant. The ground-motion prediction models proposed by Kawashima et al. (1984) and Yu and Jin (2008) are used to estimate the seismic intensities at network sites in terms of PGA and PGV, respectively. Fig. 6 shows the estimated seismic intensities of vertices and pipelines of the WDS. The minimum, mean, and maximum values of PGA (g) of vertices are 0.425,

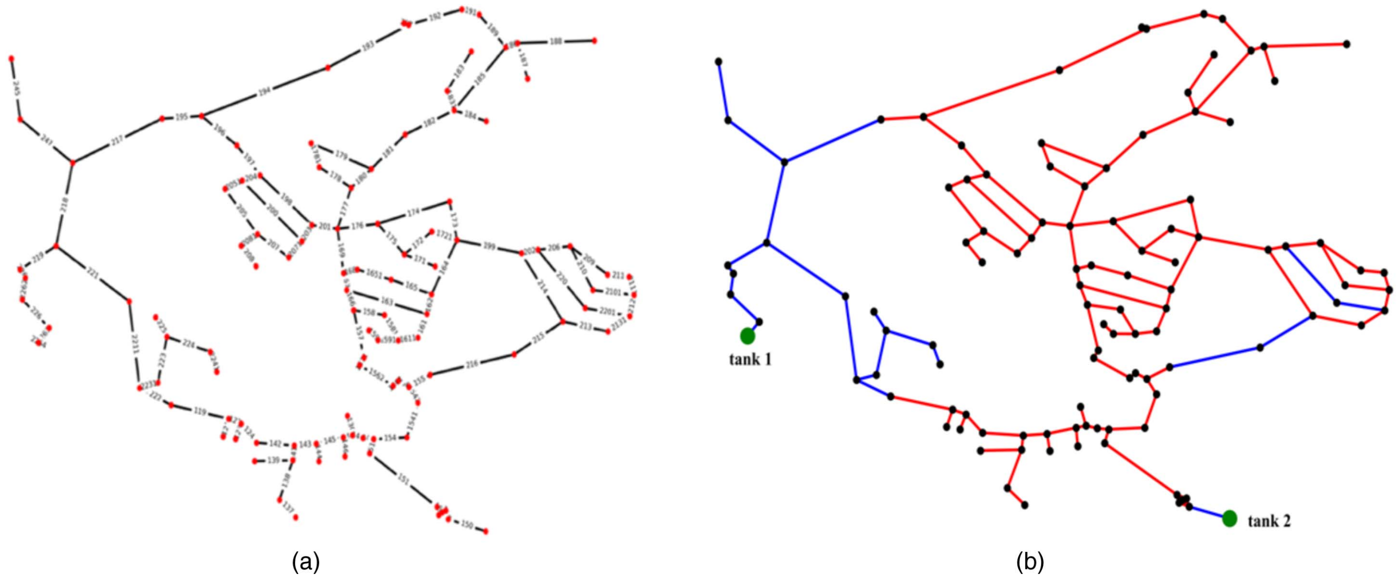

Fig. 5. Rancho Solano Zone III WDS: (a) graph model; and (b) pipeline types (CI and DI) and vertices (tanks and demand nodes).

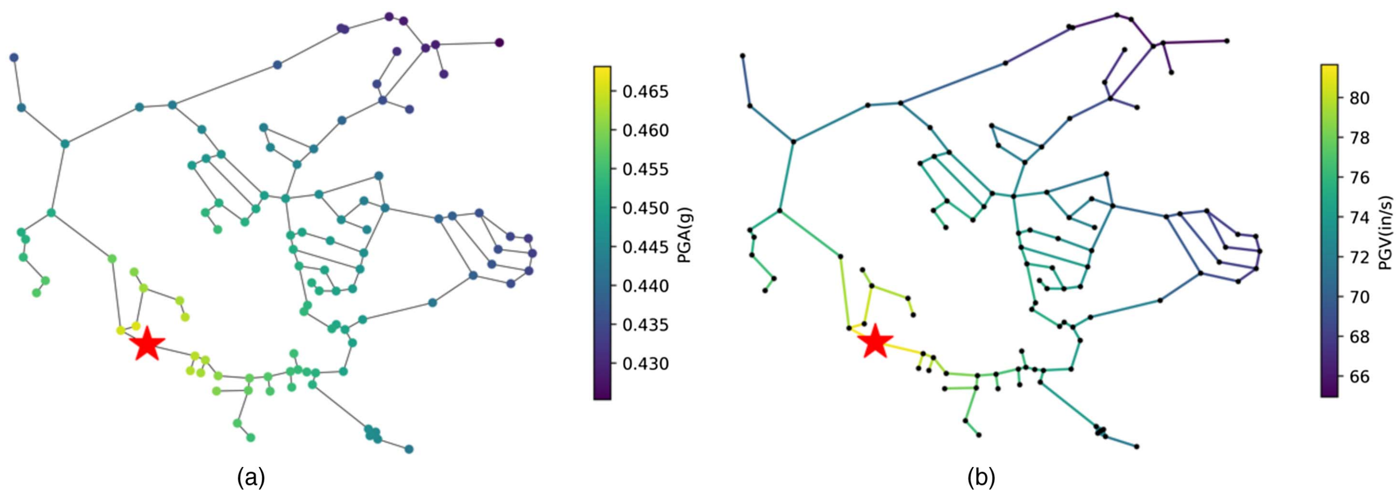

Fig. 6. Seismic intensities of (a) nodes in PGA (g); and (b) pipelines in PGV (in./s) (1 in./s = 2.54 cm/s).

0.447, and 0.468, respectively, as shown in Fig. 6(a). The minimum, mean, and maximum value of PGV (in./s) of pipelines are 64.9, 73.2, and 81.6, respectively, as shown in Fig. 6(b).

The failure probability of the pipelines is estimated using Eq. (5). The corrosivity of soil assumed for the WDS is from low to high level. Pipeline age, correction factor, ALA RR [using Eq. (3)], and modified RR after applying correction factor [using Eq. (4)] of the Rancho Solano WDS are shown in Figs. 7(a–d), respectively. It can be seen that the modified RR increased significantly for older CI pipelines if the corrosion deterioration factor is taken into account. On the other hand, the modified RR decreased for the DI pipelines by a factor of 0.75, as illustrated by Fig. 2(a). The minimum, mean, and maximum value of RR before accounting for the correction factor are 0.121, 0.137, and 0.152, respectively, as shown in Fig. 7(c). On the other hand, the minimum, mean, and maximum value of modified RR are found 0.093, 0.298, and 0.425, respectively, after accounting for the correction factor, as shown in Fig. 7(d).

The probability of exceedance of components damage states is determined from the fragility curves (as shown in Fig. 3) for estimated control intensities (Θ and PGA). The failure probability of a particular pipeline is estimated from the modified ALA fragility curves for the corresponding Θ value, whereas the failure probability of tanks is estimated from HAZUS fragility curves for corresponding PGA value (FEMA 2012). The water storage tanks of the Rancho Solano WDS are assumed as anchored steel storage tanks. Damage states of the WDS are simulated stochastically for the scenario earthquake. A uniformly generated random number is generated for each component and compared with the estimated probabilities of exceedance at various limit states for assigning the damage states, as explained in the "Damage and Cost Analysis" section and Fig. 4(a).

Figs. 8(a–d) show the control intensity (Θ) for pipeline fragility curves, the probability of leakage, the probability of breaks, and the damage states for the scenario earthquake, respectively. The minimum, mean, and maximum value of Θ are found to be 0.008, 84.02, and 391.12, respectively. The length of a pipeline segment is very important for determining the failure probability of a particular pipeline where pipeline failure probability is modeled as a function of exponential equation [as shown in Eqs. (5) and (6)] and pipeline

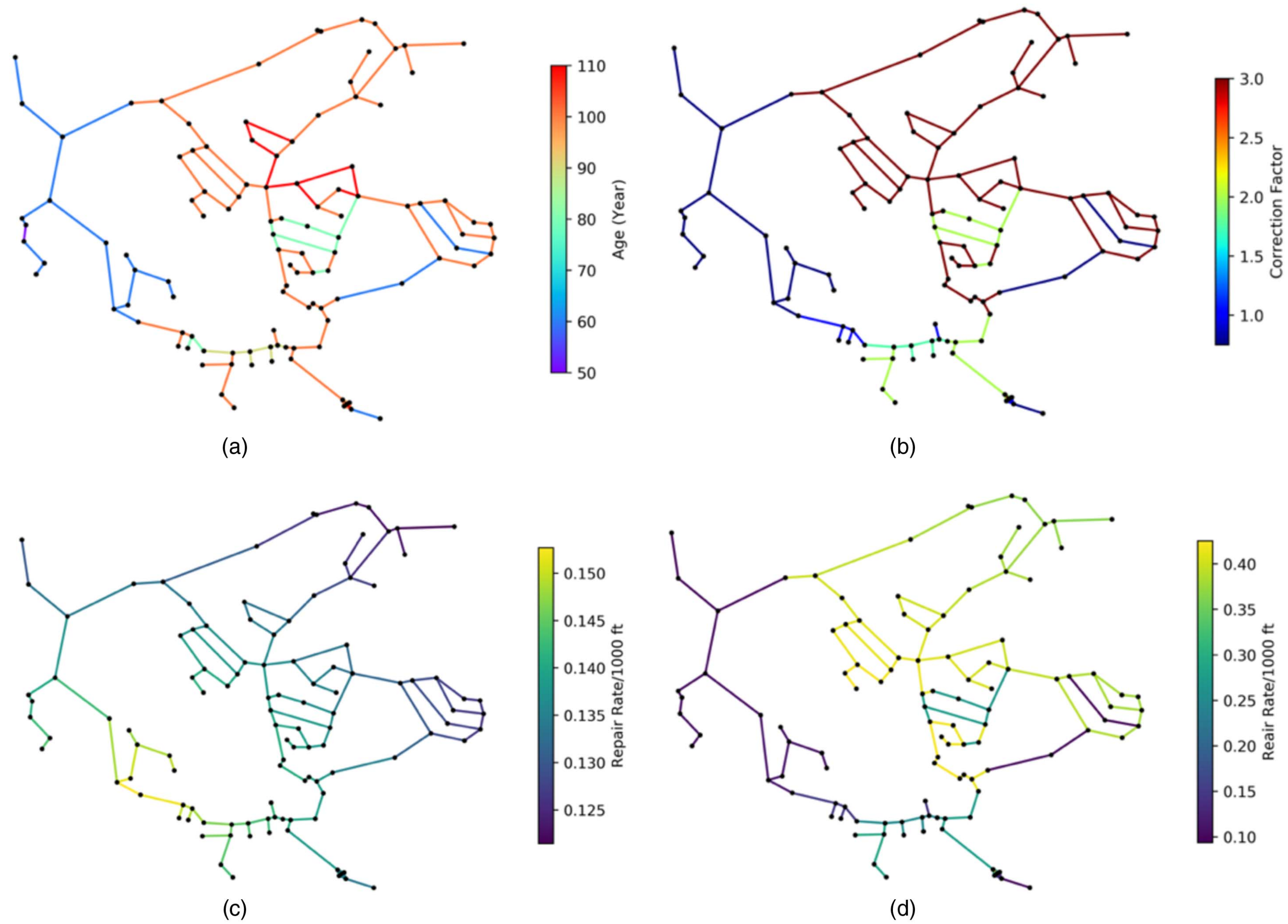

Fig. 7. (a) Pipe age; (b) correction factor; (c) repair rate before; and (d) after applying correction factor.

length. Pipeline unit length in these equations is defined in terms of 1,000 ft. Control intensity Θ values for several pipeline segments are relatively very low because the length of those pipeline segments are very small and lead to smaller failure probabilities. The probability of leak and the probability of break are estimated using Eqs. (7) and (8), respectively. Simulated damage states map is shown in Fig. 8(d). Ten and four pipelines are expected to have leakage and break, respectively, in the WDS.

It is assumed that either leakage or break will discontinue the smooth functionality of the water supply. Once damage scenario is developed, renewal actions are determined using Eq. (13). The minimum, mean, and maximum value of C_I are found to be 1.73, 3.53, and 4.59, respectively. The minimum, mean, and maximum value of failure impact index I_I are found to be 1.13, 1.76, and 2.30, respectively. The location factor of Rancho Solano WDS ranges from low to medium rating (e.g., mostly park and agricultural area and some residential). The soil embedment factor is assigned from low to high. The burial depth range is assumed to be from 1.0 to 6.5 m. The minimum, mean, and maximum value of EBC are found to be 0.01, 0.08, and 0.28, respectively. C_I, I_I, and EBC are normalized on a scale of [0, 1], as shown in Figs. 9(a–c), respectively.

Estimation of renewal cost depends on the renewal actions set by local municipalities and is available in various literature. It is assumed that the whole pipe segment will be replaced if a replacement is required. In this case, weights ω_c, ω_i, and ω_b are assumed equal to 0.6, 0.2, and 0.2, respectively, and the replacement threshold (R_t) is assumed equal to 0.5. Hence, replacement is preferable when a combined index value for a damaged pipe is higher than or equal to 0.5; otherwise, a repair is performed. Repair and replacement costs are given in Fig. 4(b) for a single break or leak per unit length. Fig. 9(d) shows the renewal action determined for the Rancho Solano WDS based on renewal rules expressed by Eq. (13).

The expected number of damages for a particular pipeline can be determined by multiplying the RR and length of the pipeline, as expressed by Eq. (14). Based on the simulated damage scenario, 14 pipelines with a total length of 2.32 km, need to be renewed after the earthquake. About 2.2 km of pipeline length need to be replaced completely, and two repair tasks need to be performed. Unit cost adjustment factors α_1 and α_2 are assumed to be 1.5 and 1.5, respectively, for Fairfield, California. Using Eq. (15), the expected repair and replacement costs are estimated to be about US$6,900 and US $9,190,500, respectively. However, the renewal cost is assumed to be the same for both CI and DI pipelines. Based on the aforementioned renewal criteria set, 12 [indicated in Fig. 9(d)] and 2 [indicated in Fig. 9(d)] components are required to be replaced and repaired, respectively, among 14 damaged components. This is because most of the pipelines are very old and it is preferable to replace them rather than repair, given that their remaining service life is low.

Immediate serviceability can be determined for the network by removing the damaged components in the graph and checking if all the demand nodes are connected to at least one source. Fig. 10(a)

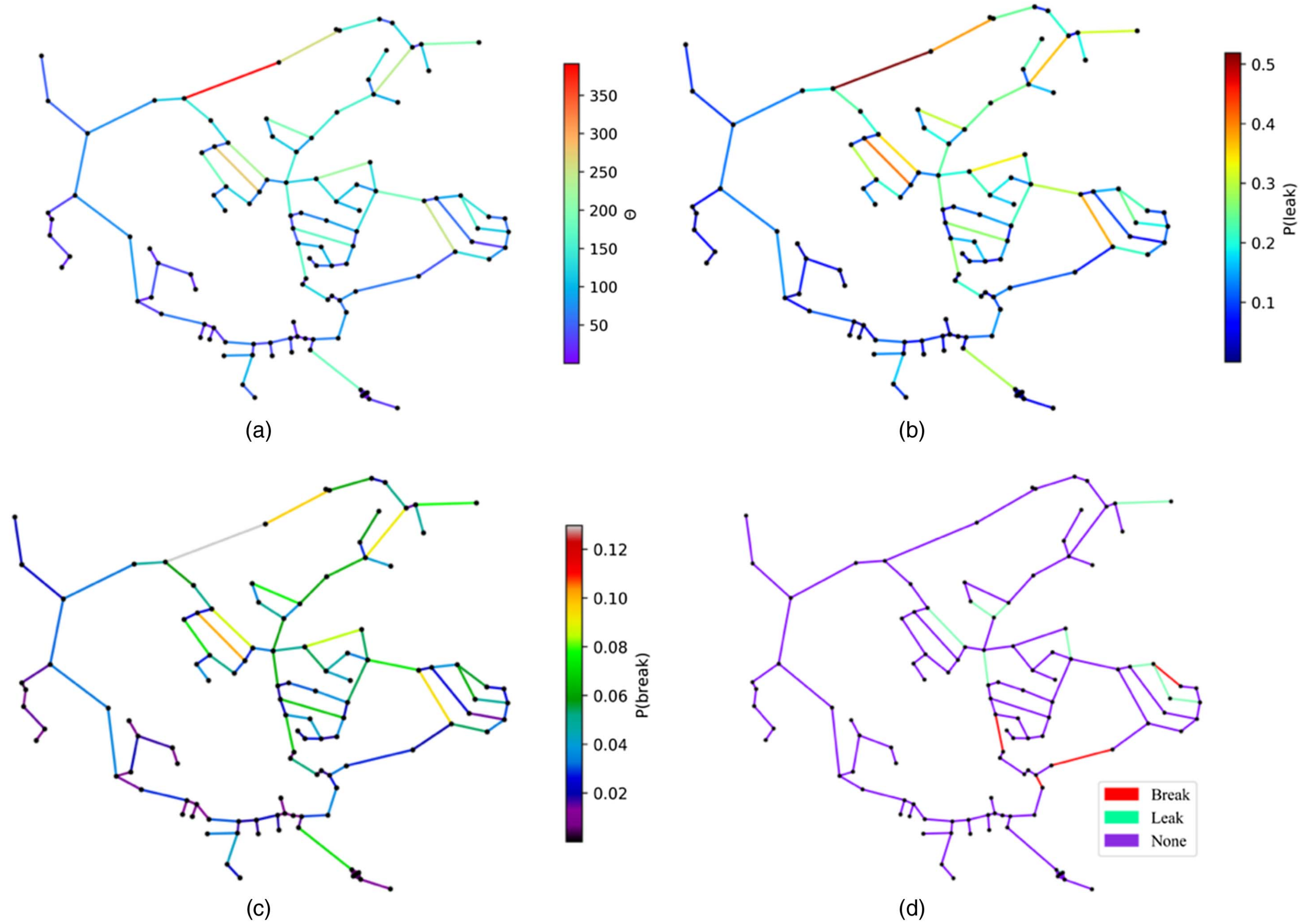

Fig. 8. (a) Control variable Θ; (b) probability of leakage; (c) probability of break; and (d) damage states.

shows the connectivity map of the WDS, where components disconnected from water sources are indicated by the circles. The connectivity map is expected to help decision makers to make a decision promptly by visually observing the damage scenario. In this case, four segments are expected to be out of water service after the earthquake. Hence, repair should be prioritized in a way that repairing a minimum number of components can significantly improve serviceability. For instance, repairing Pipeline 141 establishes connectivity to a large section, D1. Hence, priority should be given to renew Pipeline 141 than renewing other damaged pipelines.

The failure probability of sources and their expected damage are also estimated. However, rehabilitation cost is not determined for the water tanks. The probability of minor, moderate, extensive, and complete damage of Water tank 1 is found to be 0.76, 0.24, 0.05, and 0.03, respectively. The probability of minor, moderate, extensive, and complete damage of Water tank 2 is found 0.74, 0.22, 0.04, and 0.02, respectively. The damage state is simulated for these water tanks stochastically similar to the pipe damage simulation, and minor damage is expected for both water tanks. Outcomes of this study are mapped into OpenStreetMap interactively, as shown in Fig. 10(b).

Case Study II: Modena Water Distribution System

The second network presents the WDS of the city of Modena, Italy. This is a moderate-size network taken from the Centre for Water Systems (CWS) at the University of Exeter (CWS 2018). The network consists of 268 nodes (junctions), 317 elements (pipes), and 4 reservoirs (sources), as shown in Fig. 11. The network is spread over an area of 19 km^2, with a total length of 71.4 km of water pipelines. Pipeline diameter ranges of 12–30 in. (300–750 mm) were considered in this case.

A scenario earthquake was assumed to be located at 44°39′0″N; 10°55′12″E with a moment magnitude M_W 7.0 at a depth of 17 km. The minimum, mean, and maximum value of PGA (g) of vertices are 0.378, 0.419, and 0.468, respectively, as shown in Fig. 12(a). The minimum, mean, and maximum value of PGV (in./s) of pipelines are 48.3, 62.5, and 82.1, respectively, as shown in Fig. 12(b).

Soil corrosivity is assumed as low to moderate for the Modena WDS. This network is assumed to be an old network, and correction factors are estimated based on correction modifiers provided in Fig. 2. Pipeline age, correction factor, and repair rate before and after applying the correction factor of Modena WDS are shown in Figs. 13(a–d), respectively. The minimum, mean, and maximum values of RR are found 0.09, 0.117, and 0.153, respectively. A notable change was found in the new RR after accounting for the modification factor for corrosion. The minimum, mean, and maximum value of modified RR are found to be 0.067, 0.215, and 0.307 per 1,000 ft, respectively.

Fig. 14(a) shows the estimated control intensity values for pipeline fragility (Θ) of Modena WDS. The minimum, mean, and maximum value of Θ are found as 2.96, 91.84, and 495.43, respectively.

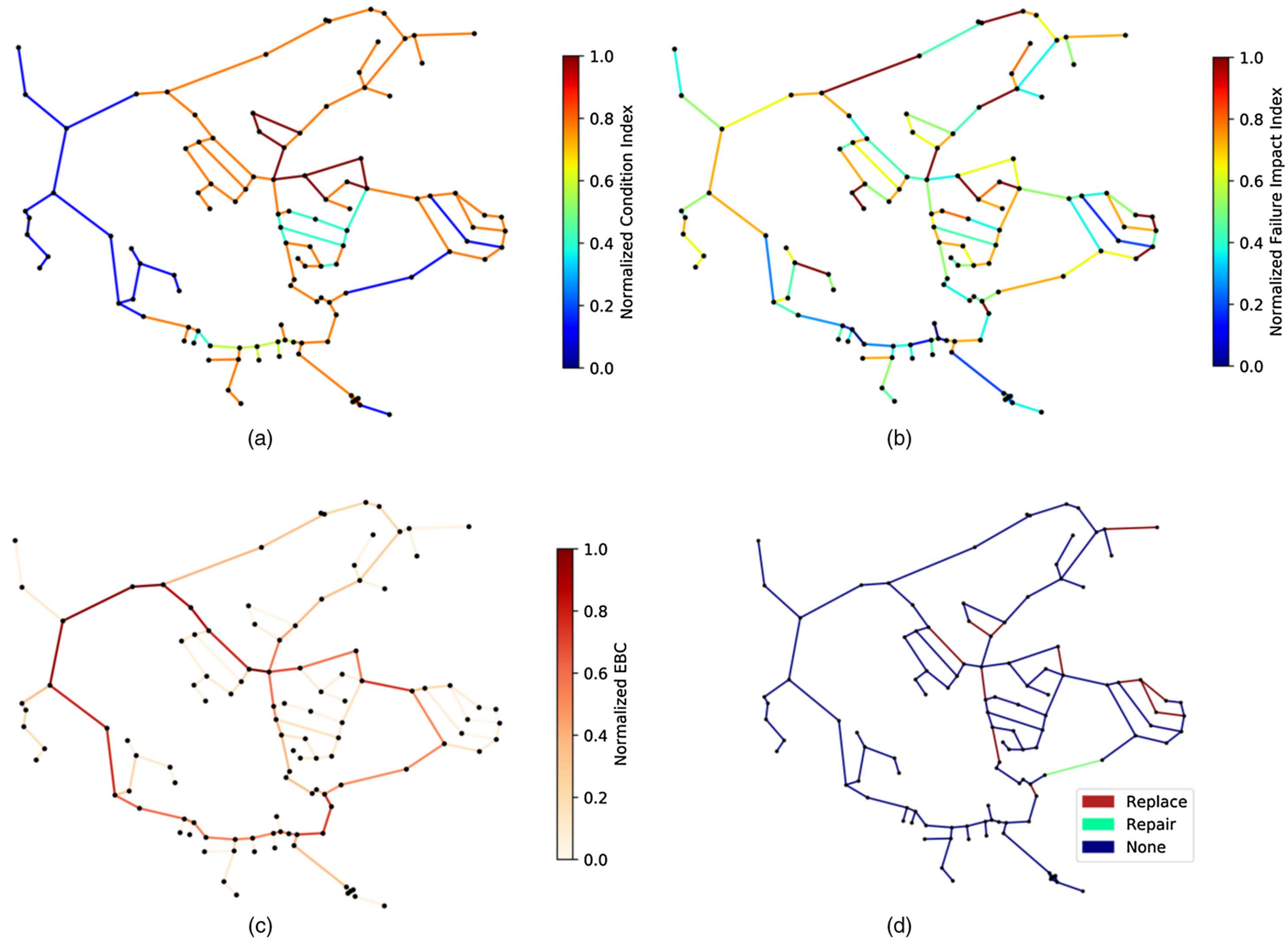

Fig. 9. (a) Normalized C_I; (b) normalized I_I; (c) normalized EBC; and (d) renewal action map.

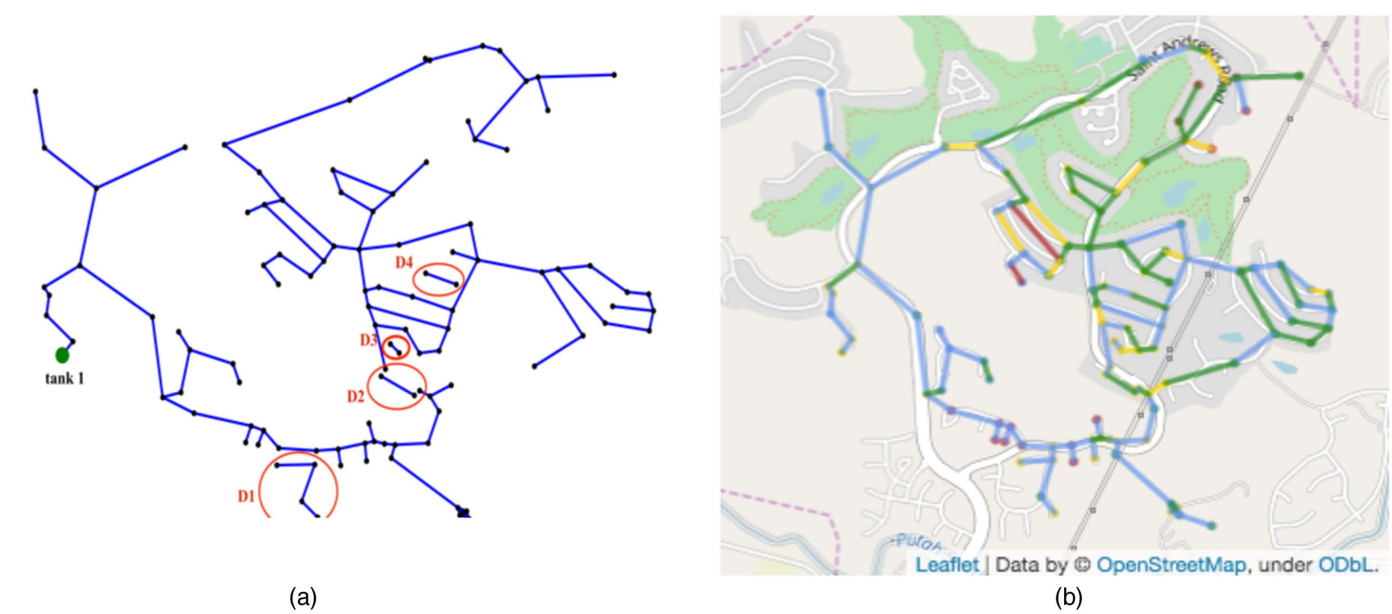

Fig. 10. (a) Connectivity map after removing damaged pipelines; and (b) WDS in OpenStreetMap (data by © OpenStreetMap, under ODbL).

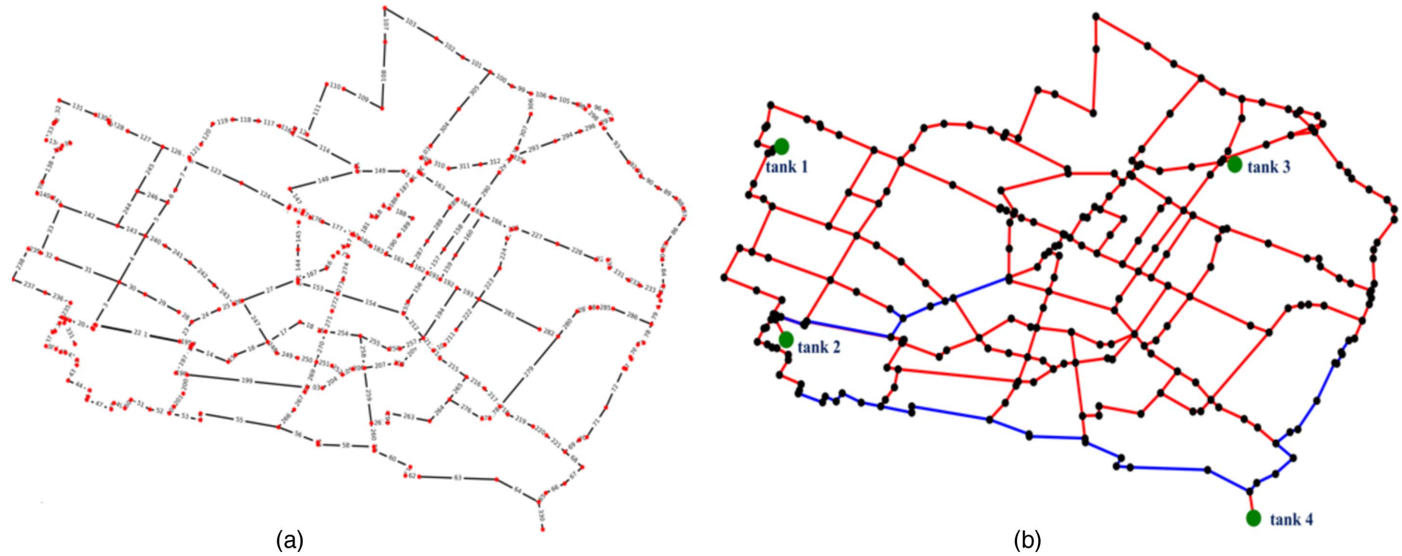

Fig. 11. Modena WDS: (a) graph model; and (b) pipeline types (CI and DI) and vertices (tanks and demand nodes).

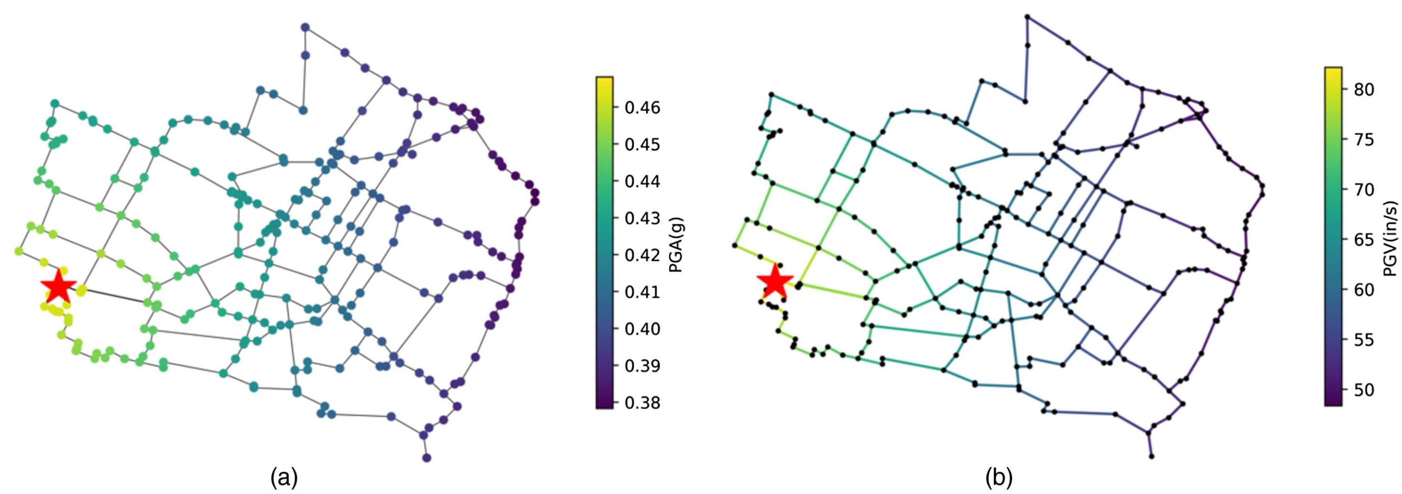

Fig. 12. Seismic intensities of (a) nodes in PGA (g); and (b) pipelines in PGV (in./s) (1 in./s = 2.54 cm/s).

The probability of a leak and probability of a break of Modena WDS are shown in Figs. 14(b and c), respectively. Similar to the previous study, the damage scenario is generated stochastically. The damage scenario map is plotted in Fig. 14(d). In this case, 36 and 11 pipelines are expected to have leakage and break, respectively, in the WDS for the given earthquake event. Four water sources are assumed as anchored steel storage tanks. The mean value of the probability of minor, moderate, extensive, and complete damage of water tanks are found as 0.71, 0.19, 0.035, and 0.02, respectively. The damage states of Tanks 1, 2, 3, and 4 are found to be moderate, minor, none, and none, respectively.

The minimum, mean, and maximum values of C_I are found to be 2.90, 3.88, and 4.60, respectively. The minimum, mean, and maximum values of I_I are found to be 1.13, 1.72, and 2.60, respectively. The location factor rating ranges from low to high (e.g., mostly residential and commercial). The soil embedment factor is assigned from low to high. The burial depth range is assumed to be from 1.0 to 6.5 m. The minimum, mean, and maximum values of EBC are found to be 0.01, 0.05, and 0.27, respectively. For determining the renewal actions of Modena WDS, C_I, I_I, and EBC are normalized on a scale of [0, 1], as shown in Figs. 15(a–c), respectively. Weights ω_c, ω_i, and ω_b in Eq. (13) are assumed equal to 0.6, 0.2, and 0.2, respectively. The replacement threshold R_t is set equal to 0.5 for determining the renewal action for each damaged pipeline. A pipeline with RA value equal to or greater than 0.5 is marked for complete replacement.

Fig. 15(d) shows the renewal action map prepared for post-earthquake maintenance of Modena WDS, where pipelines are required to be repaired and replaced, respectively, as indicated. A large portion of the pipeline network (47 out of 317) consisting of 10.65 km of pipeline length needs to be renewed after the earthquake. Twenty-four damaged pipelines with an RA value equal to or greater than 0.5, need to be replaced completely [indicated in Fig. 15(d)]. On the other hand, 23 damaged pipelines need to be repaired [indicated in Fig. 15(d)]. About 5.25 km of pipeline length need to be replaced, whereas at least 23 repair tasks are required to be performed. Unit cost adjustment factors α_1 and α_2 are assumed equal to 1.0 and 1.0, respectively, for Modena, Italy. Using Eq. (15), expected repair and replacement costs are estimated at about US$50,400 and US$16,166,000, respectively.

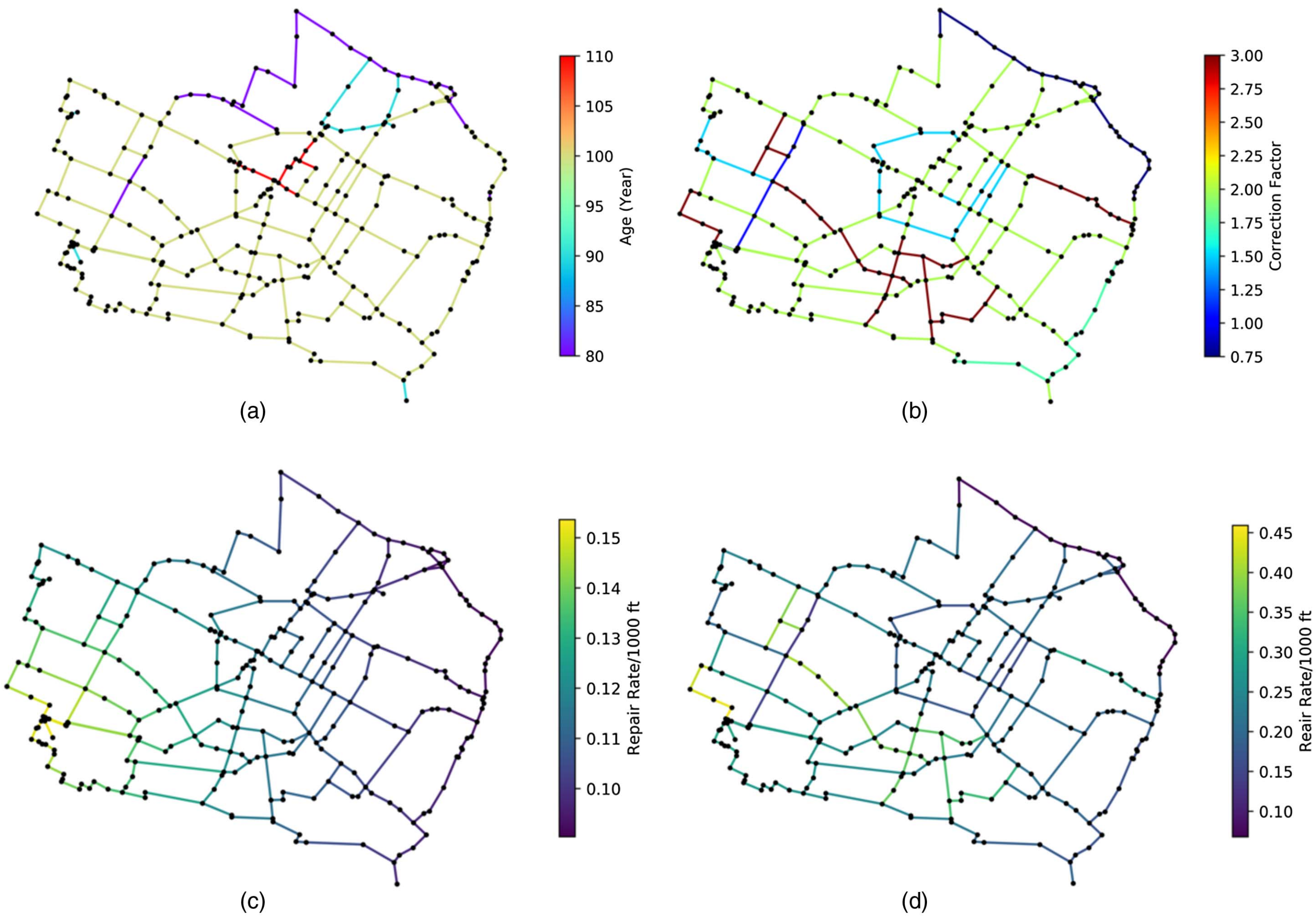

Fig. 13. (a) Pipe age; (b) correction factor; (c) repair rate before; and (d) after applying correction factor.

The damaged segments are removed from the network, and components disconnected from water sources are determined, as shown by the circles in Fig. 16. In this case, the pipelines connected to Water tank 2 and Tank 4 are damaged; hence, the community will lose the water service from two water tanks (50% of water sources) immediately after the earthquake that may lead to the extensive water crisis. There are five segments and one tank (marked by the circle) that will lose connectivity to other parts. Hence, maintenance priority should be given based on regaining water connectivity of these five parts and the water tank to the other part of the system. For example, repairing Pipeline 330 can establish connectivity of Tank 4 to the separated Segment D5; hence, priority should be given to repairing Pipeline 330 and so on.

Case Study III: Dhaka Water Distribution System

The third network is a large-size water distribution network located at in the city of Dhaka, Bangladesh. Dhaka is the capital of Bangladesh, and Dhaka WDS serves approximately 400,000 domestic and business consumers. The network is composed of 23,366 nodes and 25,067 pipes with a length of about 1,236 km. Dhaka Water Supply and Sewerage Authority (Dhaka WASA) operates this water network. According to the DWASA annual report 2013–2014, Dhaka WDS produces approximately 2,420 million L of water per day and serves about 15.6 million peoples spreading over an area of 360 km^2 (DWASA 2014). A limited effort has been made to determine the seismic risk to Dhaka WDS. The portable water network geographic information system (GIS) database was collected by the first author of this study from the Comprehensive Disaster Management Program (CDMP 2009b). Field study revealed that many of the distribution facilities were not designed properly to resist earthquake loading (e.g., lack of proper anchorage) (CDMP 2009b).

There are two major types of pipelines (e.g., brittle and ductile) present in Dhaka WDS. Brittle pipes include CI, asbestos cement, and reinforced concrete pipelines. On the other hand, ductile pipes include galvanized iron, DI, mild steel, PVC, and steel pipelines (CDMP 2009b). The existing GIS database provides only information about the major pipeline types but not information about the material classes. Hence, the brittle pipes are assumed to be made of CI, and the ductile pipes are assumed to be made of DI, PVC, and steel for the current study, as shown in Fig. 17(b). In Dhaka WDS, 3,166 and 21,901 pipes are made of brittle and ductile materials, respectively. The majority of pipelines diameters are in the range of 4–24 in. (100–600 mm) (DWASA 2014). Water sources includes pumping stations, water reservoir and aboveground tanks. However, because information about the water sources is unknown, the current study did not include damage analysis for the water sources. Figs. 17(a and b) shows the layout of Dhaka WDS in GIS and Python, respectively.

Dhaka is located in a moderate seismic zone (BNBC 2017). Active seismic faults and potential earthquake scenarios were proposed in the study performed by CDMP (CDMP 2009a). Recently, Steckler et al. (2016) identified active, shallow dipping, and locked megathrusts in the Indo-Burman ranges that pass beneath the

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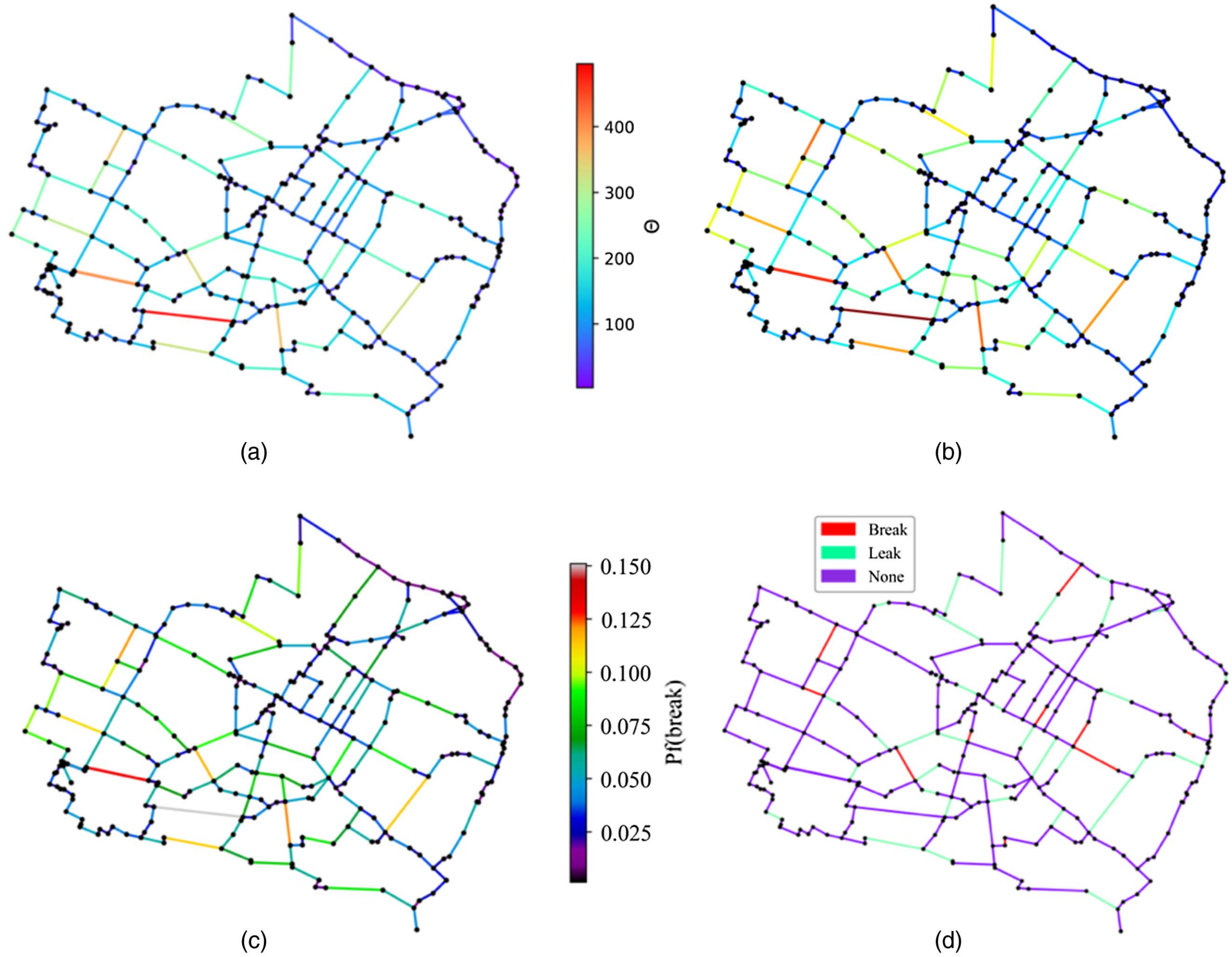

Fig. 14. (a) Control variable Θ; (b) probability of leakage; (c) probability of break; and (d) damage states.

megacity Dhaka. Their geodetic observation suggested that potential earthquakes of M_w 8.2–9.0 may occur near Dhaka city. The CDMP study also recommended using earthquake scenarios with M_w between 7.5 and 8.0 in this region for seismic vulnerability studies. A M_w 8.0 magnitude earthquake is assumed to have an epicenter located at 24°0′0″N; 90°24′0″E and a depth of 10 km, about 25 km north from the Dhaka city, as shown in Fig. 17(c). PGV (in./s) intensities of Dhaka WDS for the scenario earthquake were estimated utilizing the GMPE of Yu and Jin (2008). The maximum and minimum PGV intensities are found to be 23.05 and 64.66 in./s, respectively, as shown in Fig. 17(c).

Fig. 18(a) shows the pipe age of Dhaka WDS. This network is relatively newer than the networks used in the other two case studies. Soil corrosivity was taken from the study performed for Dhaka city by Ansary et al. (2015), and ranges from low to high. Fig. 18(b) illustrates the combined correction factor (C) of Dhaka WDS. Repair rates are estimated before and after the corrosion factor is accounted for. The minimum, mean, and maximum value of the ALA RR are found as 0.043, 0.063, and 0.121, respectively. After accounting for the correction factor in the repair rate calculation, the minimum, mean, and maximum values of the new RR are found as 0.03, 0.05, and 0.18, respectively. It can be observed that new RR values are slightly increased and decreased for brittle and ductile pipelines, respectively. Figs. 18(c and d) show the ALA RR before and after applying the correction factor, respectively.

The control intensity (Θ) for pipeline fragility curves is estimated as shown in Fig. 19(a). The probability of leakage and the probability of break are shown in Figs. 19(b and c), respectively. Damage scenarios are generated stochastically, as expressed in Fig. 4(a). It was found that 152 and 37 pipelines are expected to have leaks and breaks after the earthquake, respectively, as shown in Fig. 19(d). The damage states for the northern part of the Dhaka WDS are magnified in the circle for better visualization.

The minimum, mean, and maximum values of C_I are found to be 1.80, 2.30, and 2.80, respectively. In this case, C_I values are relatively lower for a majority of pipelines because they are relatively newer than the pipelines used in the previous cases. The minimum, mean, and maximum value of I_I are found 1.10, 1.82, and 2.60, respectively. The location factor rating ranges from low to medium (e.g. commercial, residential, and parks). The soil embedment factor is taken from Ansary et al. (2015), ranging from low to high. The burial depth range is assumed to be from 1.0 to 8.0 m. The minimum, mean, and maximum value of EBC are found to be 3.7×10^{-9}, 0.005, and 0.26, respectively. C_I, I_I, and EBC are normalized on a scale of [0, 1], as shown in Figs. 20(a–c), respectively. These indexes are combined using Eq. (13) to determine the renewal actions for 189 damaged pipelines. Weights ω_c, ω_i, and ω_b in Eq. (13) are assumed equal to 0.6, 0.2, and 0.2, respectively.

Fig. 20(d) shows the renewal action map prepared for the post-earthquake maintenance of Dhaka WDS. It can be seen that 189 with a total length of 20.48 km need to be renewed after the earthquake. For determining the renewal action for each damaged pipeline, the replacement threshold R_t was set equal to 0.5. Based on the renewal strategy, about 6.16 km of pipeline length [70 pipelines

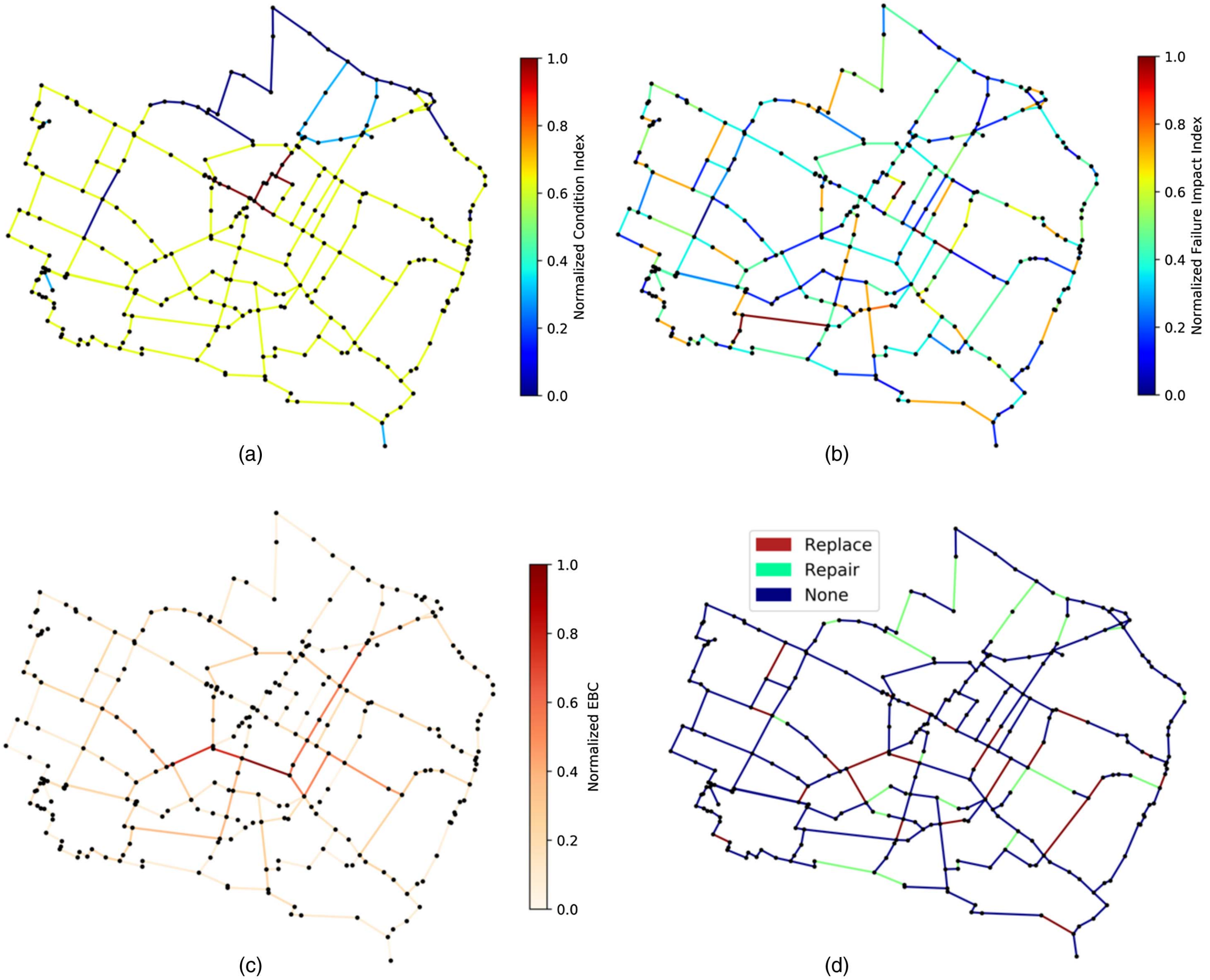

Fig. 15. (a) Normalized C_I; (b) normalized I_I; (c) normalized EBC; and (d) renewal action map.

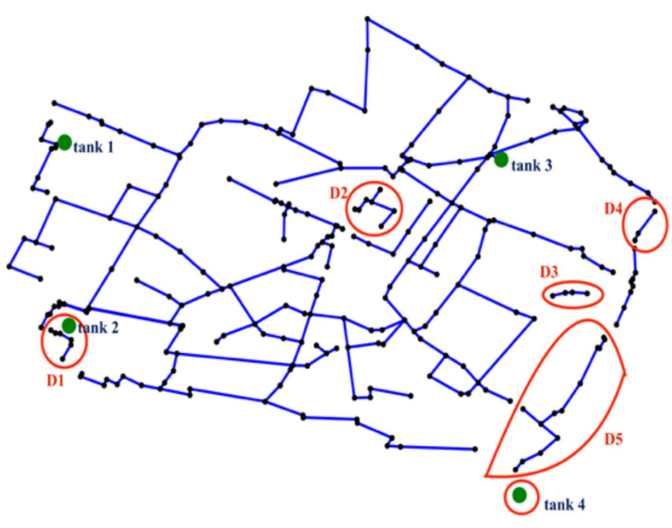

Fig. 16. Connectivity of Modena WDS (after removing the damaged pipelines).

as marked in Fig. 20(d)] need to be replaced, and 119 repair tasks [as marked in Fig. 20(d)] need to be performed after the earthquake. As mentioned previously, it was assumed that at least one repair task is required in a damaged pipeline.

Once the pipeline repair and replacement tasks are set based on the renewal strategy, the expected renewal cost is estimated using Eq. (15). Because the cost of pipeline renewal in Bangladesh is expected to be lower than the cost of pipeline renewal in Italy and the US, the unit cost adjustment factors α_1 and α_2 are assumed to be 0.9 and 0.9, respectively, for Dhaka WDS. Expected repair and replacement costs are estimated to be about US$118,250 and US$9,033,200, respectively. In this case, the average age of water pipelines is 65 years (relatively newer than the other two networks), which leads to a higher repair to replace ratio (more than 60% damaged pipelines will be repaired).

A significant part of the network will lose connectivity due to the scenario earthquake, as shown in Fig. 20(e). For instance, more than 400,000 people may be affected in the northern part of the Dhaka city if D5, D1, and D2 parts lose connectivity to the water sources. The whole Dhaka city and a variety of consumers (e.g., industrial,

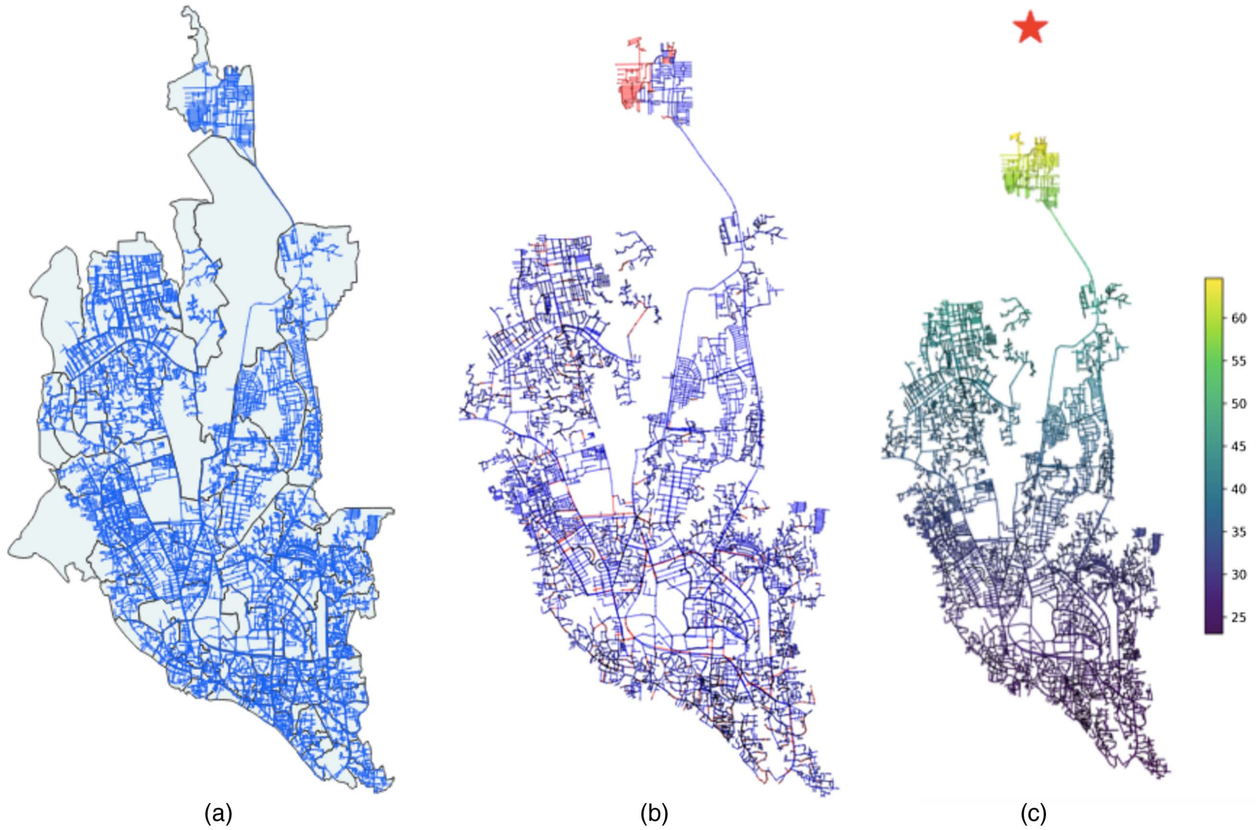

Fig. 17. Dhaka WDS: (a) graph model; (b) pipeline types (CI and DI) and vertices (demand nodes); and (c) seismic intensity of pipelines (in./s) (1 in./s = 2.54 cm/s).

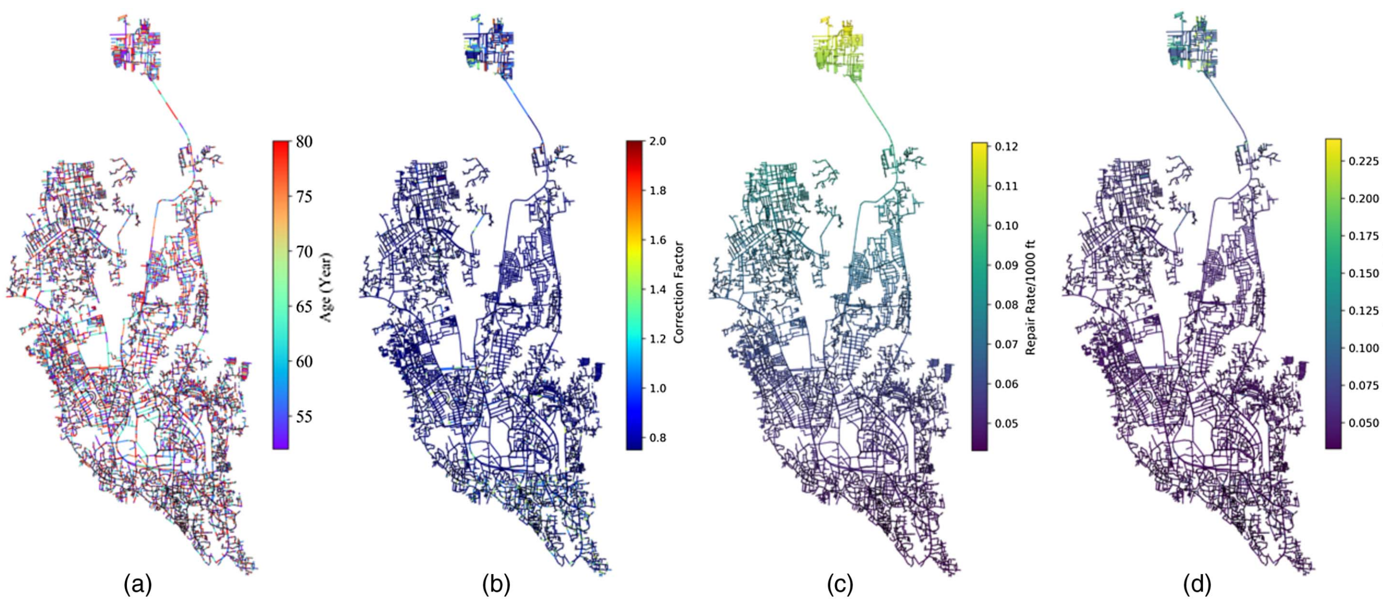

Fig. 18. (a) Pipe age; (b) correction factor; (c) repair rate before; and (d) after applying correction factor.

commercial, and residential) are relying on Dhaka WDS. Disruption of the smooth functioning of the water supply may result in substantial economic and social consequences.

The proposed framework was applied to three WDS of different sizes. The SeismoPi tool depends on several Python libraries and is computationally efficient. SeismoPi analysis was performed using a Jupyter notebook on a personal computer with 4 GB RAM and 1.6 GHz Core i5 processor. The computational times required to compute the seismic damage analysis of Rancho Solano WDS, Modena WDS, and Dhaka WDS are 25, 36, and 800 s, respectively.

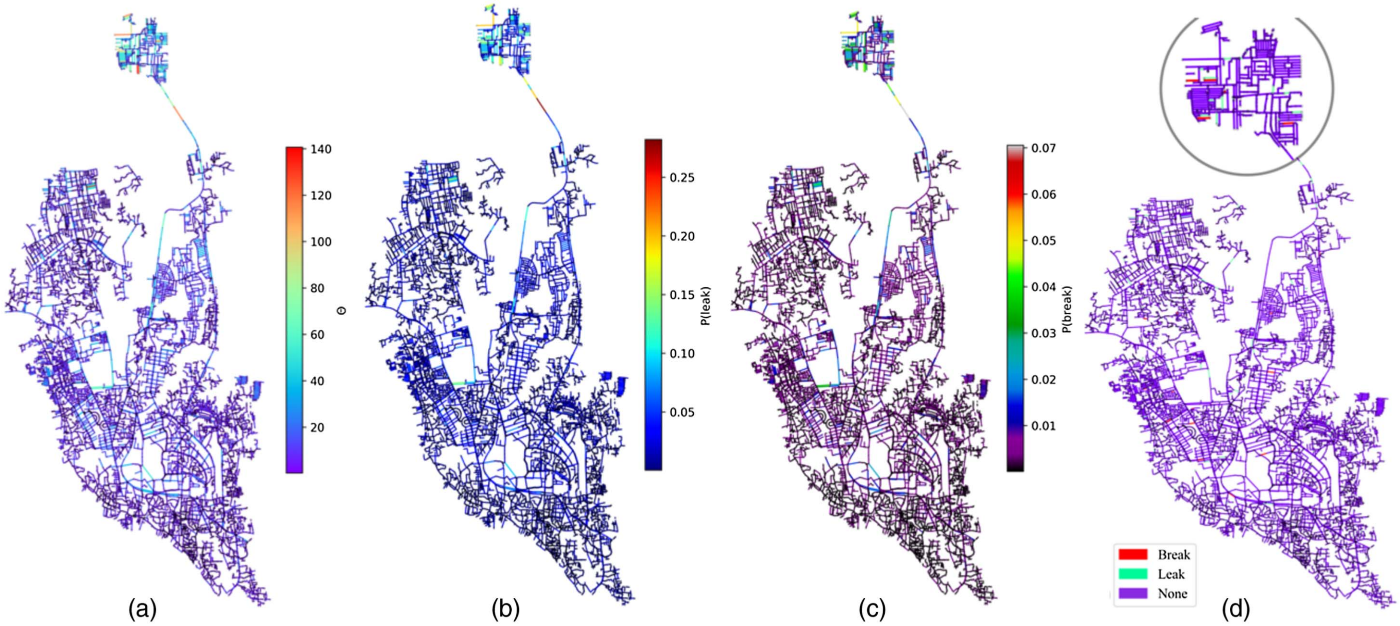

Fig. 19. (a) Control variable Θ; (b) probability of leakage; (c) probability of break; and (d) damage states.

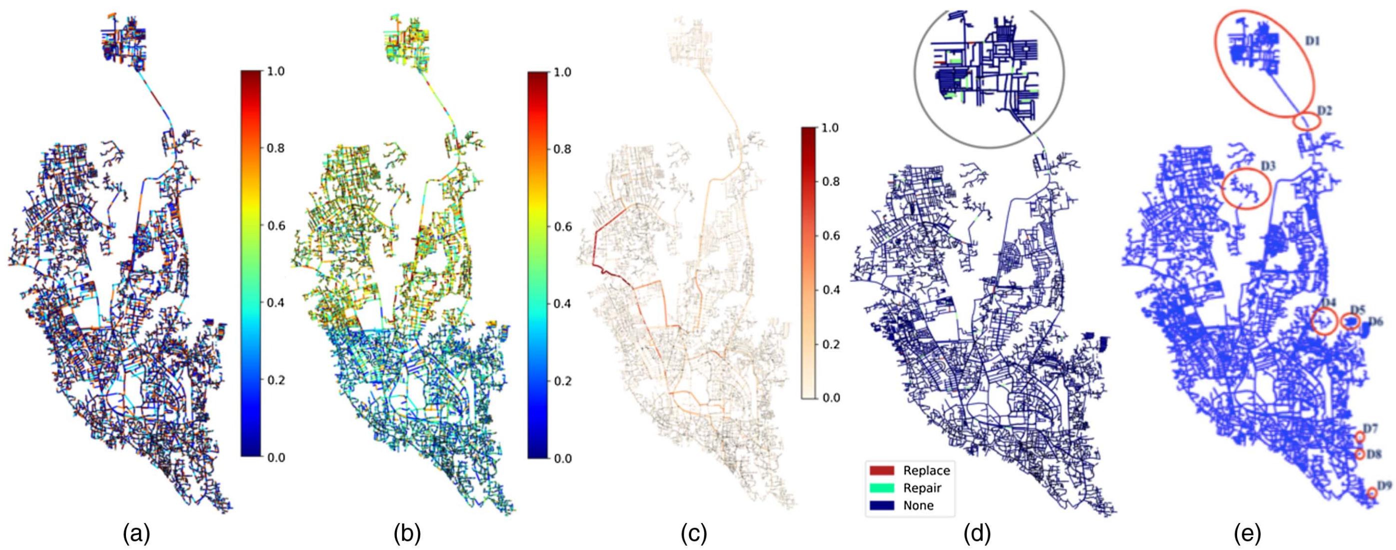

Fig. 20. (a) Normalized C_I; (b) normalized I_I; (c) normalized EBC; (d) renewal action map; and (e) connectivity map of Dhaka WDS.

The Dhaka WDS is relatively very large and complex, with 23,366 nodes and 25,067 pipelines. The time required to calculate the topological measure (i.e., EBC) increased exponentially with the increase of the number of components in the network graph.

Conclusions

A new framework is presented for developing scenario-based seismic damage and estimating the consequent renewal cost of buried WDS. The proposed framework accounts for the effect of corrosion deterioration by modifying the ALA fragility curves based on observed damage data in a past earthquake. The study also applied postearthquake maintenance strategies by accounting for the network topological characteristics, failure impact, and pipeline physical conditions. Because analyzing complex water networks composed of a large number of nodes and pipelines is computationally demanding, a method using open-source Python libraries was also developed for performing this research. The method is computationally efficient, and results can be plotted interactively on OpenStreetMap and helps decision makers to decide easily. Although the method does not perform hydraulic simulation, the centrality metric helps to gain information about the potential flow path disruption in case of disruption due to natural hazards.

Three case studies have been presented to illustrate the current methodology for small- to large-size water distribution networks. The case studies revealed that the consideration of the effect of corrosion significantly changes the repair rates and consequent failure probability of water mains. About 2.2, 8.53, and 6.21 km of water pipelines need to be replaced for Rancho Solano, Modena, and Dhaka WDS, respectively, for respective scenario earthquakes. The estimated renewal costs are found to be about US$9,197,400, US$16,216,400, and US$9,221,450 for Rancho Solano, Modena, and Dhaka WDS, respectively.

The current study has a number of limitations that need to be addressed in future research. In this research, the corrosion correction factor was developed based on the observation of a particular earthquake. The corrosion model needs to be further updated with large data from various sites. This study estimated the repair rate of pipelines due to strong ground shaking but did not consider the pipeline damage due to differential ground movement in the seismic fault zones. Because a large portion of distributed water pipelines is typically affected by seismic wave–induced ground shaking, the ALA (2001) guideline based on PGV was considered. Pipeline failure due to differential ground movement should be considered in future research. The hydraulic serviceability of the WDS was not accounted for under the disruptive conditions. Future development will focus on functionality and resilience analysis based on the hydraulic availability of WDS under various disruptive events.

Data Availability Statement

Some or all data, models, or code generated or used during the study are available in a repository online in accordance with funder data retention policies (https://github.com/rxm562/SeismoPi).

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