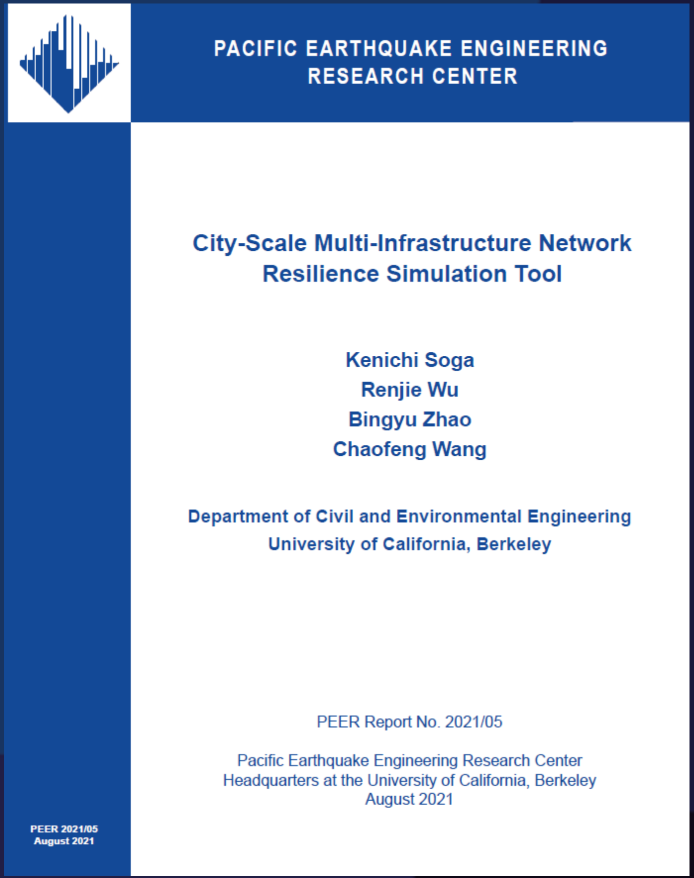
Evaluation of water distribution systems

Berkeley
CENTER FOR
Smart Infrastructure

Kenichi Soga


PACIFIC EARTHQUAKE ENGINEERING
RESEARCH CENTER

City-Scale Multi-Infrastructure Network Resilience Simulation Tool

Kenichi Soga
Renjie Wu
Bingyu Zhao
Chaofeng Wang

Department of Civil and Environmental Engineering
University of California, Berkeley

PEER Report No. 2021/05

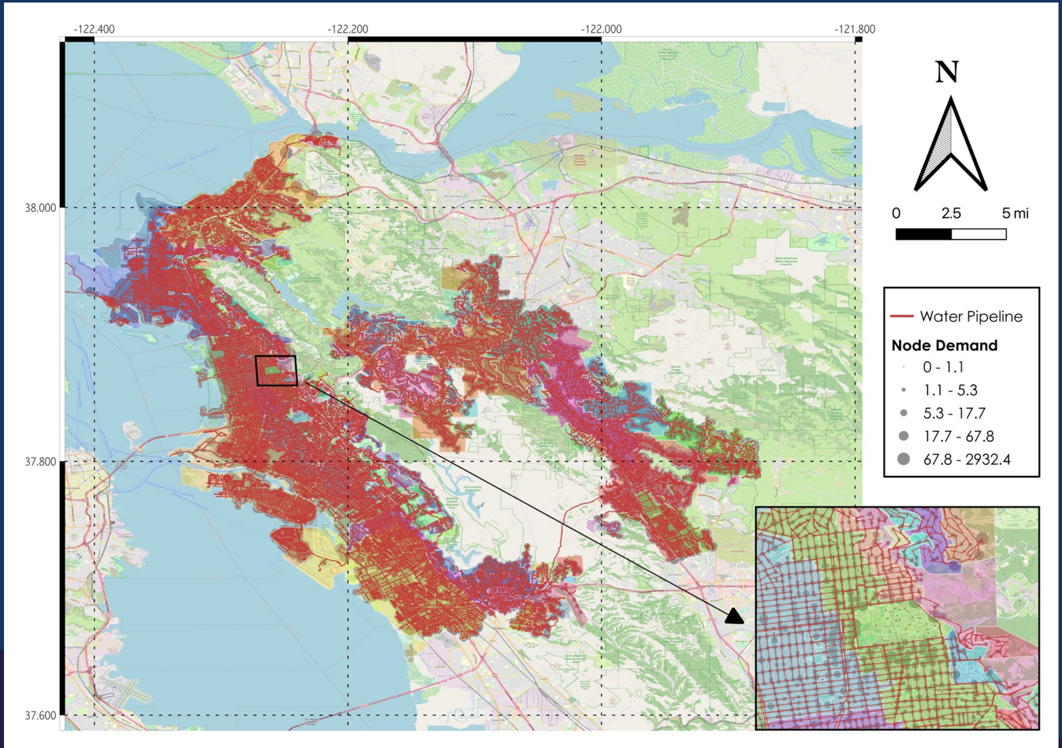
Pacific Earthquake Engineering Research Center
Headquarters at the University of California, Berkeley
August 2021

PEER 2021/05
August 2021

Berkeley
UNIVERSITY OF CALIFORNIA

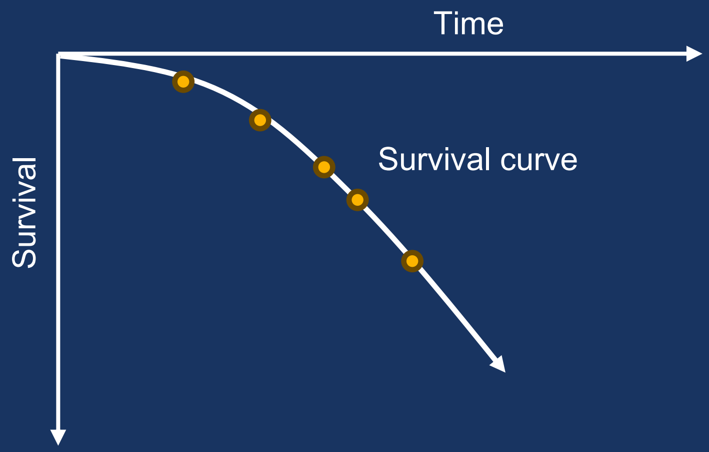
Infrastructure Owners and Agencies

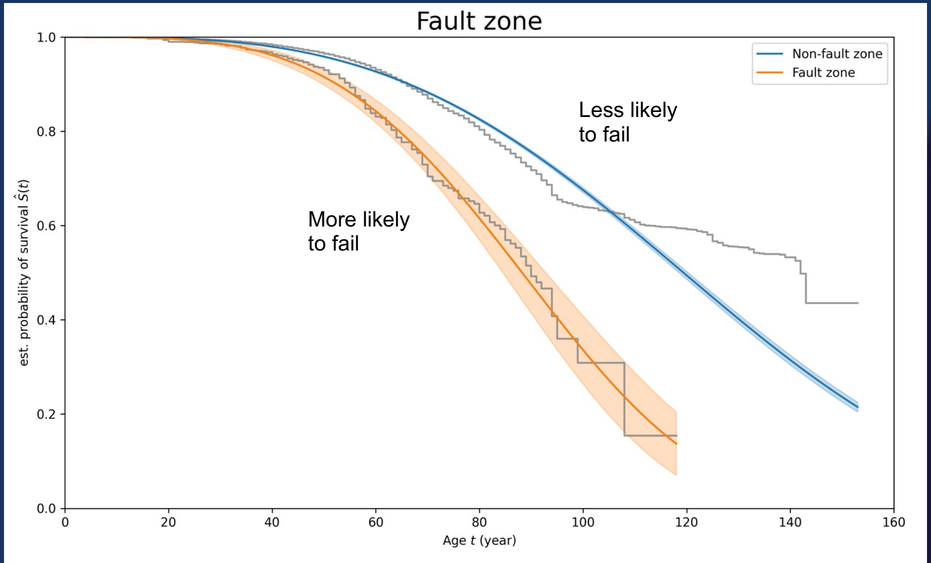
Hazard Resiliency

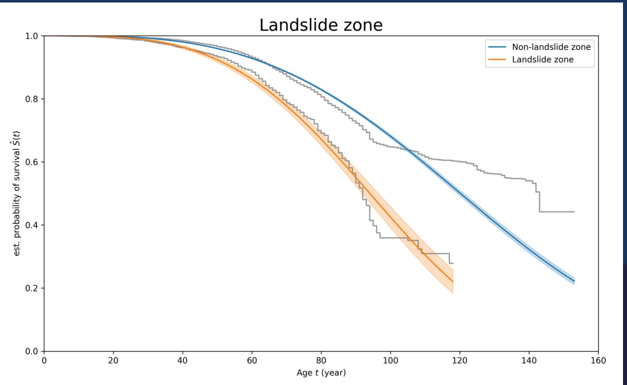


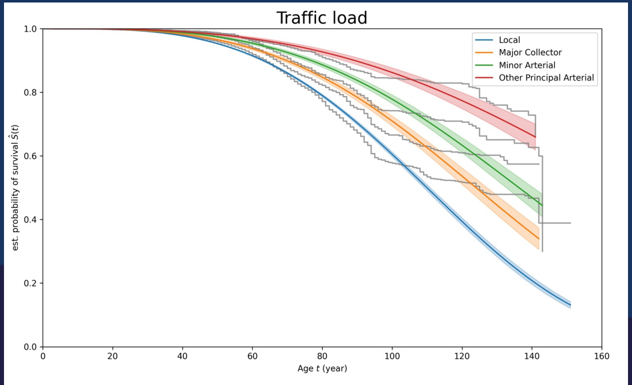
4,200 miles of pipeline
The oldest – 1877
Rebuilding every 20-25 miles/year

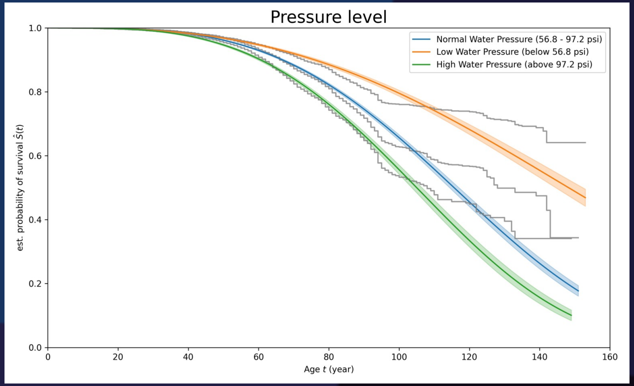
Berkeley
UNIVERSITY OF CALIFORNIA







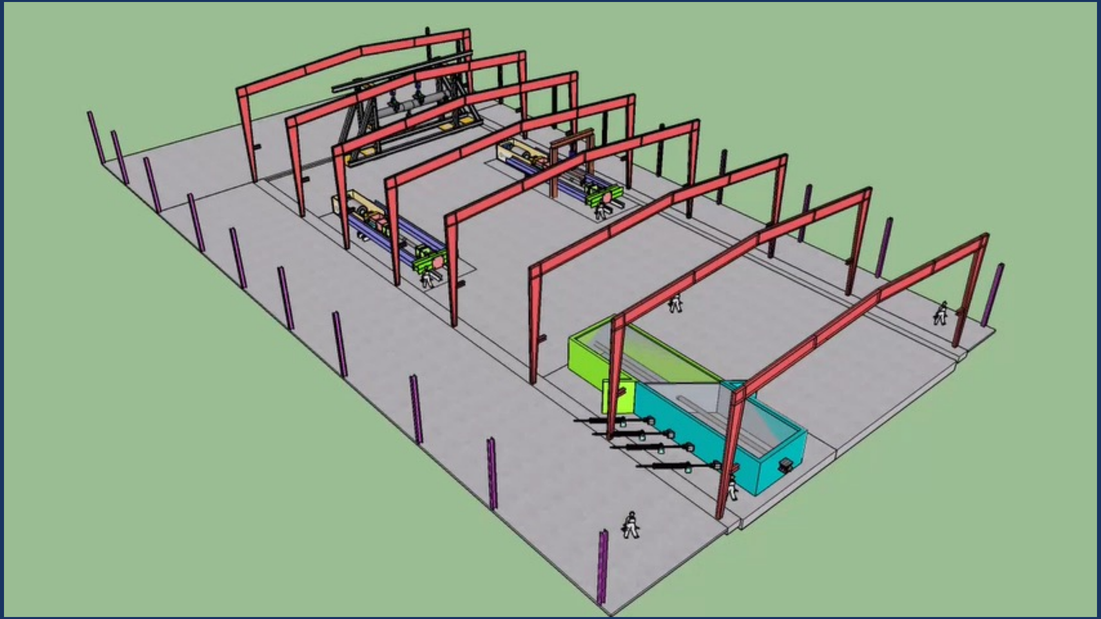




Berkeley UNIVERSITY OF CALIFORNIA

EFPIA.eu

Pipeline Testing

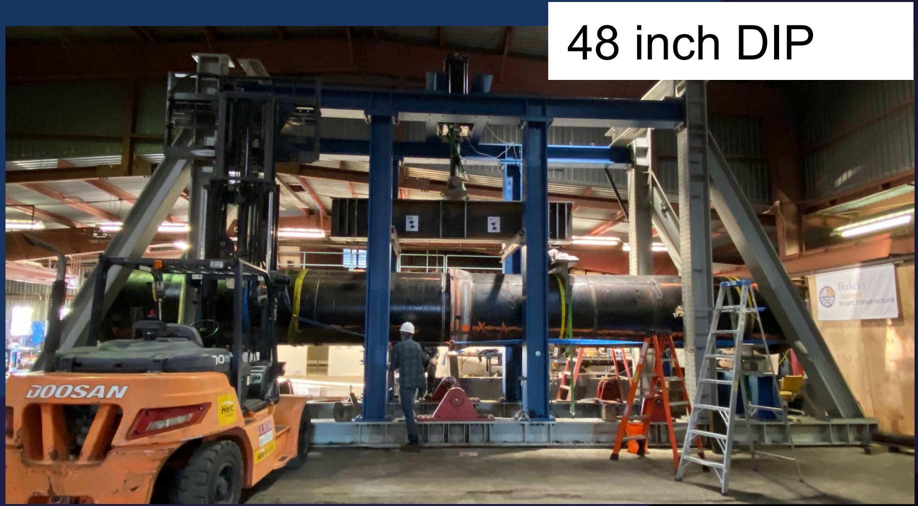


Berkeley
UNIVERSITY OF CALIFORNIA


8 inch ERDIP


8 inch iPVC


24 inch ERDIP



48 inch DIP

https://smartinfrastructure.berkeley.edu/

smartinfrastructure.berkeley.edu/research/publications/

Berkeley
CENTER FOR
Smart Infrastructure

Home | About Us | Research | Large-Scale Testing Facilities | Reports | Education | News | Contact Us

Reports

Water Infrastructure

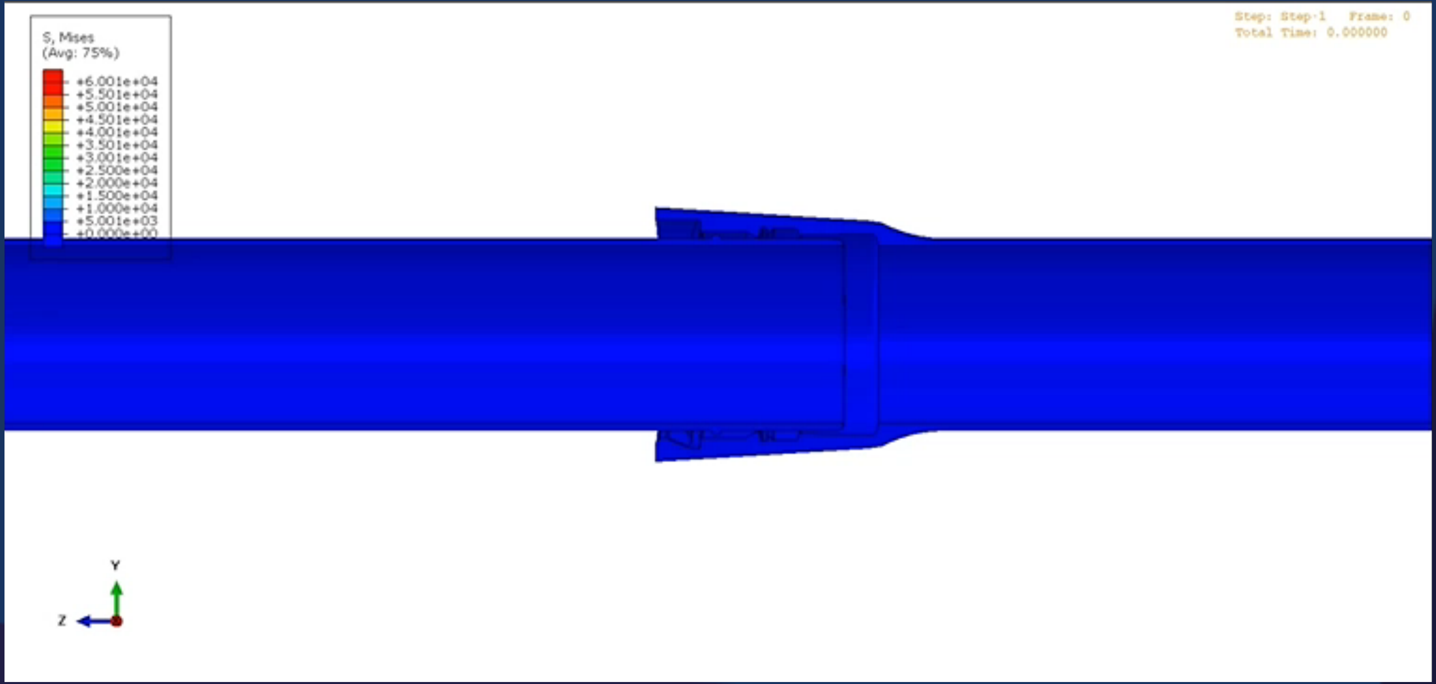
Shakhzod Takhirov, Tianyu Han, Qinglai Zhang, Kenichi Soga (2023): Comparative Shear Testing and Finite Element Analysis of PowerSeal Saddle for Service Line Installations. Center for Smart Infrastructure, University of California, Berkeley. Report. https://doi.org/10.25350/B5D59D

Download

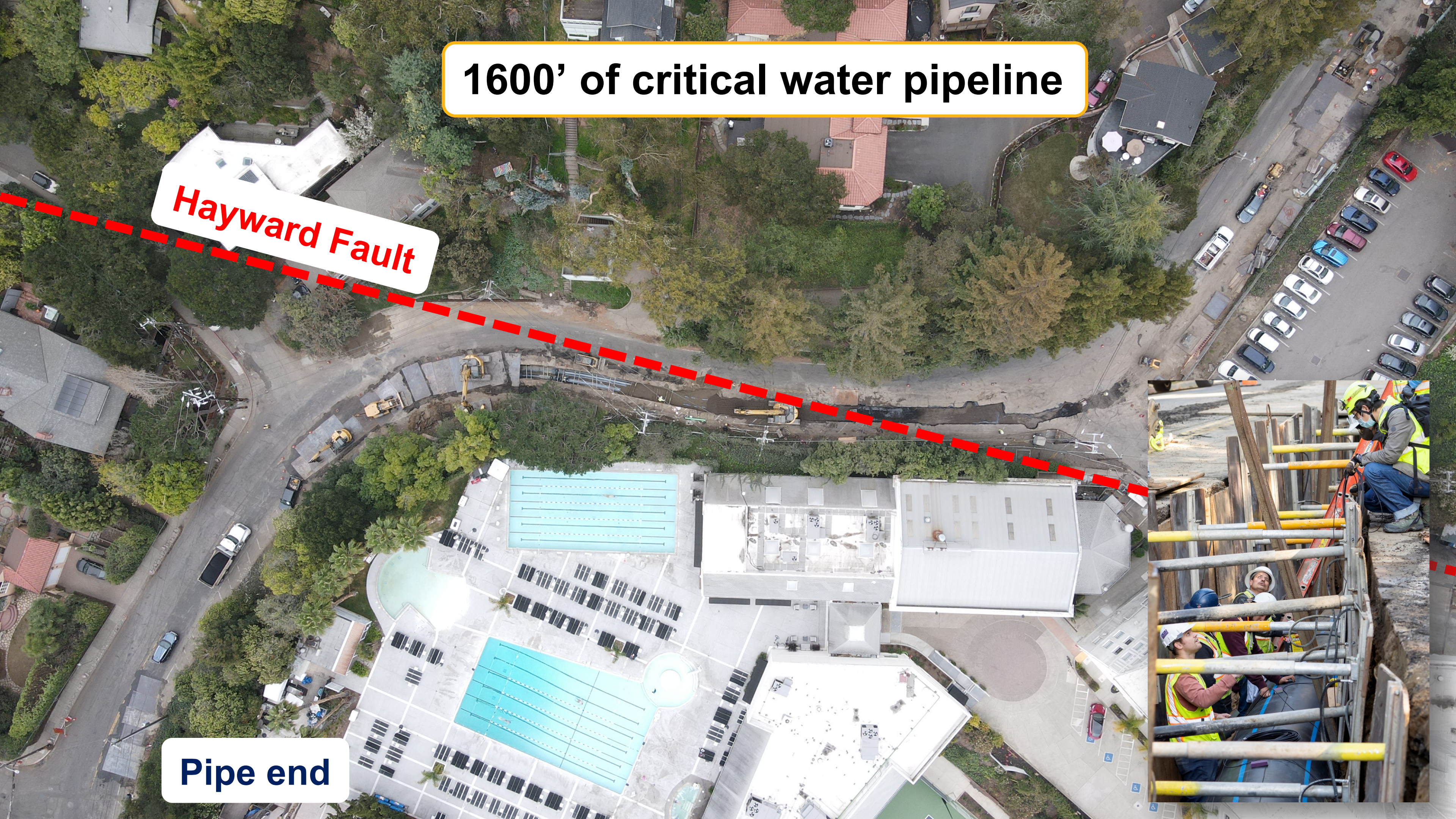
Shih-Hung Chiu, Qinglai Zhang, Shakhzod Takhirov, Kenichi Soga (2023): Direct Tension Testing of 8-in. (200-mm) Diameter TR-XTREME Ductile Iron Pipe. Center for Smart Infrastructure, University of California, Berkeley. Report. https://doi.org/10.25350/B58G64

Berkeley
UNIVERSITY OF CALIFORNIA

Biaxial Tension Test



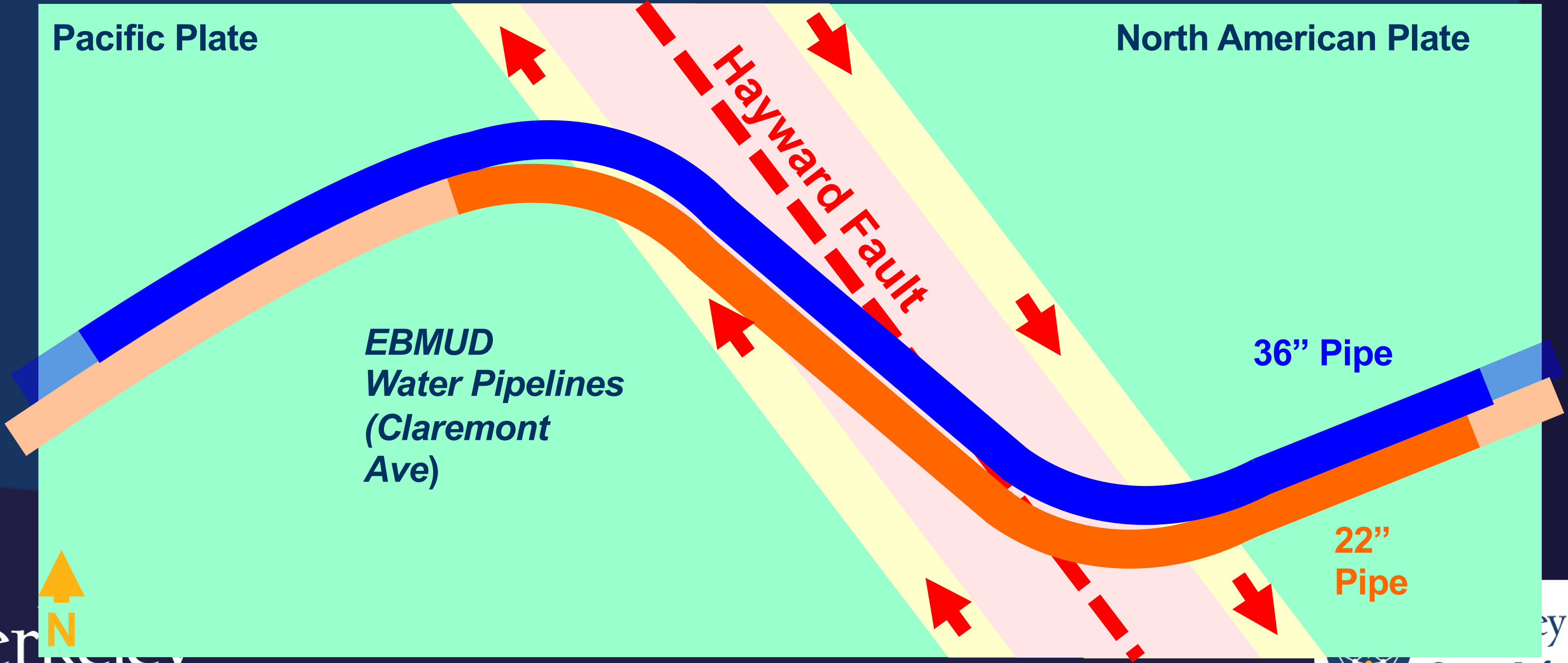
Berkeley
UNIVERSITY OF CALIFORNIA


1600’ of critical water pipeline
Hayward Fault
Pipe end

Relevance - *EBMUD*

Lifeline water pipelines provide the water for Berkeley and Oakland

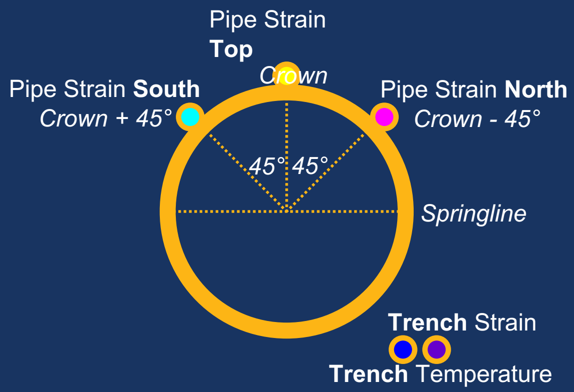
High Risk of Fault Rupture at Hayward Fault crossing (5 mm annual displacement)

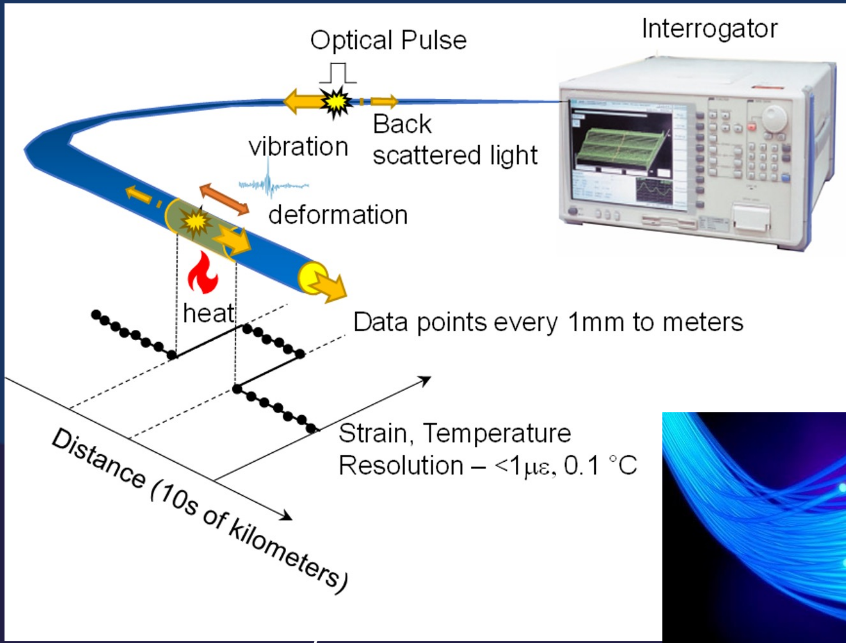


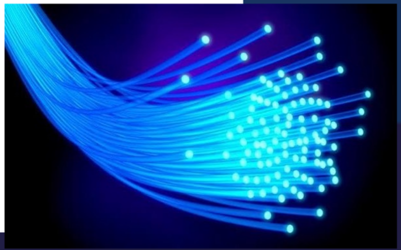
Distributed fiber optic sensing

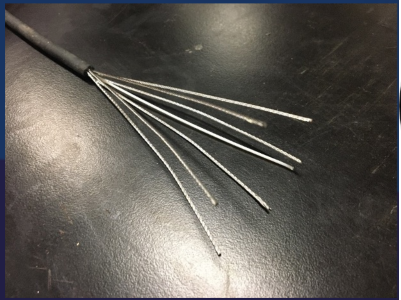
“Continuous Strain/temperature/vibration Profile” along the fibre optic cable

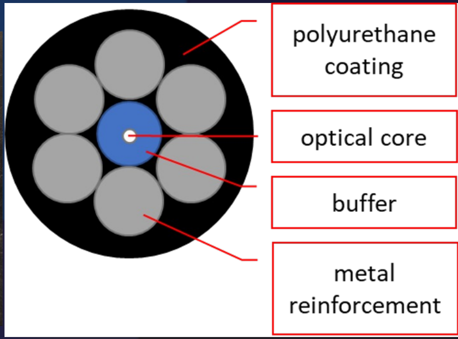
- Distributed Temperature Sensing (DTS)
- Distributed Strain Sensing (DSS)
- Distributed Acoustic/Vibration Sensing (DAS/DVS)

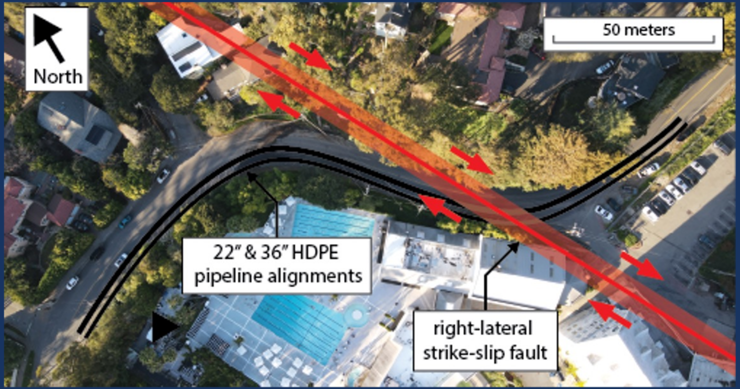


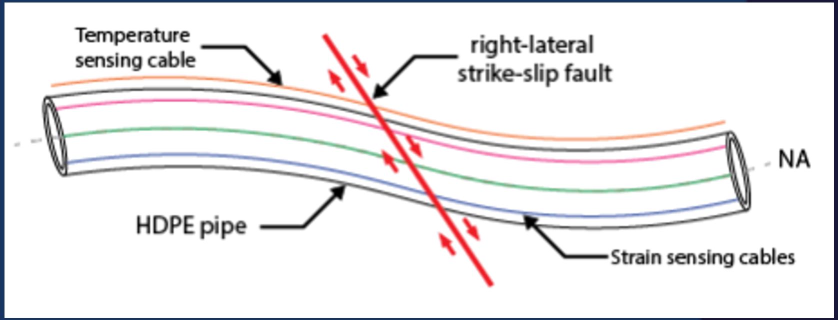


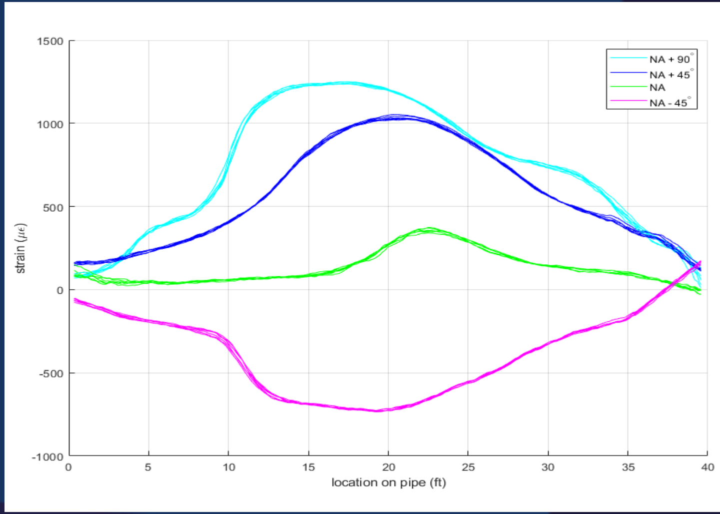








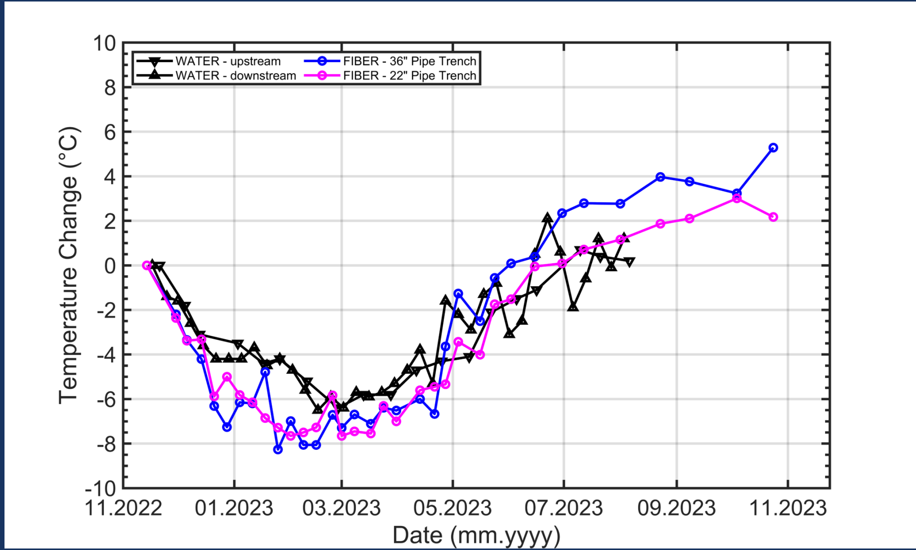




Berkeley
UNIVERSITY OF CALIFORNIA

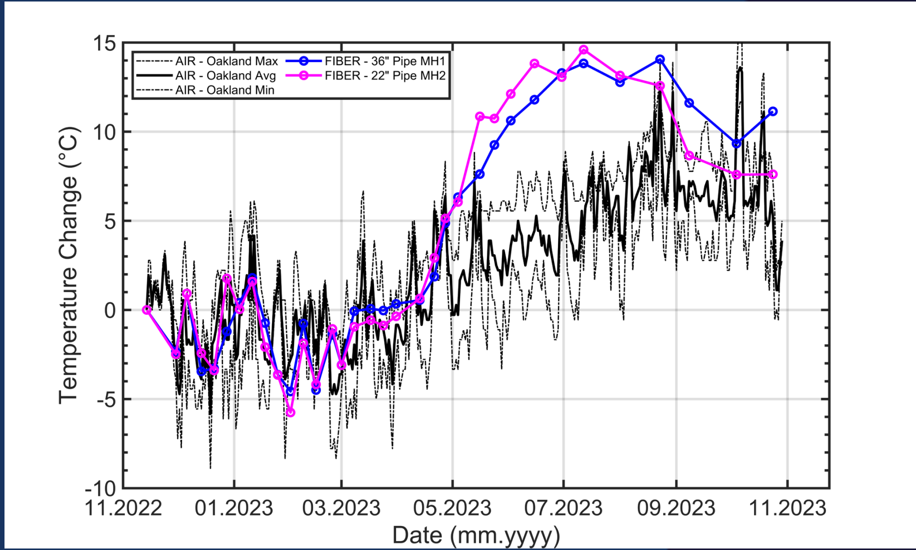
Berkeley
CENTER FOR
Smart Infrastructure

Pipeline Temperature



Seasonal water temperature trends reasonably captured by fiber temperature measurement along pipeline. Trench fiber temperature representative of groundwater temperature?

Manhole Temperature

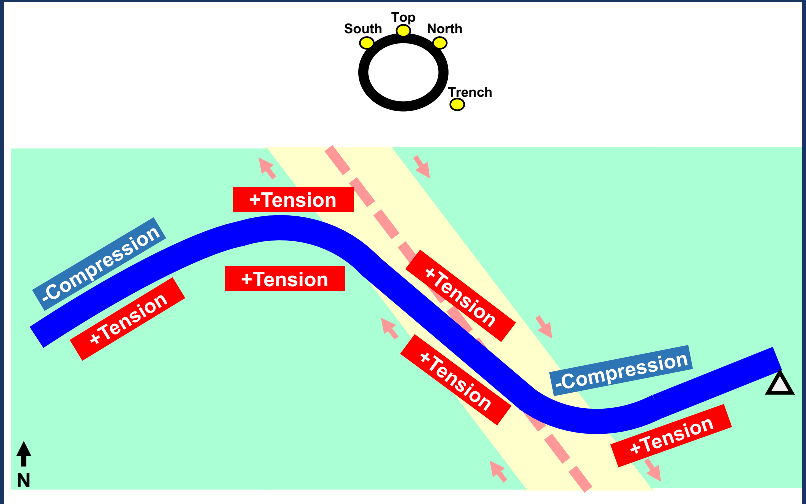


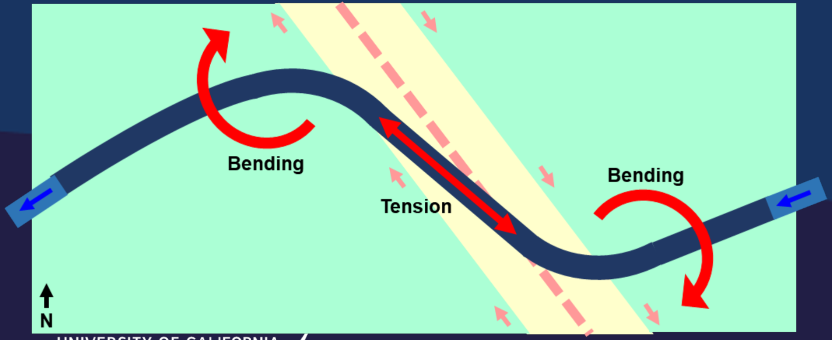
Seasonal air temperature trends reasonably captured by fiber temperature measurement near downhill manholes.

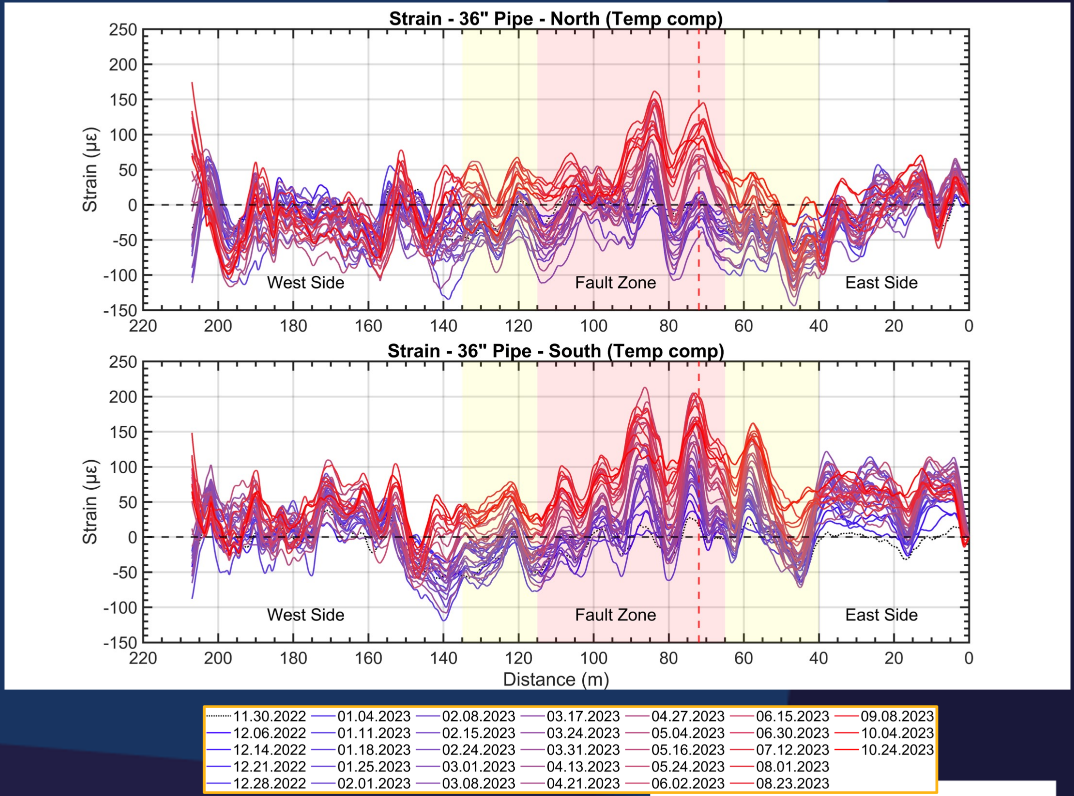
Berkeley
UNIVERSITY OF CALIFORNIA

Berkeley
CENTER FOR
Smart Infrastructure

Pipe Strain (36” Pipe) (East Fixed)







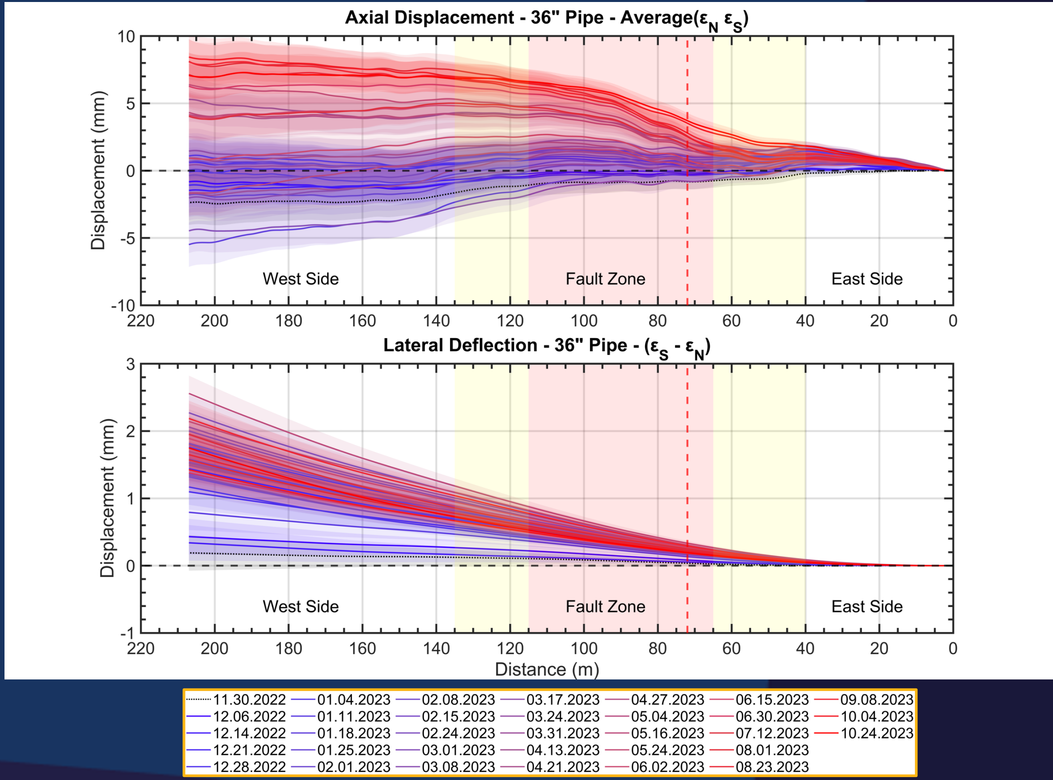
Berkeley
CENTER FOR
Smart Infrastructure

Pipeline Deformation (36” Pipe) (East Fixed)

1. Composite deformation mechanism:
   - Axial extension inside fault zone
   - Lateral deflection across fault zone

Axial Extension (mm)	Lateral Deflection (mm)
7 - 10	2 - 3

2. Further monitoring needed to differentiate contribution of annual fault displacement from environmental effects

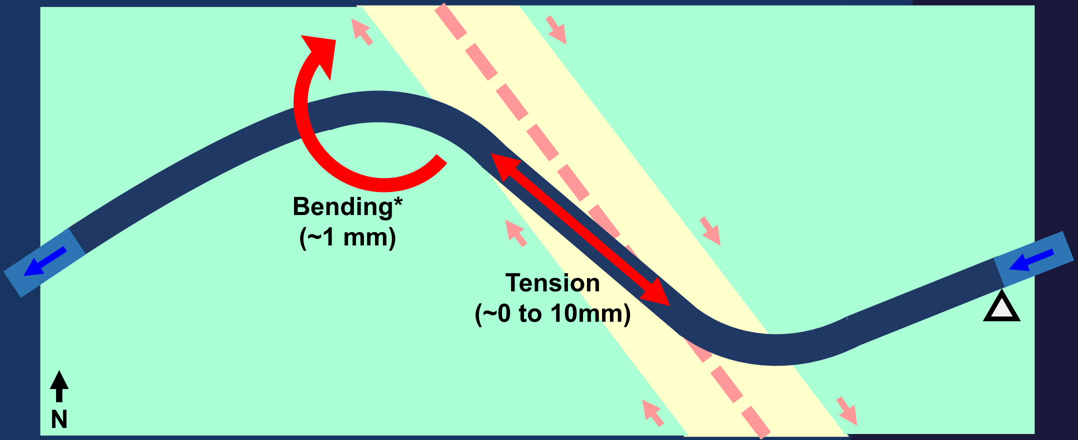


Berkeley
UNIVERSITY OF CALIFORNIA

Berkeley
CENTER FOR
Smart Infrastructure

Est. Pipe Deformation - Conclusions

1. Combo deformation mechanism:
   - axial extension (along fault)
   - northward bending (across fault)
   - assuming east end fixed
2. Further monitoring needed to distinguish fault movement-related strain from other factors



Bending* for simplified lateral bending calculation assuming east end fixed, west end free.

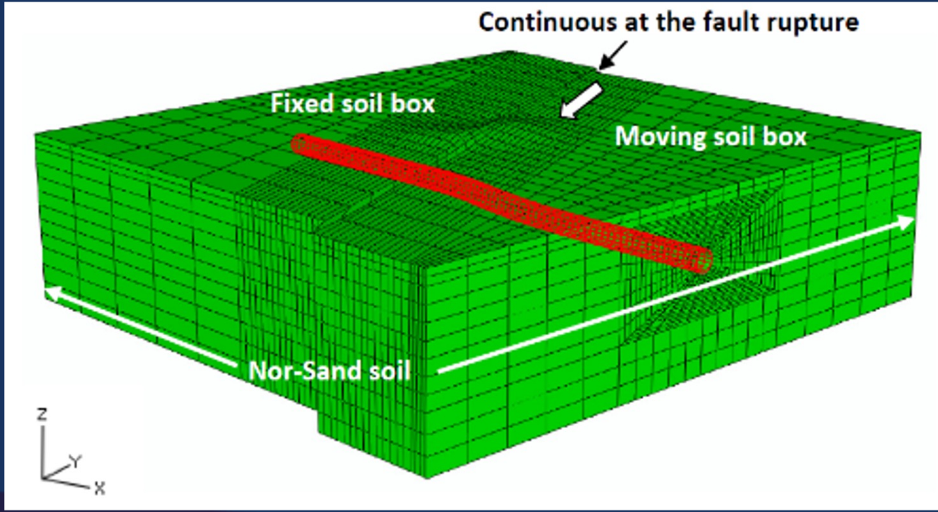
Monitoring of PG&E gas pipeline in Gilroy using distributed fiber optic sensing

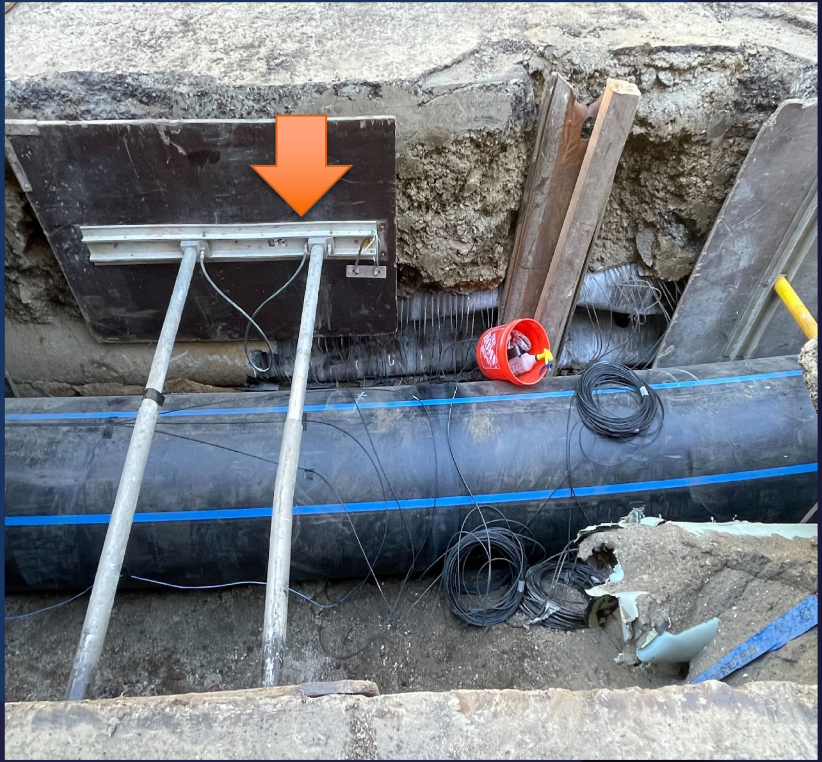
Berkeley
UNIVERSITY OF CALIFORNIA

Berkeley
CENTER FOR
Smart Infrastructure

Design…

Reality…

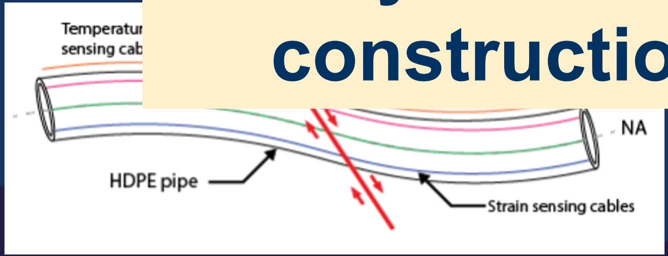


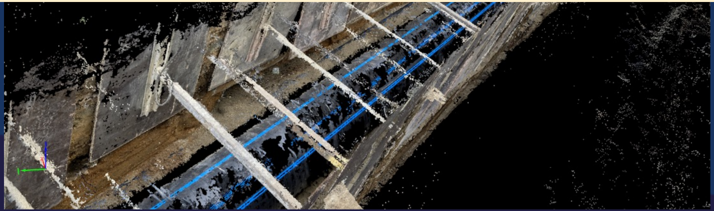


Berkeley
UNIVERSITY OF CALIFORNIA

Once we bury a pipeline, we are not going to see it for at least next 100 years.

Why not embed "intelligence" during construction for future generations?





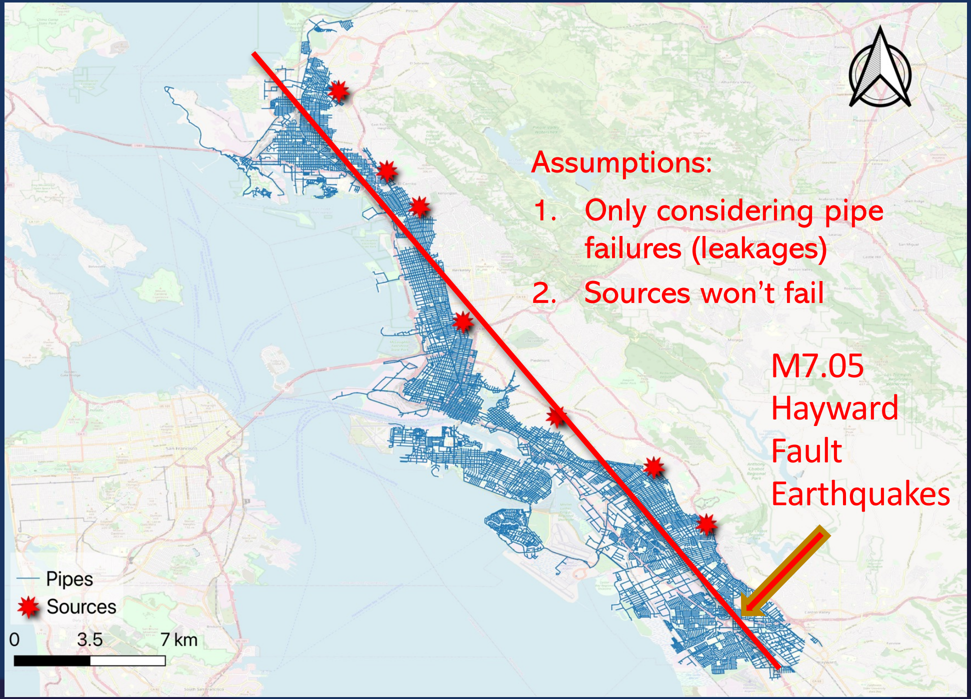
Berkeley
UNIVERSITY OF CALIFORNIA

Post-earthquake WDN hydraulics analysis

Number of pipes: 65700
7223217 ft (2201km)

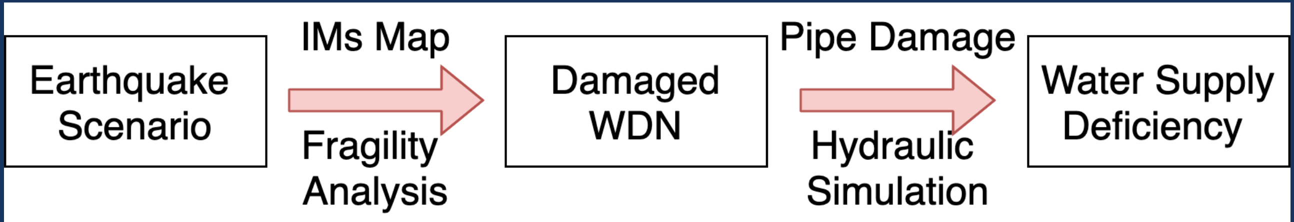
Total demand: 48610 GPM (around 40% of EBMUD demand)

Sources: 7 control stations located at the boundary of the service zone with fixed head 150ft



Berkeley
UNIVERSITY OF CALIFORNIA

Modeling approach



Use Probabilistic Seismic Hazard Analysis (PSHA) to model earthquake ground motion (epicenter uncertainties) [1].

Generate 100 earthquake scenario realizations (spatial correlated PGVs).

Map PGV values to pipes and use fragility curves to create pipe failure probability maps

Generate 100 pipe failure probability maps

Sample pipes to fail according to the pipe failure probability map

Estimate failure degree (leak hole diameter)

Monte Carlo hydraulic simulation (500 cases per scenario)

100 x 500 = 50,000 simulations

50,000 x 5 seconds = 3 days

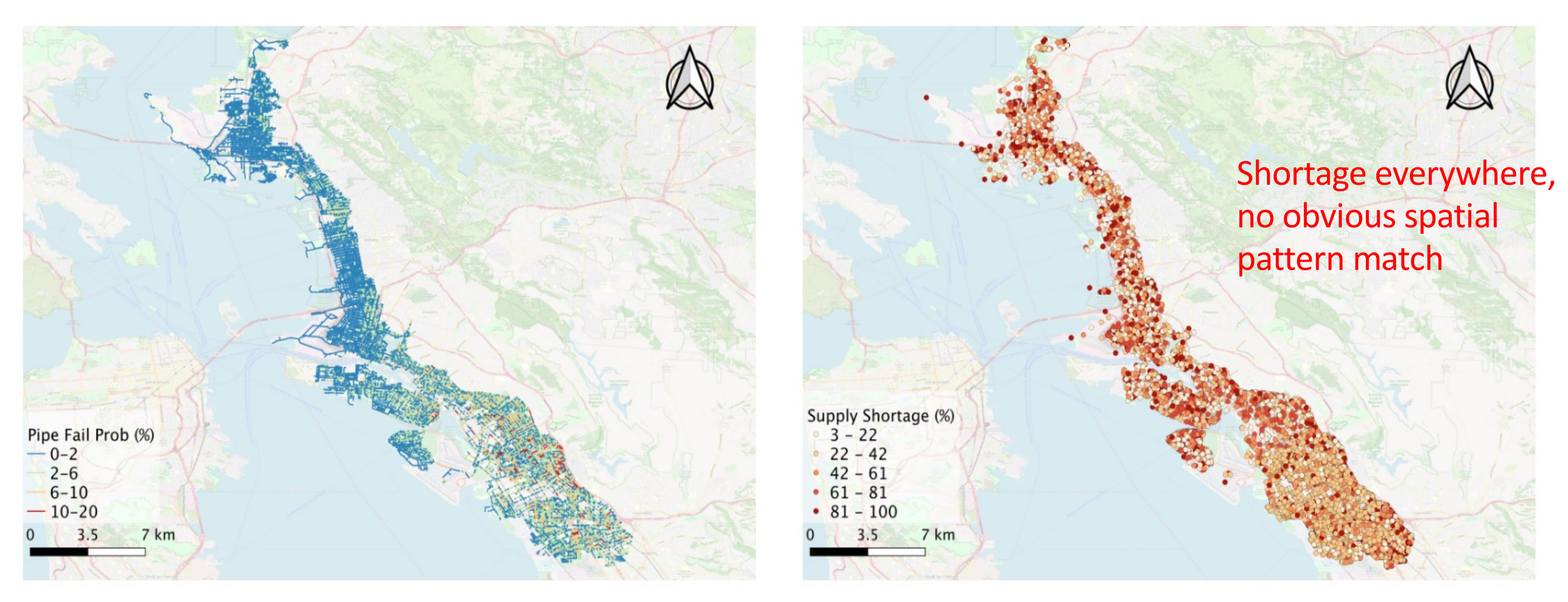
Berkeley
UNIVERSITY OF CALIFORNIA

[1] Jayaram, N. and Baker, J.W., 2009. Correlation model for spatially distributed ground-motion intensities. *Earthquake Engineering & Structural Dynamics*, *38*(15), pp.1687-1708.

Simulation results

$$S_{tot} = \frac{(demand_{tot} - supply_{tot})}{demand_{tot}} * 100$$

Water Shortage (%)



(a) Pipe fail probability (b) Demand Shortage

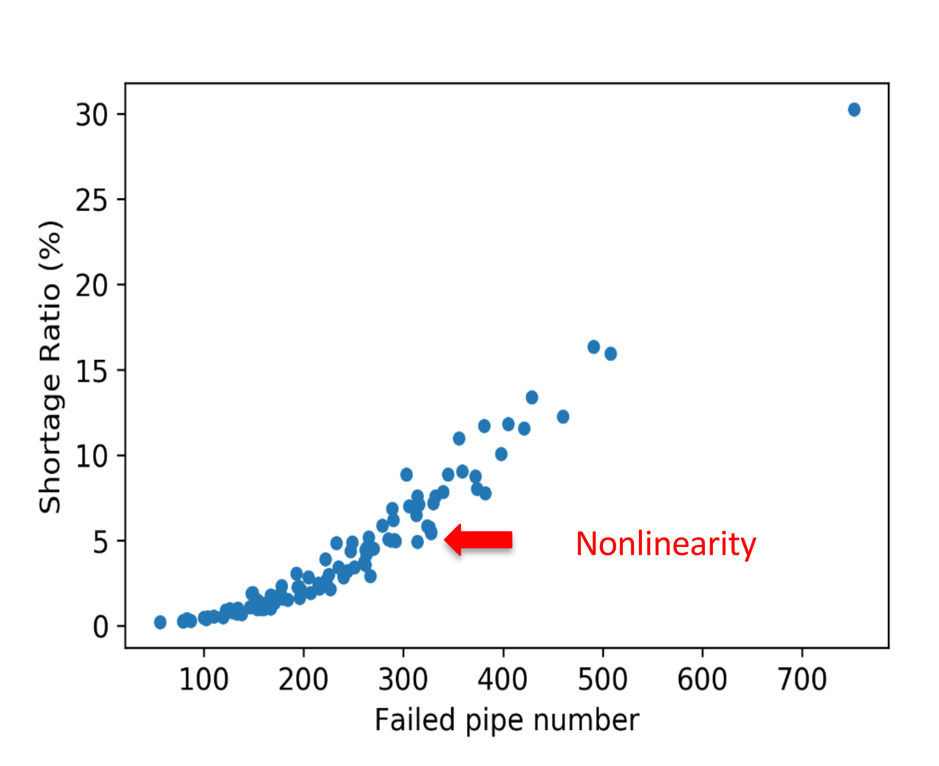
Large damage case: mean PGV value 16.87 cm/s and averaged simulated pipe break number 752

Berkeley UNIVERSITY OF CALIFORNIA

- Even under the same fault rupture event, the variance of earthquake impacts on a WDN is high (1-30 % water loss; 5-70% users impacted)

- The variance is due to the uncertainty of earthquake epicenter locations

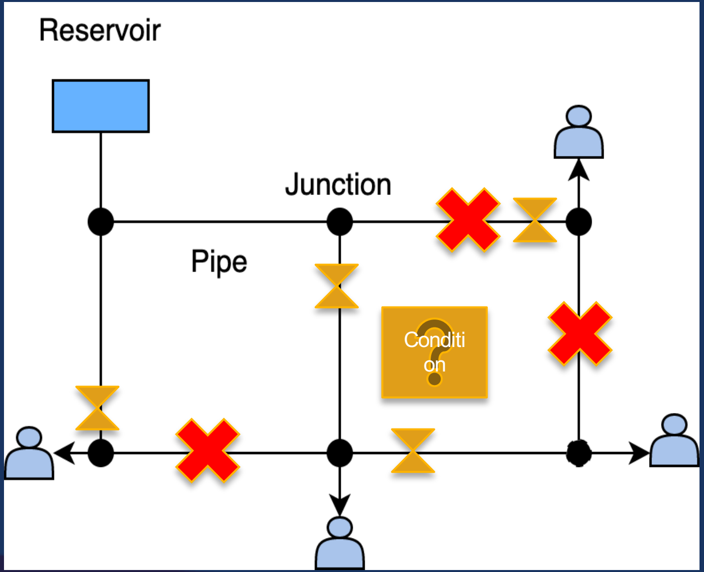
- The relationship between number of damaged pipes and water loss is nonlinear. The rate of damage increase as number of failed pipes increase



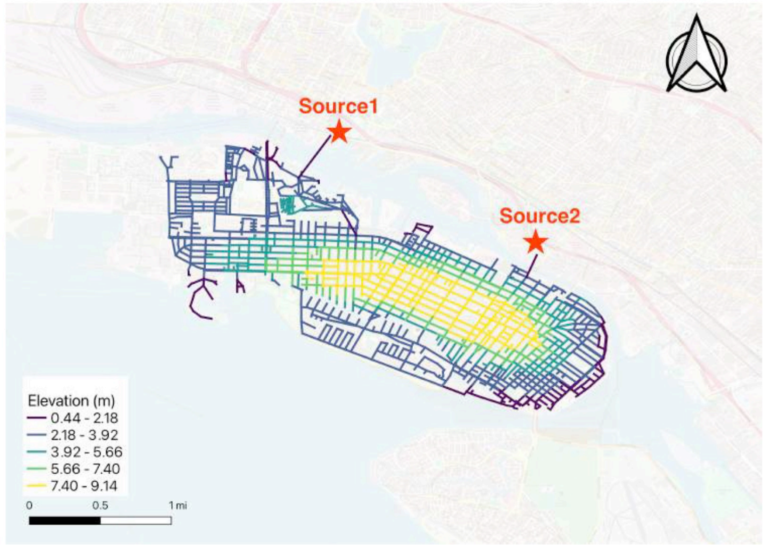
Berkeley
UNIVERSITY OF CALIFORNIA

Risk of malfunctioning valves in WDNs

Valves are as old as pipes!
Only use when bad things happened.
Not well maintained.



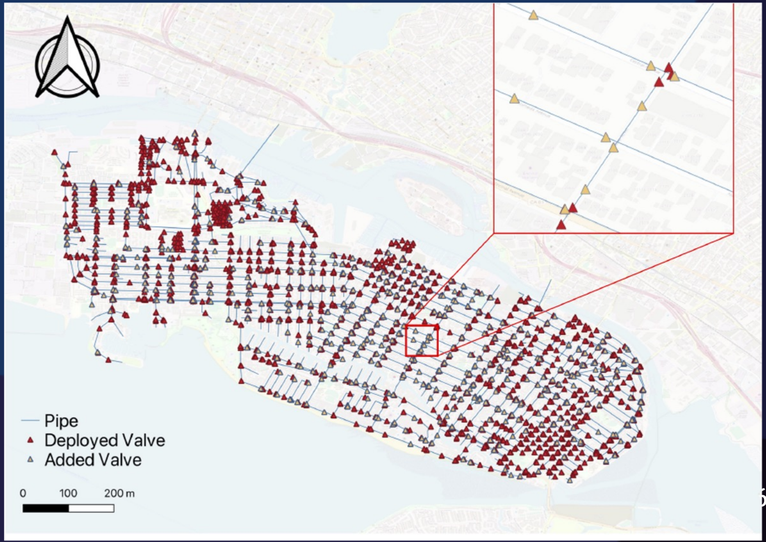
Failures



Pipe repair requires valve closures!

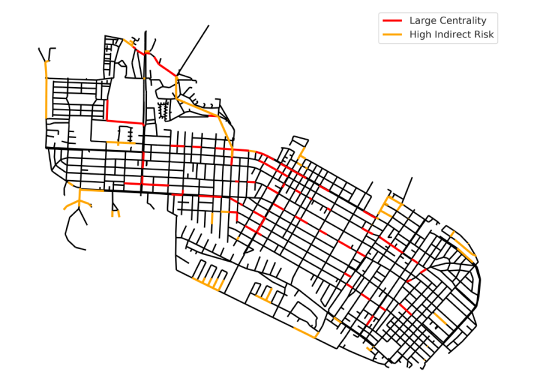
Berkeley
UNIVERSITY OF CALIFORNIA

Valve maintenance – Physics based ML

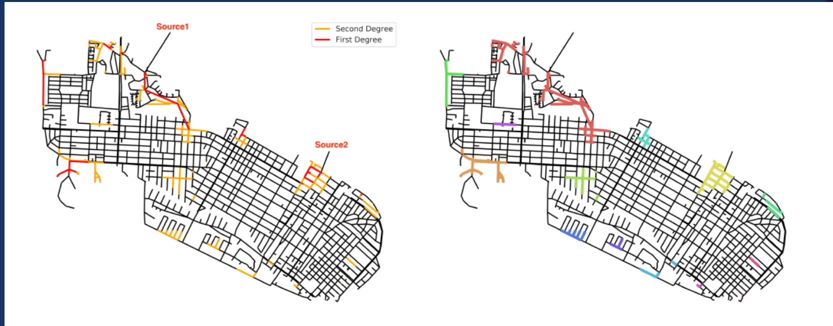


Valve maintenance – Risk based priority list

Data analytics

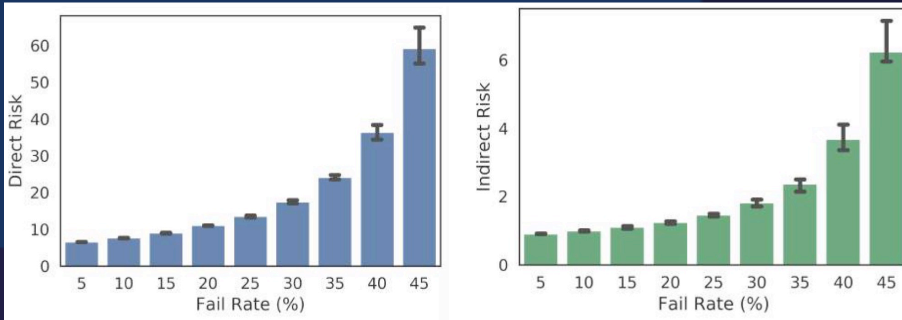


Hydraulic network



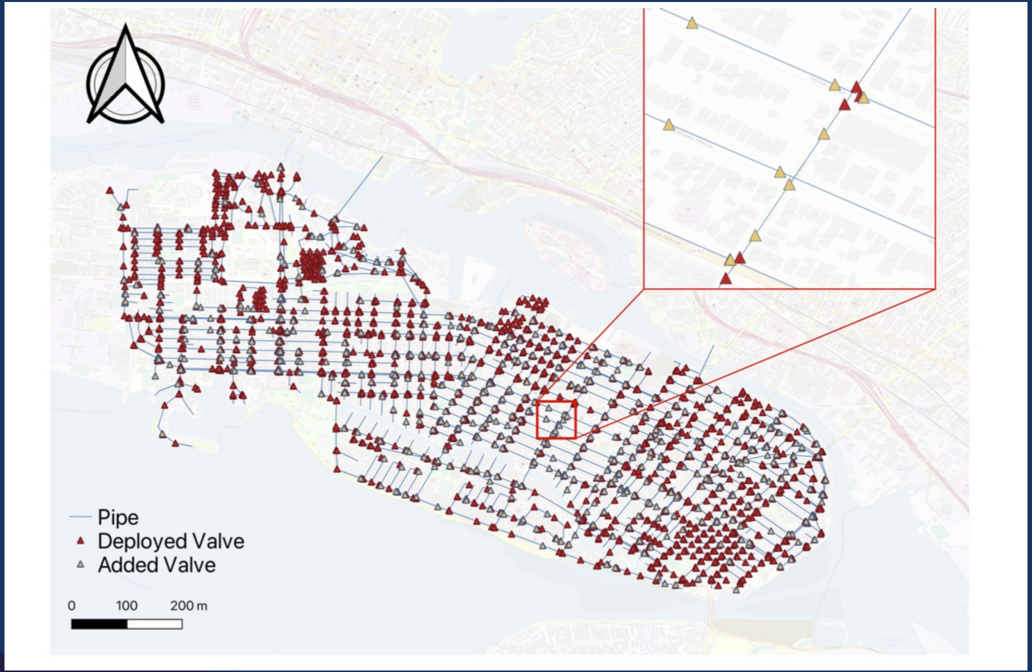
(a) Pipe isolation risk map for the network **(b)** Vulnerable regions of the network (using DB-SCAN clustering)

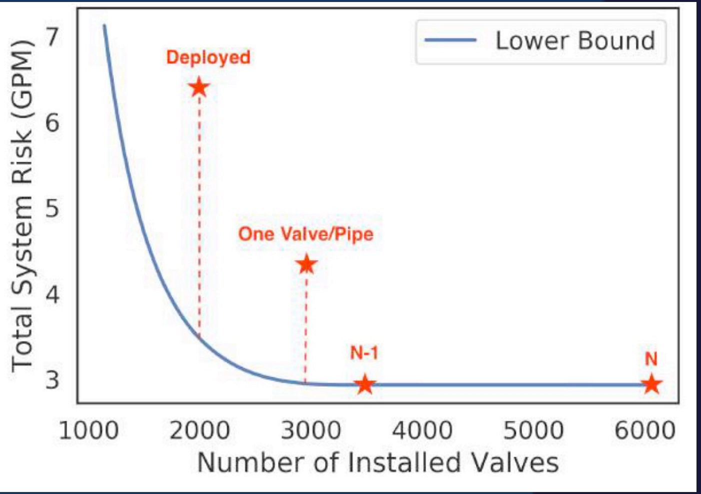
(a) Direct demand risk map (b) Indirect demand risk map

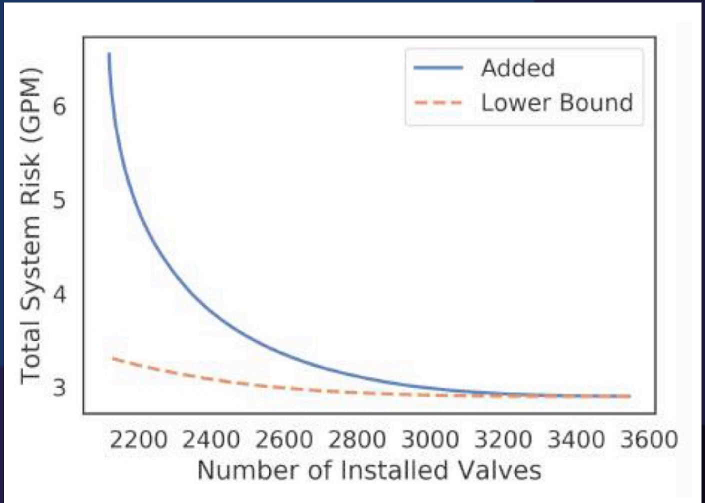


(a) Direct demand risk (b) Indirect demand risk

How to add new valves to the system





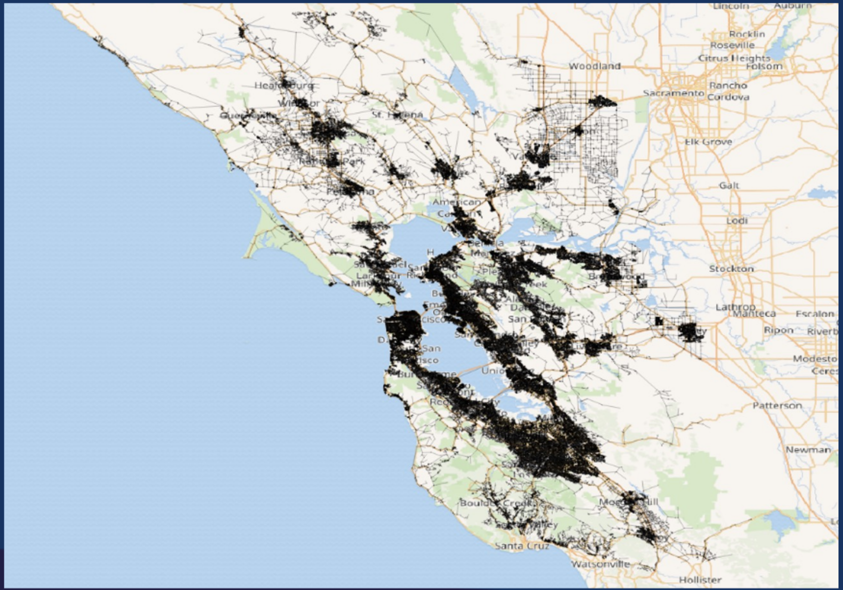


Berkeley
UNIVERSITY OF CALIFORNIA

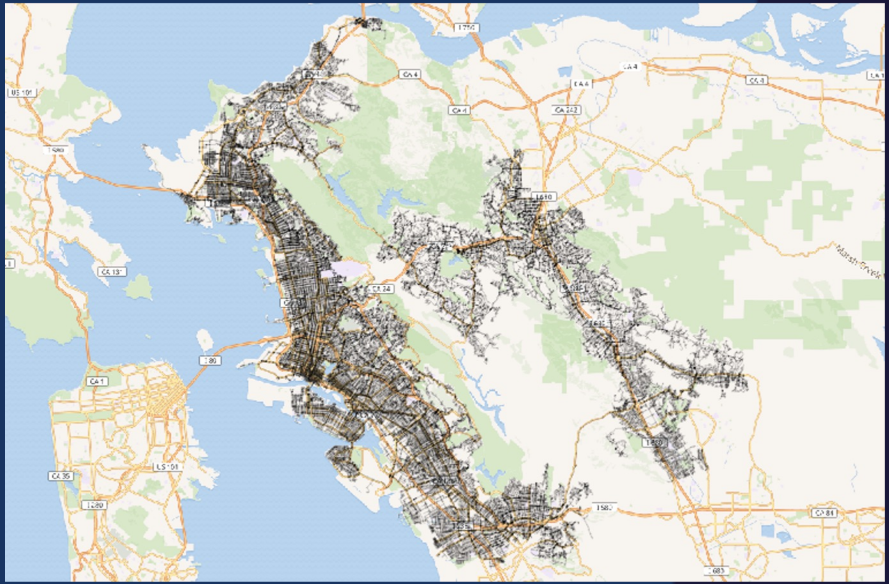
Subsurface Digital Twin

Berkeley
UNIVERSITY OF CALIFORNIA

Road Network
250k nodes, 550k edges
7 million people
13 people/road segment

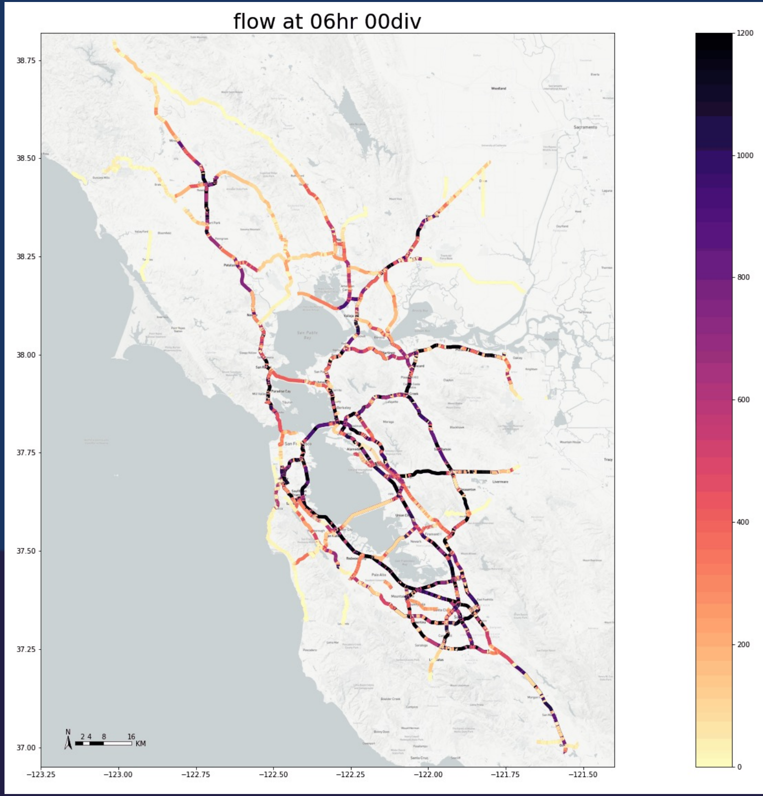


Water Network (EBMUD)
100k joints, 100k pipes
1.4 million customers
14 people/pipe segment

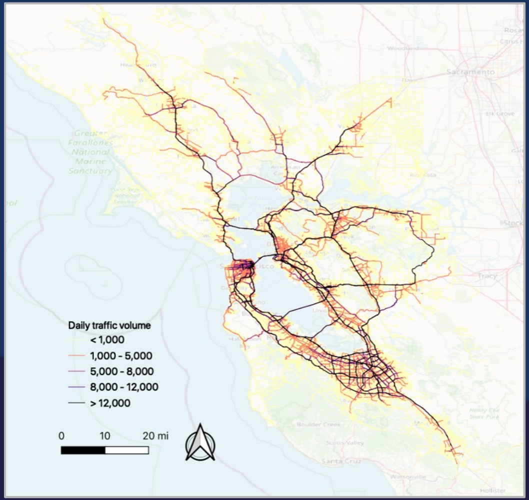


Berkeley
UNIVERSITY OF CALIFORNIA

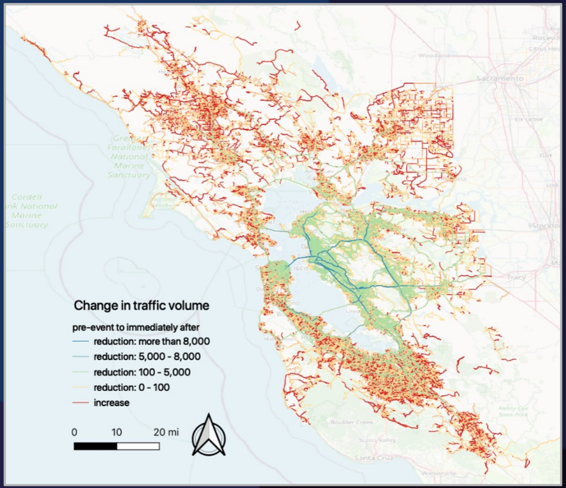
- 9 counties & 7 million people
- Road network: 549,008 links and 224,223 nodes.
- Travel demand: 15 million trips (close to the actual number of daily commute trips).
- Bay Bridge daily traffic: ~260,000



Pre-event traffic volume on Bay Area roads

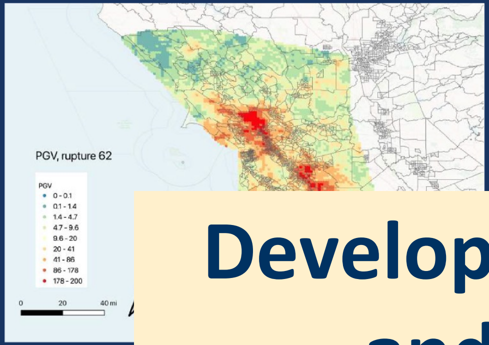


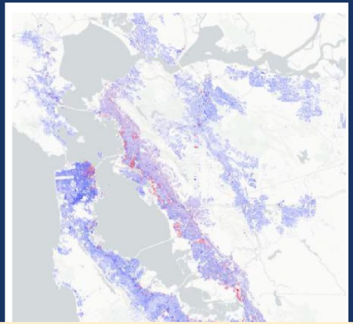
Change in traffic volume
Pre-event to immediately after

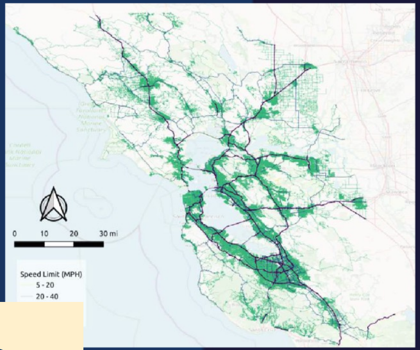


Water pipeline damage after an earthquake
Hayward Fault Earthquake in the East Bay Area

Step 1. EQ scenario + Site characterization





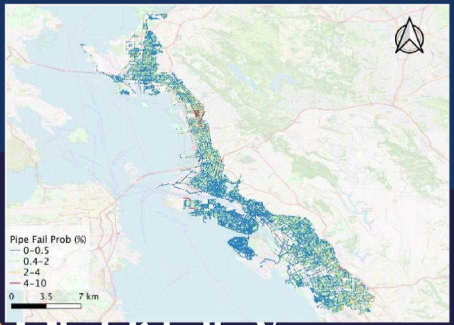


Traffic disruption

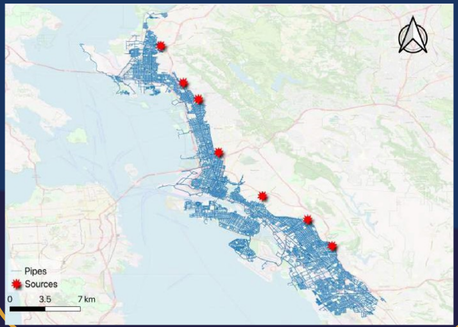
Develop strategic response and recovery plan

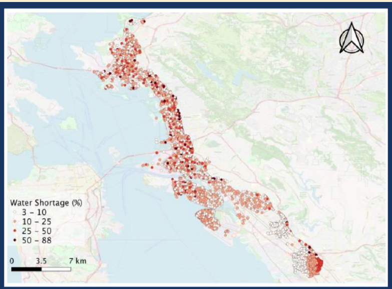
nterdependency

Step 2. Pipe damage

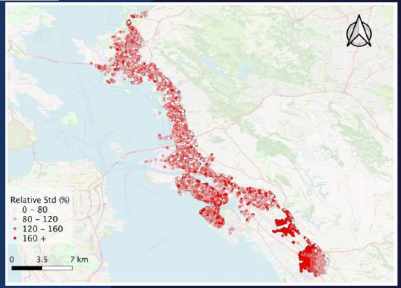


Step 3. Water network





Average water shortage



Standard deviation

UNIVERSITY OF CALIFORNIA