Proactive Seismic Rehabilitation Decision-Making for Water Pipe Networks Considering Earthquake-Induced Transient Strains and Geotechnical Instability

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ABSTRACT

Buried water pipelines suffer damage (breaks or leaks) due to seismic events. Any type of break or any significant amount of leak after seismic events can reduce the serviceability of a water network. Proactive seismic rehabilitation decision-making is essential to reduce the losses and increase the serviceability of a water pipe network after a seismic event. Although water pipelines are vulnerable to permanent ground deformation (PGD) due to earthquake-induced geotechnical instability (landslide and liquefaction hazards) in susceptible zones, a combination of damage due to induced transient strains and earthquake-induced geotechnical hazards (landslide and liquefaction) has not been considered at network-level in existing proactive seismic rehabilitation decision-making models of water pipe networks. This research presents a simulated annealing-based optimization methodology to determine the most critical pipes of a water pipe network vulnerable to seismic events considering a combination of PGD (damages due to landslide and liquefaction in susceptible zones), PGV and PGA (damages due to induced transient strains) for a certain budget constraint. Once the earthquake characteristics (e.g., magnitude, epicenter) were identified using deaggregation analysis, peak ground acceleration (PGA) and peak ground velocity (PGV) were calculated at the location of each pipe using the ground motion prediction equation (GMPE). The value of PGA and PGV was used to study landslide and liquefaction hazards providing a hybrid empirical-mechanical-based estimation of PGD. A three-phase geotechnical approach was used both for landslide and liquefaction hazards, representing (i) susceptibility analysis, (ii) triggering analysis, and (iii) estimation of PGD. The seismic repair rate of each pipe was then calculated based on the value of PGV and PGD. A stochastic combinatorial optimization problem was formulated considering budget limitations that maximize post-earthquake serviceability of the water pipe network and identify the most critical pipes of a network. The stochastic optimization problem was solved using a simulated annealing-based optimization algorithm. Modena network, a benchmark network, was assumed as the test network for the application of the methodology considering the location of the network in California. The approach was verified by comparing the result with an existing method where the value of PGD was assumed to be zero. The comparative study results showed that the inclusion of landslide and liquefaction hazards significantly affect the identified critical pipes of the water pipelines. Also, the maximum achievable serviceability index for the selected rehabilitation budget was reduced significantly if landslide and liquefaction hazards were considered. It can be concluded that landslide and liquefaction hazards must be considered in susceptible zones with existing proactive seismic decision-making models. The proposed methodology is a novel approach to considering a

combination of earthquake-induced geotechnical instability and damages due to induced transient strain for network-level proactive seismic rehabilitation decision-making and can aid water pipe network managers as a decision-support tool.

INTRODUCTION

Water pipe networks are regarded as one of the most important infrastructures, and they are vulnerable to seismic leaks and breaks (Yerri et al. 2017; O'Rourke et al. 2014). Water pipe networks must be rehabilitated to improve the post-earthquake serviceability and reduce the damage after an earthquake event (Eidinger and Davis 2012; Davis 2016).

Seismic rehabilitation decision-making models work as a decision-making tool for infrastructure managers to determine the critical pipes of a water pipe network. Wang et al. (2010) used a prioritization approach and seismic vulnerability assessment method for seismic rehabilitation of water pipe networks. Wu and Baker (2017) developed an optimization approach for comprehensive seismic vulnerability analysis. Pudasaini and Shahandashti (2018) developed a genetic algorithm-based optimization algorithm and identified the most critical pipes of a water pipe network considering PGV. Shahandashti and Pudasaini (2019) used a simulated annealing-based methodology to develop a seismic rehabilitation decision-making model for a water pipe network considering spatial correlation between seismic intensities developed due to transient strains. Roy et al. (2021) and Roy et al. (2022) identified the effects of network uncertainty on network-level seismic rehabilitation decision-making models of water pipe networks. Shavreen et al. (2022) developed a risk-based algorithm for network-level seismic rehabilitation decision-making models of water pipe network considering damages due to transient strains.

Current network-level seismic rehabilitation decision-making models lack consideration of the combined effects of damage due to earthquake-induced transient strains and geotechnical instability. Damages due to induced geotechnical instability can have a significant impact on seismic rehabilitation decision-making. Therefore, this study was performed to develop a seismic rehabilitation decision-making approach considering earthquake-induced transient strains and geotechnical instability combinedly.

METHODOLOGY

To identify the most critical pipes of water pipe networks for seismic rehabilitation decision-making by combining the effects of damages due to geotechnical instability due to landslide and liquefaction (PGD) and damages due to transient strain (PGV and PGA), the methodology can be divided into two segments: formulation of the optimization problem and solution of the formulated optimization problem.

Optimization Problem Formulation

The optimization problem was formulated aiming to maximize the serviceability after a seismic event within the budget constraint. The pipeline serviceability index (PSI) was selected as the serviceability indicator for this study (Shi 2006; Roy et al. 2022). The mathematical representation of the developed problem is as follows:

$$max_{n \in N} E[PSI(n)] \tag{1}$$

subject to

$$Cost(n) \leq Budget \quad (2)$$

where N = set of all possible seismic rehabilitation decisions for the selected budget constraint; $Cost(n)$ = total cost of the utilities for rehabilitation based on policy n; $E[PSI(n)]$ = average value of PSI for rehabilitation policy n (average over selected number of Monte Carlo Runs and total number of PGV and PGA fields)

Calculation of the Value of *E[PSI(n)]*

The process of calculating the average value of PSI for rehabilitation policy *n* considering the combination of PGD, PGV, and PGA can be divided into seven steps: deaggregation analysis to identify the scenario earthquake properties (e.g., magnitude); creating PGA and PGV map based on the results of deaggregation analysis; calculating the value of PGV and PGA for each pipe based on GMPE equation; calculation of the value of PGD for each pipe based on landslide and liquefaction model; seismic repair rate calculation for each pipe based on the value of PGV and PGD; Monte Carlo simulation; calculating value of average value of PSI for rehabilitation policy *n*. The process is demonstrated in Fig. 1. Each step of calculating the value of *E[PSI(n)]* is described in the subsequent sections.

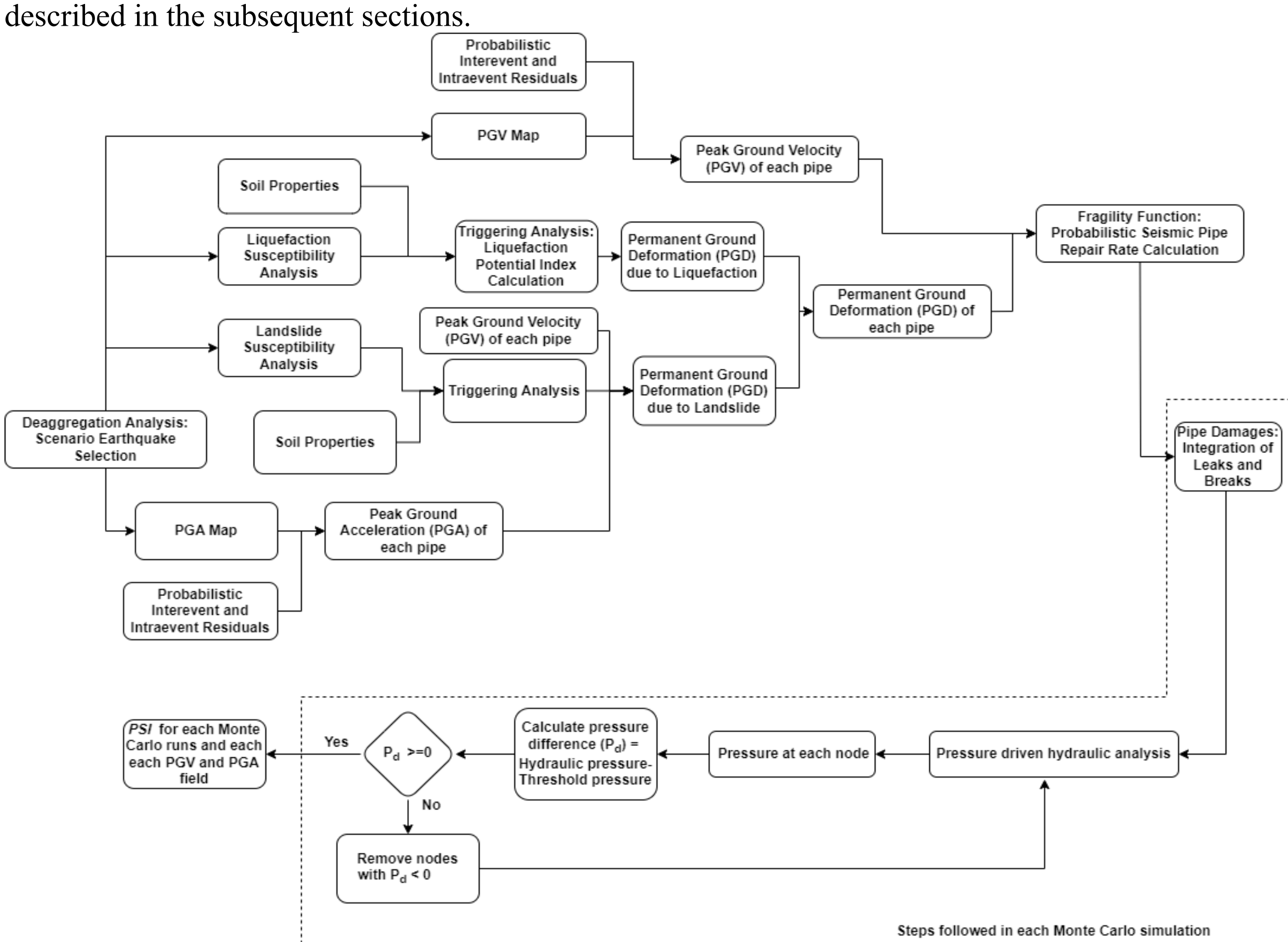

Fig. 1. Process of calculating the value of *PSI* for each Monte Carlo run and each PGV and PGA field.

Scenario Earthquake Selection

A Deaggregation analysis was conducted to select the scenario earthquake (Shahandashti and Pudasaini 2019; Adachi 2007). Spatial correlation of seismic intensity measures is important for network-level analysis of distributed water pipe networks and scenario earthquake enables the consideration of that spatial correlation (Zanini et al. 2016, 2017; Weatherhill et al. 2013; Adachi 2007). USGS (2018) was used for deaggregation analysis.

Calculation of PGV and PGA

Peak ground velocity (PGV) and peak ground acceleration (PGA) were two of selected three intensity measures (IM) for this study. After selection of the scenario earthquake, the value of these two intensity measures (PGV and PGA) was calculated based on the selected GMPE (Abrahamson and Silva 2007). The equation to calculate the IMs is shown in Eq. 3.

$$log_{10}\,(IM) = f\left(M_i, R_{ij}, \theta_i\right) + \sigma_B v_i + \sigma_W \varepsilon_{ij} \qquad (3)$$

The value of $f\left(M_i, R_{ij}, \theta_i\right)$ was inferred from generated PGV and PGA map (Field et al. 2005). $\sigma_B v_i$ and $\sigma_W \varepsilon_{ij}$ are the interevent and intraevent residuals, respectively.

Calculation of PGD using Landslide and Liquefaction Model

Permanent Ground Deformation (PGD) for landslide and liquefaction were calculated for each pipe using three steps: (1) susceptibility analysis; (2) triggering analysis; (3) PGD calculation.

The susceptibility analysis due to landslide was conducted using empirical failure domains (Keefer 1984). These domains are functions of earthquake magnitude and epicentral distance and help to categorize if damage due to landslide can or cannot occur (Risi et al. 2018). The landslide triggering analysis was conducted using Newmark's method (Newmark 1965). From the triggering analysis, the value of critical acceleration (a_c) was calculated. The value of PGD for each pipe due to landslide was calculated based on Eq. 4 (Saygili and Rathje 2008).

$$\ln PGD = -1.56 - 4.58 * \left(\frac{a_c}{PGA}\right) - 20.84 * \left(\frac{a_c}{PGA}\right)^2 + 44.75 * \left(\frac{a_c}{PGA}\right)^3 + 30.5 * \left(\frac{a_c}{PGA}\right)^4 - 0.64 * lnPGA + 1.55 * \ln\ PGV \qquad (4)$$

The susceptibility analysis due to liquefaction was conducted using empirical failure domains developed by Galli (2000). The triggering analysis was conducted if the epicentral distance and the magnitude distance fell inside the domain. The triggering analysis was conducted by calculating the value of liquefaction potential index (LPI) using Eq. 5 (Iwasaki et al. 1982).

$$LPI = \int_0^{20} F_z w(z) dx \qquad (5)$$

where, z = depth below ground surface (meter, m); $w(z) = 10 - 0.5z$; F_z = function derived from factor of safety (*FS)*.

$$F_z = 0 \text{ for } FS \geq 1.2$$
$$F_z = 1 - FS \quad \text{for } FS < 0.05$$
$$F_z = 2 * 10^{-6} e^{-18.427FS} \quad \text{for } 1.2 > FS > 0.95$$

The value of *FS* was calculated using Eq. 6.

$$FS = \frac{CSR}{CRR} \tag{6}$$

where, *CRR* and *CSR* are the cyclic resistance ration and the cyclic stress ration, respectively.

The value of *CSR* was calculated based on soil properties, vertical stress, total stress, PGA value, and earthquake magnitude (Seed and Idriss 1971; Risi et al. 2018). The value of *CRR* was calculated based on the value of soil properties, soil shear stress, and earthquake magnitude (Kayen et al. 2013).

The value of PGD for each pipe due to liquefaction was calculated based on the value of *LPI* using Eq. 7 (Schmertmann 1978; Tanabe and Takada 1988; Bardet et al. 1999; Risi et al. 2018).

$$PGD = 0 \quad if\ 0 < LPI < 5$$
$$PGD = PGD_{Settlement} \quad if\ 5 < LPI < 15 \tag{7}$$
$$PGD = \sqrt{PGD_{settlement}^2 + PGD_{Lateral\ Spread}^2} \quad if\ LPI > 15$$

Calculation of Seismic Repair Rate

Seismic repair rate (SRR) of each pipe was calculated based on the value of PGV and PGD using Eq. 8 and Eq. 9 (ALA 2001)

$$SRR = K_1 * 0.00187 * PGV \tag{8}$$
$$SRR = K_2 * 1.06 * (PGD)^{0.319} \tag{9}$$

K_1 and K_2 are seismic fragility modification factors depending on pipe properties (pipe diameter; pipe material, pipe joint type) and soil corrosivity. The *PGV* of each pipe calculated using GMPE was used in Eq. 8. The maximum *PGD* of each pipe from landslide and liquefaction model was used in this study.

Integration of Leaks and Breaks

After calculating the value of SRR, the number of leaks and breaks for each pipe were identified based on the value of SRR using Eq. 10 and Eq. 11.

$$\#\ of\ leaks = (0.8 * SRR_{PGV} + 0.2 * SRR_{PGD}) * L \tag{10}$$
$$\#\ of\ breaks = (0.2 * SRR_{PGV} + 0.8 * SRR_{PGD}) * L \tag{11}$$

Leaks and breaks were integrated with the network and the value of *E[PSI(n)]* was calculated for the selected rehabilitation policy *n* (Shahandashti and Pudasaini 2019).

A simulated annealing-based optimization algorithm was used in this study to obtain a solution to the optimization problem represented by Eq. (1) and Eq. (2) (Shahandashti and Pudasaini 2019).

APPLICATION

Modena network, assumed to be in Pasadena (State of California), was used in this study to demonstrate the application of the described methodology. Deaggregation analysis was conducted at that location and the scenario earthquake was identified. Five budget constraints were selected for this study: 2.5 million, 5 million, 7.5 million, 10 million, and 12.5 million. 20 random intraevent and interevent residuals were added to create 20 random PGV and PGA fields for the selected 3000 number of Monte Carlo runs (Shahandashti and Pudasaini 2019).

RESULTS

Using the described methodology and cost of rehabilitation of each pipe (Shahandashti and Pudasaini 2019), rehabilitation policies were identified for the selected budget constraints along with the maximum value of *PSI*. The critical pipes identified for each budget constraint are shown in Fig. 2 using highlighted lines.

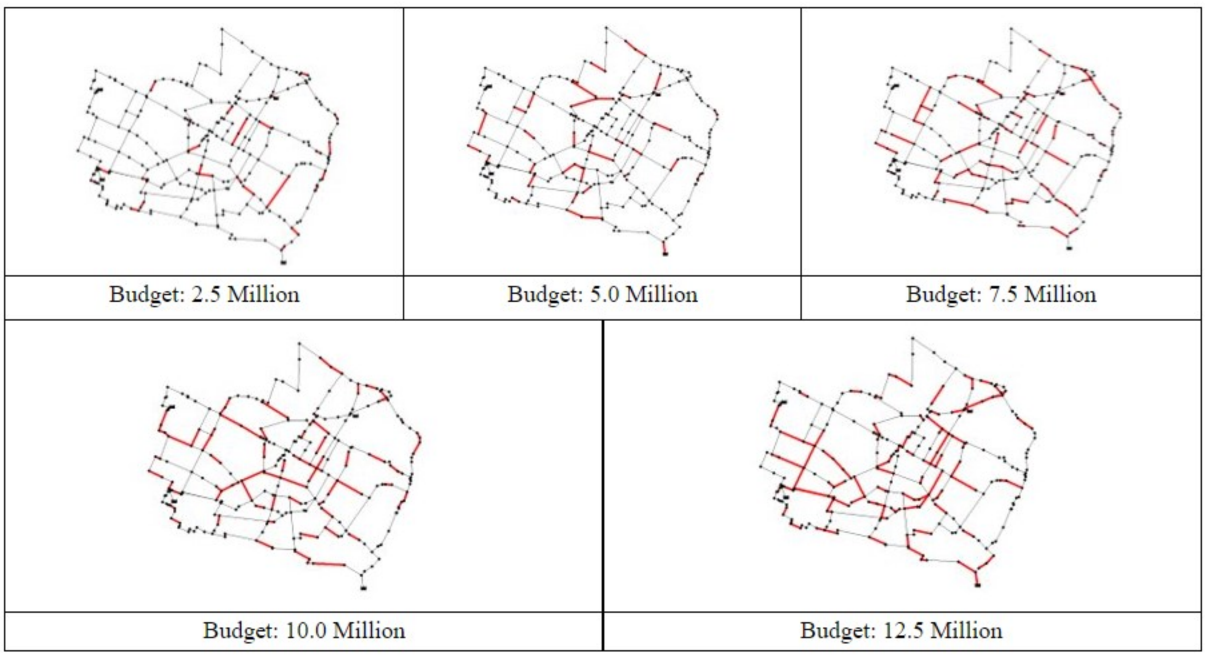

Fig. 2. Identified critical pipes considering combined effect of earthquake induced transient strains and geotechnical instability.

VALIDATION

For validation of the results, the proposed methodology was applied considering transient strains only (*PGD=0)*. The critical pipes identified for each budget constraint are shown in Fig. 3 using highlighted lines. Table 1 summarizes the maximum achievable *E[PSI]* for each budget constraints (both considering *PGD=0* and *PGD≠ 0*).

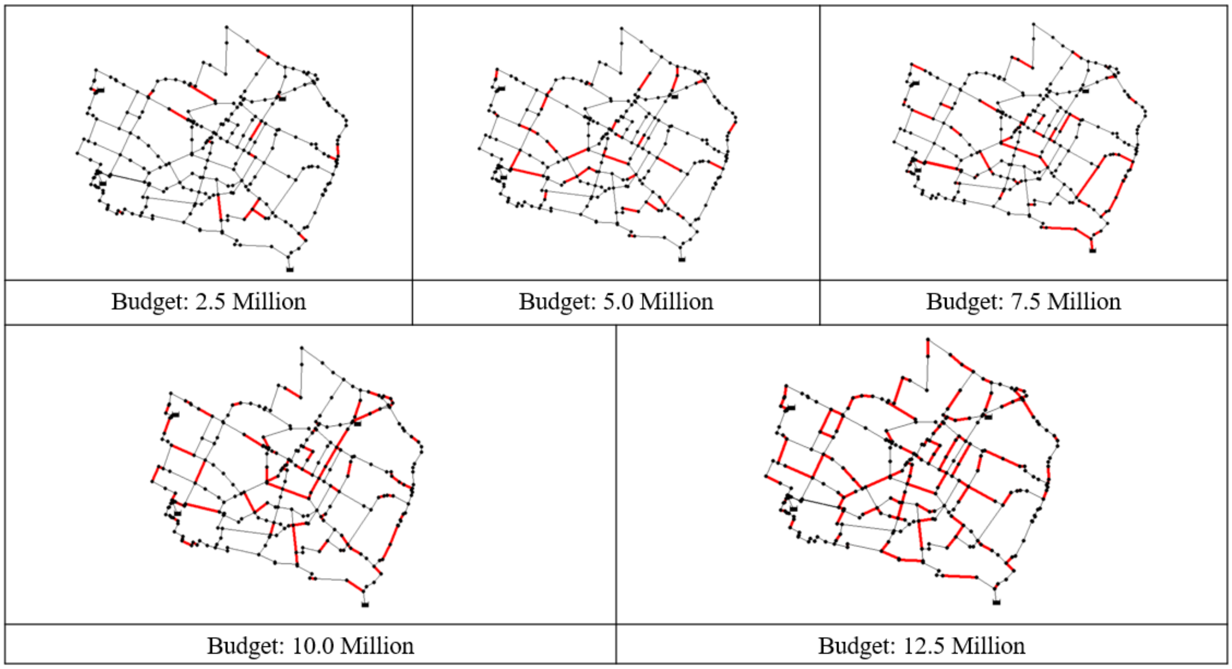

Fig. 2. Identified critical pipes considering the effect of earthquake induced transient strains (*PGD=0)*.

Table 1. Result of implementing proposed methodology in Modena network and validation (*PGD=0)*

Policy No.	Rehabilitation Cost Upper Bound	Combined Effect of Transient Strains and Geotechnical Instability			Effect of Transient Strains Only (*PGD = 0)*		
		Actual Cost of Rehabilitation	E(PSI)	Solution Time (hr.)	Actual Cost of Rehabilitation	E(PSI)	Solution Time (hr.)
1	2.5 million	2,499,450.00	0.85469	293.67	2,498,484.00	0.89126	290.51
2	5 million	4,999,680.00	0.87733	295.38	4,999,600.00	0.90352	292.37
3	7.5 million	7,493,899.00	0.89395	288.98	7,499,755.00	0.92112	292.84
4	10 million	9,999,360.00	0.91806	290.51	9,999,146.00	0.93953	288.85
5	12.5 million	12,499,423.00	0.93185	287.67	12,496,460.00	0.95309	290.14

CONCLUSION

The paper presents a simulated annealing-based optimization algorithm that considers the combined effect of damage due to transient strains and earthquake-induced geotechnical instability to identify the most critical pipes of a water pipe network vulnerable to seismic events. The methodology is composed of a Monte Carlo simulation-based procedure to generate spatially correlated intensity measures (PGV and PGA fields), a three-stage procedure to calculate the value of PGD, and a simulated annealing-based optimization approach to identify the critical pipes. The application of the methodology to a benchmark network and the validation results demonstrate the importance of considering the combined effect of PGV and PGD in network-level seismic rehabilitation decision-making models at susceptible zones. The maximum achievable serviceability for a limited budget constraint reduces by 6-7% at landslide and liquefaction-susceptible zones. The methodology presented herein provides the infrastructure stakeholders with a tool that can help them to make seismic rehabilitation decisions when they have a limited budget available considering the combination of developed transient strains and geotechnical instability due to earthquakes.

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