A number of major water supply programs have recently been undertaken to achieve water supply network resilience in the face of major earthquakes…This session includes a panel that integrates discussion of these issues across all the programs.
DETERMINING WATER DISTRIBUTION SYSTEM PIPE REPLACEMENT GIVEN RANDOM DEFECTS
– Case Study of San Francisco’s Auxiliary Water Supply System

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Professor of Infrastructure Risk Management (ret.), Kyoto University

David Myerson
San Francisco Public Utilities Commission

Douglas York and Eugene Ling
San Francisco Public Works
Larger Project’s Team and Advisors

City and County of San Francisco Team:
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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
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
Current approach

- Single pipe failure? Correct but intuitively unsatisfying
- Two pipe failures? Correct if probability accounted for rigorously
- N pipe failures? Very difficult
- Disaster → N pipe failures

Issue:
- How to prioritize pipe replacement, accounting for multiple simultaneous failures, hydraulic connectivity...?
“Most Important Pipe” (MIP) problem


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)
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 \( \rightarrow \) deficit = 1000 gpm

FRA 2: 3000 – 2500 \( \rightarrow \) deficit = 500 gpm

Sum all deficits = 1500 \( \rightarrow \) to be minimized

N simulations:

<table>
<thead>
<tr>
<th>Deficit ( j )</th>
<th>FR = Leakage in pipe ( i ) of simulation ( j )</th>
<th>Weights ( i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500</td>
<td>124 142 32 86 0 324 0 ...</td>
<td>w1</td>
</tr>
<tr>
<td>2657</td>
<td>0 345 0 0 0 487 0 ...</td>
<td>w2</td>
</tr>
<tr>
<td>1387</td>
<td>23 0 0 0 432 0 0 ...</td>
<td>w3</td>
</tr>
<tr>
<td>4231</td>
<td>....</td>
<td></td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Weights:
- \( w1 \)
- \( w2 \)
- \( w3 \)

---

OPTIMIZING WATER DISTRIBUTION SYSTEM PIPE REPLACEMENT: SAN FRANCISCO AWSS (ID 523)
**PIPE Algorithm (cont.)**

Solve for weights $w_i$

Weights accurately model sys

Deficit $j$

<table>
<thead>
<tr>
<th>1500</th>
<th>124</th>
<th>142</th>
<th>32</th>
<th>86</th>
<th>0</th>
<th>324</th>
<th>0 ...</th>
</tr>
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<tr>
<td>2657</td>
<td>0</td>
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<td>0 ...</td>
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<td>4231</td>
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</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$\sum FR_1 \quad \sum FR_2 \quad \ldots$

$\Rightarrow$ Pipe $i$'s Average Deficit Contribution =

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

$FR$ = Leakage in pipe $i$ of simulation $j$

Weights $i$

$w_1$

$w_2$

$w_3$

$\Rightarrow$ Deficit $j$

$1500 \quad 142 \quad 32 \quad 86 \quad 0 \quad 324 \quad 0 ...$

$2657 \quad 345 \quad 0 \quad 0 \quad 0 \quad 487 \quad 0 ...$

$1387 \quad 0 \quad 0 \quad 0 \quad 0 \quad 432 \quad 0 ...$

$4231 \quad 0 \quad 0 \quad 0 \quad 0 \quad ... \quad ...$

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$FR$ = Leakage in pipe $i$ of simulation $j$

Weights $i$

$w_1$

$w_2$

$w_3$
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
Steps in the analysis

Monte Carlo – thousands of trials

RR | PGV (T. O’Rourke)

Ground shaking (Baker)

Permanent Ground Deformation (PGD)

Building density and material (fuel)

System Demands

Ground shaking

Areas

Perman Deform

RR | PGD (M. O’Rourke)
Application to AWSS – fire following earthquake demands

Burn Density (and water needs)
Stanford ground motion simulation approach

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

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

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

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

Permanent Ground Deformation
Permanent Ground Deformation

Mechanistic fragility curve – M. O’Rourke
Ground strain to repair rate calculation
System Analysis – Pipe Importance by ADC

Legend
Pipe Rank
- 1 - 25
- 26 - 50
- 51 - 100
- 101 - 200
- 201 - 6379
## 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>-</td>
<td>-</td>
<td>$</td>
<td>-</td>
<td>89.86%</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>
</tr>
<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>
</tr>
<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>
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.
Thank you

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