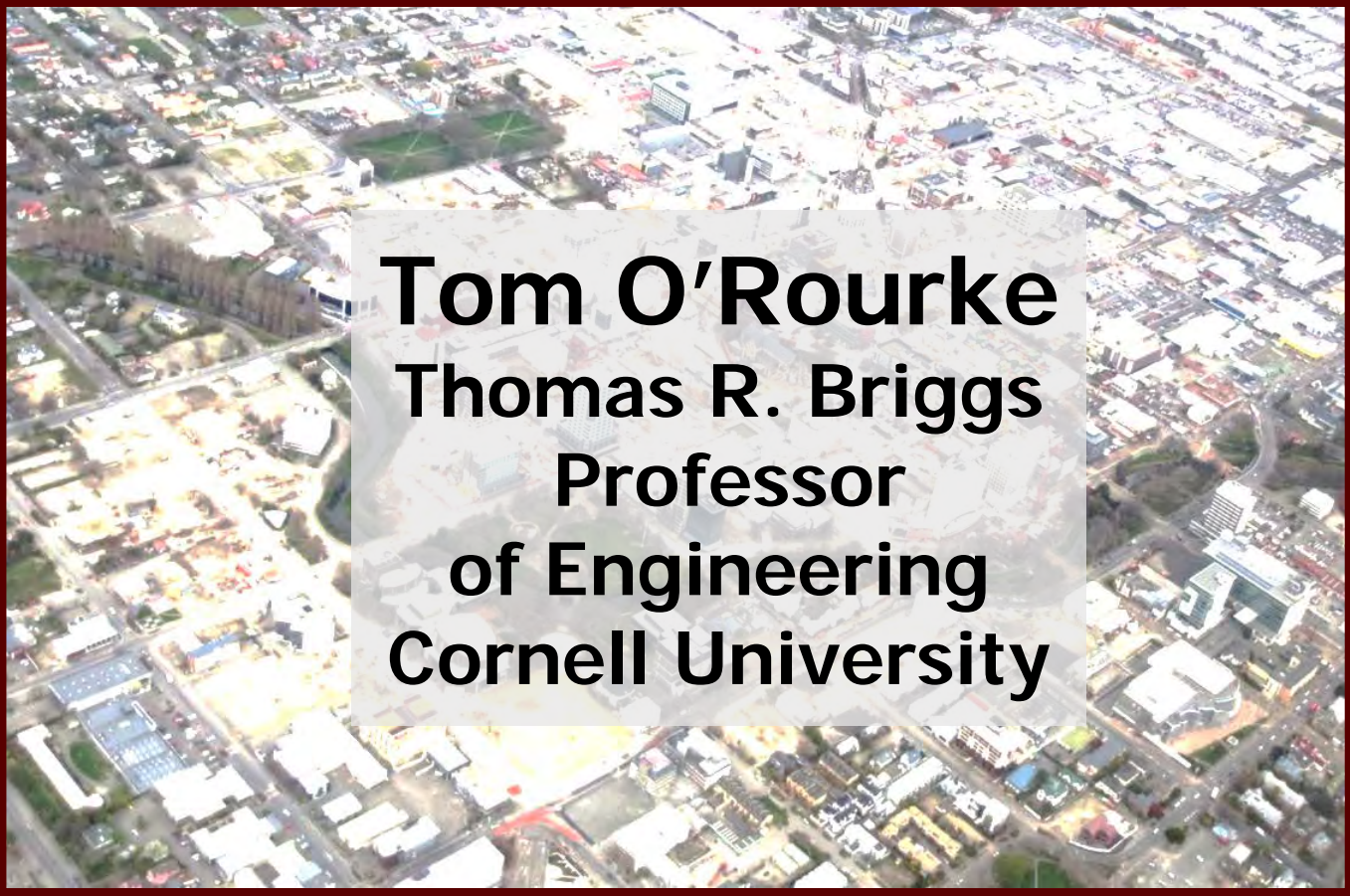


# HAZARD RESILIENT INFRASTRUCTURE



**Tom O'Rourke**  
Thomas R. Briggs  
Professor  
of Engineering  
Cornell University



# TOPICS

- **Hurricanes and Earthquakes**
- **Infrastructure Characteristics**
- **San Francisco**
- **Los Angeles**
- **Hazard Resilient Infrastructure**

A grayscale photograph of a construction site. In the foreground, a grid of steel reinforcement bars (rebar) is laid out on the ground. Several workers in hard hats and work clothes are visible in the background, some standing and others working. The scene is outdoors, with some structures and equipment visible in the distance.

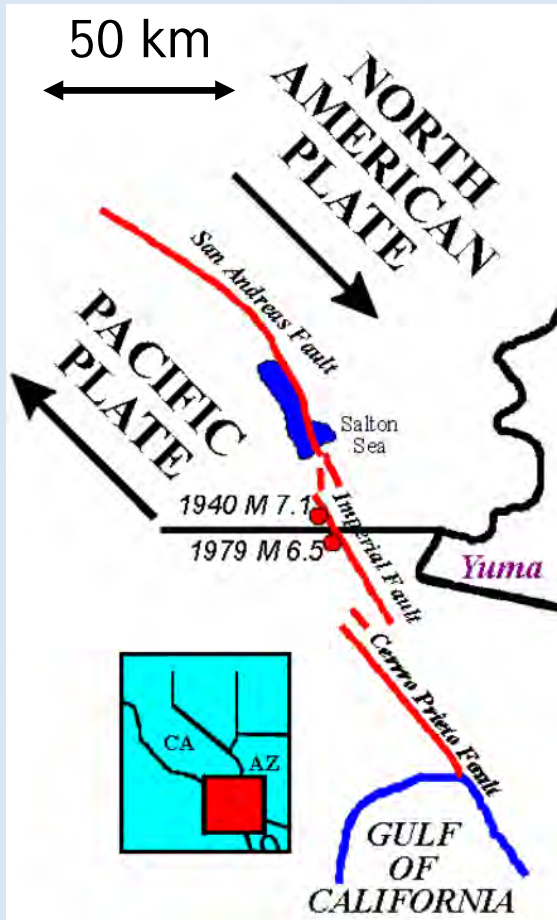
# TOPIC

- **Earthquakes and Hurricanes**

# UNITED STATES MEXICO BORDER



# IMPERIAL FAULT



## Imperial Fault

1979 Imperial Valley  
1940 El Centro  
Earthquakes



# RECENT EARTHQUAKES IN MEXICO



# HURRICANES

**2005  
Hurricanes**

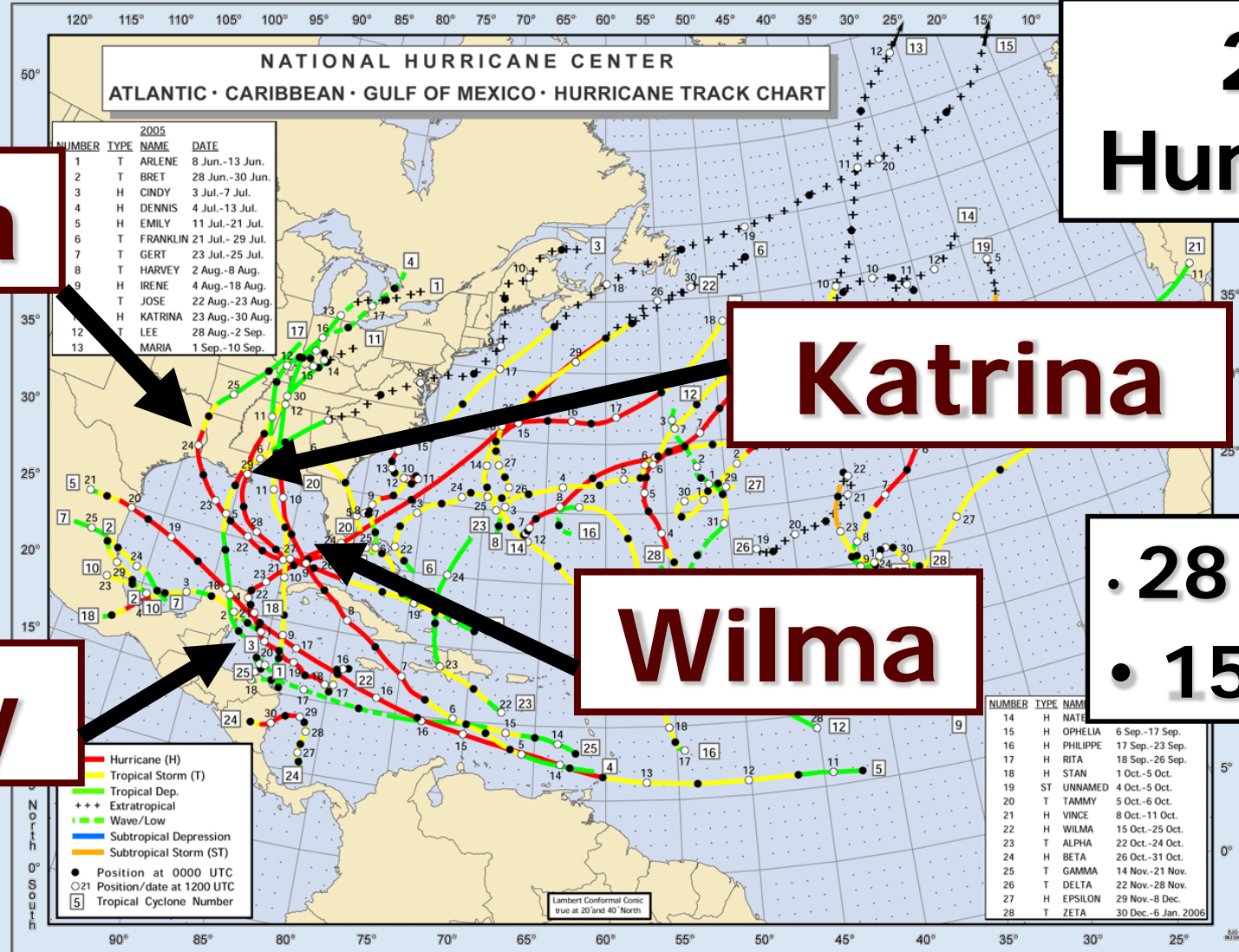
**Rita**

**Katrina**

**Wilma**

**Emily**

- 28 Storms
- 15 Hurricanes



# REVOLUTION IN POLICY

## September 11:

- Protection of Critical Infrastructure



## Hurricane Katrina:

- Resilient Communities

A grayscale photograph of a construction site. In the foreground, a grid of steel reinforcement bars (rebar) is laid out on the ground. Several workers in hard hats and work clothes are visible in the background, some standing and some working. The scene is an active construction area, likely for a large building or infrastructure project.

# TOPIC

- **Infrastructure Characteristics**

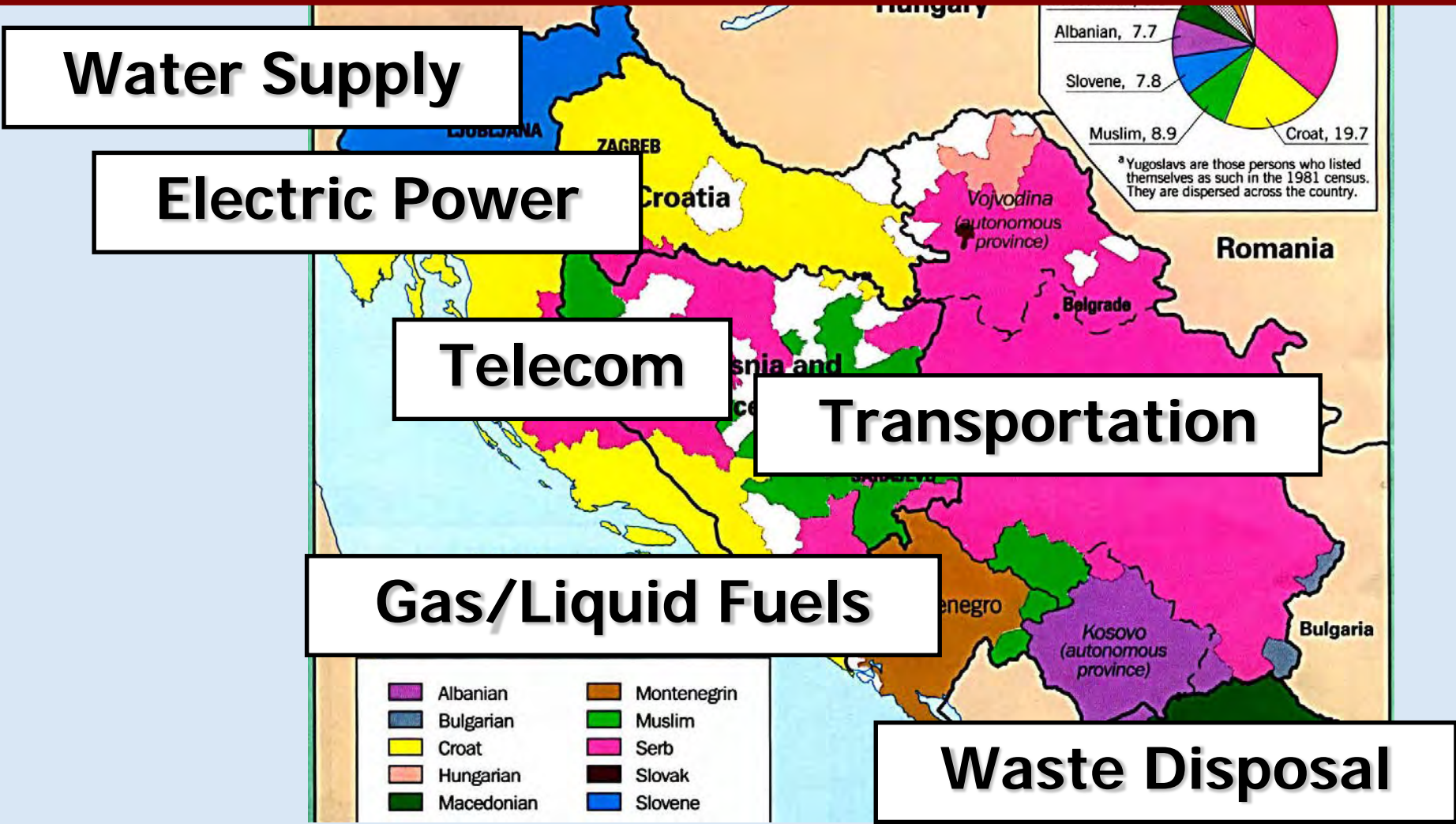
# LIFELINE SYSTEMS

- Electric Power
- Gas and Liquid Fuels
- Telecommunications
- Transportation
- Wastewater Facilities
- Water Supply
- Flood Control & Levees



After Peerenboom, Fisher, and Whitfield, 2001

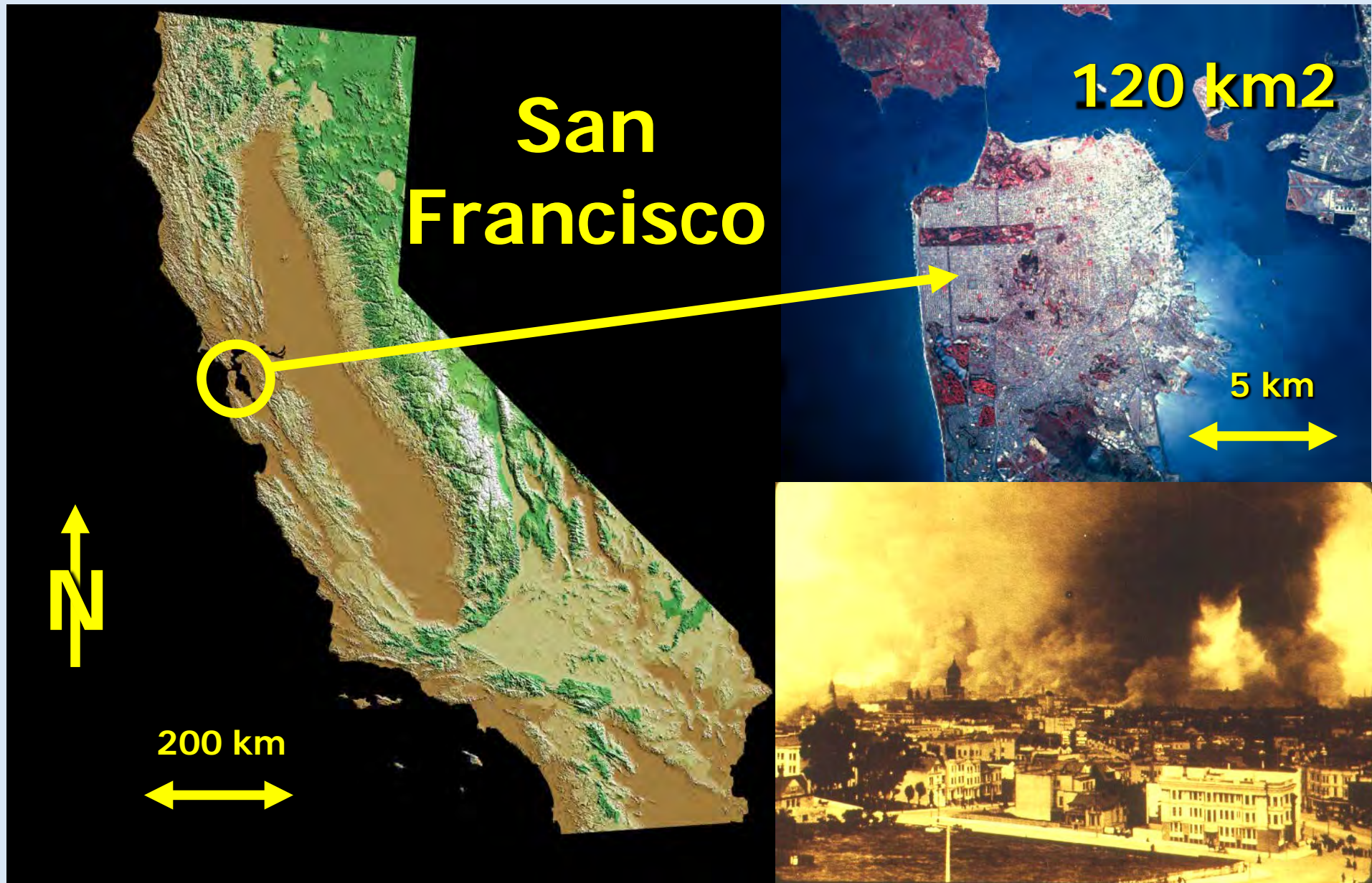
# INSTITUTIONAL INTERDEPENDENCIES

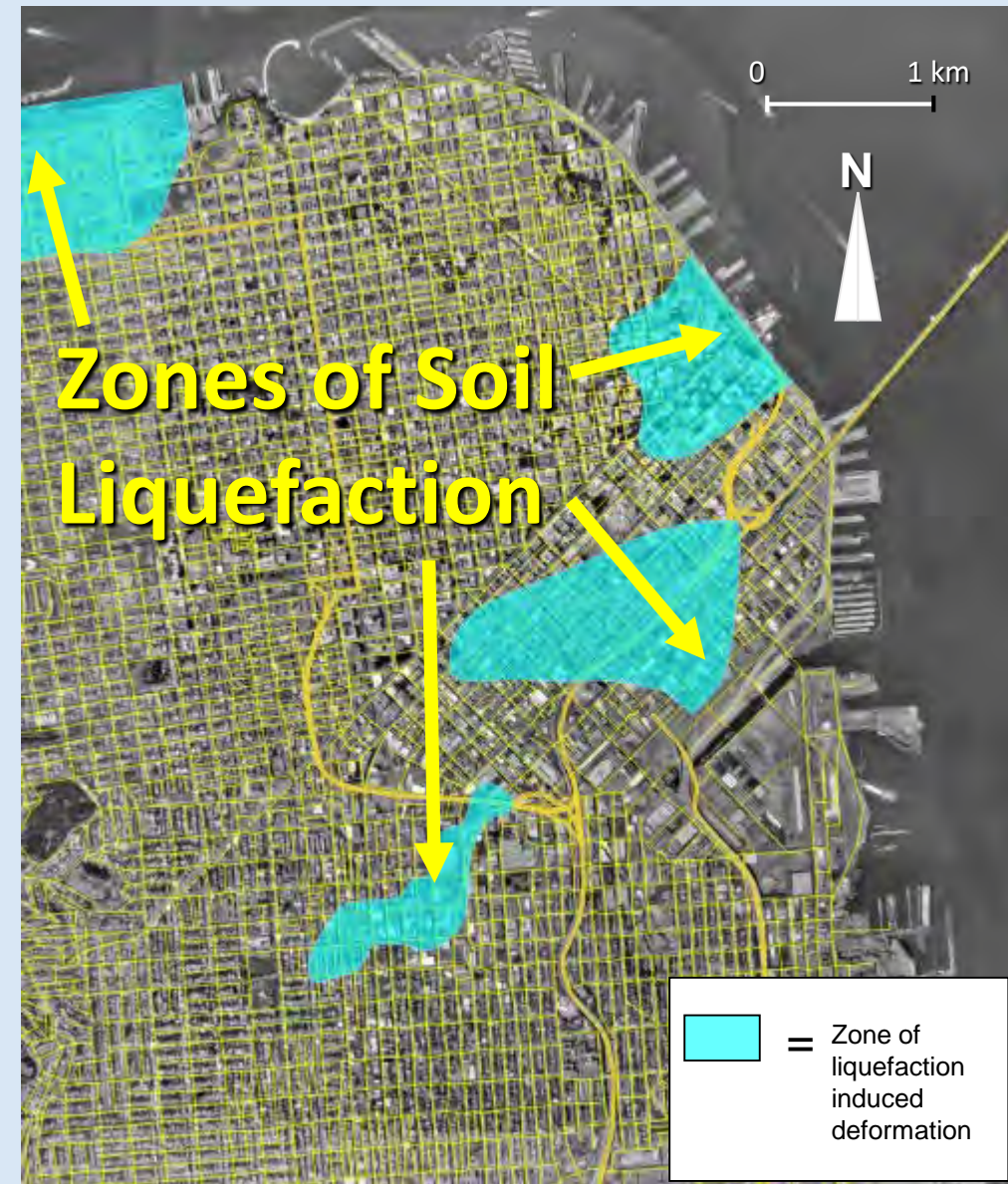


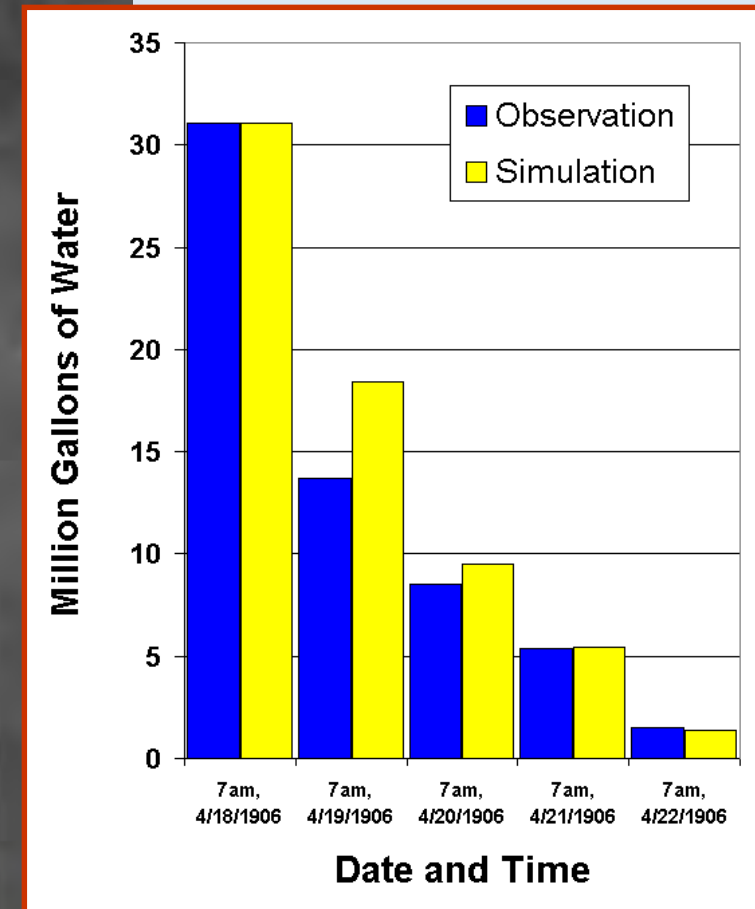
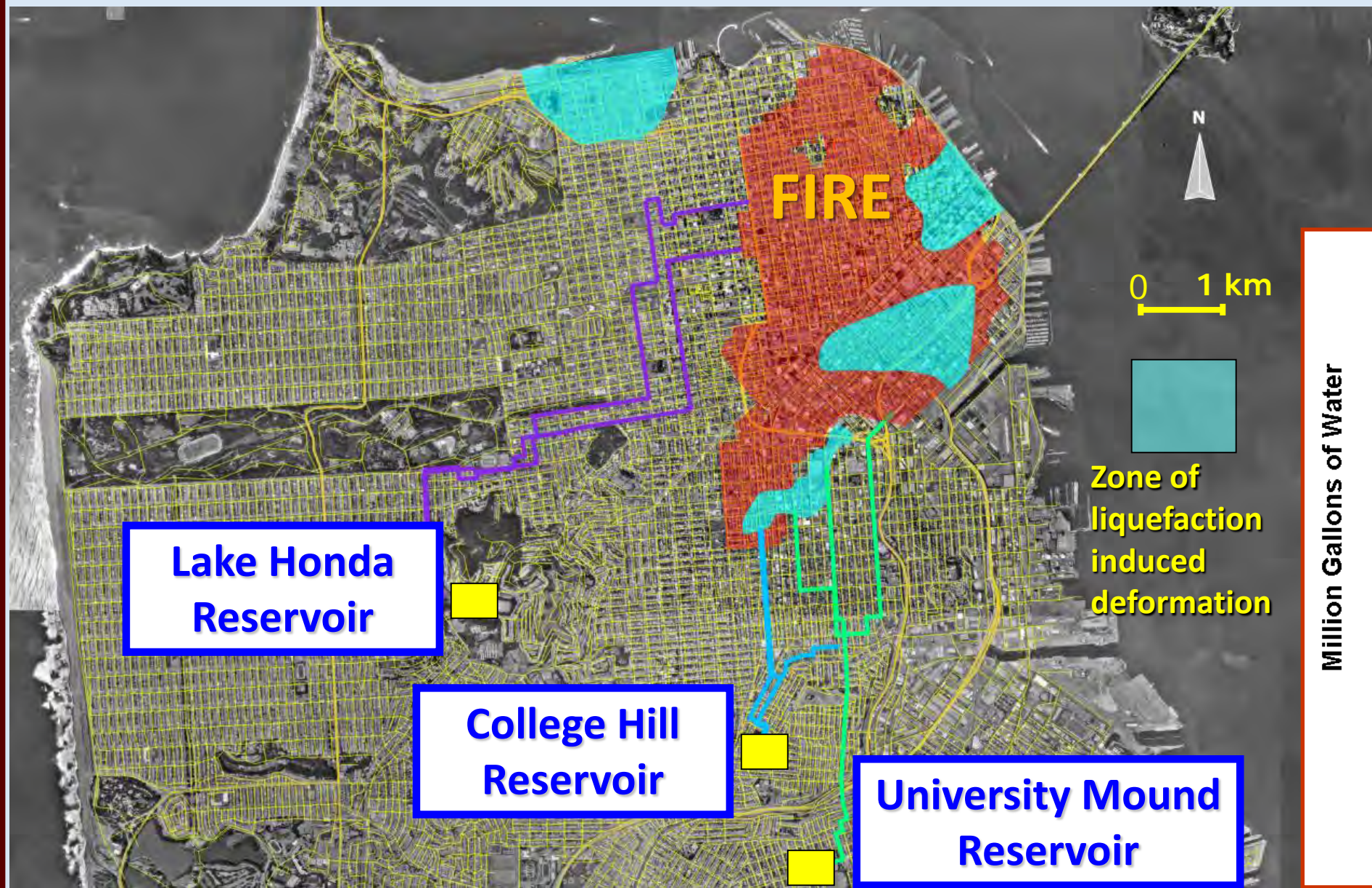


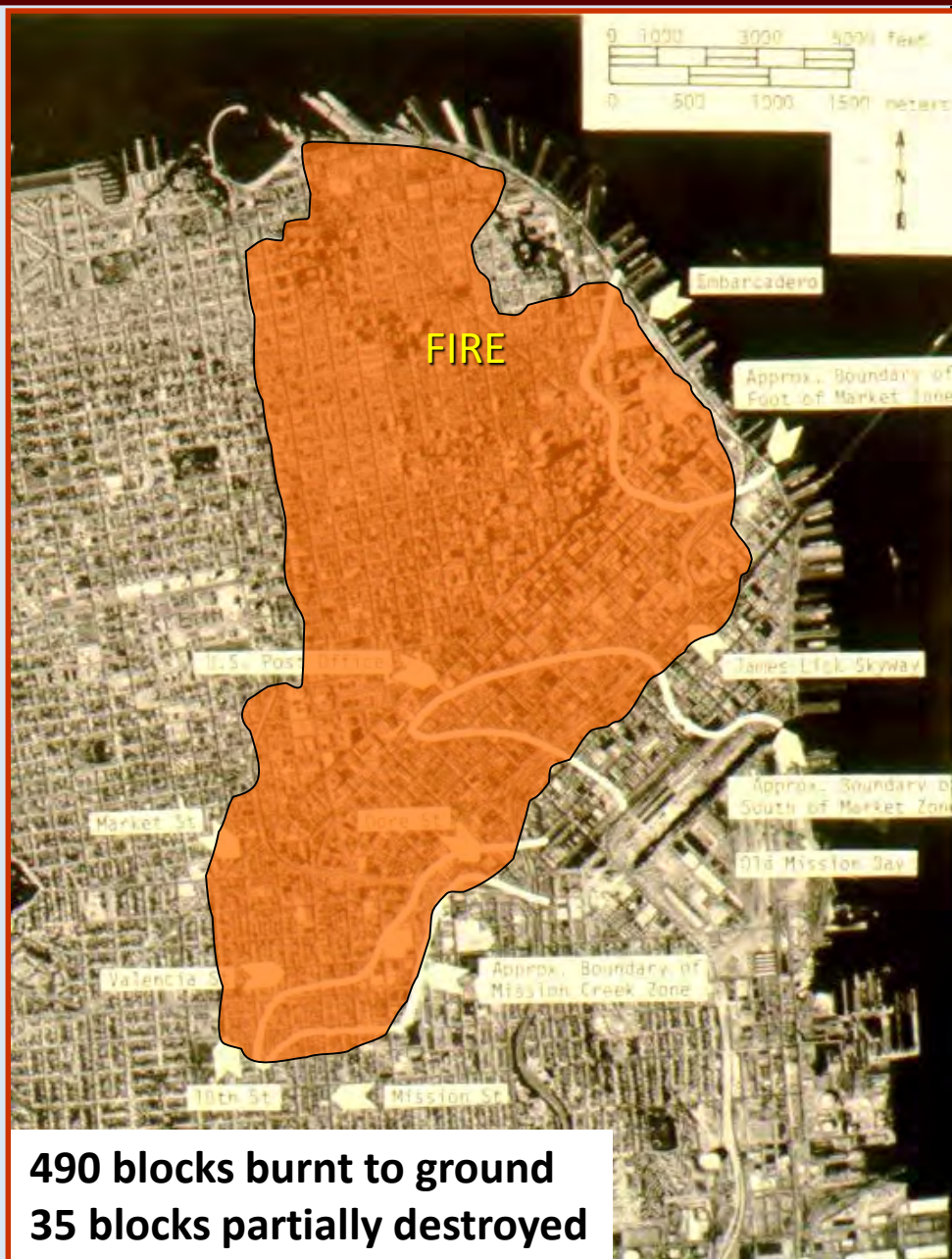
# TOPIC

- **San Francisco**





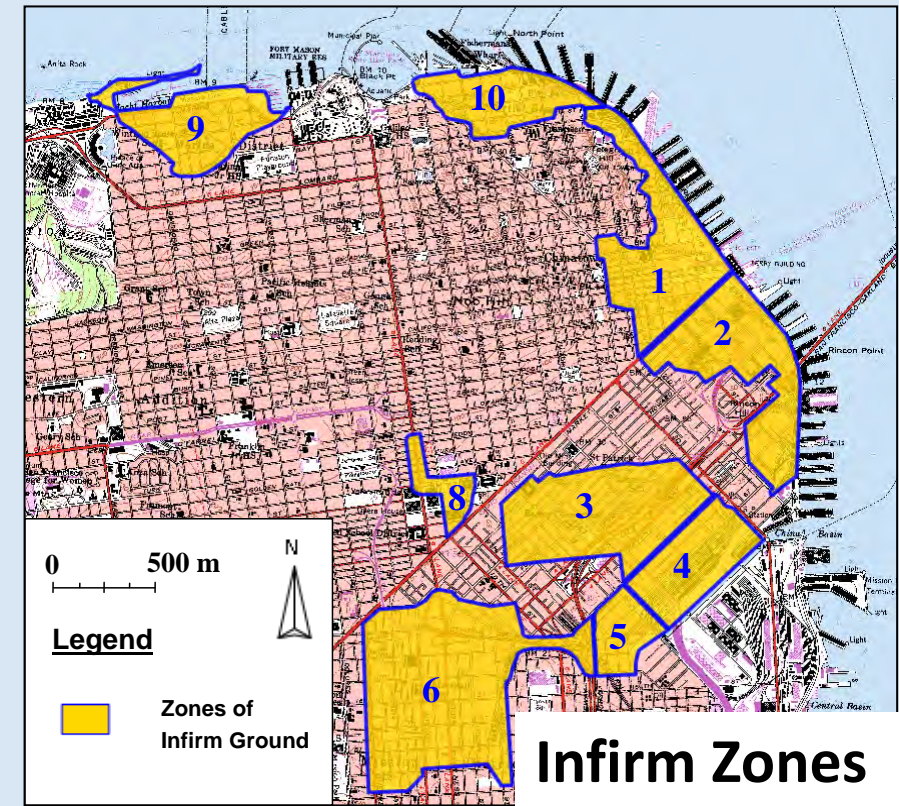
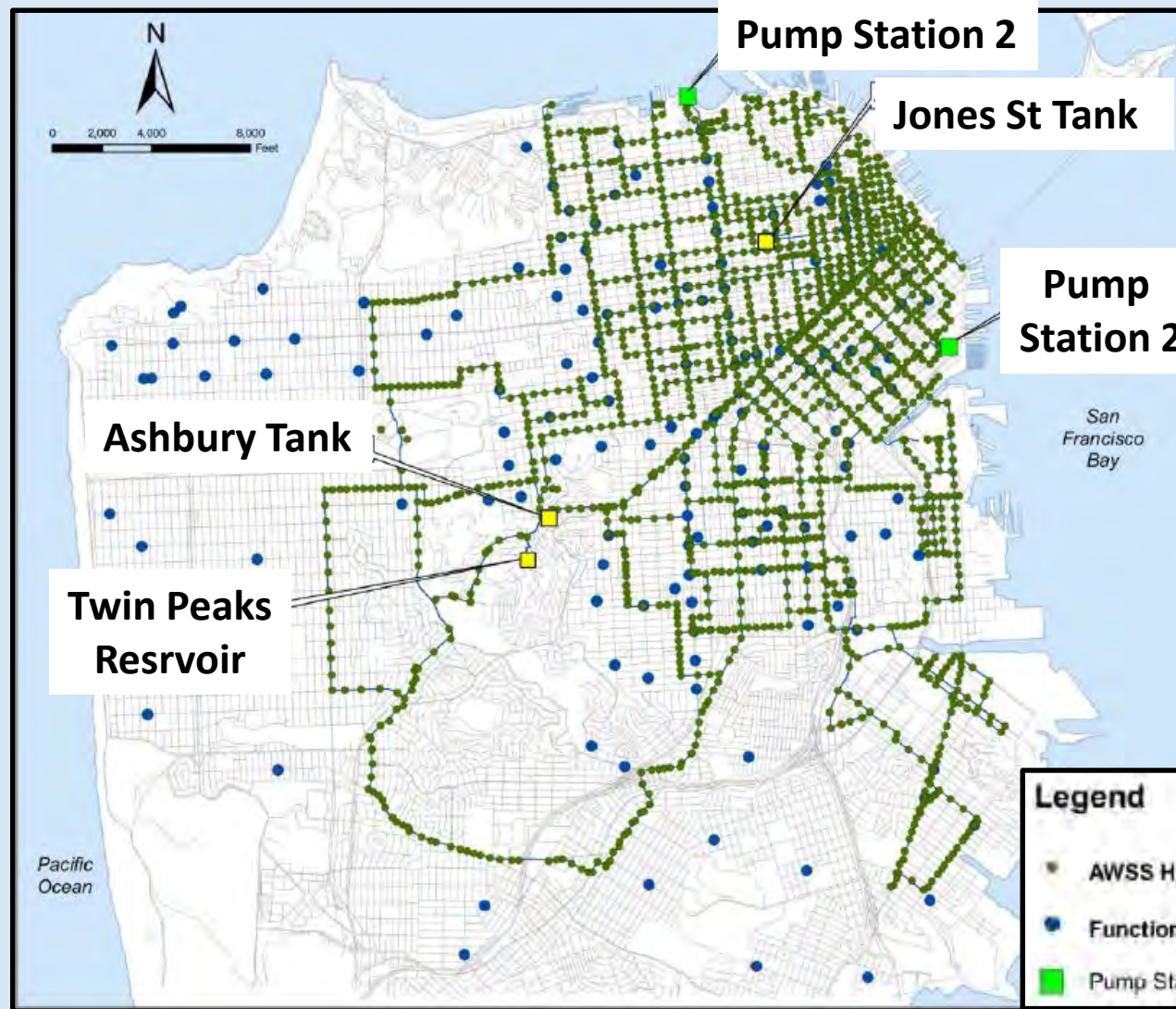




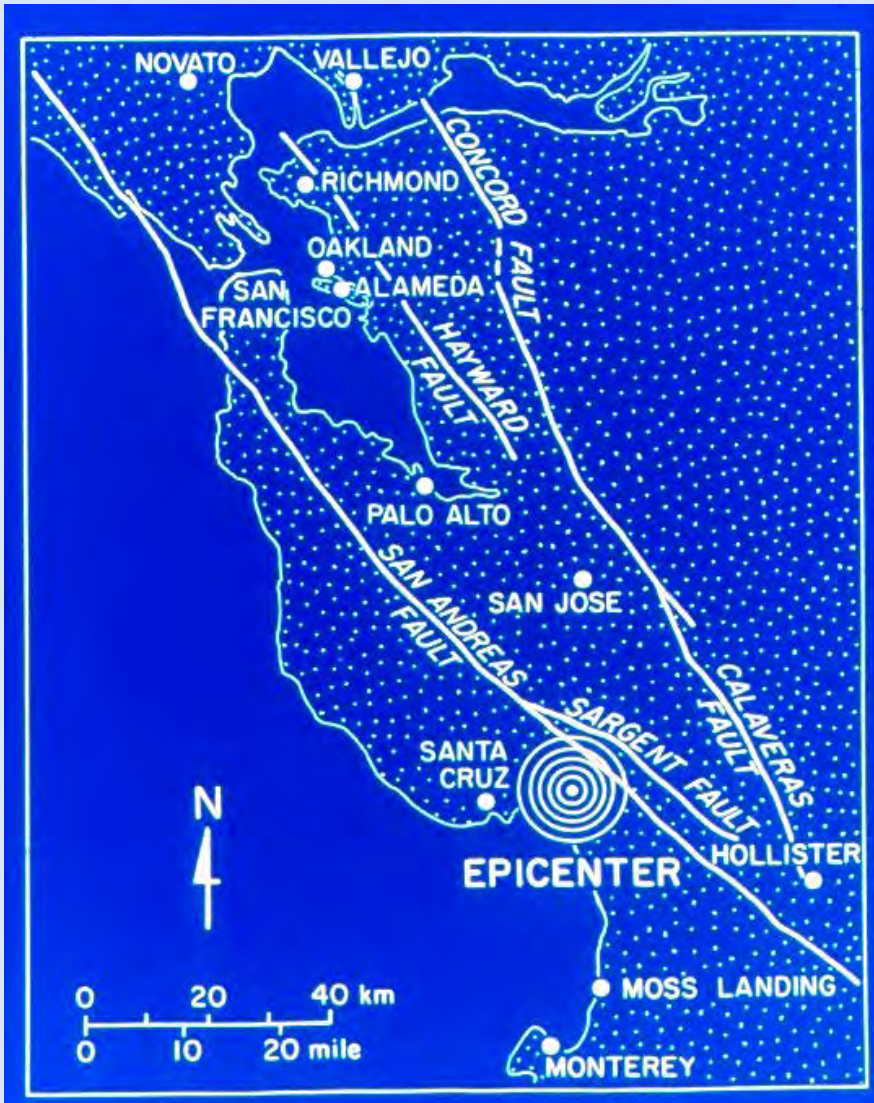
**490 blocks burnt to ground  
35 blocks partially destroyed**



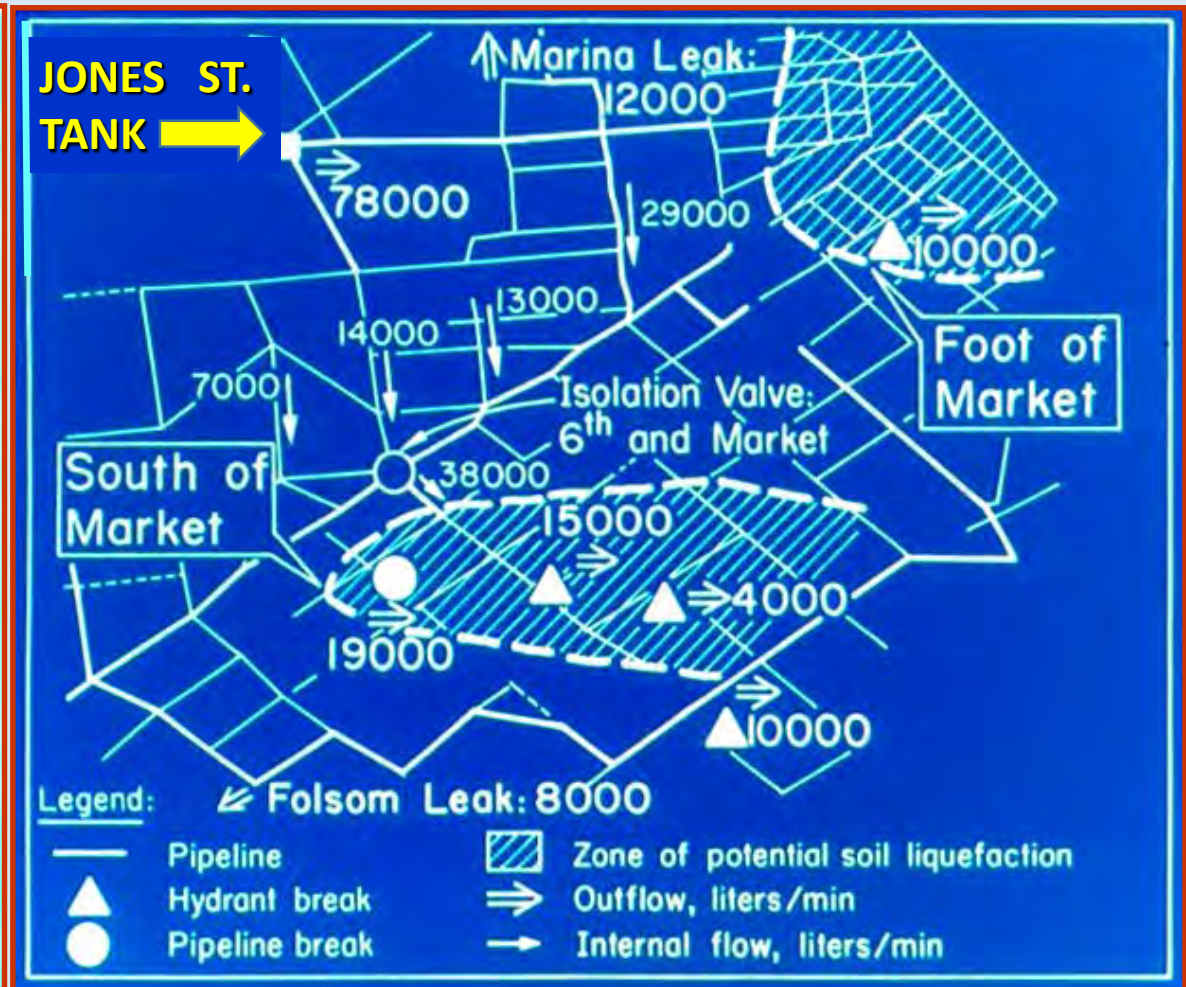
# AUXILIARY WATER SUPPLY SYSTEM



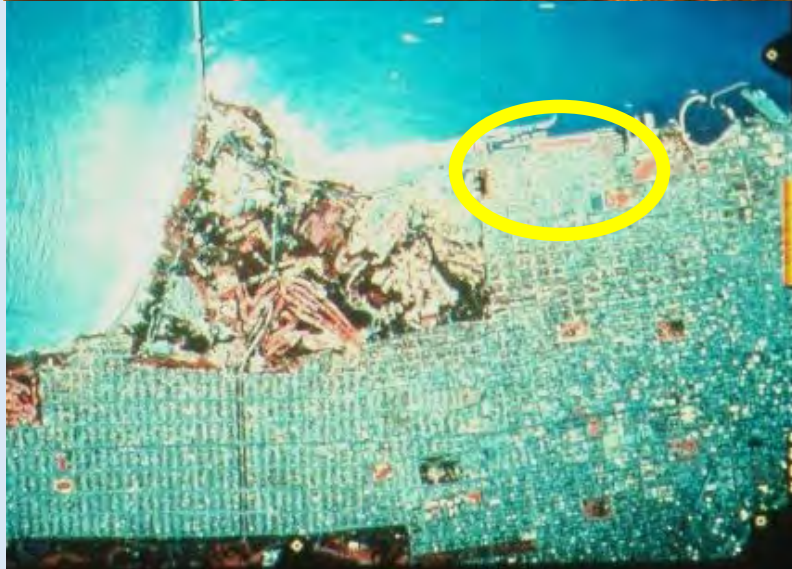
# LOMA PRIETA EARTHQUAKE



# HYDRAULIC NETWORK MODELING



# PORTABLE WATER SUPPLY SYSTEM



# PORTABLE WATER SUPPLY SYSTEM

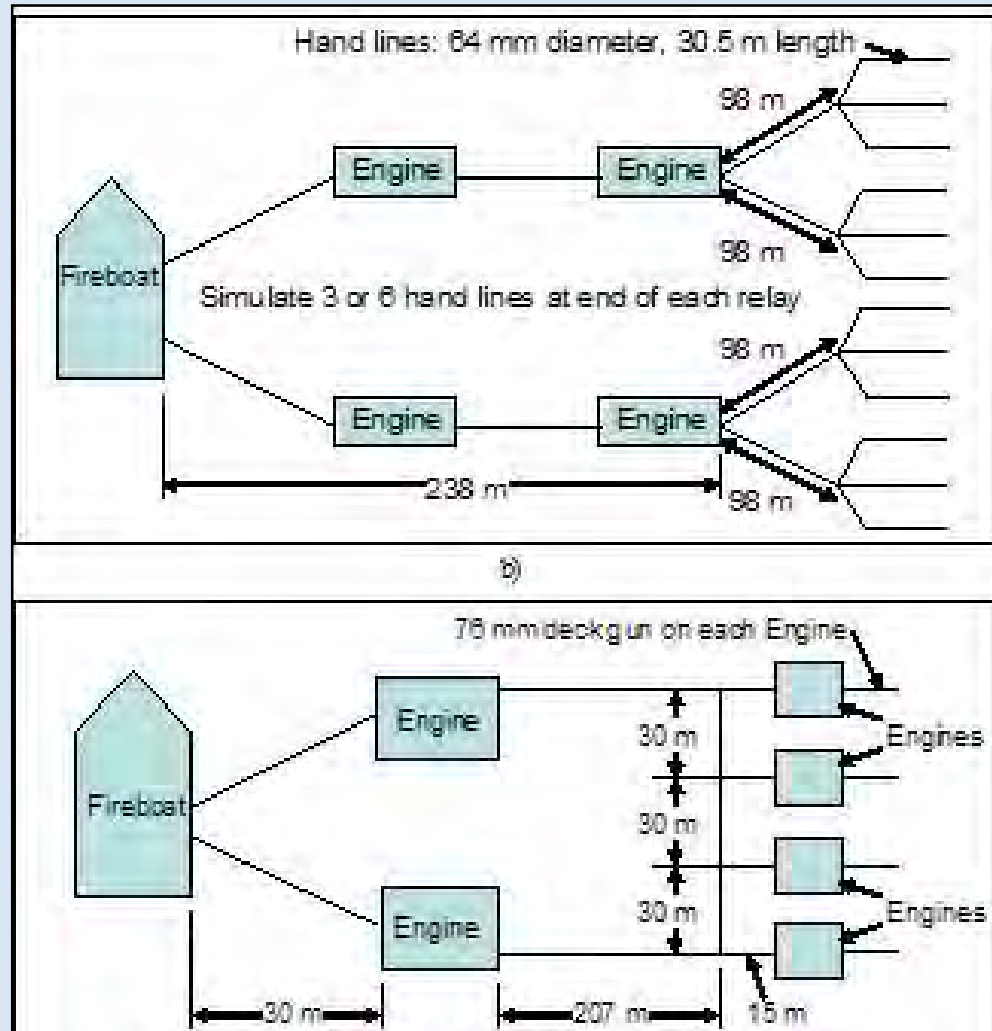


# WORLD TRADE CENTER DISASTER



**Fireboats:**  
**Firefighter** Pipelines ~ 4500 gpm  
**McKean** ~ 300 liters/sec  
**Smoke II**  
**Kane** ~ 7500 gpm  
~ 500 liters/sec

# FIREFIGHTING PROTOCOL



- Looped deployment of fireboat & engines most effective
- In San Francisco looped approach is used with monitors or deck guns on each engine



# WATER SYSTEM IMPROVEMENT PROGRAM



# EARTHQUAKE SAFETY AND EMERGENCY RESPONSE BOND

## 2010 EARTHQUAKE SAFETY AND EMERGENCY RESPONSE BOND



AWSS

Projects and Programs	Cost (millions)
AWSS Core Facilities	\$35.0
Critical Firefighting Facilities and Infrastructure	134.3
Public Safety Building	243.0
<b>Total</b>	<b>\$412.3</b>



Neighborhood Fire Stations	\$65.1 M
Firefighting Cisterns	\$36.6 M
Firefighting Pipes and Tunnels	\$32.6 M
<b>Total CFFI</b>	<b>\$134.3 M</b>



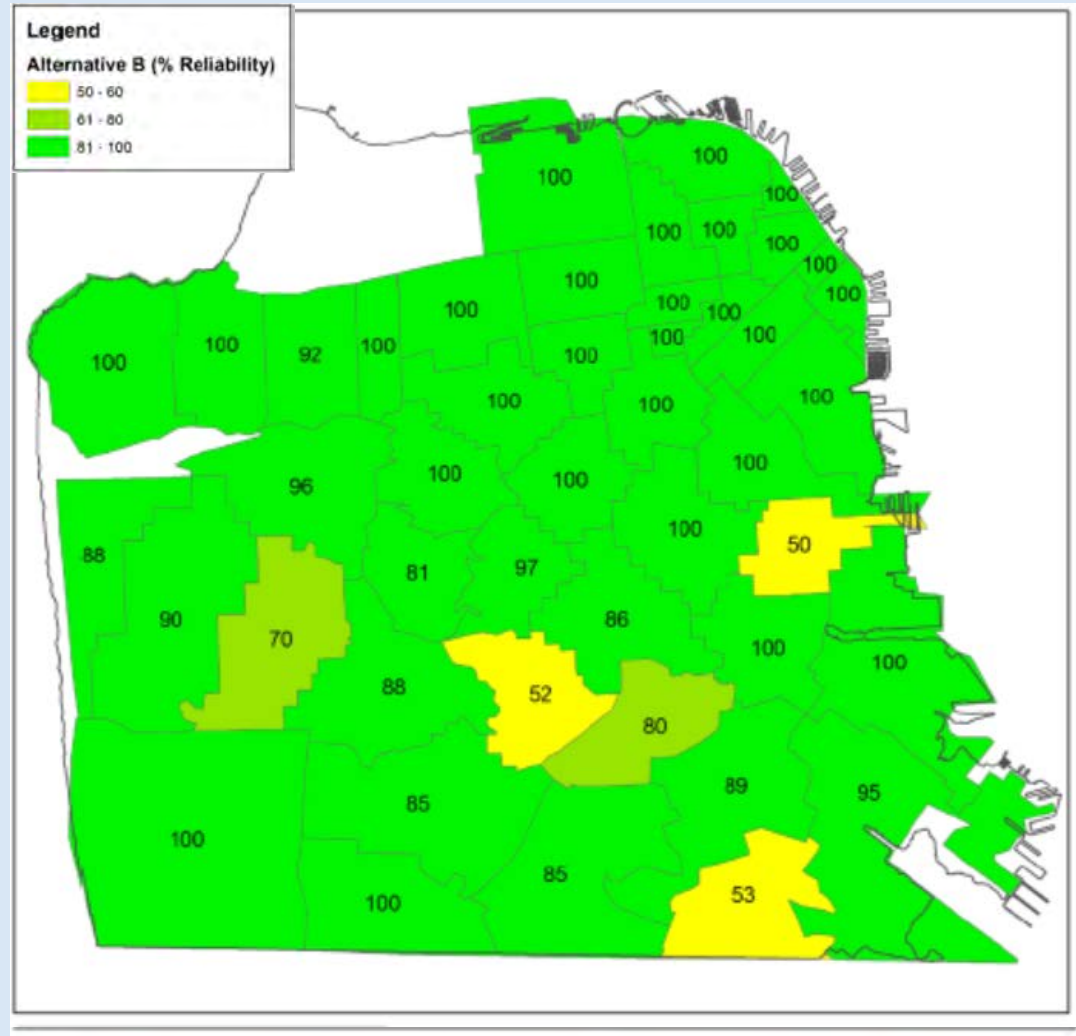
### ESER 2014 projects and programs

### Budget (millions)

Neighborhood Firehouses	\$85
Emergency Firefighting Water System	\$55
District Police Stations and Infrastructure	\$30
Motorcycle Police and Crime Lab	\$165
Medical Examiner Facility	\$65
<b>Total</b>	<b>\$400 million</b>

# SAN FRANCISCO AUXILLIARY WATER SUPPLY PERFORMANCE CRITERIA

- 7.8 Mw  
Deterministic EQ
- Water Demands in  
Fire Response  
Areas
- Monte Carlo AWSS  
Network  
Simulations



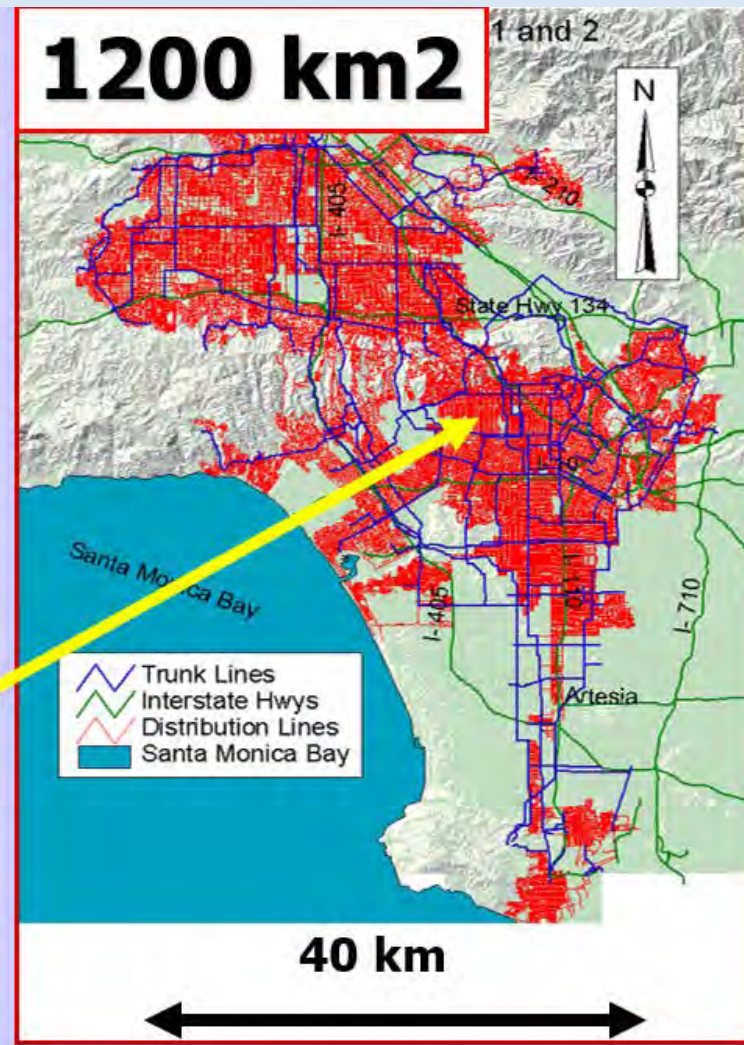
# **LESSONS LEARNED FROM SAN FRANCISCO**

- **Interdependencies of Critical Infrastructure and Geohazards**
- **Liquefaction Is Key Hazard Affecting Water Supply System**
- **Successful Use of Geohazards and Hydraulic Network Model for Community Protection in Actual Earthquake**

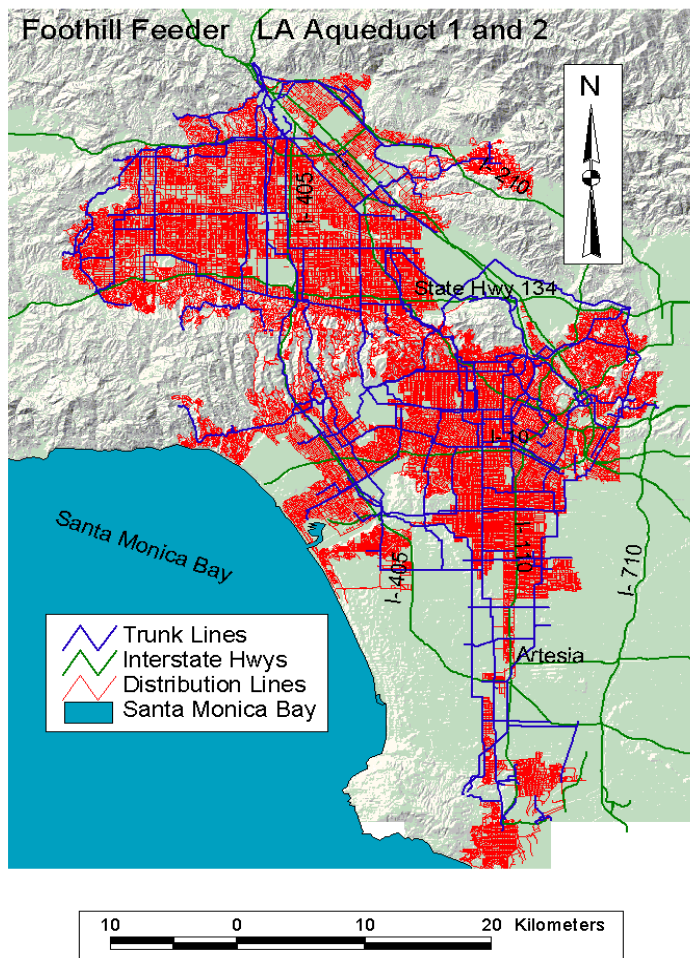


# TOPIC

- Los Angeles

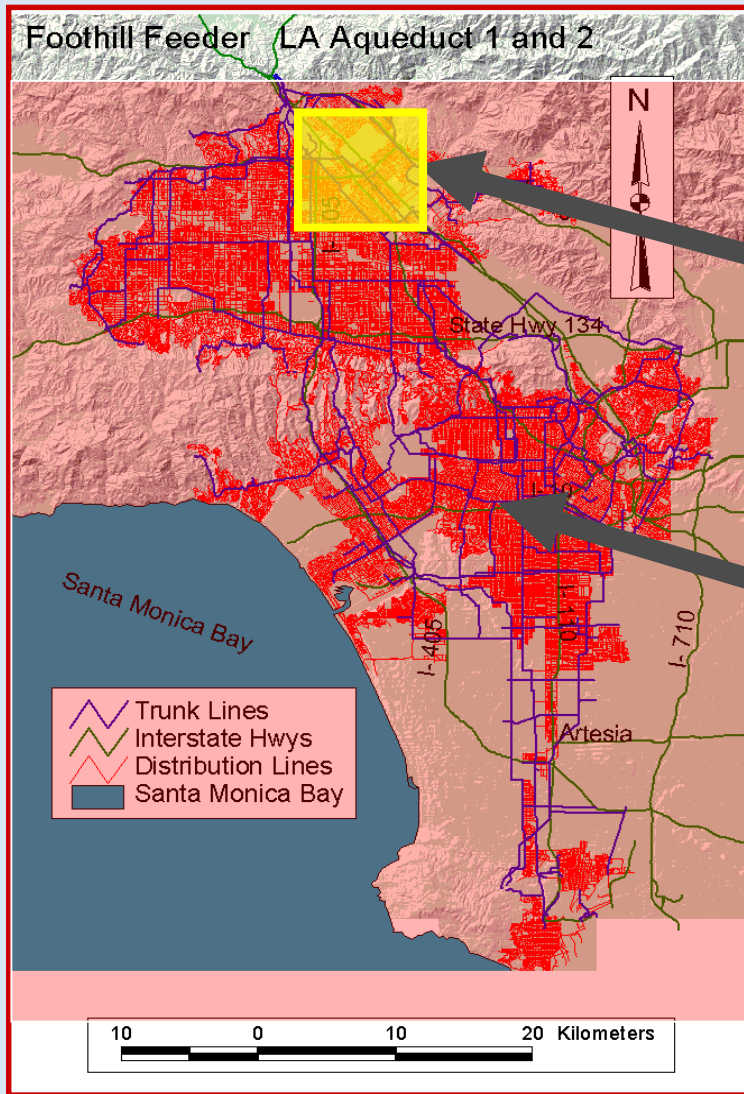


# LOS ANGELES DEPARTMENT OF WATER AND POWER DECISION SUPPORT SYSTEM



- Serves 4.3 Million People
- 12,000 km Distribution & Trunk Pipelines
- 1200 km<sup>2</sup>
- Simulates 12,000 km pipelines & facilities
- Comprehensive seismic & geohazards
- Special software for damaged hydraulic network analysis
- System risk & reliability
- Water & electric interdependencies
- Economic/social impacts

# MULTI-MODAL SIMULATION



Simulation for Ground Failure, Accidents, Human Threats



Probabilistic Simulation for System-wide Seismic Wave Effects

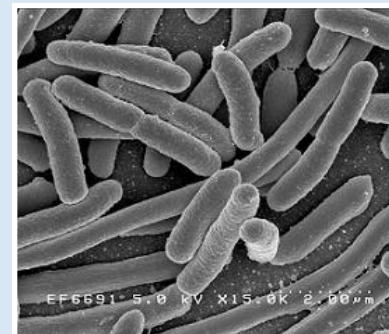
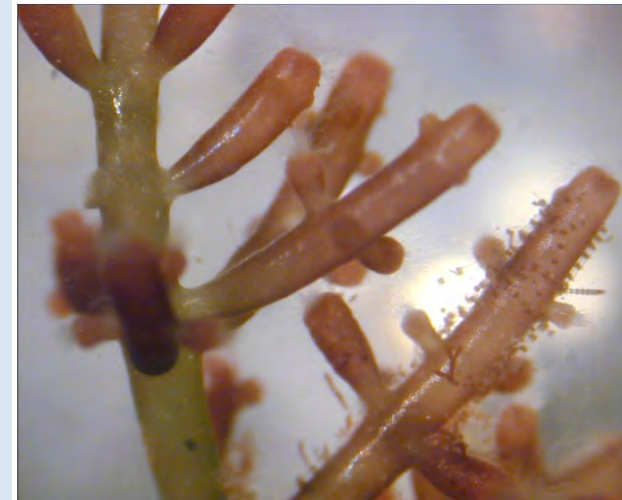


Combined Simulation for Permanent Ground Deformation & Seismic Wave Effects

# ENVIRONMENTAL REQUIREMENTS



**Disinfectant  
By-Products**



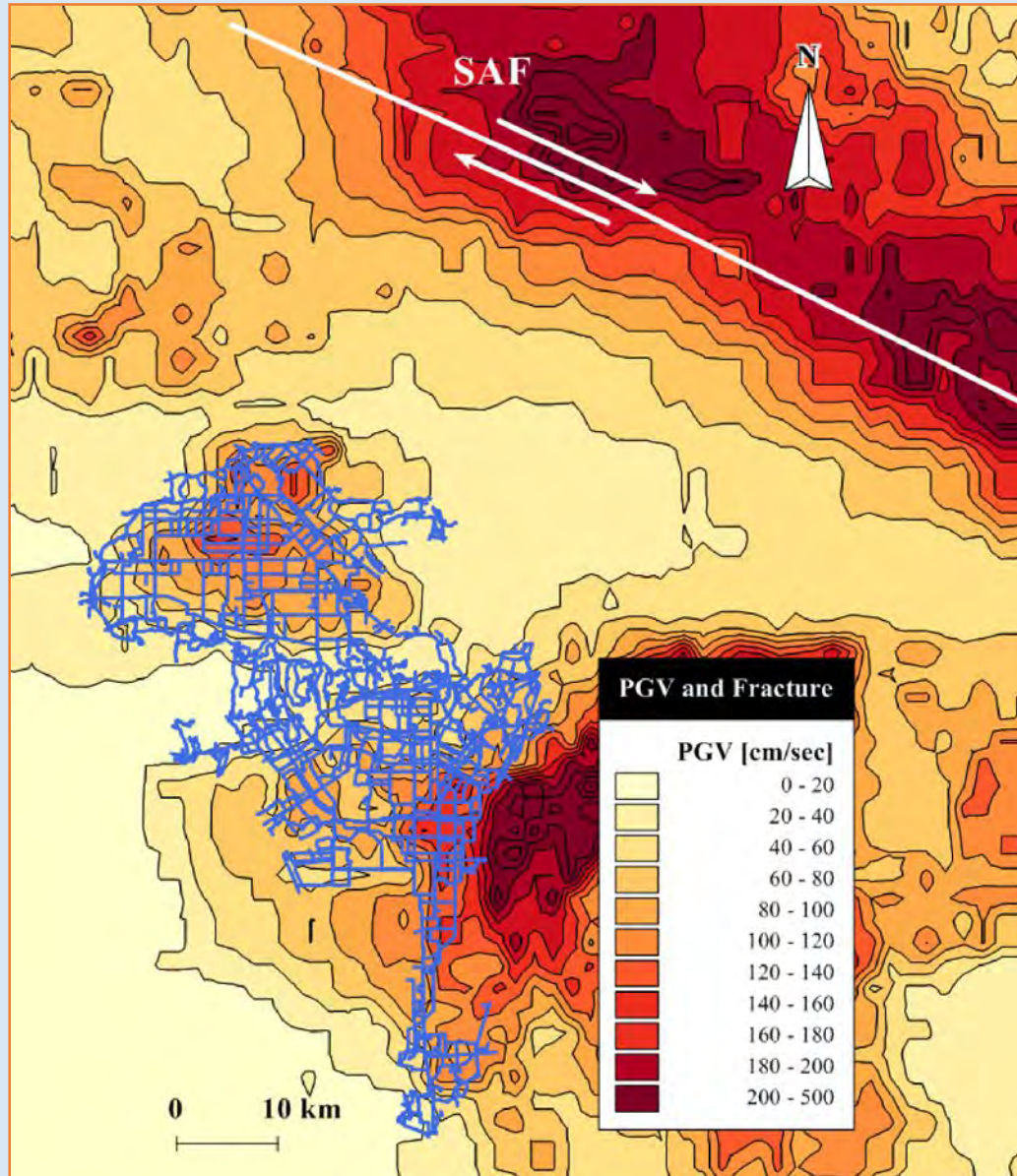
# GREAT CALIFORNIA SHAKEOUT

## 7.8 M<sub>w</sub> San Andreas Fault Earthquake



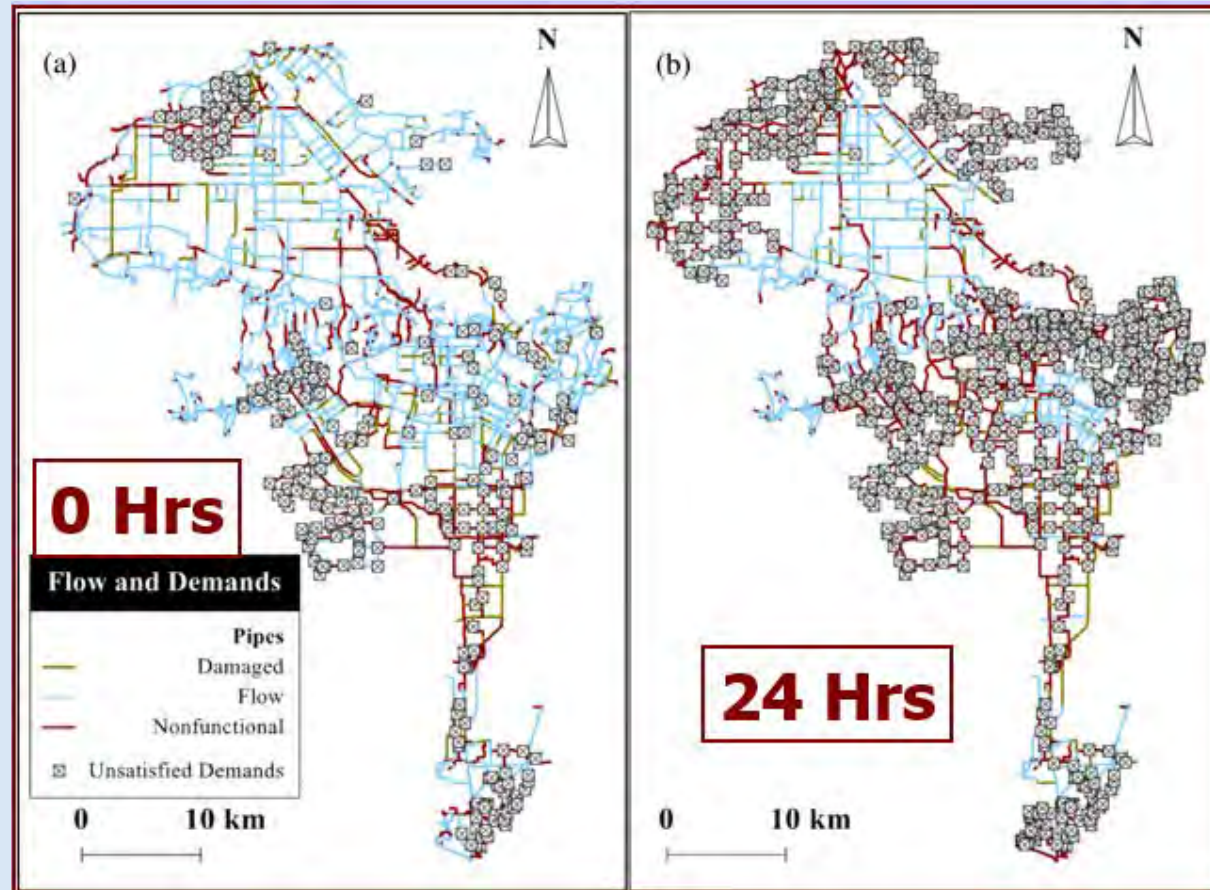
# GREAT CALIFORNIA SHAKEOUT

- Maximum PGVs close to 200 cm/s in Los Angeles
- Use correlations between PGV and RR to model damage in trunk line and distribution system

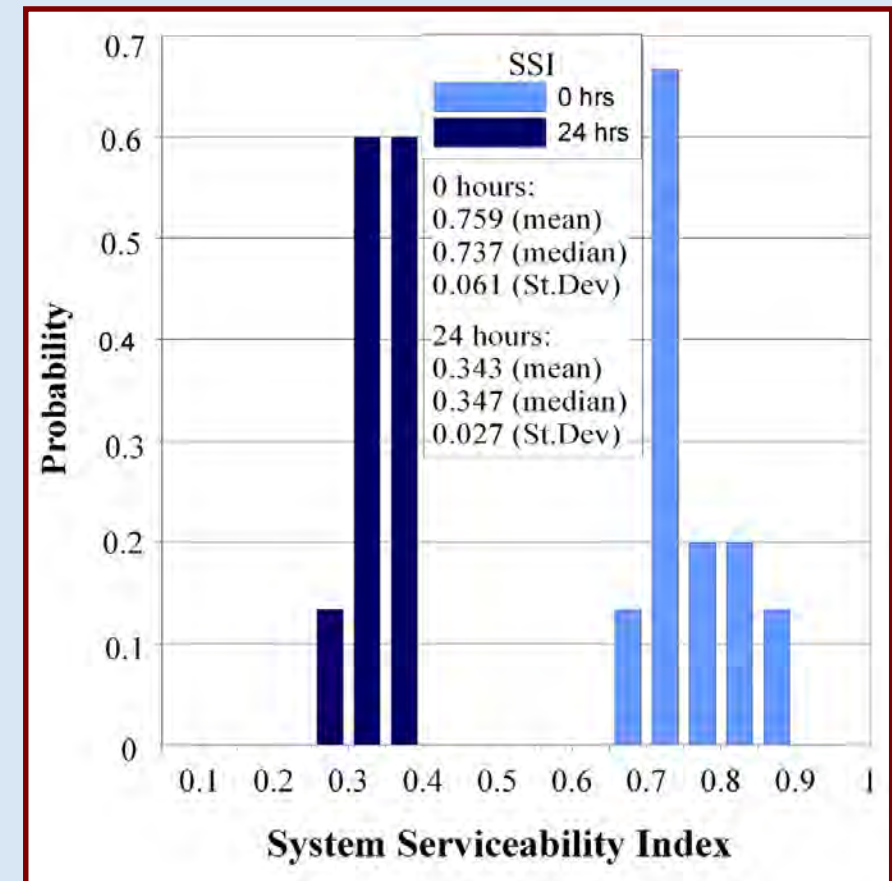


# LADWP SYSTEM SIMULATION

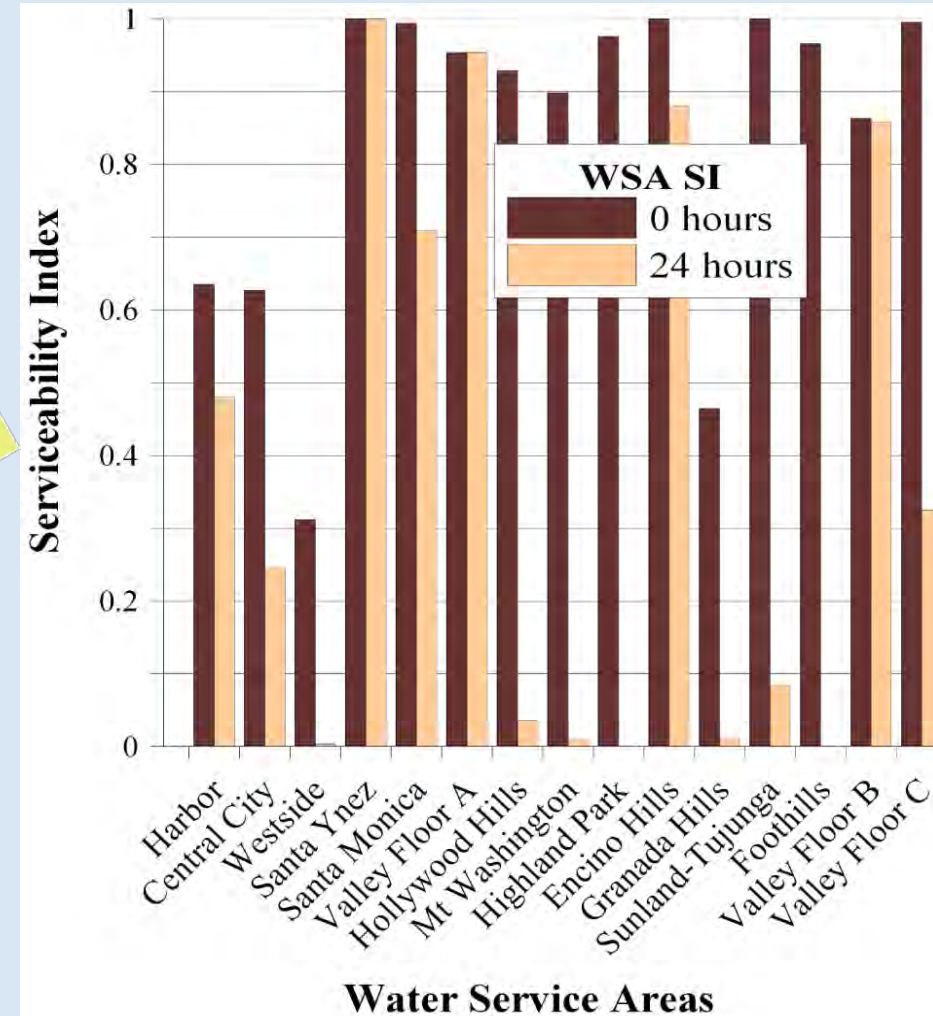
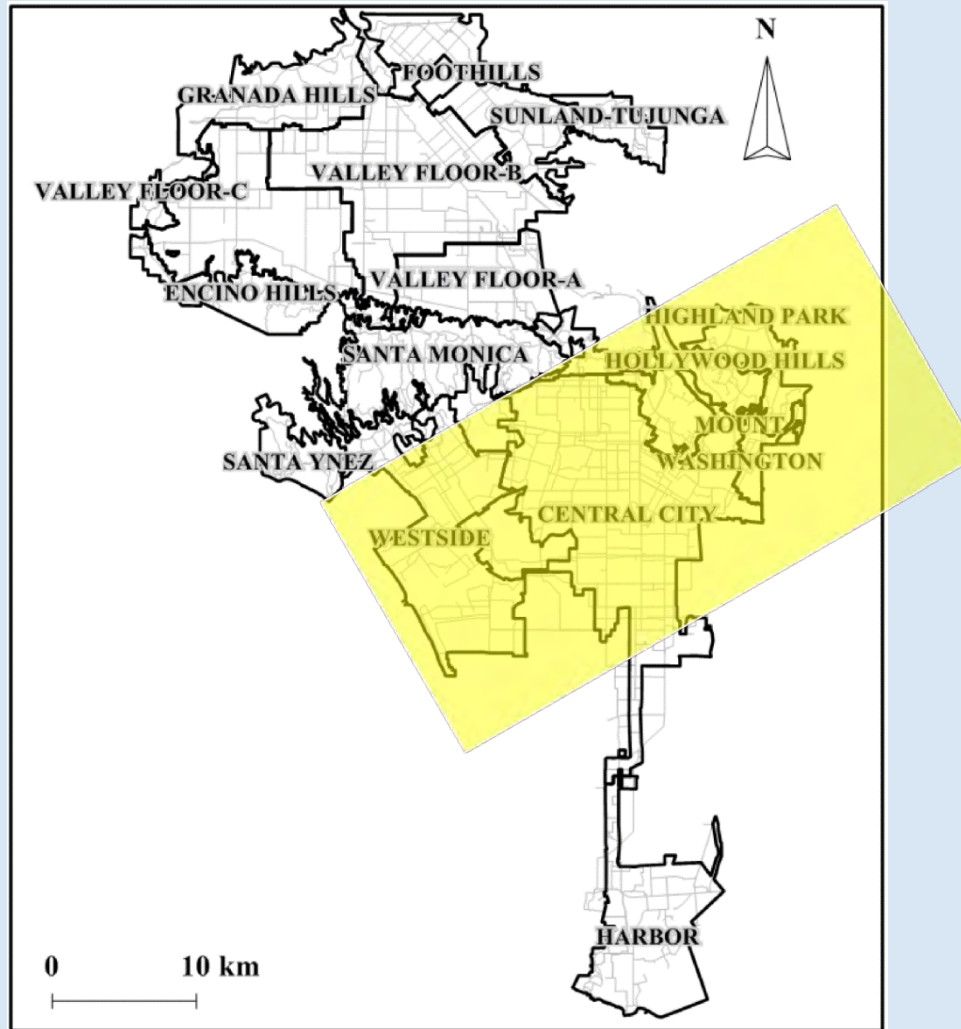
Time dependent effects from loss of local reservoirs



SSI is the ratio of water available at all system nodes after the EQ to water available before the EQ

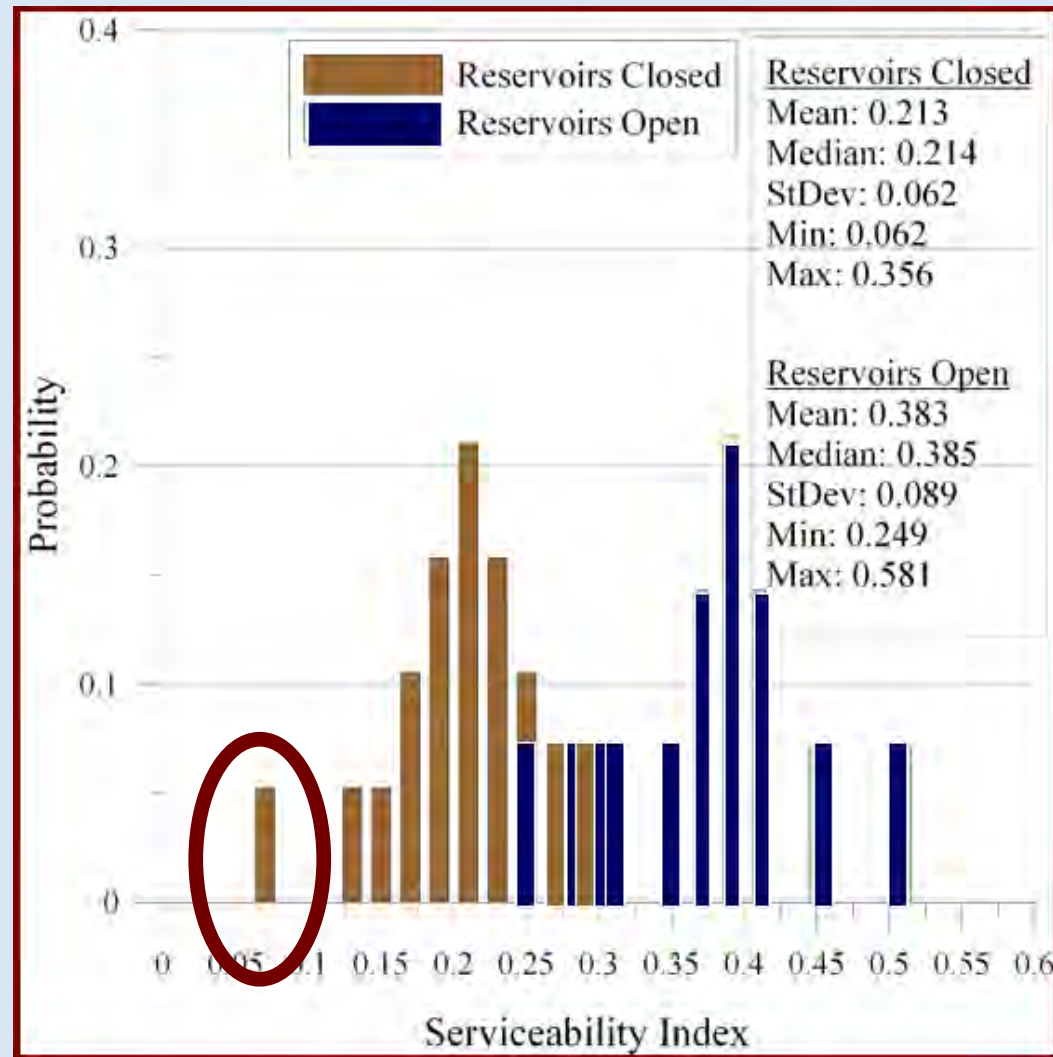


# WATER SERVICE AREAS



# EMERGENCY USE OF RESERVOIRS

SI for most populated areas of Los Angeles (Westside, Central City, Highland Park, and Mount Washington) performance with reservoirs on and off

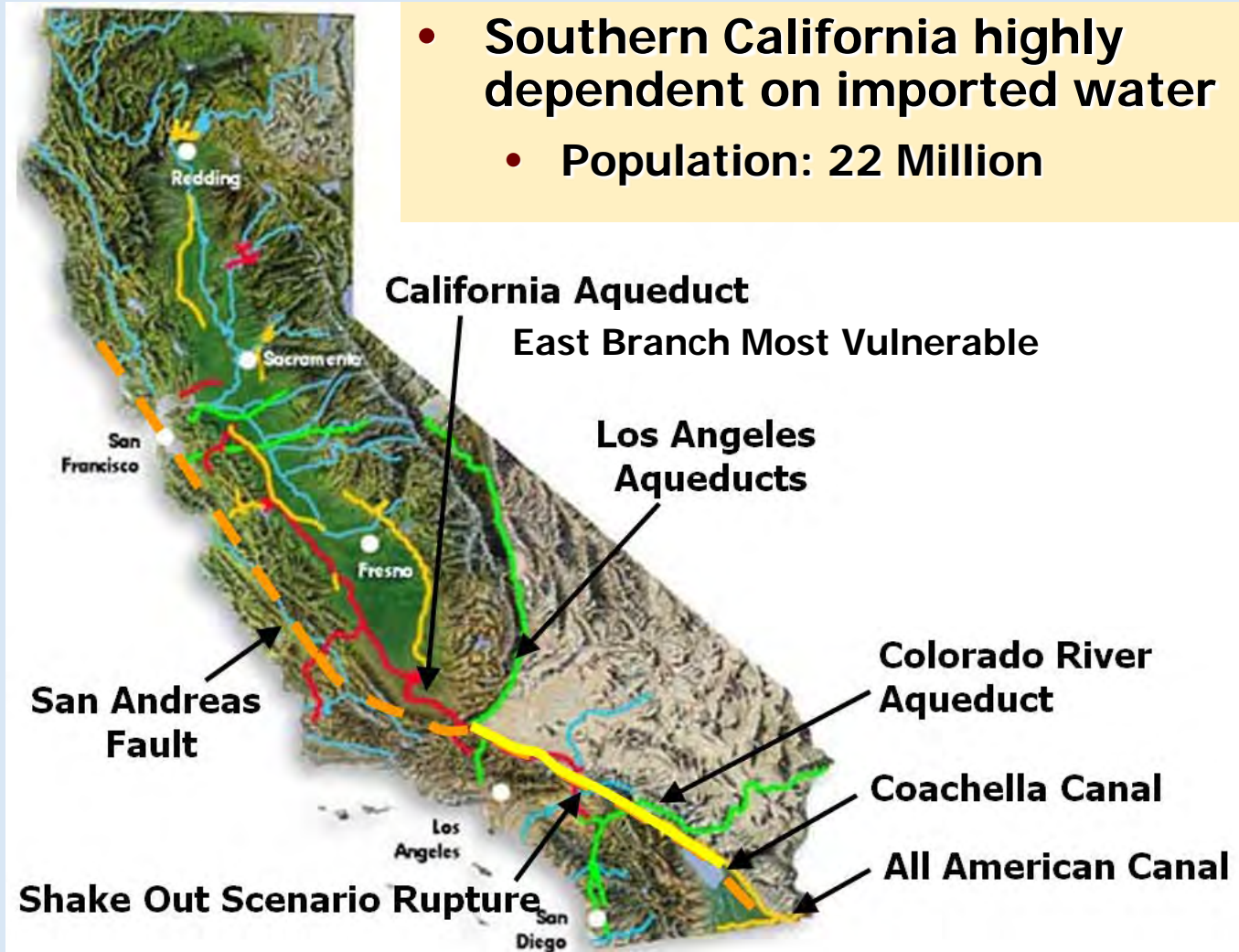


# LOS ANGELES RESILIENCE



- Strengthen Buildings
  - Soft story/non-ductile concrete
- Fortify Water System
  - Fire protection, resilient water pipelines
- Enhance Telecommunications

# SOUTHERN CALIFORNIA WATER SUPPLY



## 70% Imported Water:

- California Aqueduct
- Los Angeles Aqueducts
- Colorado River Aqueduct

## 30% Ground Water

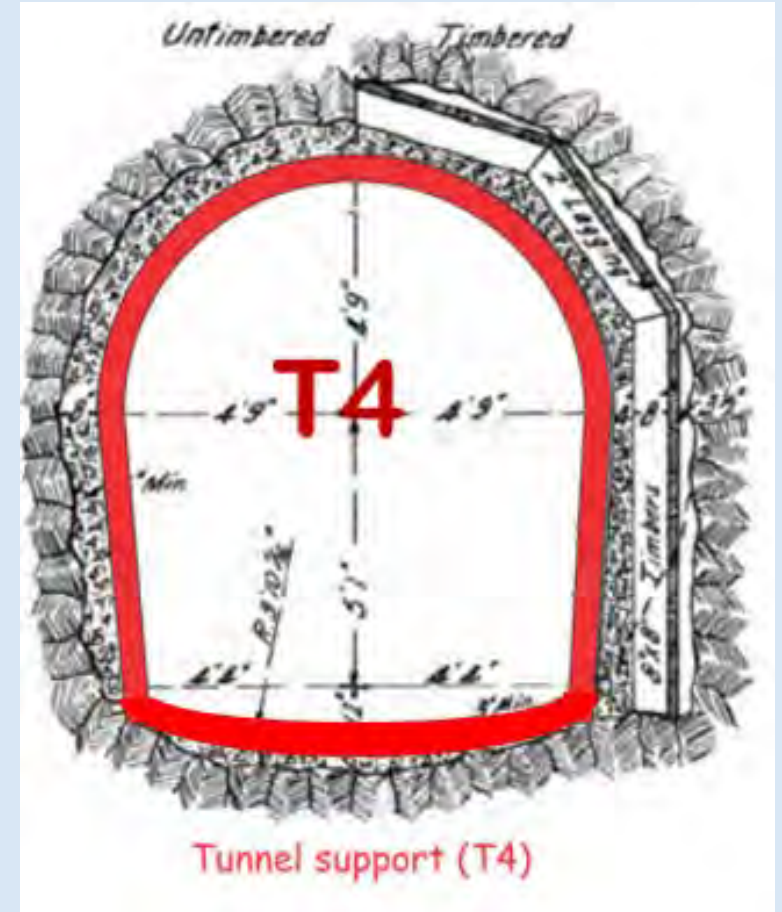
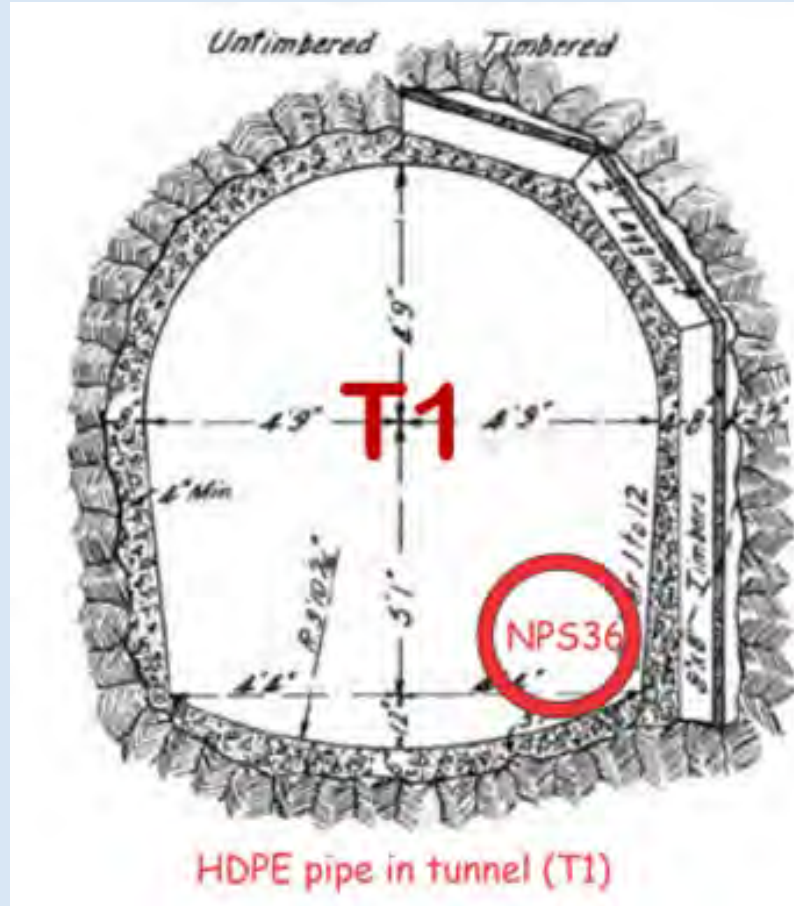
# LOS ANGELES AQUEDUCTS

- 3.3m Horizontal Fault Displacement (ShakeOut)
- 2.9m Wide Elizabeth Tunnel



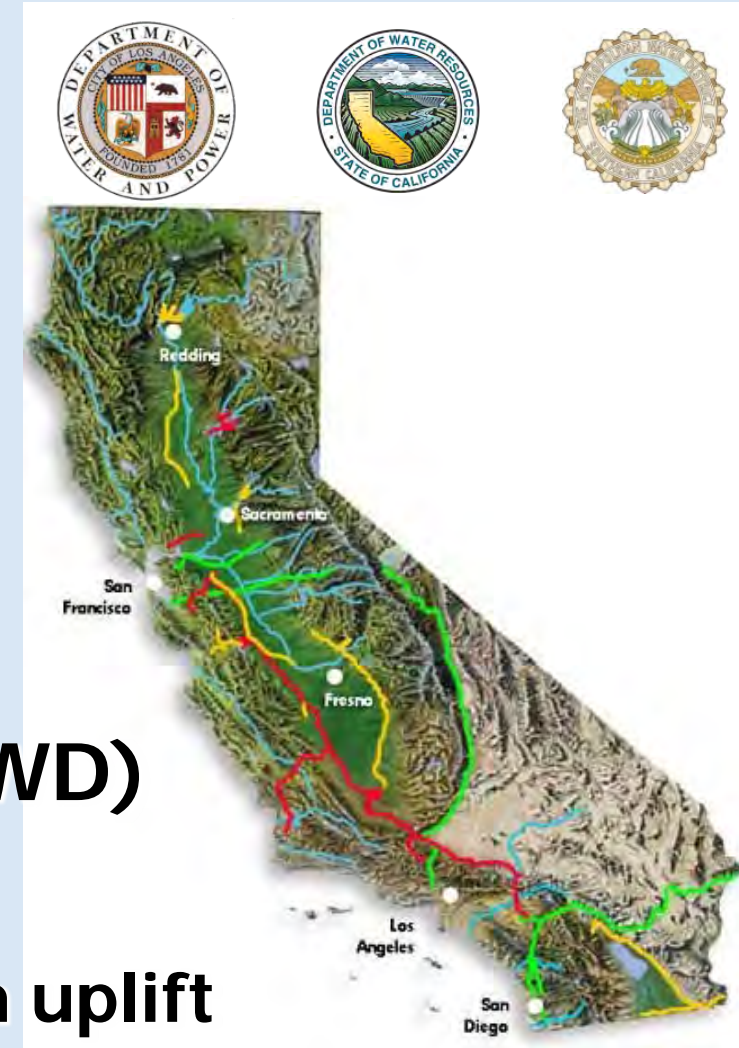
# LOS ANGELES AQUEDUCTS

- 3.3m Horizontal Fault Displacement (ShakeOut)
- 2.9m Wide Elizabeth Tunnel



# SEISMIC RESILIENT WATER SUPPLY TASK FORCE

- CA Aqueduct (CA DWR)
  - 49 billion m<sup>3</sup>/yr
  - Faulting Rupture >25 places
- LA Aqueducts (LADWP)
  - 390 million m<sup>3</sup>/yr
  - Elizabeth Tunnel
- Colorado River Aqueduct (MWD)
  - 900 million m<sup>3</sup>/yr
  - Multiple fault ruptures & > 1 m uplift



# **LESSONS LEARNED FROM LOS ANGELES**

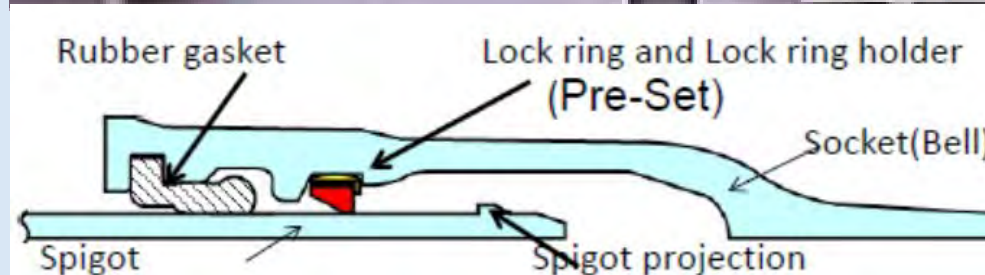
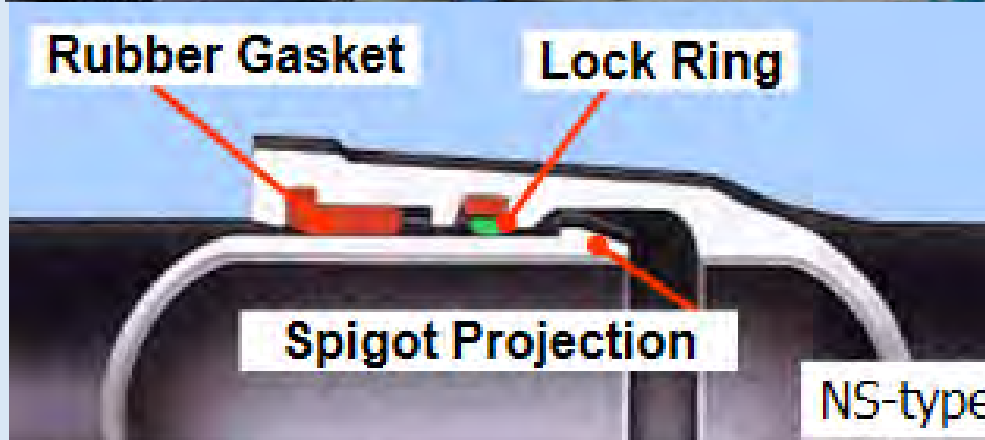
- **State-of-the-Art Decision Support System**
- **Emergency Response Strategy for Major Earthquakes**
- **Key Aspect of Organization Resilience Is Ability to Improvise**
- **Historic Collaboration for Resilience of Southern California Water Supply**



# TOPIC

- **Next Generation Hazard Resilient Infrastructure**

# NEXT GENERATION HAZARD-RESILIENT PIPELINES

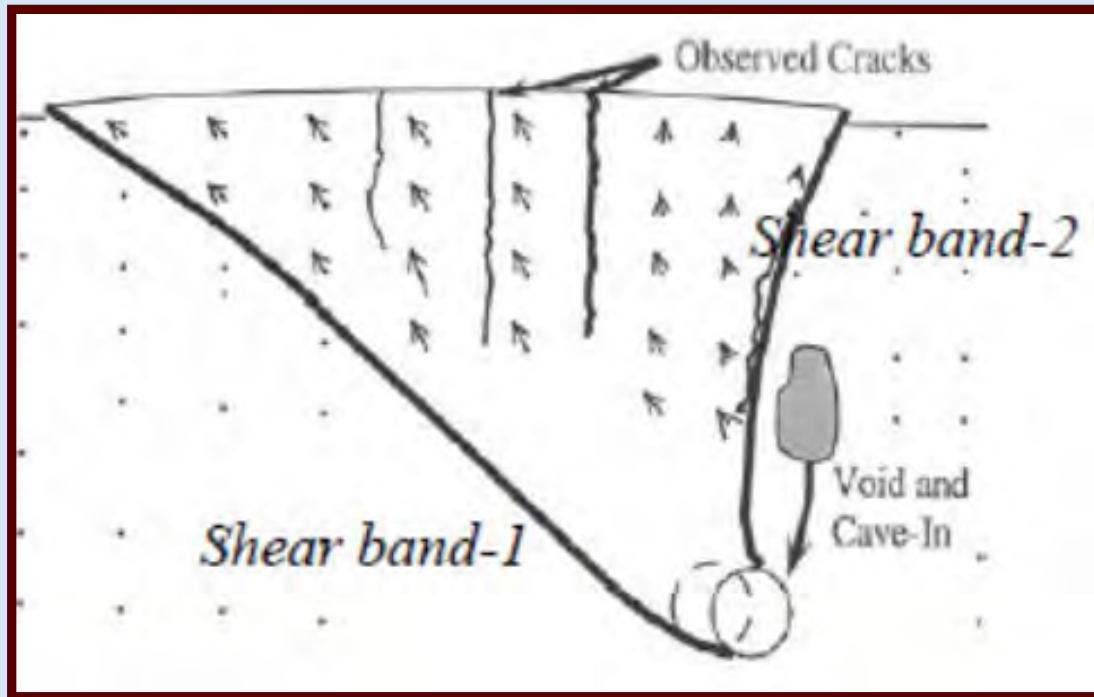


Wall Street Journal Photo



# EXTREME SOIL-PIPELINE INTERACTION

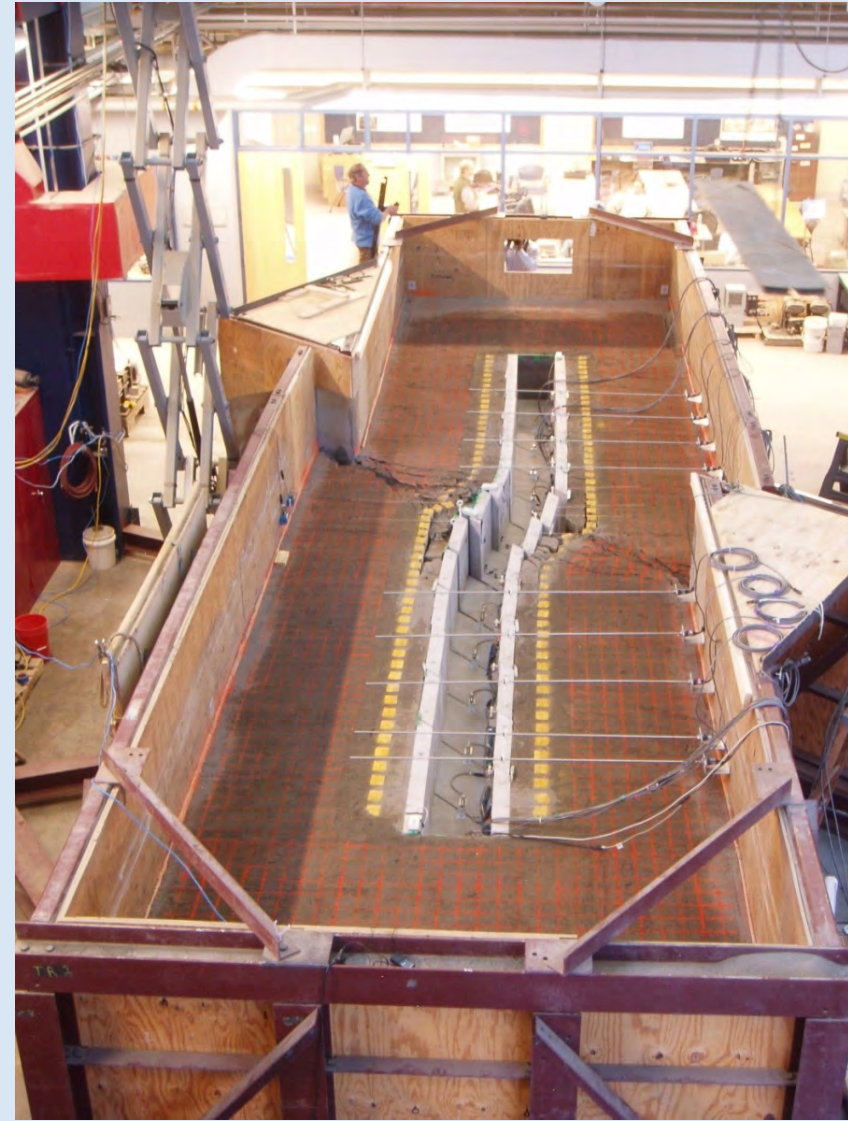
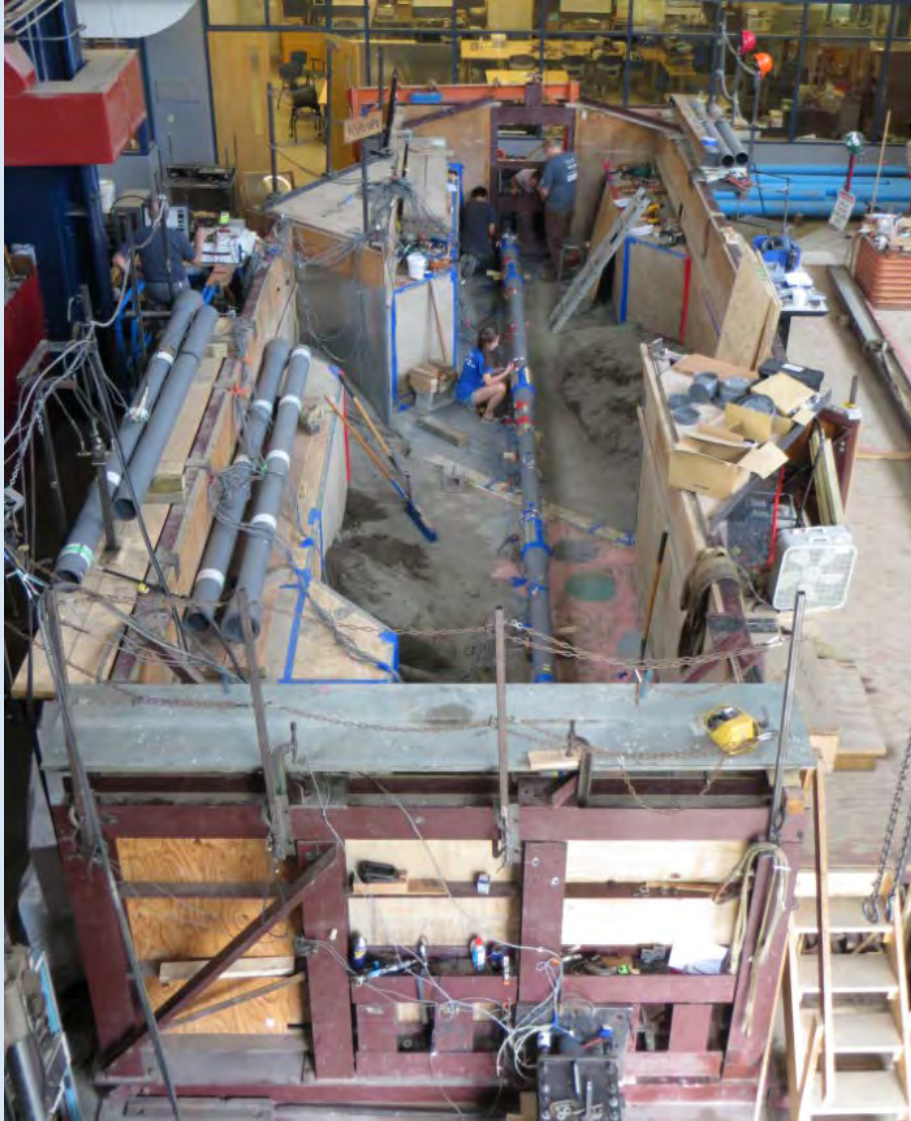
Soil Material & Geometric  
Nonlinearities



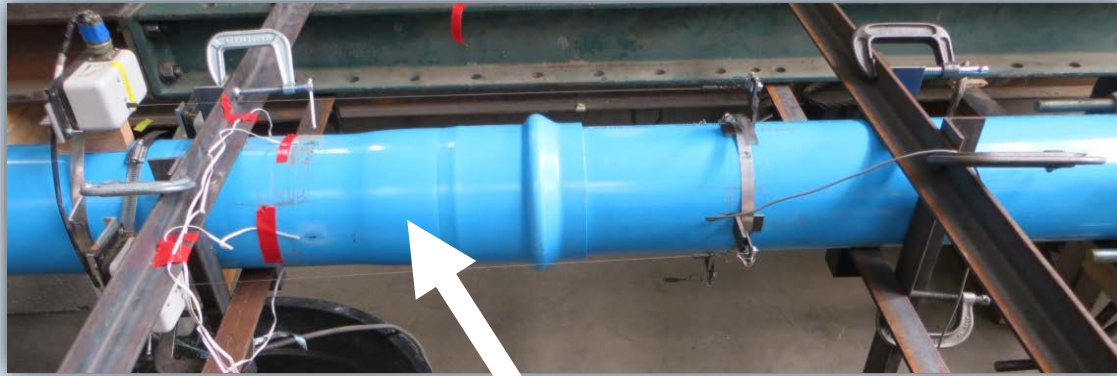
Pipeline Material &  
Geometric Nonlinearities



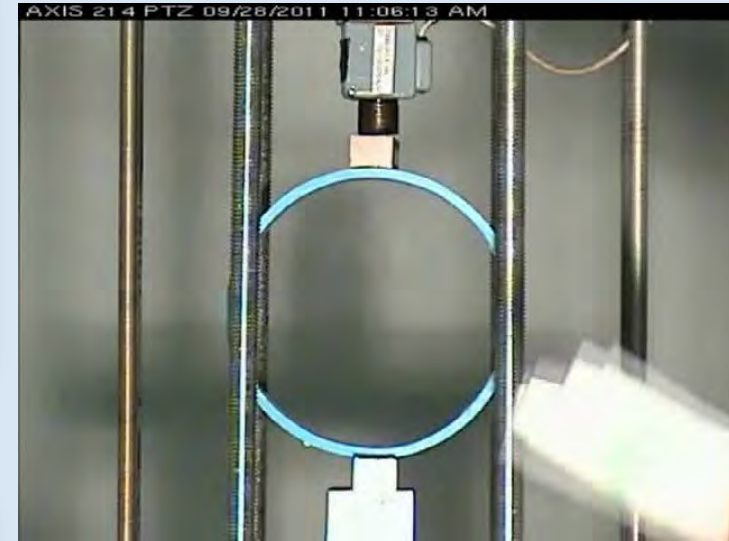
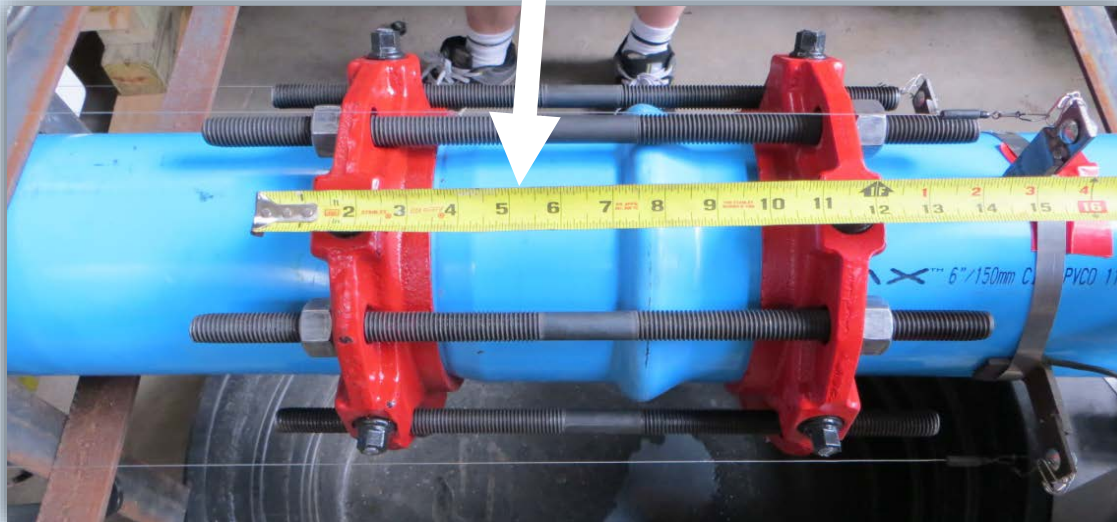
# LARGE-SCALE TESTING: NEXT GENERATION INFRASTRUCTURE



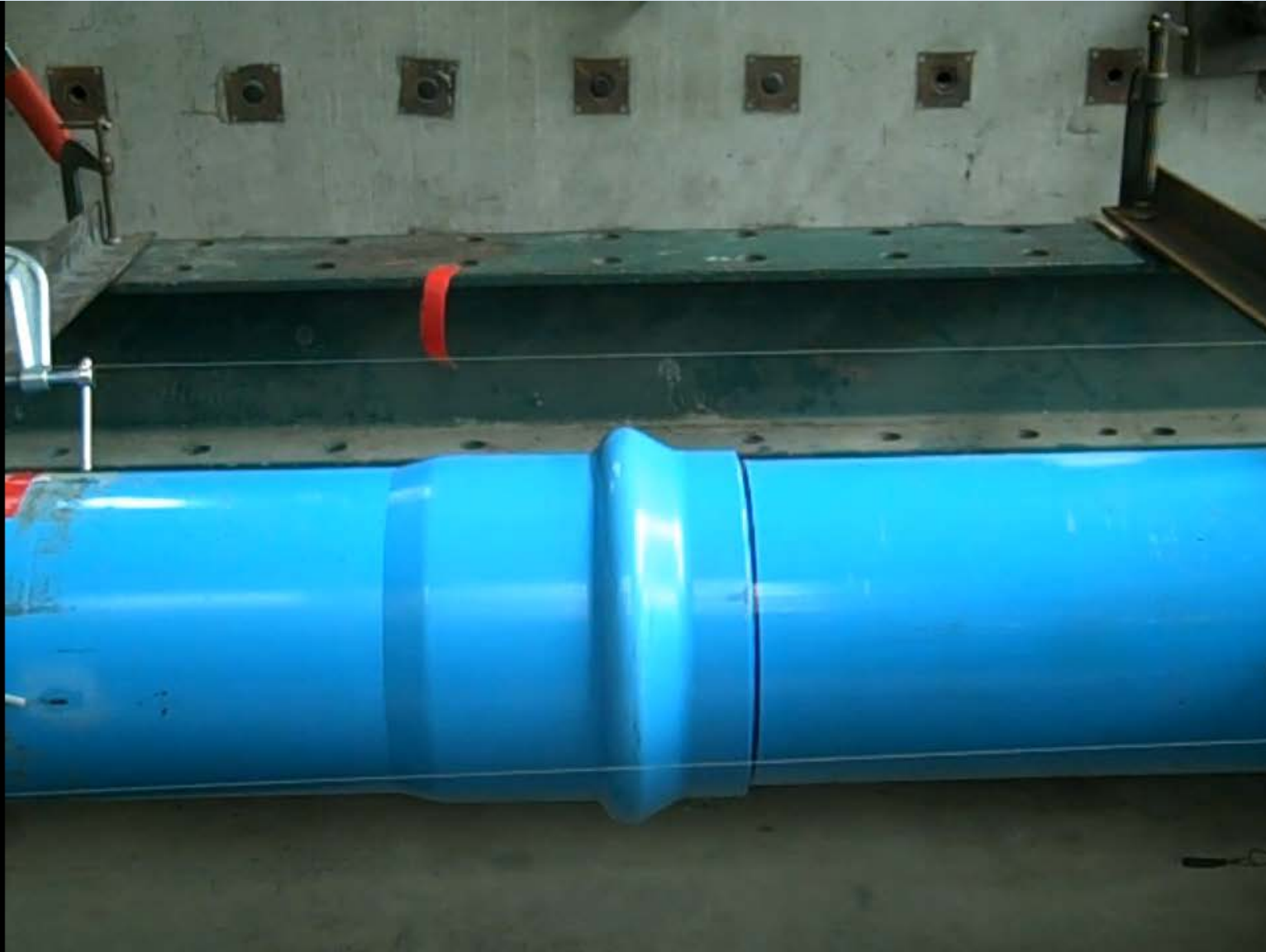
# ORIENTED POLYVINYL CHLORIDE (PVCO) JOINTS



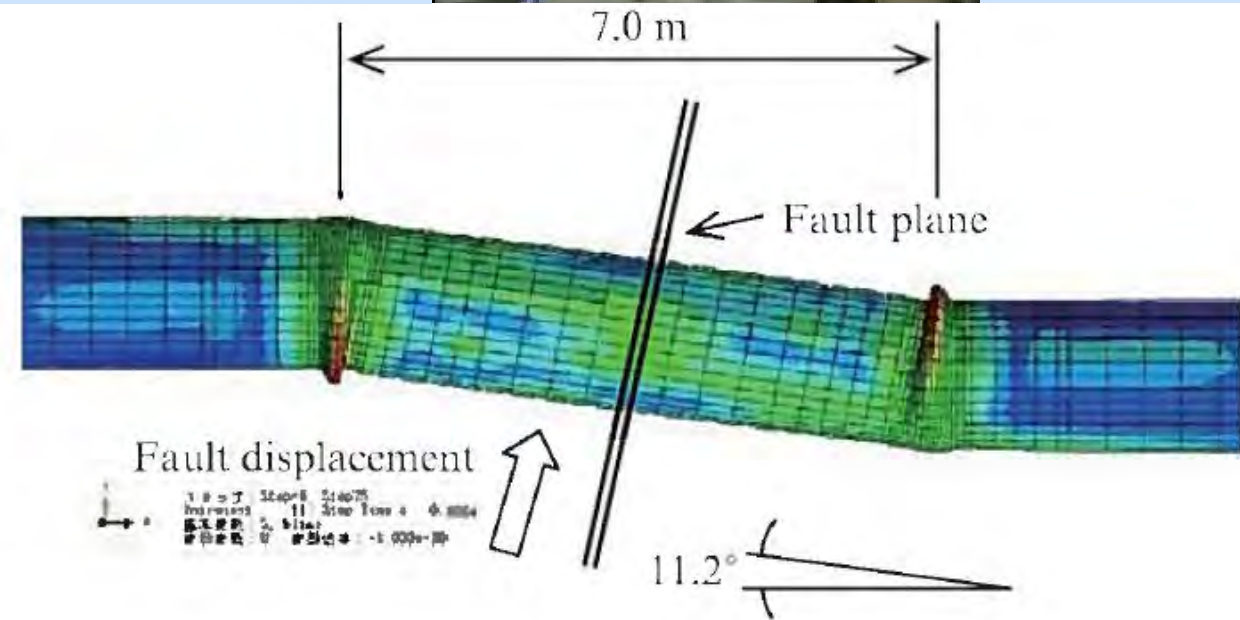
Spigot Compressed into Bell



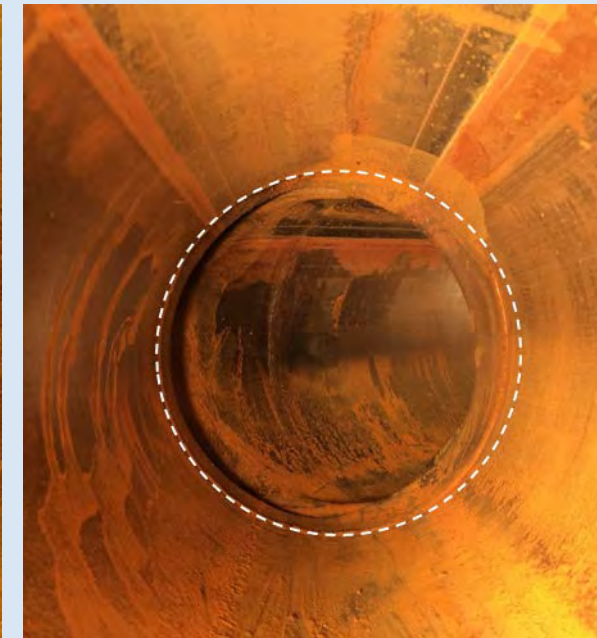
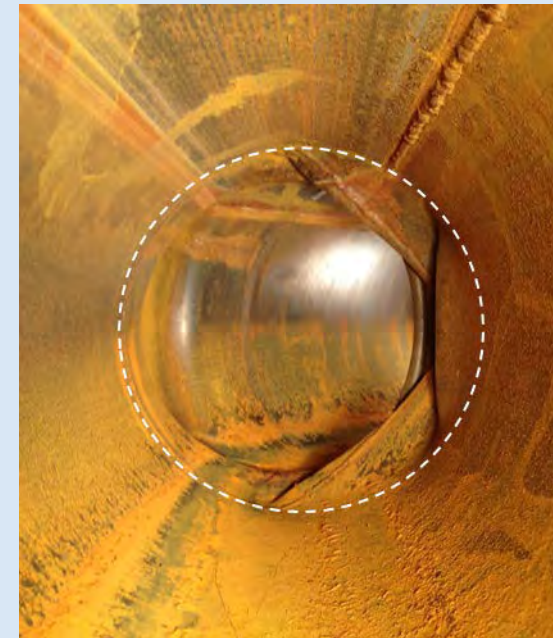
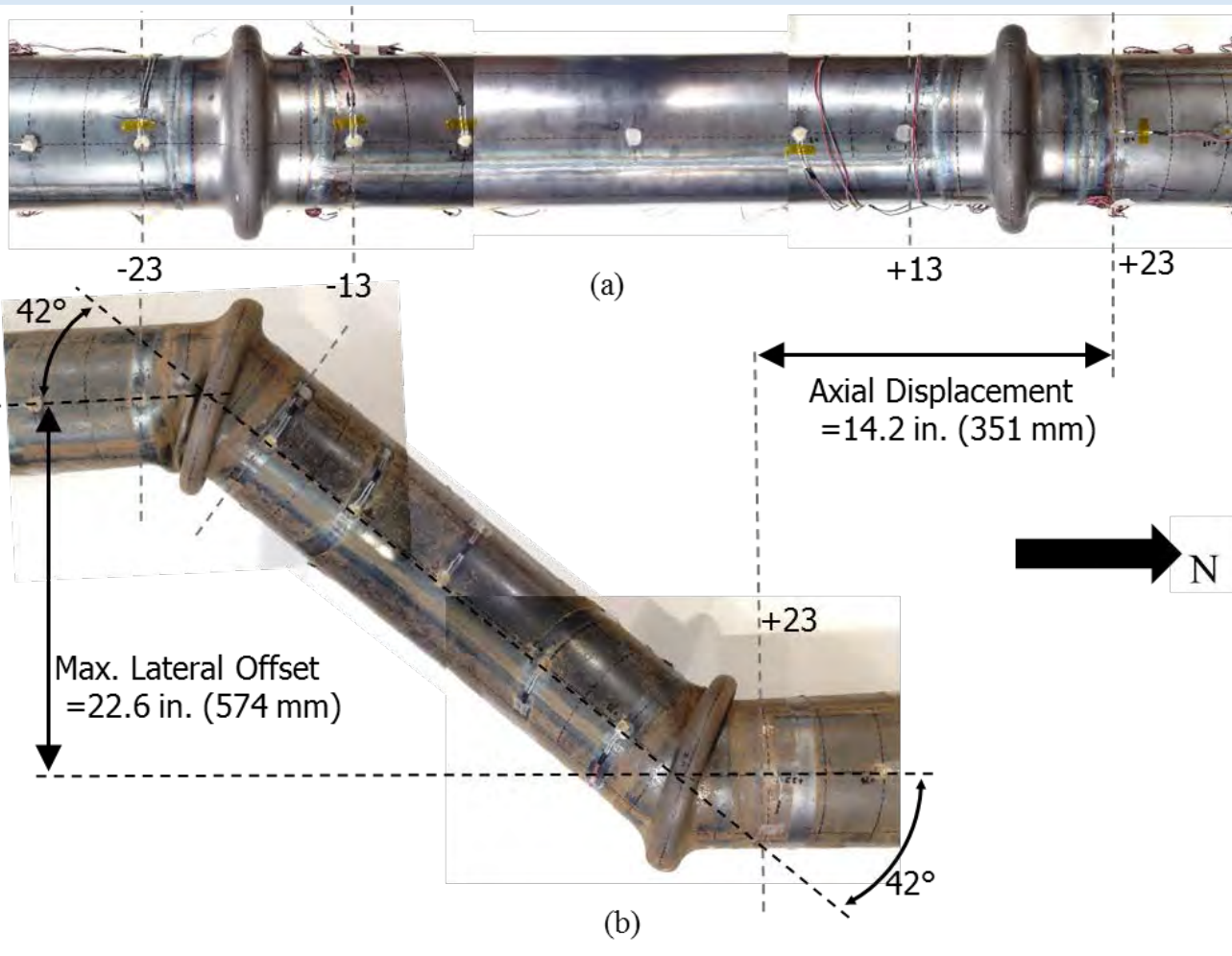
# ORIENTED POLYVINYL CHLORIDE (PVCO) JOINTS



# CONTROLLED BUCKLING



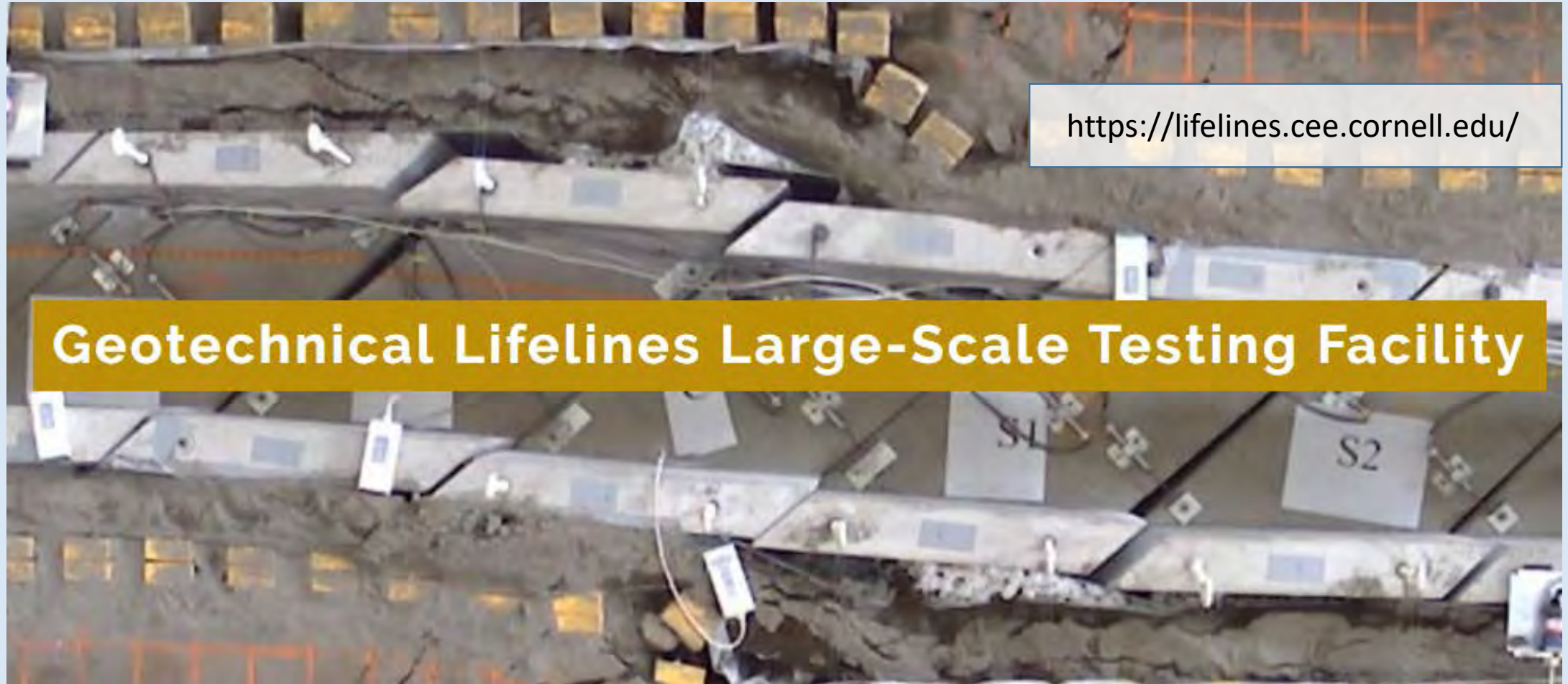
# CONTROLLED BUCKLING



# LESSONS: NEXT GENERATION (HAZARD-RESILIENT) PIPELINES

- Paradigm Shift in Pipeline Technology
- Market-Driven Research Funded by Industry
- Can't Have Resilience Unless You Have a *Market*
- Next Generation Hazard-Resilient Pipeline Simulation Models

# CORNELL LARGE-SCALE LIFELINES LABORATORY



# ADVANCED SENSORS

- Collaboration Among University of Cambridge, Cornell, and UC Berkeley
- Demonstrate Proof of Concept
  - Distributed Fiber Optics
    - Joint Movement
    - Pipeline Bending Strains & Displacement
  - Time Domain Reflectometry
    - Leakage
  - Underground Wireless
    - Data Transmission *Without* Wires



# LESSONS: NEXT GENERATION (HAZARD-RESILIENT) PIPELINES

- Paradigm Shift in Pipeline Technology
- Market-Driven Research Funded by Industry
- Can't Have Resilience Unless You Have a *Intelligence*
- Next Generation Hazard-Resilient Pipeline Simulation Models