Water Research Foundation

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Water Distribution System Pipe Replacement Given Random Defects

Case Study of San Francisco's Auxiliary Water Supply System

Charles Scawthorn
SPA Risk LLC and Visiting Researcher, Univ. California, Berkeley
Professor of Infrastructure Risk Management (ret.), Kyoto University

David Myerson
San Francisco Public Utilities Commission

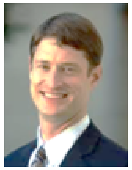
Douglas York and Eugene Ling
San Francisco Public Works

10th JWWA/WRF/CTWWA Water System Seismic Conference
October 18-21, 2017 ● Tainan, Taiwan

Larger Project's Team and Advisors

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

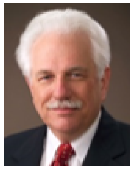
Advisors



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



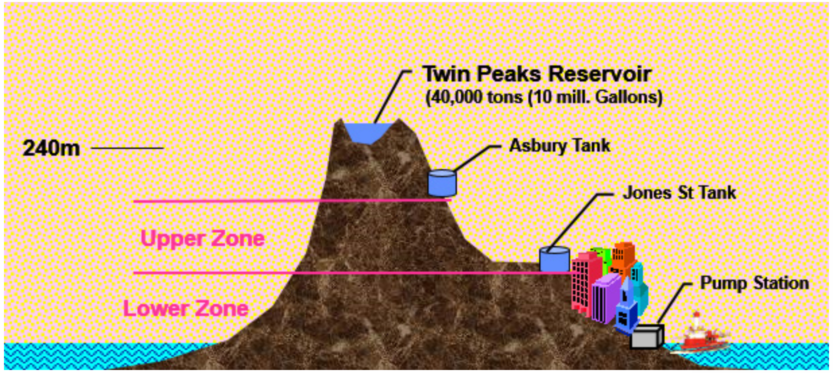
Charles Scawthorn, Prof. (ret.), Kyoto University
system reliability, fire following earthquake, pipe vulnerability

Outline

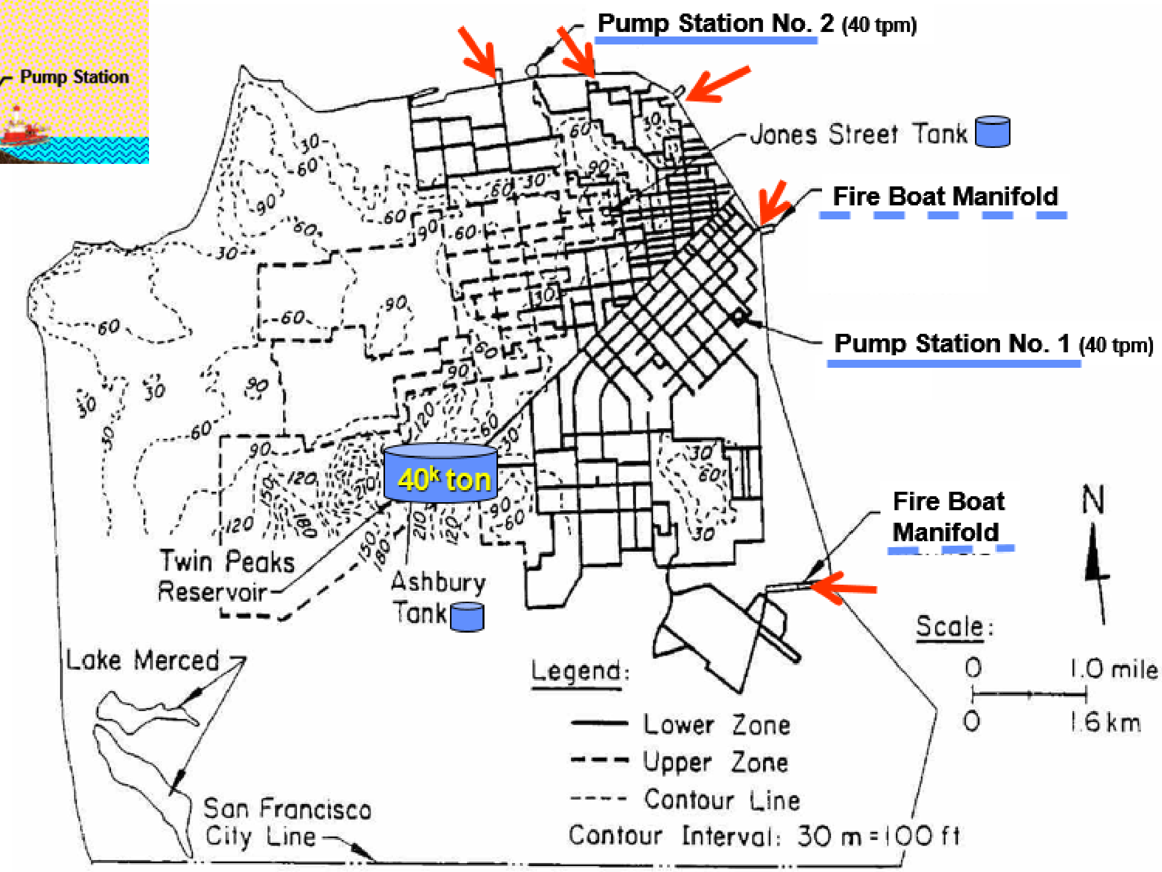
- Project impetus
- Problem – how to identify which pipe to remediate so as to contribute most to system reliability?
- Solution - **PIPE Algorithm**
  (Pipe Importance and Priority Evaluation)
- Application to San Francisco's AWSS system
- Results
- Summary

Project Impetus – fire following earthquake

San Francisco Auxiliary Water Supply System (AWSS)



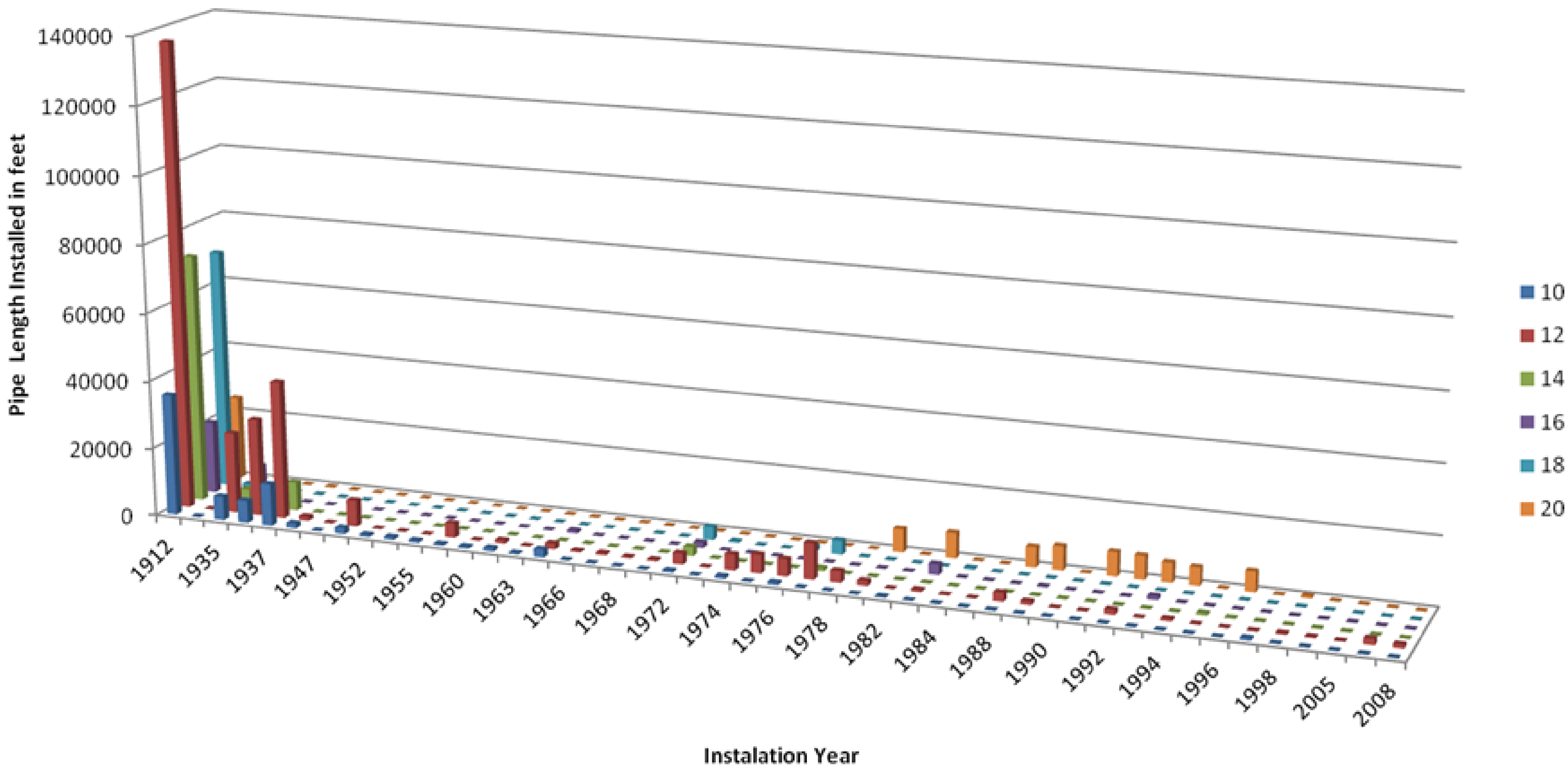
- 200 km. extra heavy wall pipe (mostly CI)
- 2 x 10,000 gpm (667 lps) pump stations
- Many other features…



Major pipe replacement need

AWSS pipeline network

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



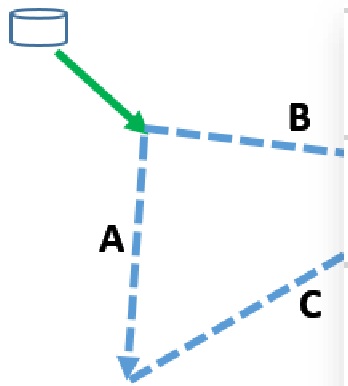
Problem Statement

- 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

“most important pipe” problem – simplest case



	L (ft)	Diam (in)	vuln	
			L*H	largest diam
			*H	shortest path
			*H	most vuln

ch would you fix?

p pipes	cases = 2^p
3	8
4	16
5	32
10	1024
100	1.3E+30
1000	1E+301

Cases	A	B	
0	2889	475	
1	0	557	
2	3000	0	3(
3	0	557	
4	0	0	
5	0	557	
6	0	0	
7	0	0	

	fr(f|H		
	h1		
A	0.00005		
B	0.00050	0.010	0.10
C	0.00500	0.100	1.00

fix pipe	E(flow)
A	99.1%
B	99.2%
C	99.8%

“Most Important Pipe” (MIP) problem

Long history – unsolved until this Assessment

1. Atiquzzaman, M., Liong, S., & Yu, X. (2006). Alternative Decision Making in Water Distribution Network with NSGA-II. *JOURNAL OF WATER RESOURCES PLANNING AND MANAGEMENT*, *132*(2), 2004–2008.
2. Al-Zahrani, M., & Syed, J. L. (2004). Hydraulic Reliability Analysis of Water Distribution System. *Journal of The Institution of Engineers*, *1*(1). Journal Article.
3. Ang, W. K., & Jowitt, P. W. (2006). Solution for Water Distribution Systems under Pressure-Deficient Conditions. *Journal of Water Re... es Planning and Management*, *132*(3, June), 175–182.
4. Dasic, T., & Djordjevic, B. (n.d.). *Method for water distribution systems reliability a...*
5. Farmani, R., Walters, G. A., & Savic, D. A. (2005). Trade... ...twork. *JOURNAL OF WATER RESOU...*
6. Fragi... ...urban water networks. *Earthquake Engng Struct. Dyn.*, *43*, 357–374.
7. Fujiw... ...eliability analysis of water distribution networks in consideration of equity, redistribution, and pressure dependent dema... *WATER RESOURCES RESEARCH*, *34*(7), 1843–1850.
8. Germanopoulos, G. (1986). Assessing the reliability of supply and level of service for water distribution systems. *Prof. Inst. Civil Engrs.*, *80*(June), 413–428.
9. Gomes, J., & Karney, B. W. (2005). Water Distribution System Reliability under a Fire Flow Condition : In *Impacts of Global Climate Change* (pp. 1–12). EWRI.
10. Ozger, S. S. (1994). A SEMI-PRESSURE-DRIVEN APPROACH TO RELIABILITY ASSESSMENT OF WATER DISTRIBUTION NETWORKS, 1–8.
11. Schaetzen, W. de, Taylor, D., MacPherson, G., & Naiduwa, C. (2006). FIRE FLOW ANALYSIS FOR OPTIMAL NETWORK IMPROVEMENT. *8th Annual Water Distribution Systems Analysis Symposium*. Conference Paper, Cincinnati, Ohio, USA.
12. Schneiter, C. R., Haimes, Y. Y., Li, D., & Lambert, J. H. (1996). Capacity reliability of water distribution networks and optimum rehabilitation decision making Maintenance. *Water Resources Research*, *32*(7), 2271–2278.
13. Torii, A. J., & Lopez, R. H. (2012). Reliability Analysis of Water Distribution Networks Using the Adaptive Response Surface Approach. *Journal of Hydraulic Engineering*, *138*(March), 227–236
14. Wagner, B. J. M., Shamir, U., & Marks, D. H. (1988). WATER DISTRIBUTION RELIABILITY: ANALYTIC METHODS. *Journal of Water Resources Planning and Management*, *114*(3).
15. Wagner, B. J. M., Shamir, U., & Marks, H. (1988). WATER DISTRIBUTION RELIABILITY: SIMULATION METHODS. *Ournal of Water Resources Planning and Management*, *114*(3), 276–294.
16. Wang, Y., Au, S.-K., & Fu, Q. (2010). Seismic Risk Assessment and Mitigation of Water Supply Systems. *Earthquake Spectra*, *26*(1), 257–274.
17. Wu, Y., Xu, Y., Tan, Y., & Chen, J. (2010). Hydraulic State Estimation of Post-Earthquake Water Distribution Systems. *Water Distribution System Analysis 2010*. Conference Paper, Tucson, AZ.

Solution: PIPE Algorithm

Pipe Importance and Priority Evaluation (PIPE) Algorithm

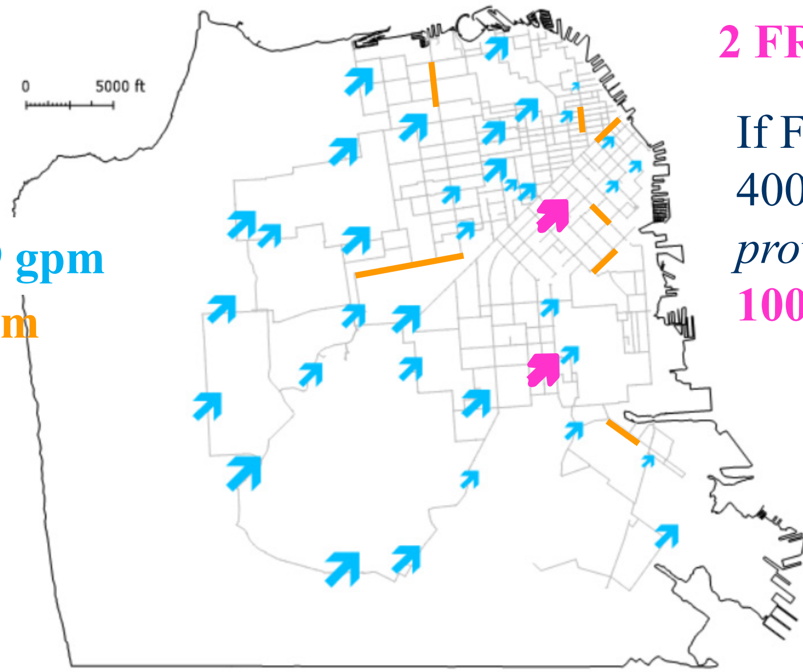
1. Monte Carlo simulation (Python wrapper on EPANET, adapted to do Pressure-driven hydraulic analysis (PDA, (considers multiple simultaneous pipe breaks and leaks given pipe vulnerabilities, PGV and PGD)
2. Regression analysis → *Average Deficit Contribution (ADC)*
3. *ADC* = each pipes' average contribution 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

N simulations:

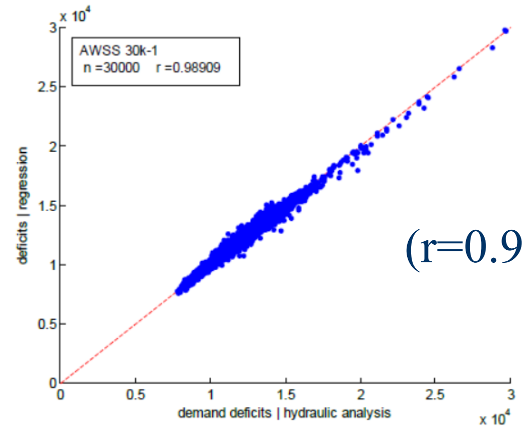
pipes *i*

Deficit *j*		FR = Leakage in pipe *i* of simulation *j*	Weights *i*
1500	=	124 142 32 86 0 324 0 ...	w1
2657		0 345 0 0 0 487 0 …	w2
1387		23 0 0 0 432 0 0...	w3
4231		….	…
…			

PIPE Algorithm (cont.)

Solve for weights w_i

Weights accurately model syst



(r=0.986)

Deficit j — FR = Leakage in pipe i of simulation j — Weights i

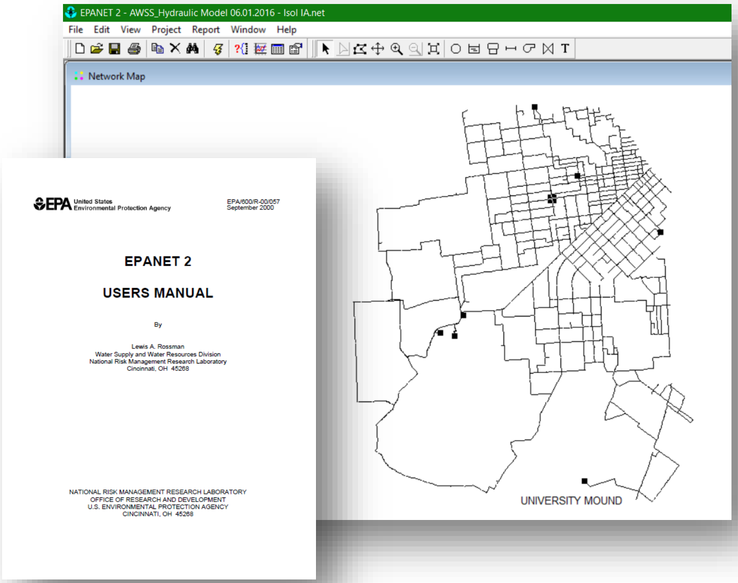
$$\begin{vmatrix}1500\\2657\\1387\\4231\\\dots\end{vmatrix} = \begin{vmatrix}124 & 142 & 32 & 86 & 0 & 324 & 0\dots\\ 0 & 345 & 0 & 0 & 0 & 487 & 0\dots\\ 23 & 0 & 0 & 0 & 432 & 0 & 0\dots \\ & & & \dots & & & \end{vmatrix} \begin{vmatrix} w1\\ w2\\ w3\\ \dots\end{vmatrix}$$

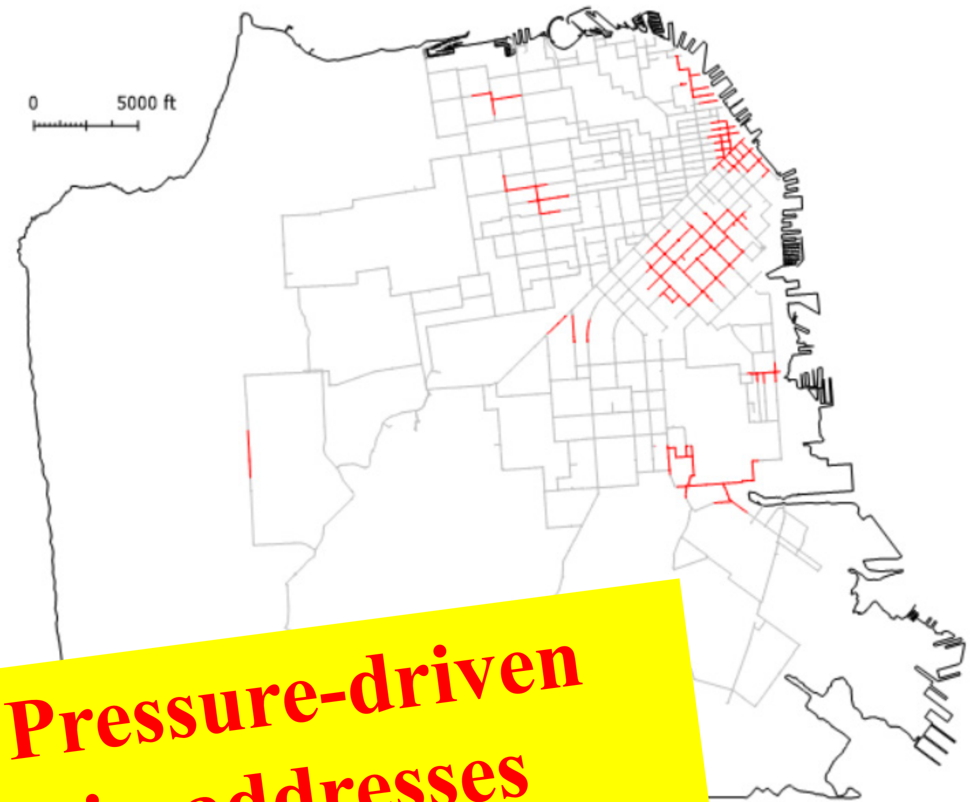
$\sum FR_1$ $\sum FR_2$ …

→ **Pipe *i* 's Average Deficit Contribution =**

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

Analysis Tools





EPANET: very fast hydraulic analysis

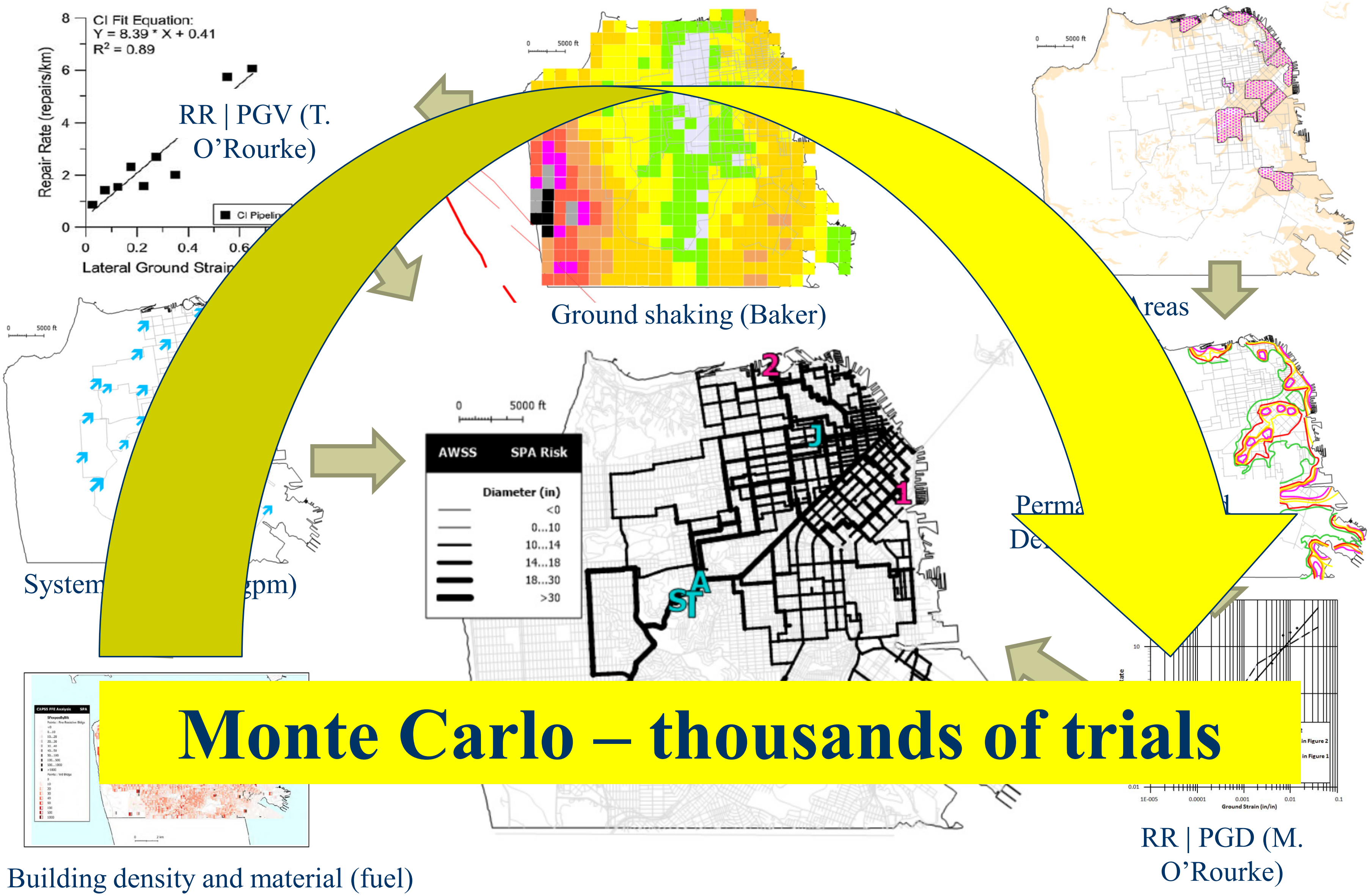
(general, not seismic, demand driven, cannot account for negative pressures …)

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. <u>The pipe with highest *ADC* is the pipe that contributes most to the demand's deficit</u>, 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*

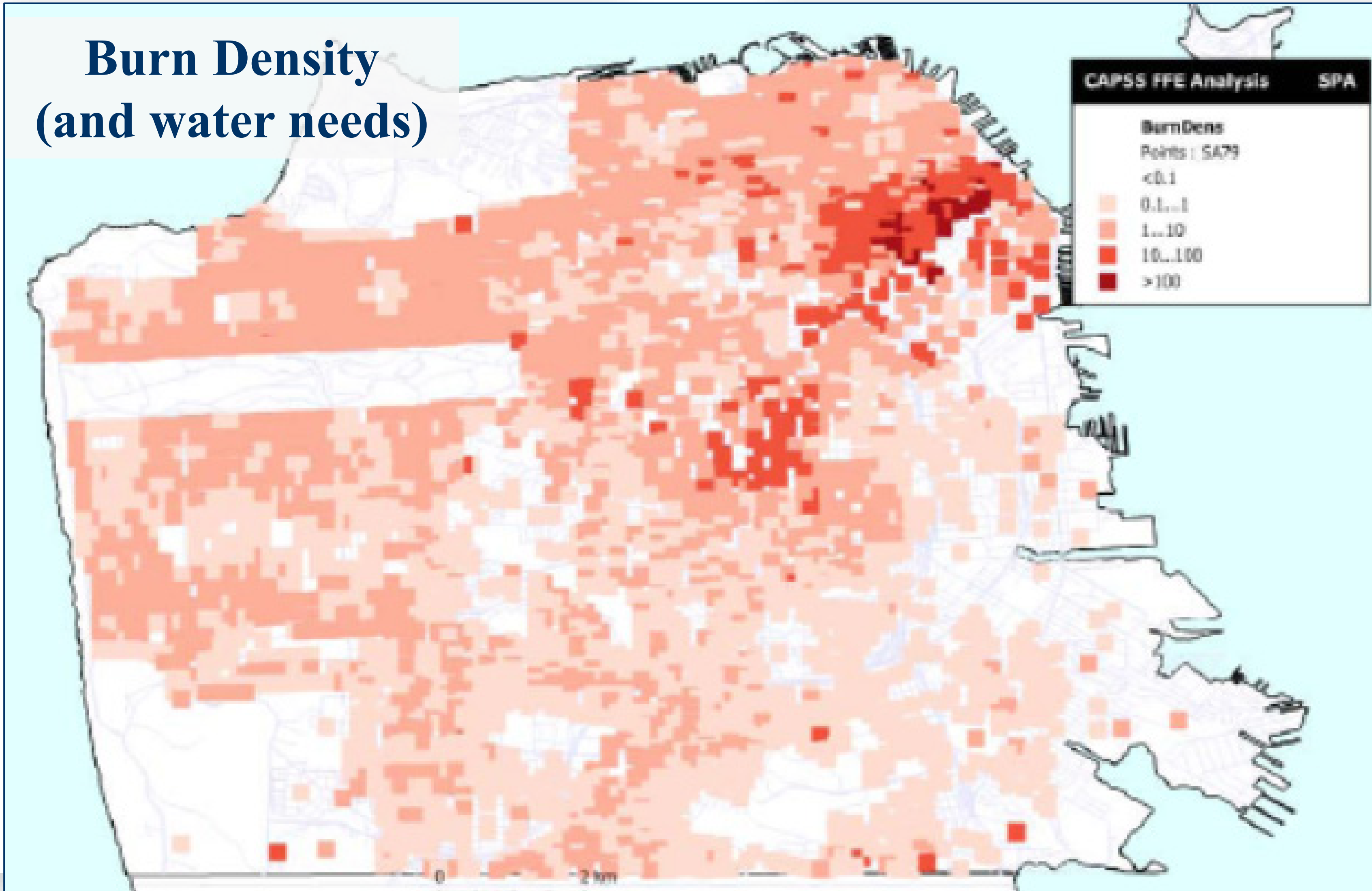
Steps in the analysis



Monte Carlo – thousands of trials

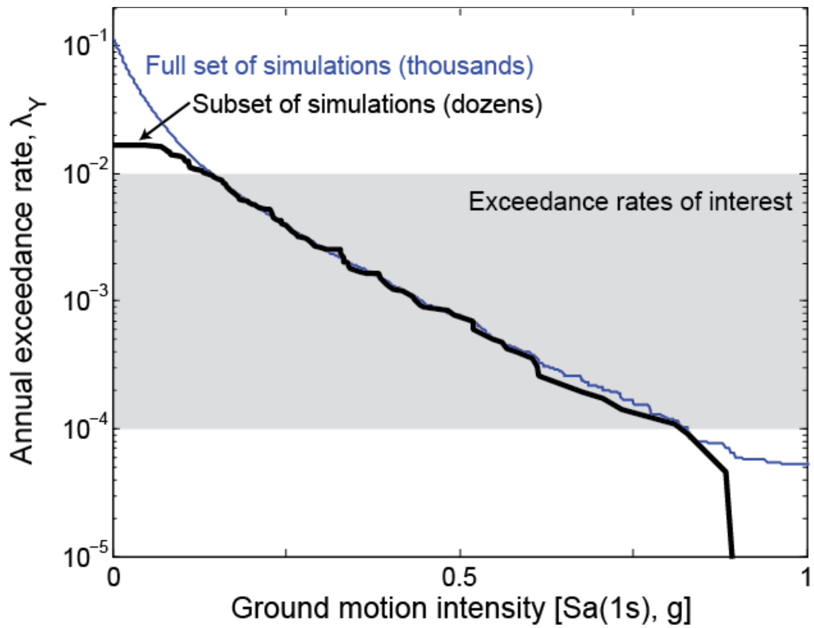
Application to AWSS – fire following earthquake demands

Burn Density (and water needs)

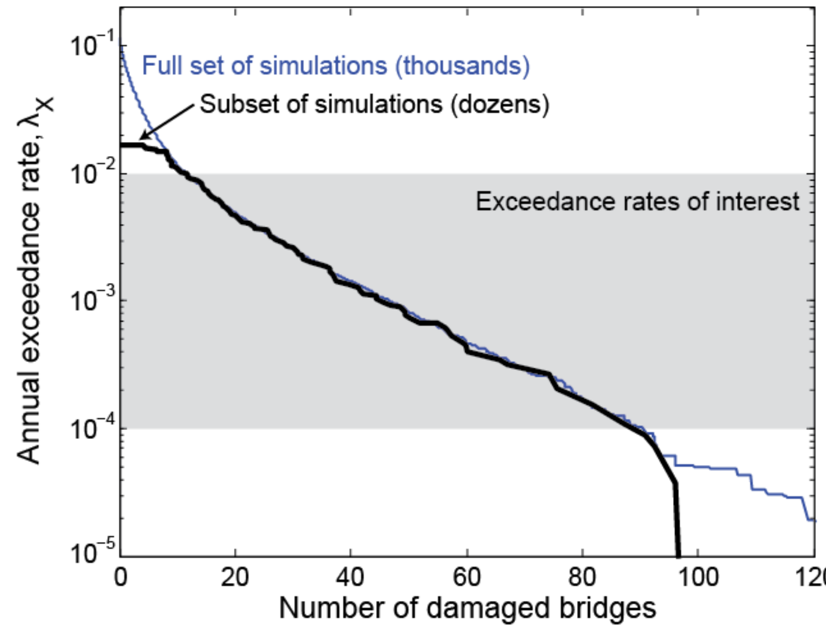


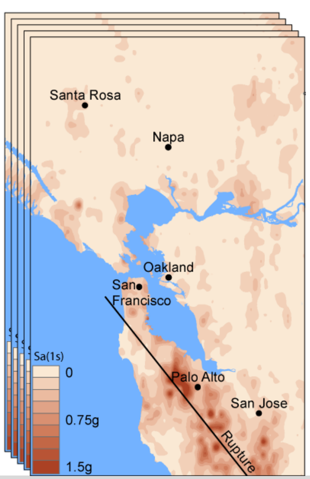
Ground motions considering uncertainty

Ground motion hazard at a site



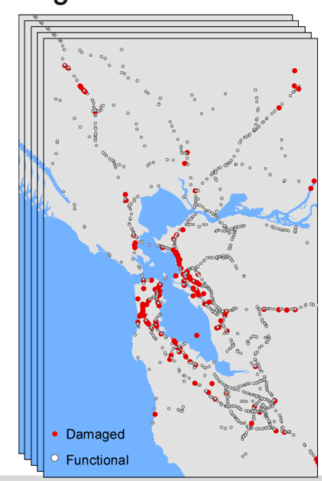
Proxy performance metric hazard





Select a subset of maps and reweight, to reproduce ground motion hazard at multiple sights and a proxy performance metric

Miller and Baker (2015). "Ground-motion intensity and damage map selection for probabilistic infrastructure network risk assessment using optimization." *EQ Engineering & Structural Dynamics*, 44(7), 1139–1156.

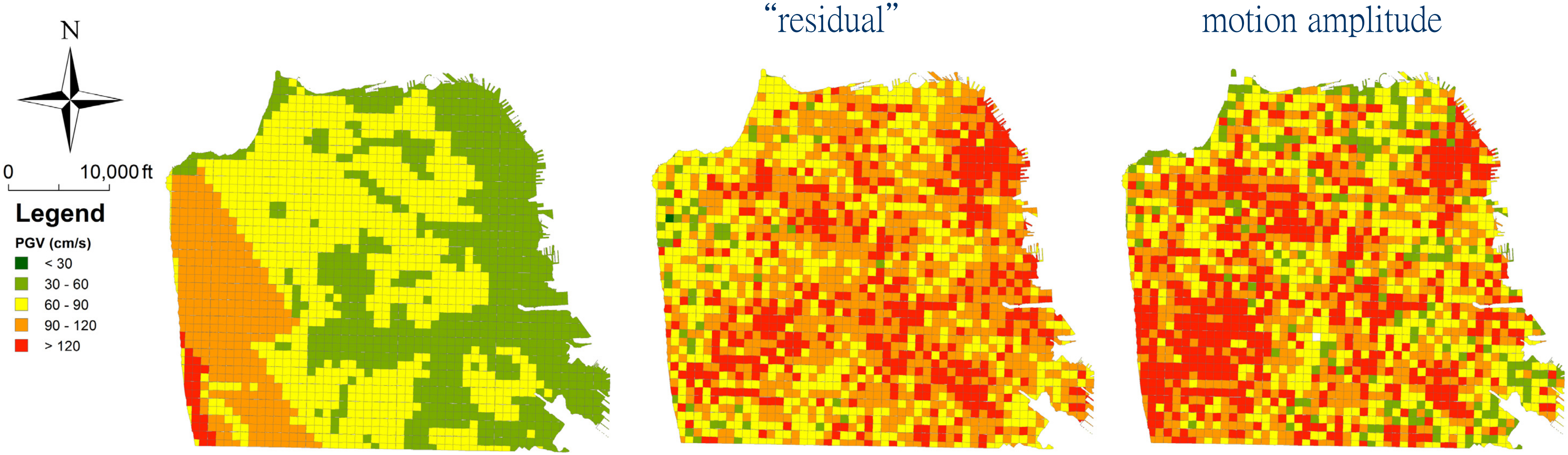


Stanford ground motion simulation approach

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

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

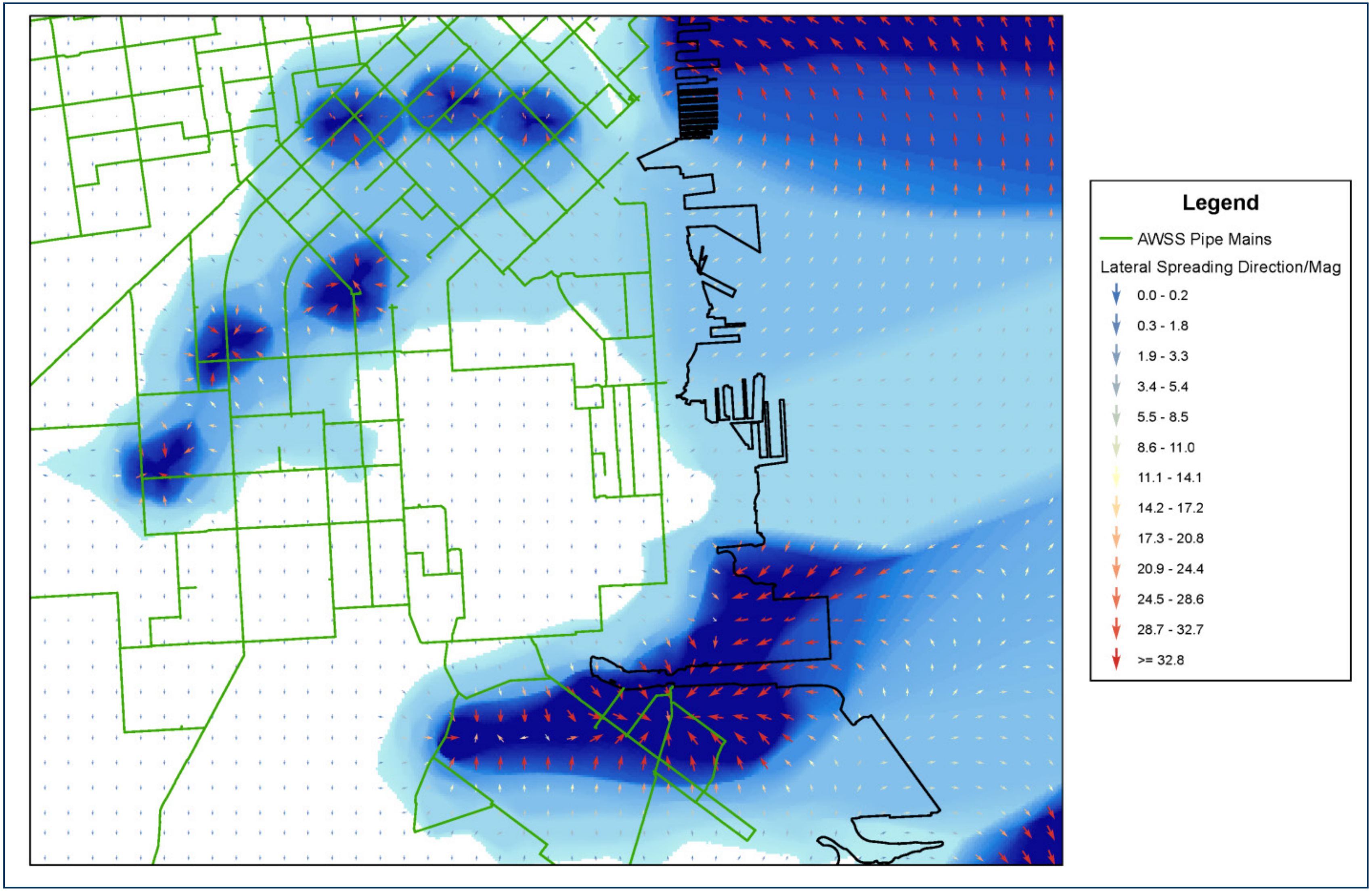
Median prediction + Spatially correlated "residual" = Total ground motion amplitude



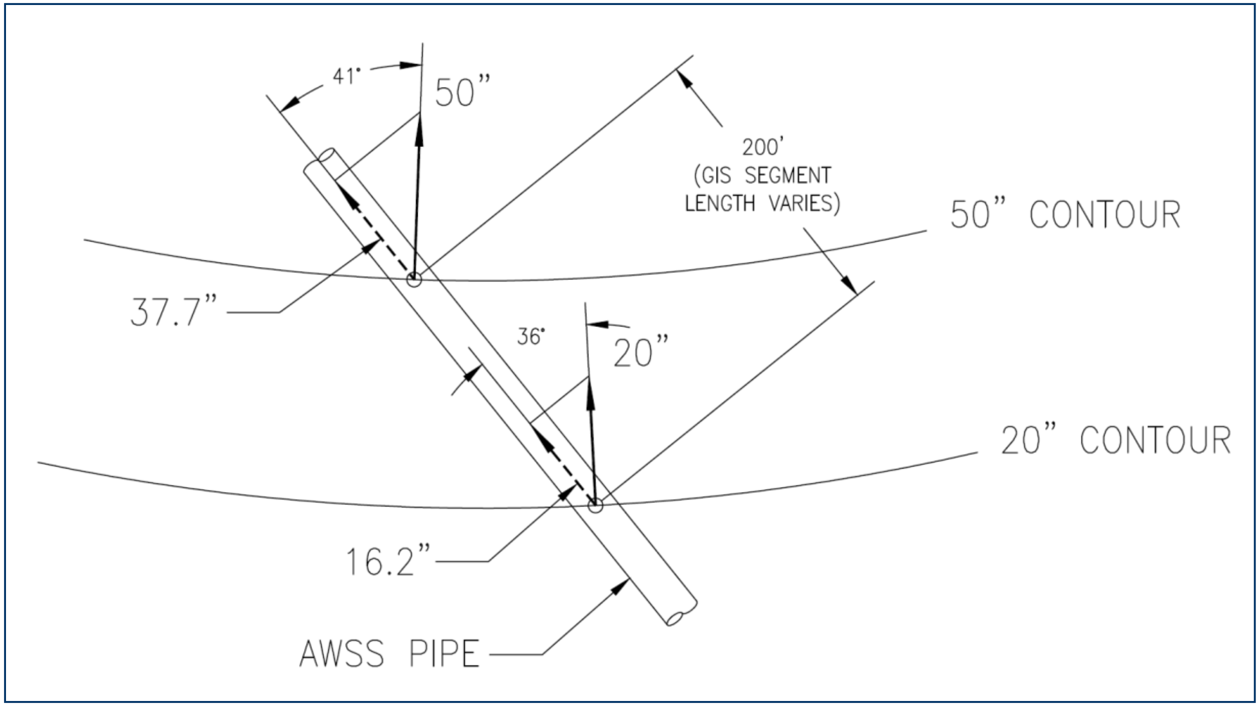
Residuals are empirically calibrated from past earthquakes and account for ground motion variability

Miller and Baker (2015). "Ground-motion intensity and damage map selection for probabilistic infrastructure network risk assessment using optimization." *EQ Engineering & Structural Dynamics*, 44(7), 1139–1156.

Permanent Ground Deformation

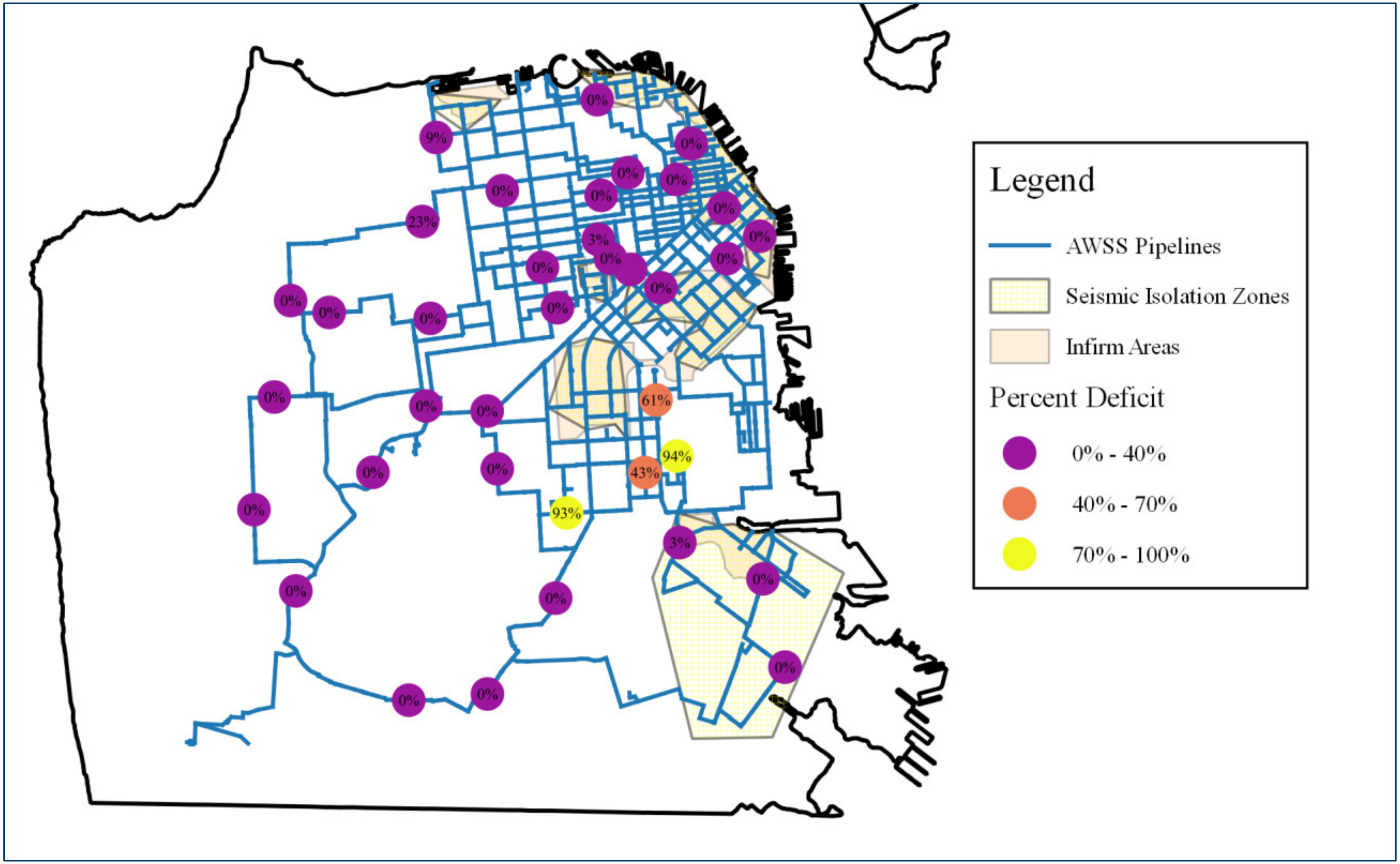


Permanent Ground Deformation



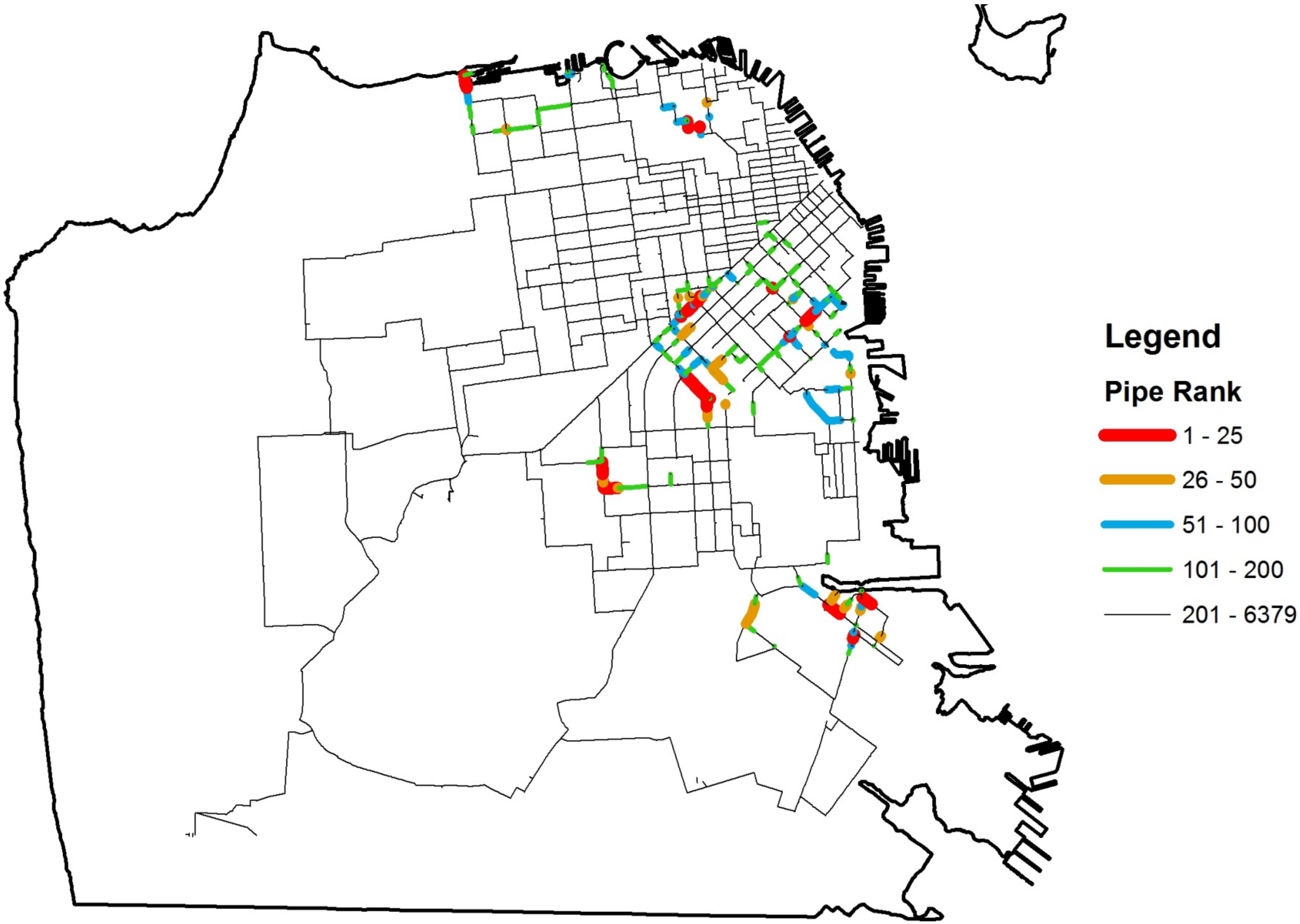
Mechanistic fragility curve – M. O' Rourke
Ground strain to repair rate calculation

Damaged Network Performance

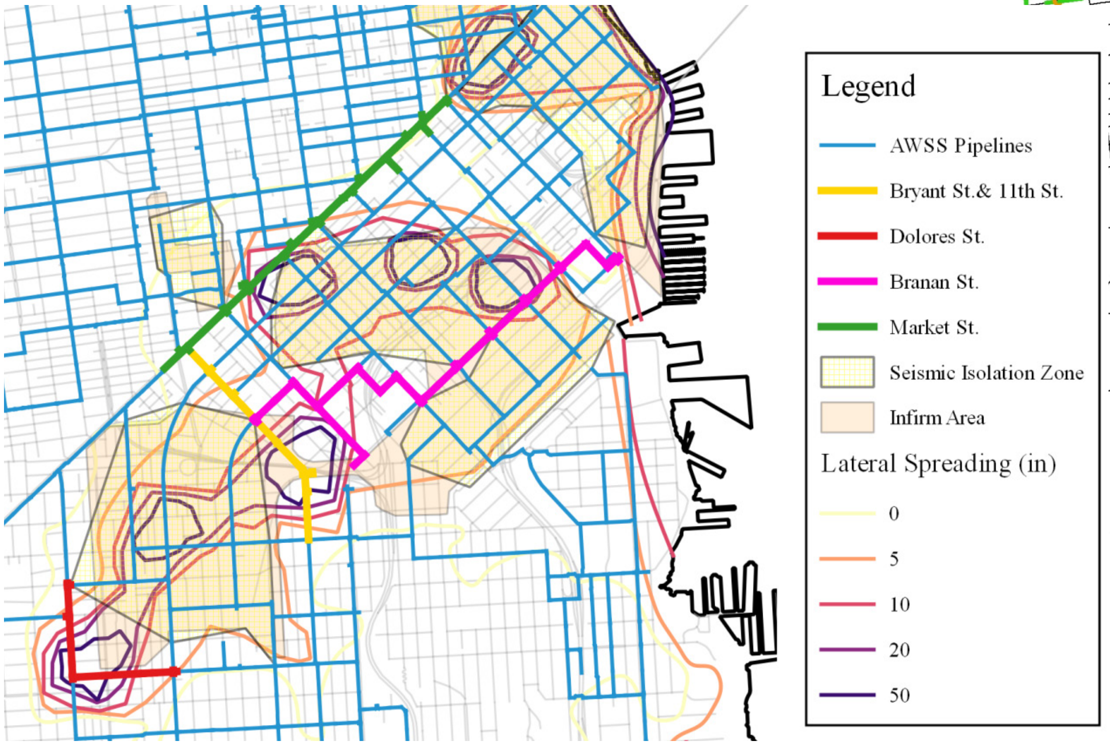


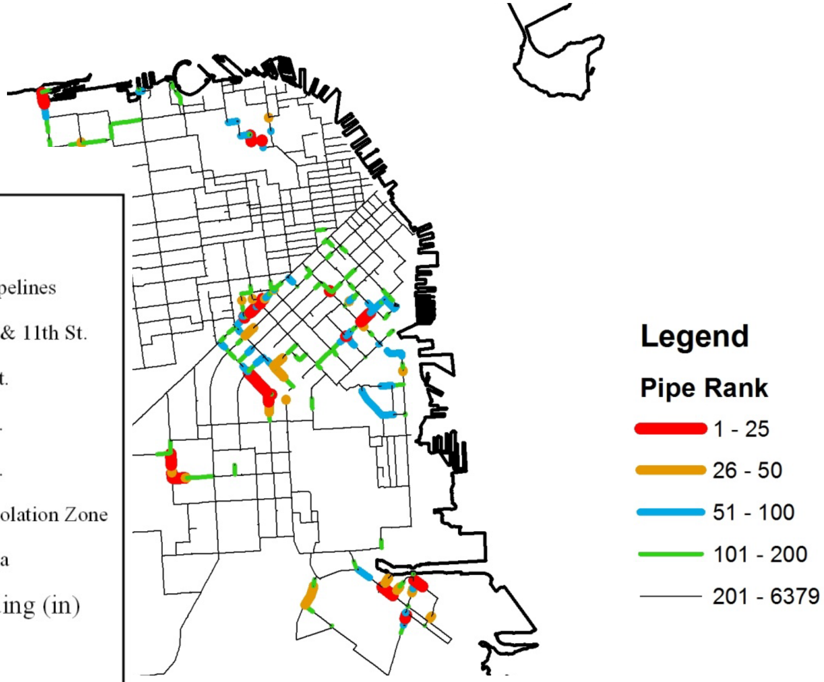
Post Earthquake Base Case

System Analysis – Pipe Importance by ADC



System Analysis – Pipe Importance by ADC

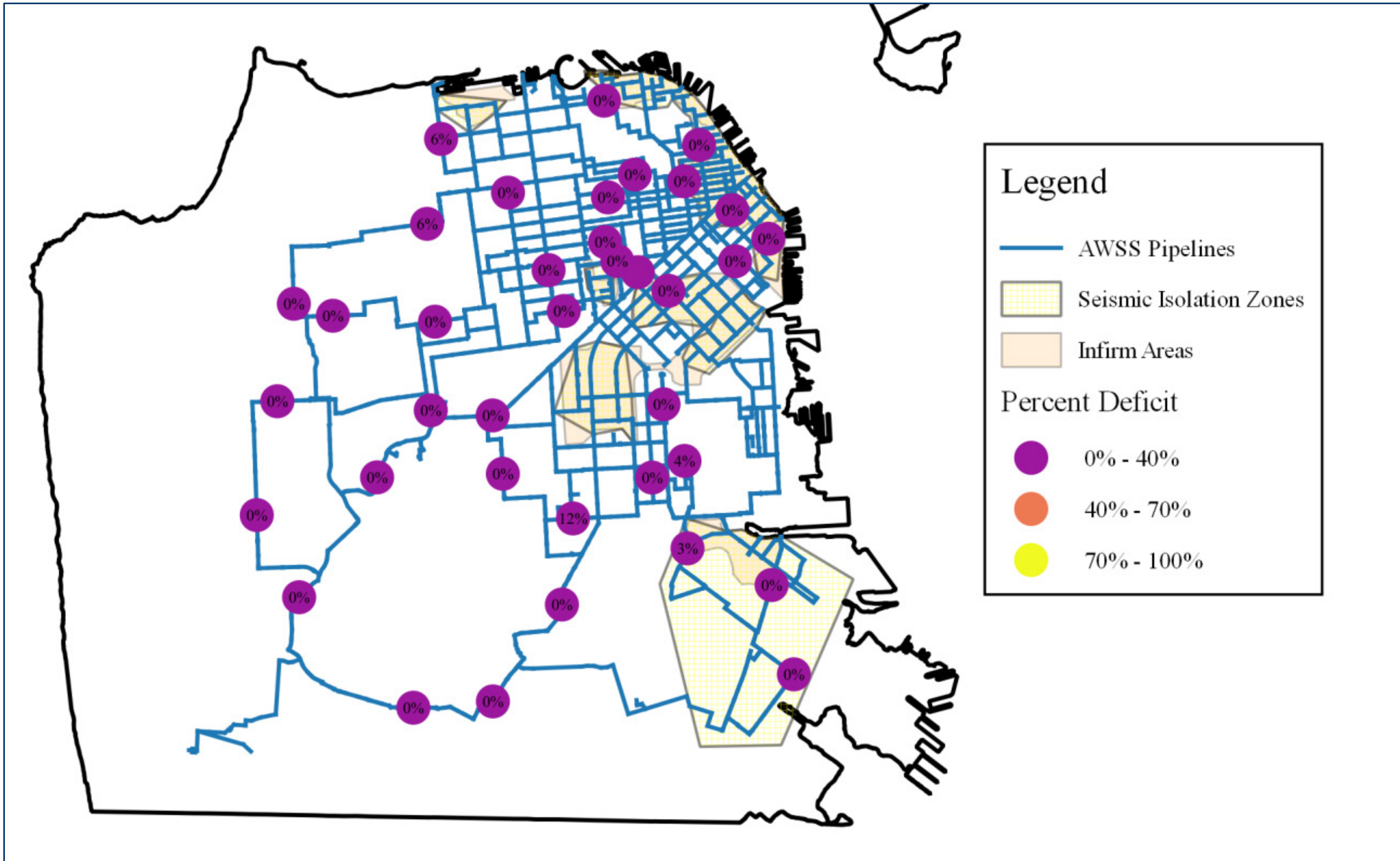




System Analysis – Results

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

System Analysis – Pipe Importance by ADC



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

cscawthorn@sparisk.com