Water Distribution System Pipe Replacement Given Random Defects

Case Study of San Francisco's Auxiliary Water Supply System

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City and County of San Francisco Team:
- Davis Myerson, Project Manager, SFPUC
- Eugene Ling, Project Engineer, SFPW
- Douglas York, Assistant Engineer, SFPW

Advisors

- Jack Baker, Assoc. Prof., Stanford University
  *ground motions and uncertainty*

- Mike O’Rourke, Prof., Rensselaer Polytechnic Inst.
  *segmented pipe / permanent ground deformation*

- Tom O’Rourke, Prof., Cornell University
  *buried pipe / seismic shaking*

- Charles Scawthorn, Prof. (ret.), Kyoto University
  *system reliability, fire following earthquake, pipe vulnerability*
Outline

• Project impetus
• Problem – how to identify which pipe to remediate so as to contribute most to system reliability?
• Solution - PIPE Algorithm  
  (Pipe Importance and Priority Evaluation)
• Application to San Francisco’s AWSS system
• Results
• Summary
Project Impetus – fire following earthquake
San Francisco Auxiliary Water Supply System (AWSS)

- 200 km. extra heavy wall pipe (mostly CI)
- 2 x 10,000 gpm (667 lps) pump stations
- Many other features…
Major pipe replacement need

AWSS pipeline network
- Over 127 miles of 10” - 20” CIP & DIP Mains

<table>
<thead>
<tr>
<th>Year</th>
<th>10”</th>
<th>12”</th>
<th>14”</th>
<th>16”</th>
<th>18”</th>
<th>20”</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1912</td>
<td>13.54</td>
<td>46.44</td>
<td>17.78</td>
<td>6.74</td>
<td>13.61</td>
<td>4.67</td>
<td>102.78</td>
</tr>
<tr>
<td>1935</td>
<td>0.48</td>
<td>9.56</td>
<td>0.73</td>
<td>1.24</td>
<td>1.88</td>
<td>11.07</td>
<td>24.96</td>
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<td>1.88</td>
<td>11.07</td>
<td>24.96</td>
</tr>
</tbody>
</table>

Pipe Length Installed in feet

Installation Year

Installal Year
Problem Statement

• AWSS pipe network > 130 miles, 60% from ~1912
• Aging, Infirm areas, possible corrosion…
→ Which to replace / abandon?
• In other words, which pipes are the Most Important Pipes (MIP)?
  • Meaning of Important?
    • Breaks most frequently?
    • Pipe that protects the greatest value?
    • Pipe that carries the most water?...
  • Determining MIP must consider many factors:
    • Hydraulics and place in the network (e.g., source vs. deadend)
    • Condition, age… (i.e., vulnerability)
    • Hazard (shaking, liquefaction…)
    • Size of likely fires
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“most important pipe” problem – simplest case

If you can fix only one pipe, which would you fix?
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**Solution: PIPE Algorithm**

**Pipe Importance and Priority Evaluation (PIPE) Algorithm**

1. Monte Carlo simulation (Python wrapper on EPANET, adapted to do Pressure-driven hydraulic analysis (PDA, (considers multiple simultaneous pipe breaks and leaks given pipe vulnerabilities, PGV and PGD)
2. Regression analysis → *Average Deficit Contribution (ADC)*
3. $ADC = \text{each pipes’ average contribution to flow deficit}$ (all simulations, considering FRA demands, hydraulics and breaks)
4. Rank pipes by ADC → highest ADC is “most important pipe” (this pipe has the highest contribution to average deficit in demand)
PIPE Algorithm

EXAMPLE

Total Demand: 63,989 gpm
Leakage: 25,000 gpm

2 FRAs don’t get required fire flow
If FRA 1 required fire flow = 4000 gpm and AWSS can only provide 3000 gpm → deficit = 1000 gpm
FRA 2: 3000 – 2500
→ deficit = 500 gpm

Sum all deficits = 1500 → to be minimized

Deficit \( j \)

| 1500 |
| 2657 |
| 1387 |
| 4231 |
| ... |

FR = Leakage in pipe \( i \) of simulation \( j \)

| 124 | 142 | 32 | 86 | 0 | 324 | 0 | ... |
| 0 | 345 | 0 | 0 | 0 | 487 | 0 | ... |
| 23 | 0 | 0 | 0 | 432 | 0 | 0 | ... |
| ... |

Weights \( i \)

| w1 |
| w2 |
| w3 |
| ... |
PIPE Algorithm (cont.)

Solve for weights $w_i$

Weights accurately model system

$$\begin{align*}
\text{Deficit } j & \\
1500 & | 124 & 142 & 32 & 86 & 0 & 324 & 0 & \ldots \ \sum^{FR_1} \\
2657 & | 0 & 345 & 0 & 0 & 0 & 487 & 0 & \ldots \ \sum^{FR_2} \\
1387 & | 23 & 0 & 0 & 0 & 432 & 0 & 0 & \ldots \ \\
4231 & | \ldots \\
\ldots & | \ldots \\
\text{FR} &= \text{Leakage in pipe } i \text{ of simulation } j \\
\text{Weights } i & \\
& \begin{bmatrix}
w_1 \\
w_2 \\
w_3 \\
\vdots \\
\end{bmatrix}
\end{align*}$$

$\rightarrow$ Pipe $i$’s Average Deficit Contribution =

$$ADC_i = \left( \sum_{j=1}^{N} FR(i, j) \right) \frac{w_i}{N}$$

$$(r=0.986)$$
Analysis Tools

EPANET: very fast hydraulic analysis (general, not seismic, demand driven, cannot account for negative pressures ...)

Need: Pressure-driven analysis, addresses reliability, identifies MIP
PIPE Algorithm (Summary)

1. ADC is calculated for all pipes
2. Pipes are ranked in descending ADC order.
3. The ranking is the relative importance of each pipes’ contribution to the average of deficits for all simulations.
4. The pipe with highest ADC is the pipe that contributes most to the demand’s deficit, 2nd highest ranked pipe contributes next most, and so on.
5. If the highest ranked pipe is mitigated, that mitigation contributes most to overall average deficit reduction, and so on.
6. The approach incorporates:
   • Ground motion → Damage
   • Monte Carlo simulation (i.e., uncertainty)
   • Pressure-driven hydraulic modeling (no negative pressures)
   • PIPE algorithm identifies “most important pipe”
7. The approach is:
   • Accurate
   • State-of-the-art / New (i.e., not done before)
   • Published ASCE Pipeline Conference...to be submitted for journal
Steps in the analysis

Monte Carlo – thousands of trials

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Application to AWSS – fire following earthquake demands

Burn Density (and water needs)
Select a subset of maps and reweight, to reproduce ground motion hazard at multiple sights and a proxy performance metric.

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Stanford ground motion simulation approach

60,000 simulations (all events) → 91 simulations (all events) → 15 EQ Scenarios

For a given rupture scenario (e.g., M7.9 San Andreas):

Median prediction + Spatially correlated “residual” = Total ground motion amplitude

Residuals are empirically calibrated from past earthquakes and account for ground motion variability

Permanent Ground Deformation

Legend

- AWSS Pipe Mains
- Lateral Spreading Direction/Mag
  - 0.0 - 0.2
  - 0.3 - 1.6
  - 1.9 - 3.3
  - 3.4 - 5.4
  - 5.5 - 8.5
  - 8.6 - 11.0
  - 11.1 - 14.1
  - 14.2 - 17.2
  - 17.3 - 20.8
  - 20.9 - 24.4
  - 24.5 - 28.6
  - 28.7 - 32.7
  - >= 32.8
Permanent Ground Deformation

Mechanistic fragility curve – M. O’ Rourke
Ground strain to repair rate calculation
Damaged Network Performance

Post Earthquake Base Case

Legend
- AWSS Pipelines
- Seismic Isolation Zones
- Infirm Areas

Percent Deficit
- 0% - 40%
- 40% - 70%
- 70% - 100%
System Analysis – Pipe Importance by ADC

Legend
Pipe Rank
- 1 - 25
- 26 - 50
- 51 - 100
- 101 - 200
- 201 - 6379
System Analysis – Pipe Importance by ADC
## System Analysis – Results

<table>
<thead>
<tr>
<th>Project</th>
<th>Length (ft)</th>
<th>ADC</th>
<th>Cost</th>
<th>GPM Supplied</th>
<th>GPM Increase</th>
<th>$/GPM Increase</th>
<th>% Supplied</th>
<th>Worst FRA % Supplied</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$-</td>
<td>57,499</td>
<td></td>
<td>$-</td>
<td>89.86%</td>
<td>5.82%</td>
</tr>
<tr>
<td>1</td>
<td>5,956</td>
<td>5,055</td>
<td>$7,540,000</td>
<td>59,887</td>
<td>2,388</td>
<td>$3,156</td>
<td>93.59%</td>
<td>31.41%</td>
</tr>
<tr>
<td>2</td>
<td>3,982</td>
<td>1,130</td>
<td>$4,210,000</td>
<td>58,202</td>
<td>703</td>
<td>$5,994</td>
<td>90.96%</td>
<td>17.65%</td>
</tr>
<tr>
<td>3</td>
<td>11,810</td>
<td>2,696</td>
<td>$16,700,000</td>
<td>58,076</td>
<td>577</td>
<td>$28,937</td>
<td>90.76%</td>
<td>12.02%</td>
</tr>
<tr>
<td>4</td>
<td>8,927</td>
<td>1,911</td>
<td>$13,040,000</td>
<td>57,992</td>
<td>493</td>
<td>$26,454</td>
<td>90.63%</td>
<td>10.95%</td>
</tr>
<tr>
<td>1 &amp; 2</td>
<td>9,938</td>
<td>6,185</td>
<td>$11,750,000</td>
<td>60,953</td>
<td>3,454</td>
<td>$3,402</td>
<td>95.26%</td>
<td>55.84%</td>
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<tr>
<td>1 &amp; 2 &amp; 3</td>
<td>21,747</td>
<td>8,880</td>
<td>$28,450,000</td>
<td>61,933</td>
<td>4,434</td>
<td>$6,416</td>
<td>96.79%</td>
<td>72.56%</td>
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<tr>
<td>1 &amp; 2 &amp; 3 &amp; 4</td>
<td>30,674</td>
<td>10,791</td>
<td>$41,490,000</td>
<td>63,096</td>
<td>5,597</td>
<td>$7,413</td>
<td>98.60%</td>
<td>87.81%</td>
</tr>
</tbody>
</table>
System Analysis – Pipe Importance by ADC

Legend
- AWSS Pipelines
- Seismic Isolation Zones
- Infirm Areas

Percent Deficit
- 0% - 40%
- 40% - 70%
- 70% - 100%
Conclusions

- A new method, the *Pipe Importance and Priority Evaluation (PIPE)* Algorithm, has been developed that allows identification of which pipe contributes most to system deficit, given complexities of hydraulic demands, network topology and seismic (or other) impacts.
- The PIPE algorithm has been applied to a large real world water system requiring high reliability.
- Under non-earthquake conditions the AWSS (i.e.,) meets 100% of demands.
- With Infirm Areas *isolated* after an earthquake, the system will lose ~43,000 gpm through leaks and breaks and have a demand deficit of ~6,500 gpm. (~63,000 gpm and ~8600 gpm with IA’s open)
- Application of the PIPE algorithm efficiently identified the least cost pipe replacement program.
Water Distribution System Pipe Replacement Given Random Defects

Thank you
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