CASE SCHOOL OF ENGINEERING
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Seismic Damage and Renewal Cost Analysis of Buried Water Pipelines: A Python-based Computational Framework

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Abstract

The existing age-old buried water pipeline infrastructures in the USA are at risk. Significant damage is observed after past earthquakes. There is evidence that the intensity of seismic damage of buried pipes is amplified due to the effect of corrosion on pipe walls. Seismic vulnerability assessment guidelines often ignored the effect of corrosion deterioration in pipelines' seismic performance. Therefore, this paper modifies the ALA 2001 seismic fragility of buried pipelines by incorporating a modification factor for corrosion observed after a past earthquake. The utility manager also finds difficulty prioritizing rehabilitation actions for damaged water pipes immediately after an earthquake. Graph theory is utilized to find the importance of components in the system. Since the Water Distribution Systems are often large and complex, they require a large amount of computational effort to estimate seismic damage and subsequent maintenance actions. A python-based computation framework is developed for determining seismic damage, renewal cost, and strategies. A scenario-based analysis is performed to demonstrate the proposed approach for a mid-size real water network.

ALA 2001 Repair Rate Extension

Repair Rate Estimation (ALA, 2001):

$$\mathbf{RR = k_1 \times (0.00187) \times PGV}$$

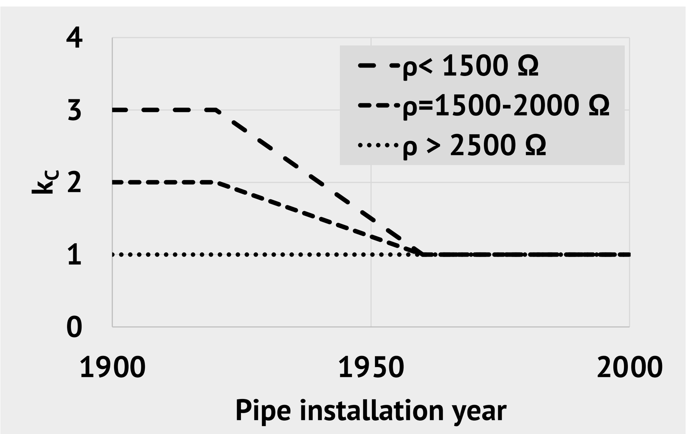
k_1 : ALA modification factor for ground shaking

Modification for corrosion (K_C) is proposed based on the observation from 2014 Napa Earthquake:

$$\mathbf{RR} = \underbrace{\mathbf{k_1 \times k_C}}_{\text{Correction Factor: } C} \mathbf{\times 0.00187 \times PGV = C \times 0.00187 \times PGV}$$

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

(Eidinger, 2015)



K_c for Cast Iron Pipe

ALA 2001 Fragility: Statistically-Based Approach

Seismic Fragility of Pipeline:

$$\mathbf{P_f = 1 - e^{-RR \times L}} \qquad P_f\text{: probability of failure}$$

Seismic Fragility (after modification):

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

About 80% and 20% of seismic damages are leaks and breaks, respectively (FEMA 2012). Seismic fragilities for Leak and Break are defined as below:

$$\mathbf{P_{leak} = 1 - e^{-0.00187\Theta}}$$

$$\mathbf{P_{break} = 0.25 \times P_{leak}}$$

Ground Motion Prediction Models

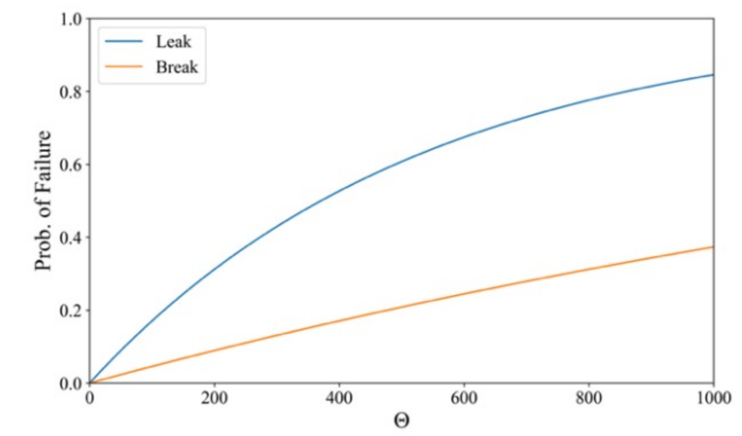
Intensity at site is estimated using Ground Motion Prediction Equations:

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

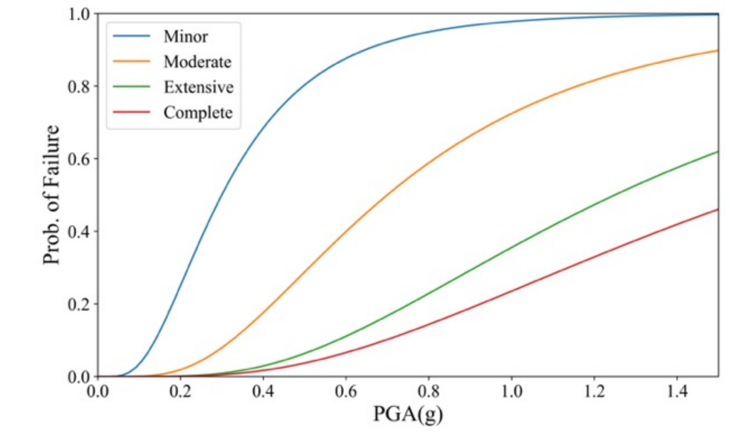
$$PGA = 403.8 \times 10^{0.265M}(R+30)^{-1.218}$$

(Kawashima et al. 1984; Yu and Jin 2008)

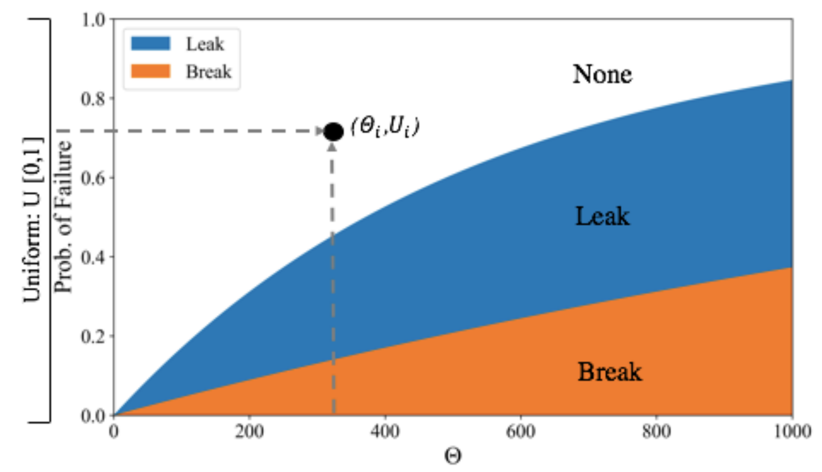
Fragility Analysis



Pipelines (modified in this study)



On-ground storage tanks (FEMA 2012)



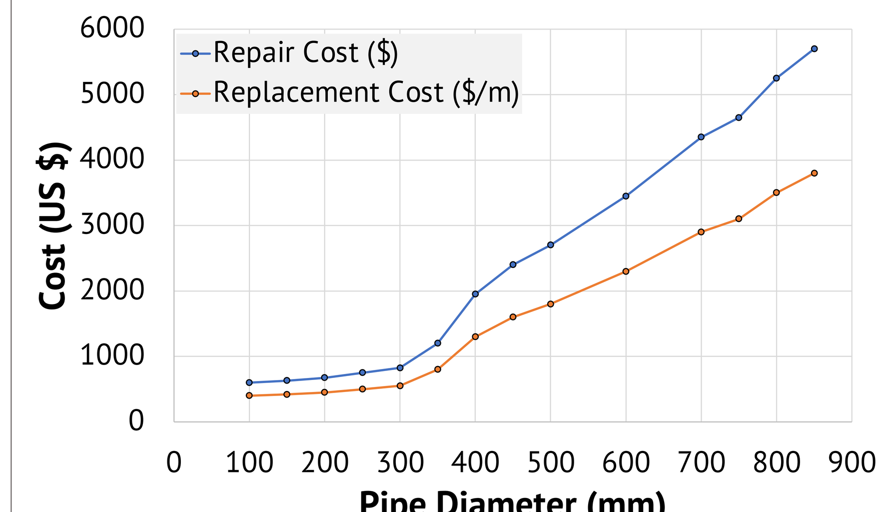
Stochastic damage scenario development

The expected damage state is assigned based on the control axis value (e.g., Θ for the pipe, PGV for tanks) & a random number generated from a uniform distribution U[0,1].

Damage state is assigned where intersection of Θ & U[0,1] falls

Renewal Analysis

Average damage repair and replacement cost for unit length :



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

α_1, α_2 : unit cost adjustment factors for location
n_{rp} , n_{rr} : no. of pipes to be repaired & replaced
n_{d_i} : number of damages
L_j : length of a pipe

Current structural condition, Condition Index:

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

T : year (Newton and Vanier, 2006)

Degree of impact of the failure, Failure Impact Index:

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

f_l : location factor, f_s : soil factor
f_z : size factor, f_d : depth factor.
(McDonald and Zhao, 2001)

Criticality of a Component within WDS, Edge Betweenness:

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

$\tau_{s,u}(l)$: no. of shortest paths passes through l from nodes s to u (Barthélemy 2011)

Renewal Actions:

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

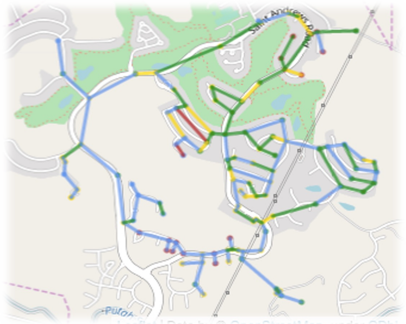
$\omega_c, \omega_i, \omega_b$: weights of C_I, I_I, and EBC, respectively
R_t : the replacement threshold, to be set by water utility

Conclusions

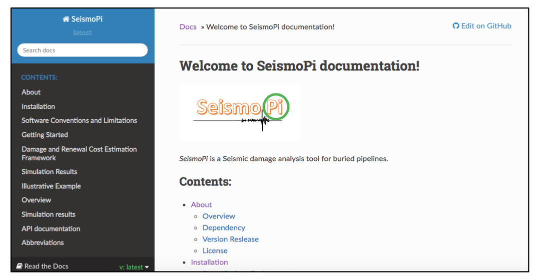
- The proposed framework accounts for the effect of corrosion deterioration by modifying the ALA fragility curves based on observed damage data.
- The SeismoPi tool is computationally efficient, and results can be plotted interactively on OpenStreetMap to support asset management decision-making.
- While the current approach does not perform hydraulic simulation, the edge betweenness metric helps to gain information about the potential flow path disruption due to an earthquake.

SeismoPi Python Tool

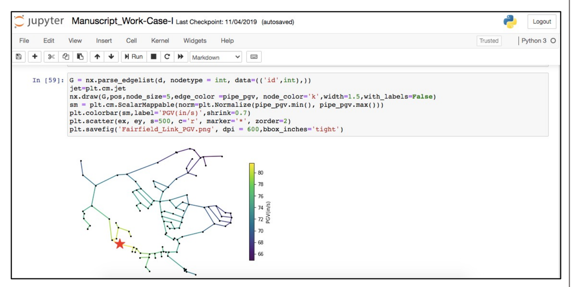
A python based open-source interactive tool named **SeismoPi** is developed for estimating seismic damage and renewal strategies.



OpenStreetMap using SeismoPi



Web Documentation



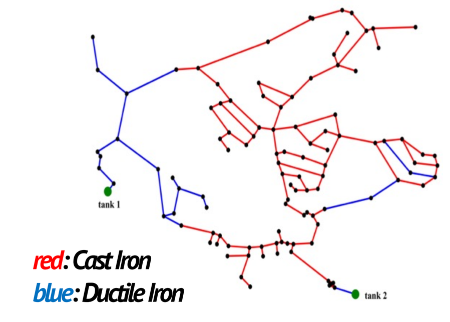
Jupyter Notebook

Available	: https://github.com/rxm562/SeismoPi
Input file	: Comma-Separated Values (.CSV)

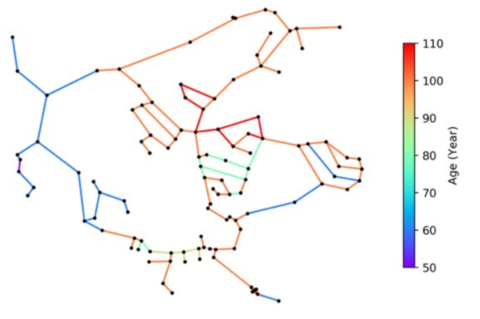
Case Study

Rancho Solano Water Network (Fairfield, CA):
112 junctions, 126 pipes, 2 elevated water tanks, Dia: 400 - 600 mm, Age: 60-110 yrs

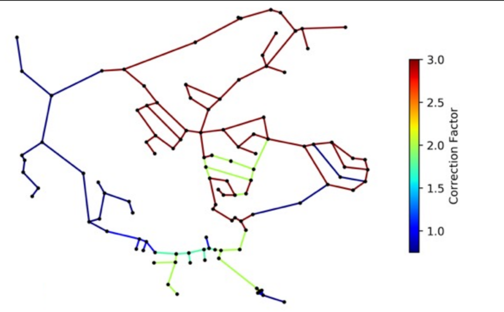
Earthquake Scenario:
Magnitude: M_W 7.0,
Epicentre : 122.07 W, 38.27 N marked with (★)



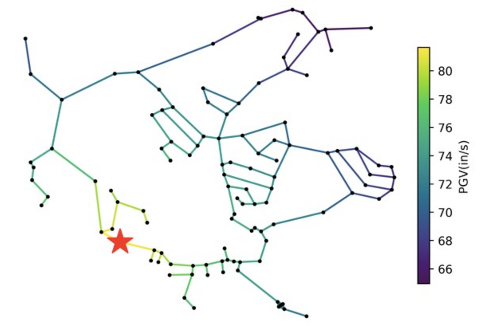
WDS



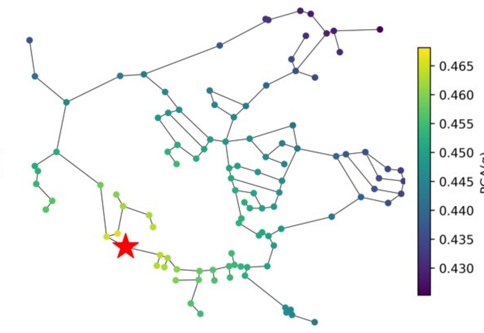
Age



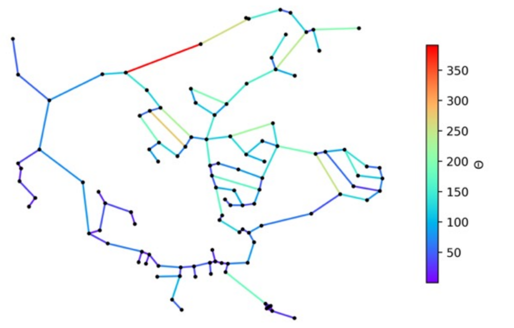
Correction Factor, C



PGV (in/s)

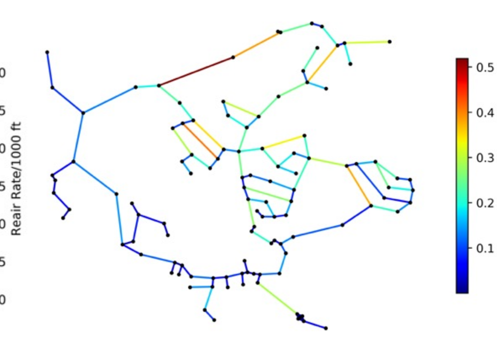


PGA (g)

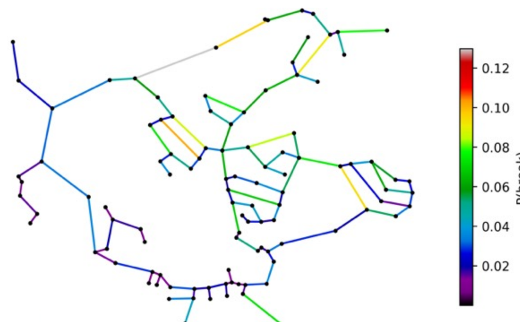


Control Variable, Θ

Repair Rate

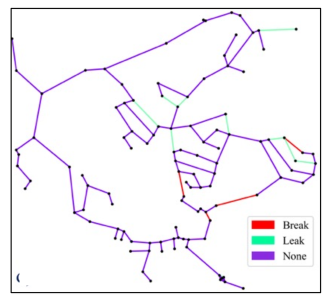


P_{leak}



P_{break}

Damage and Renewal Analysis:

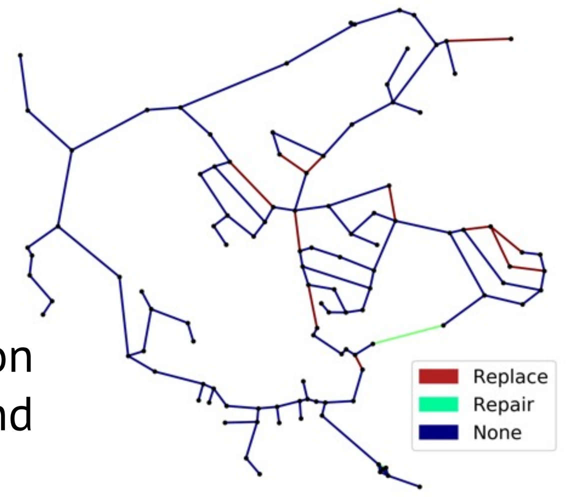


Damage State

C_I I_I EBC

R_t = 0.5 if RA>R_t then Replace, otherwise Repair

α_1, α_2	: 1.5,1.5
Repair length	: 2.2 km of pipe
Repair cos	: US$ 6,900
Replacement cost	: US$ 9,190,500



The consideration of the effect of corrosion significantly changes the repair rates and consequent failure probability of pipes.

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