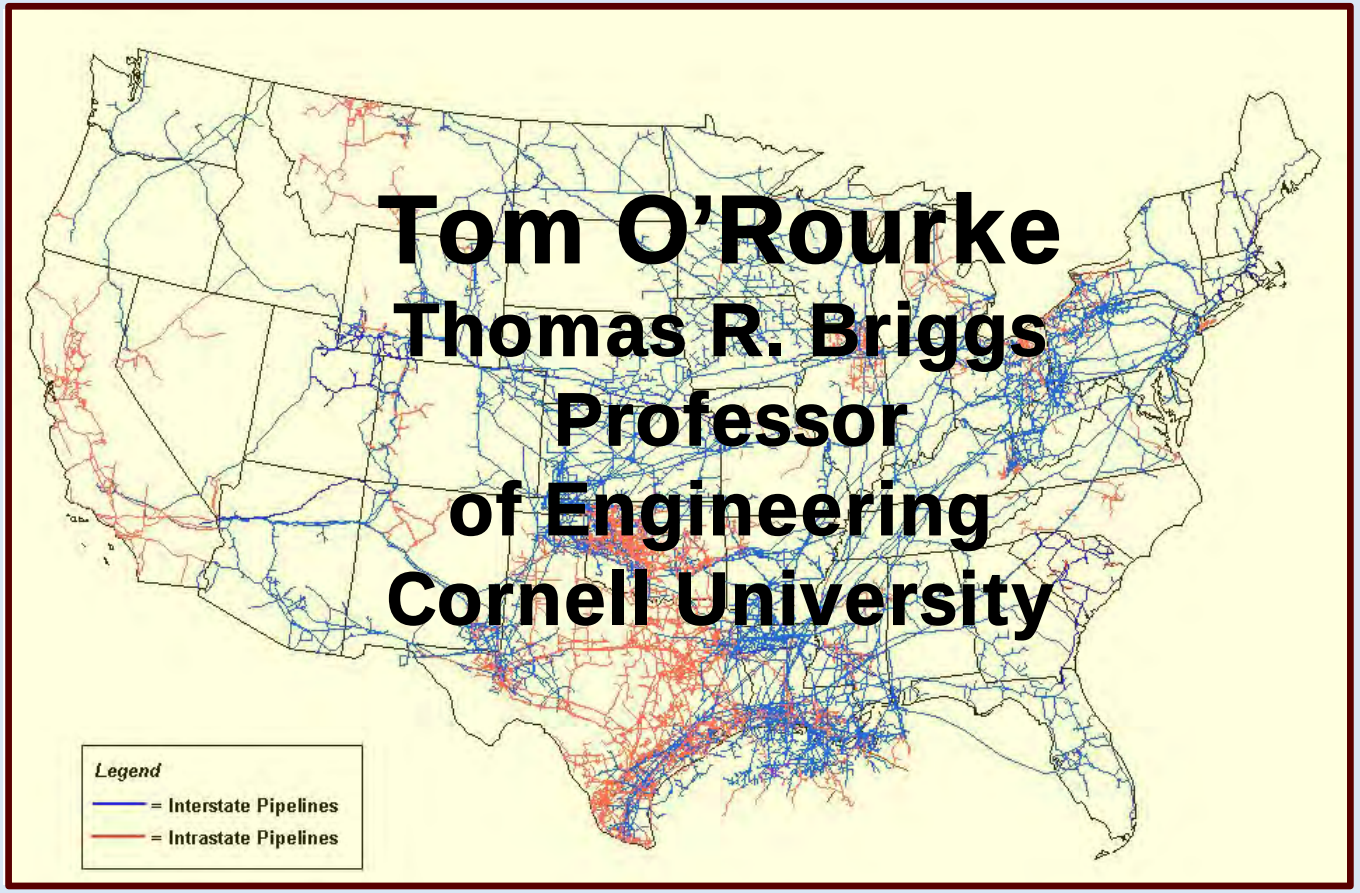
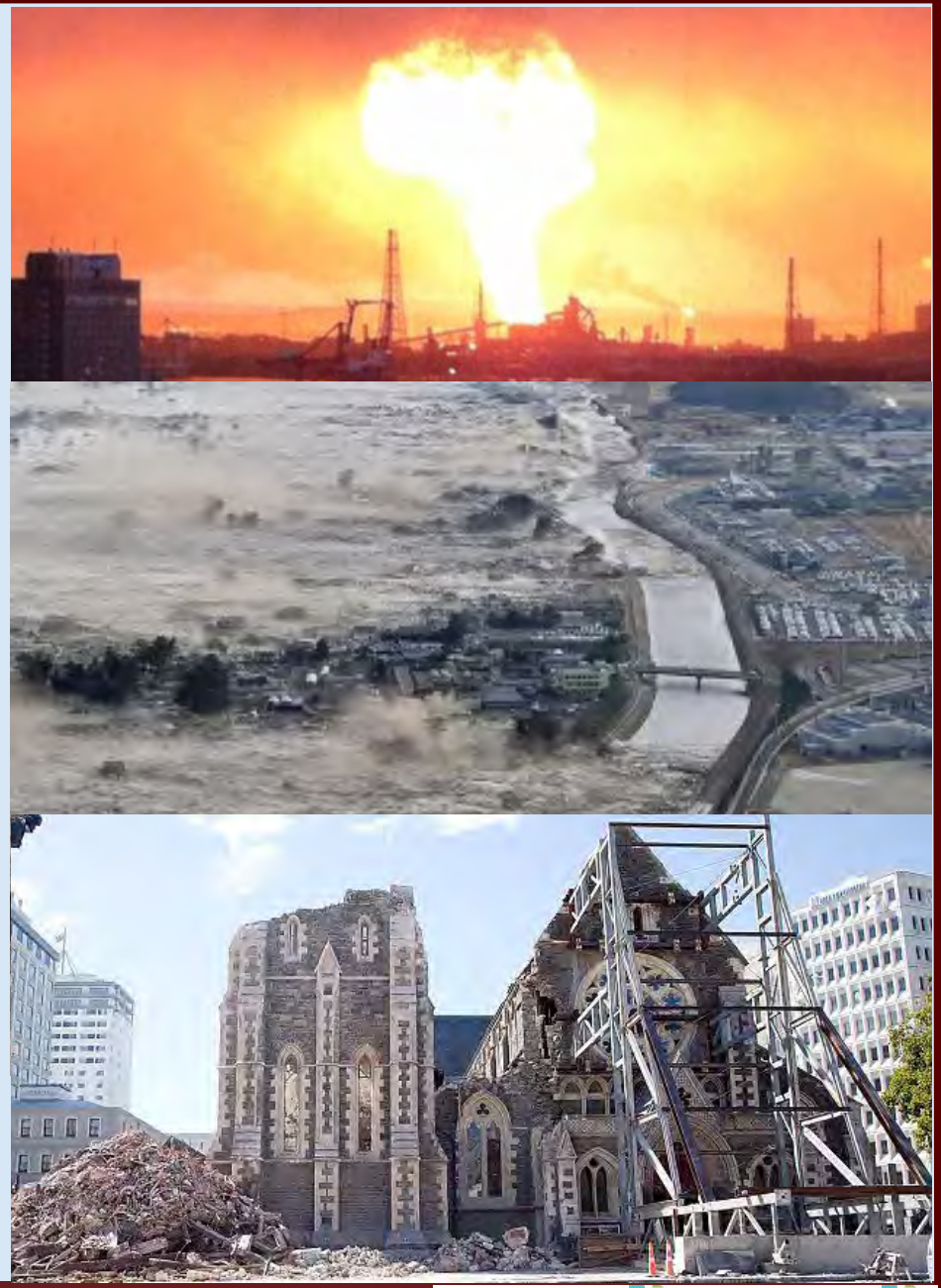
SEISMIC RESILIENT PIPELINES

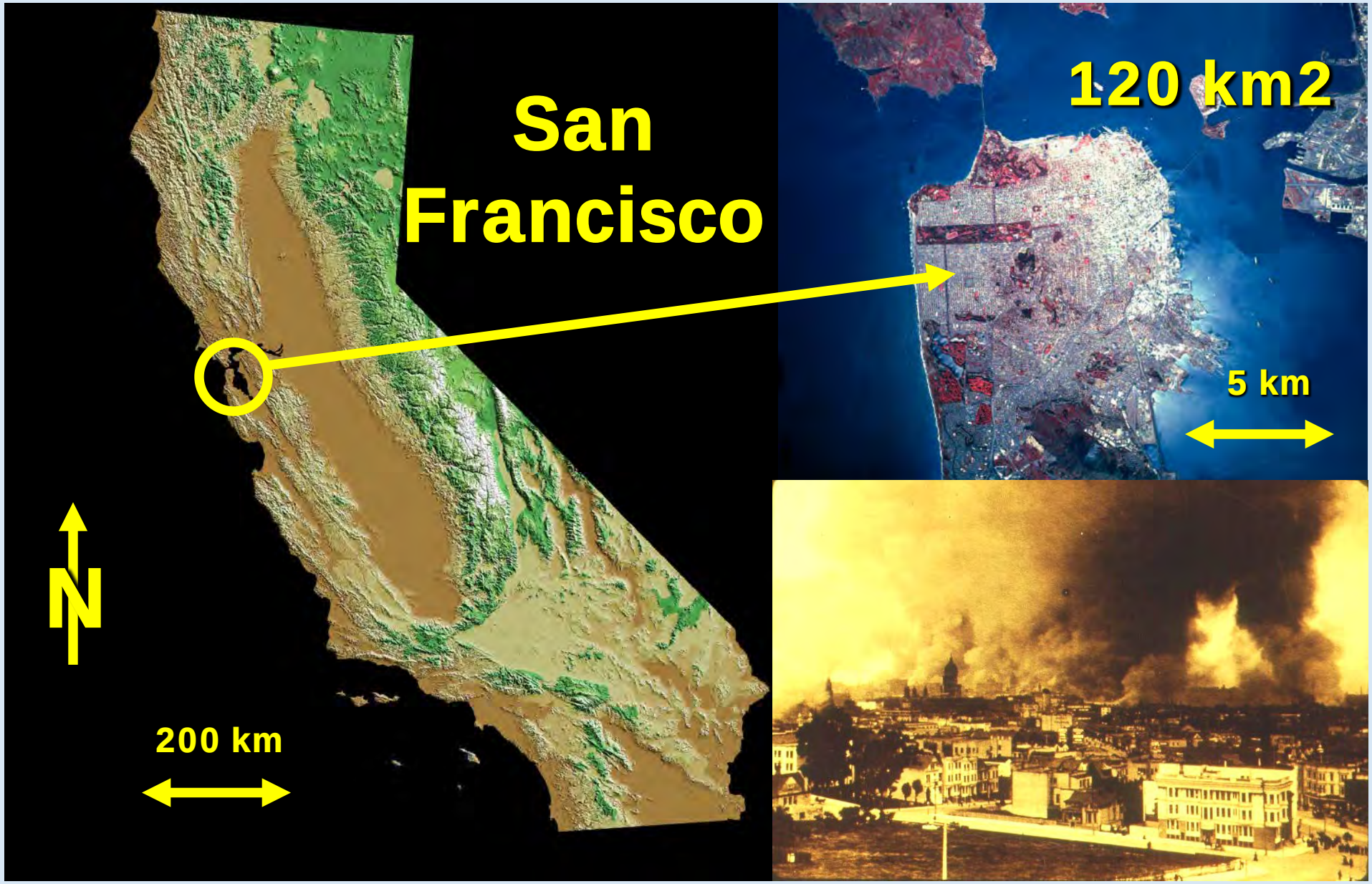


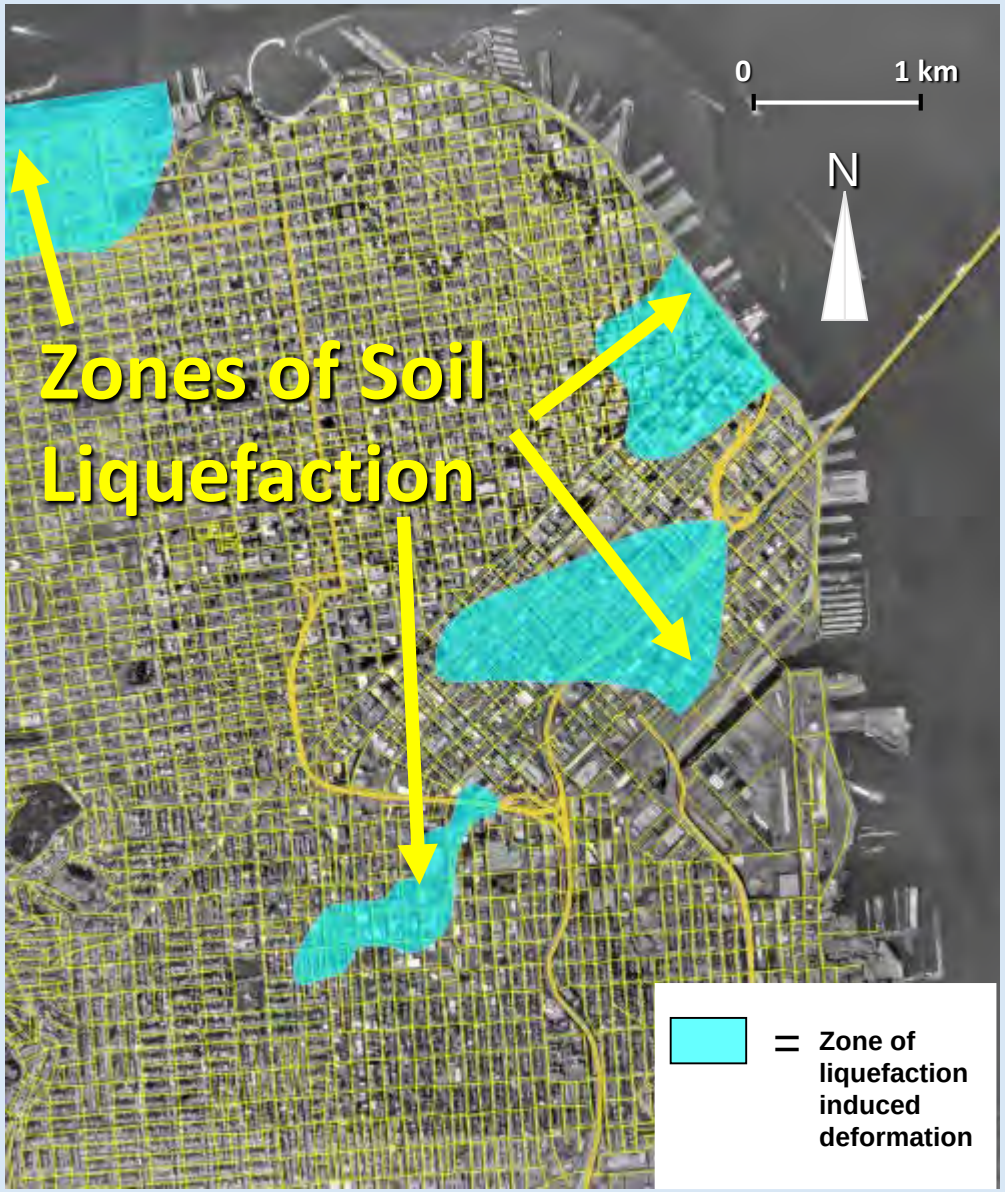
Tom O'Rourke
Thomas R. Briggs
Professor
of Engineering
Cornell University



TOPICS

- San Francisco
- Los Angeles
- New Zealand
- Earthquake Effects
- Next Generation Pipelines
- Pipeline Intelligence


San Francisco
120 km2
5 km
N
200 km



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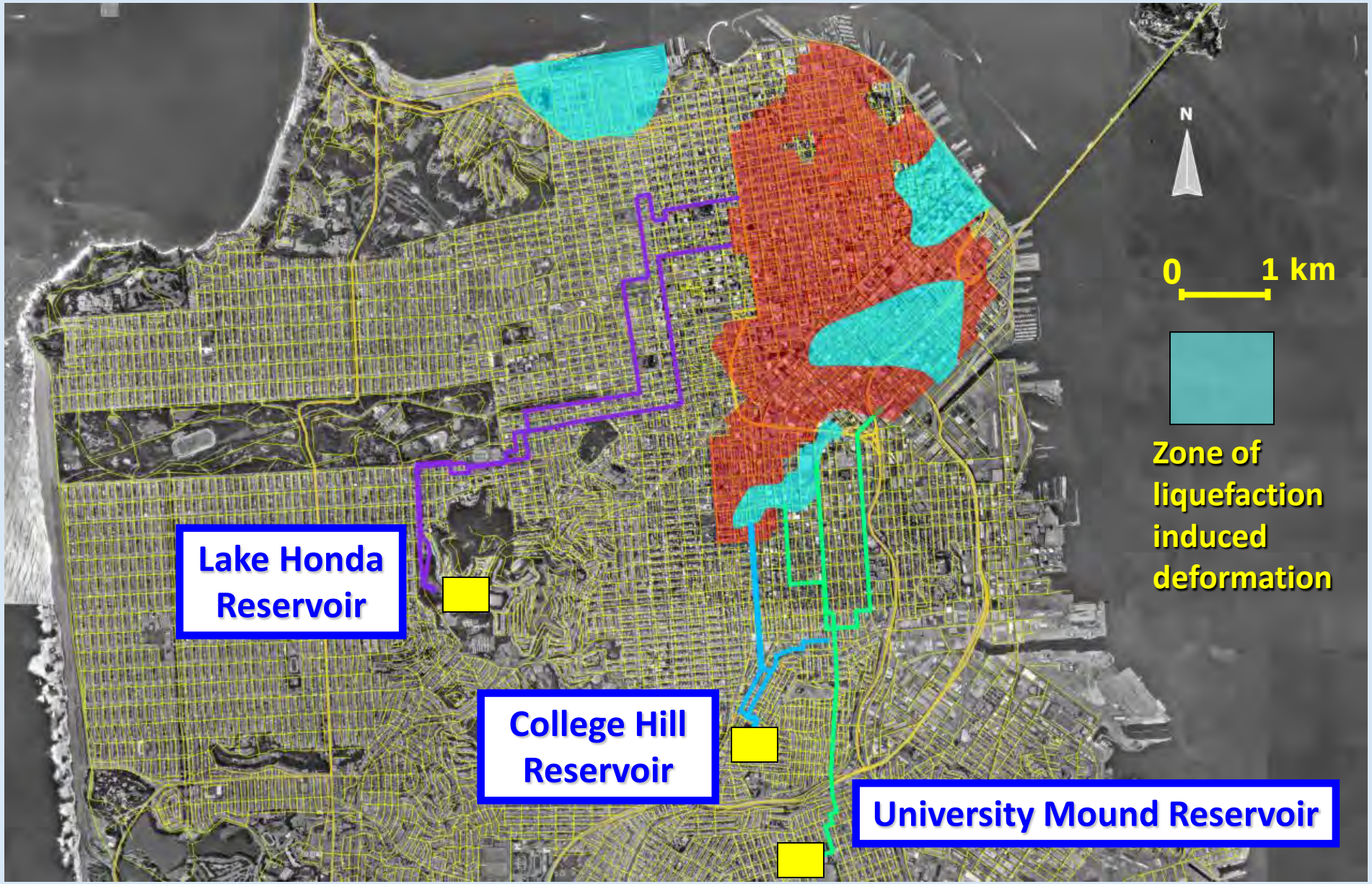
SEISMIC RESILIENT PIPELINES

SCAG SCAG



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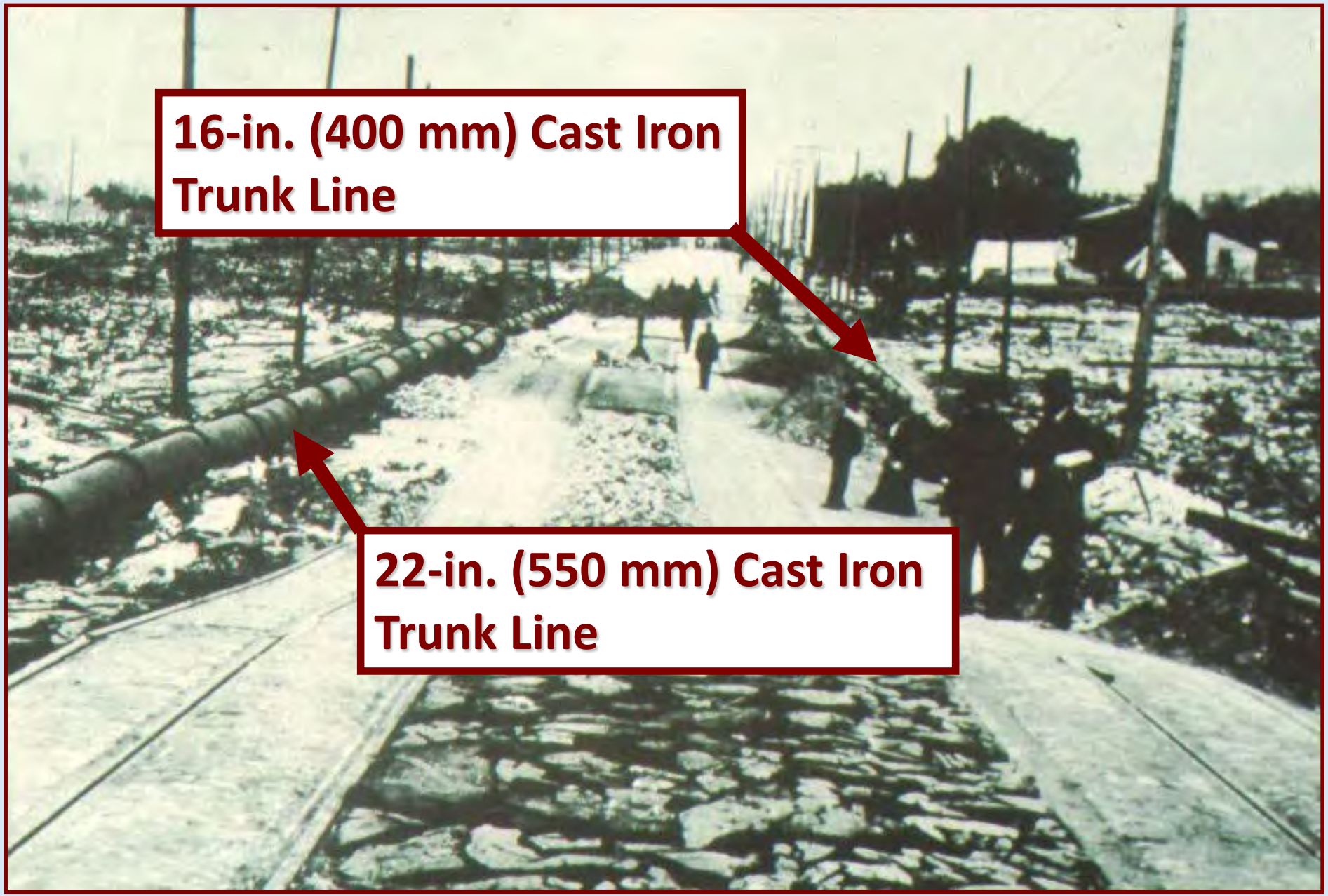
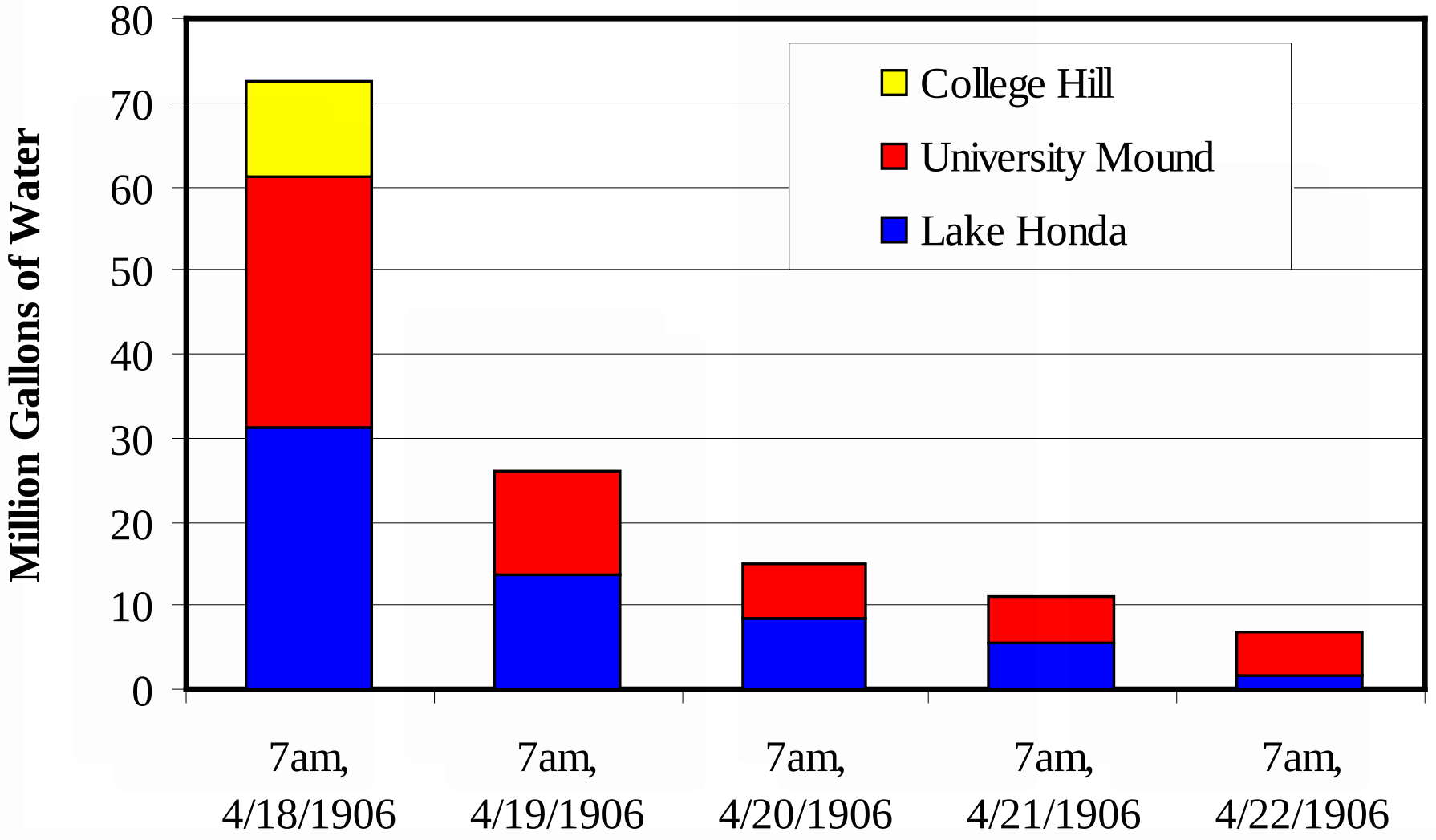
SEISMIC RESILIENT PIPELINES

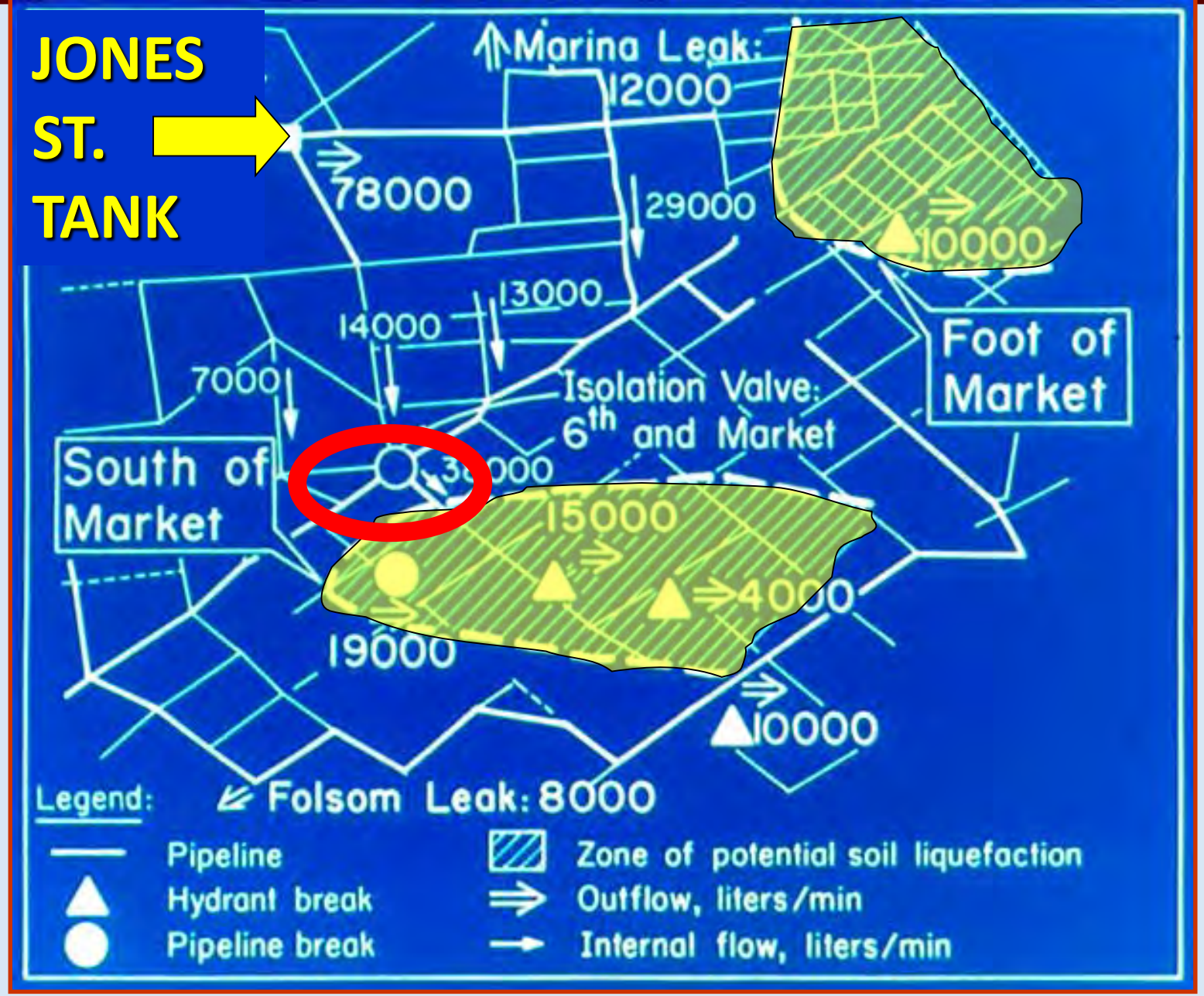
SCAG SCAG


16-in. (400 mm) Cast Iron Trunk Line
22-in. (550 mm) Cast Iron Trunk Line

1906 Earthquake Water Loss



AUXILIARY WATER SUPPLY SYSTEM


JONES ST. TANK
Marina Leak: 12000
78000
29000
10000
13000
14000
7000
Isolation Valve: 6th and Market
Foot of Market
South of Market
15000
4000
19000
10000
Folsom Leak: 8000
Legend:
Pipeline
Hydrant break
Pipeline break
Zone of potential soil liquefaction
Outflow, liters/min
Internal flow, liters/min

1989 LOMA PRIETA EARTHQUAKE

EARTHQUAKE SAFETY AND EMERGENCY RESPONSE BOND

Projects and Programs	Cost (millions)
AWSS Core Facilities	$35.0
Critical Firefighting Facilities and Infrastructure	134.3
Public Safety Building	243.0
Total	**$412.3**

Neighborhood Fire Stations	$65.1 M
Firefighting Cisterns	$36.6 M
Firefighting Pipes and Tunnels	$32.6 M
Total CFFI	**$134.3 M**

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
Total	**$400 million**

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SEISMIC RESILIENT PIPELINES

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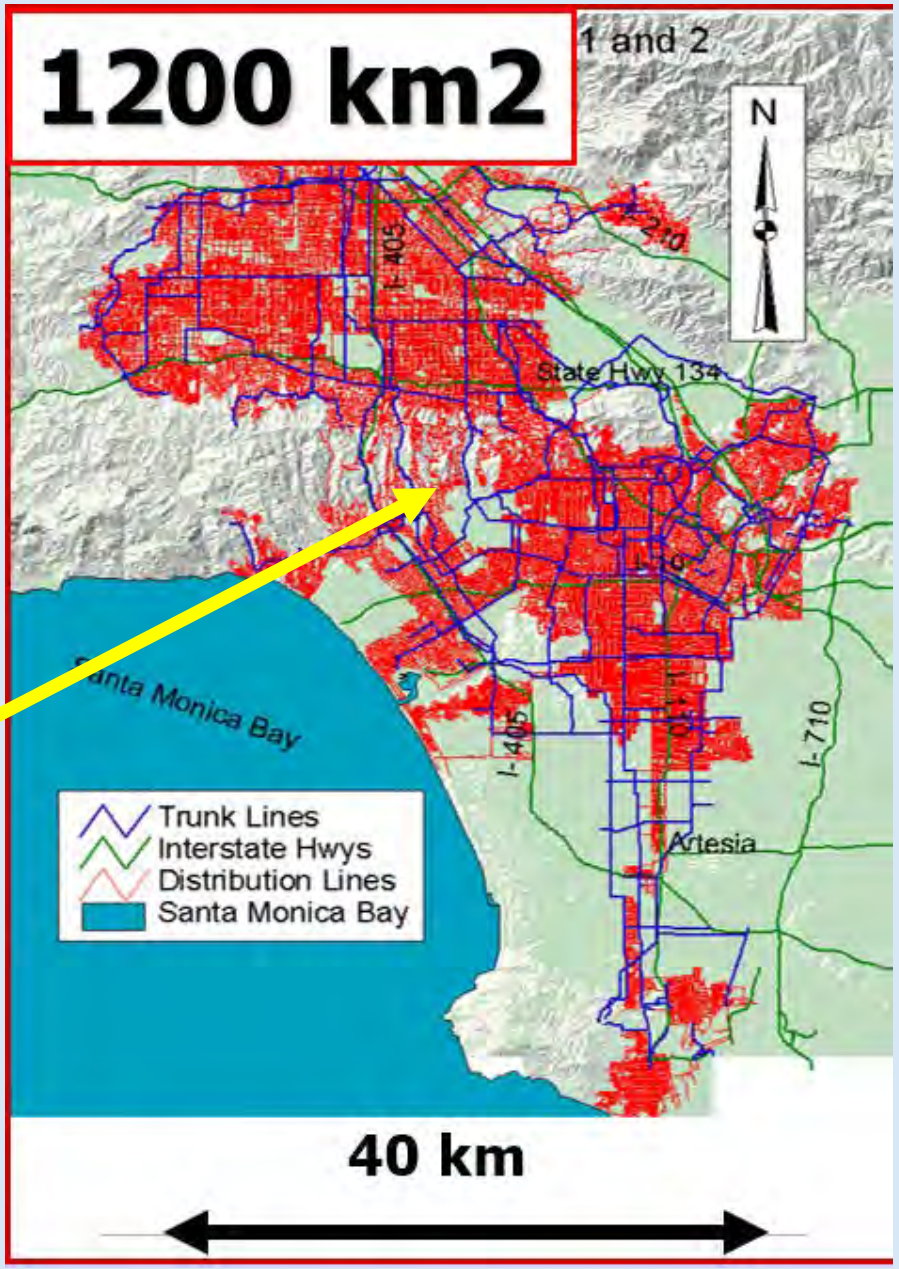
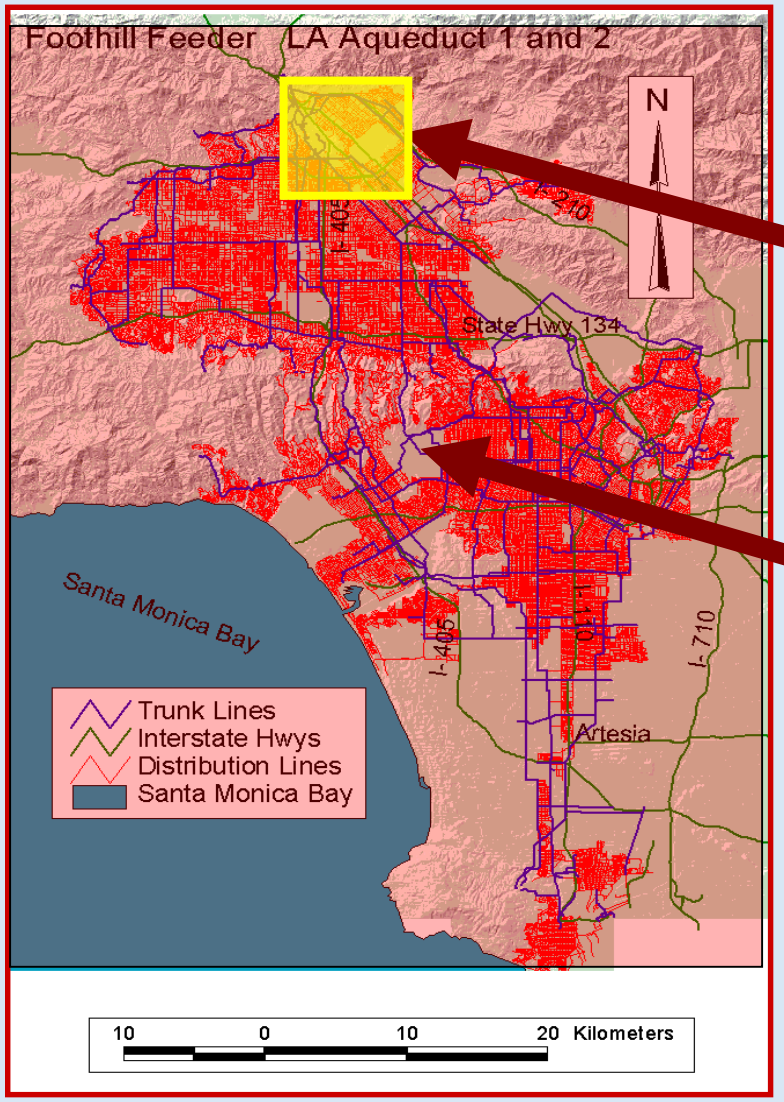
Los Angeles
N
200 km


1200 km2
1 and 2
N
I-405
I-210
State Hwy 134
I-10
I-110
I-405
I-710
Santa Monica Bay
Artesia
Trunk Lines
Interstate Hwys
Distribution Lines
Santa Monica Bay
40 km

MULTI-MODAL SIMULATION

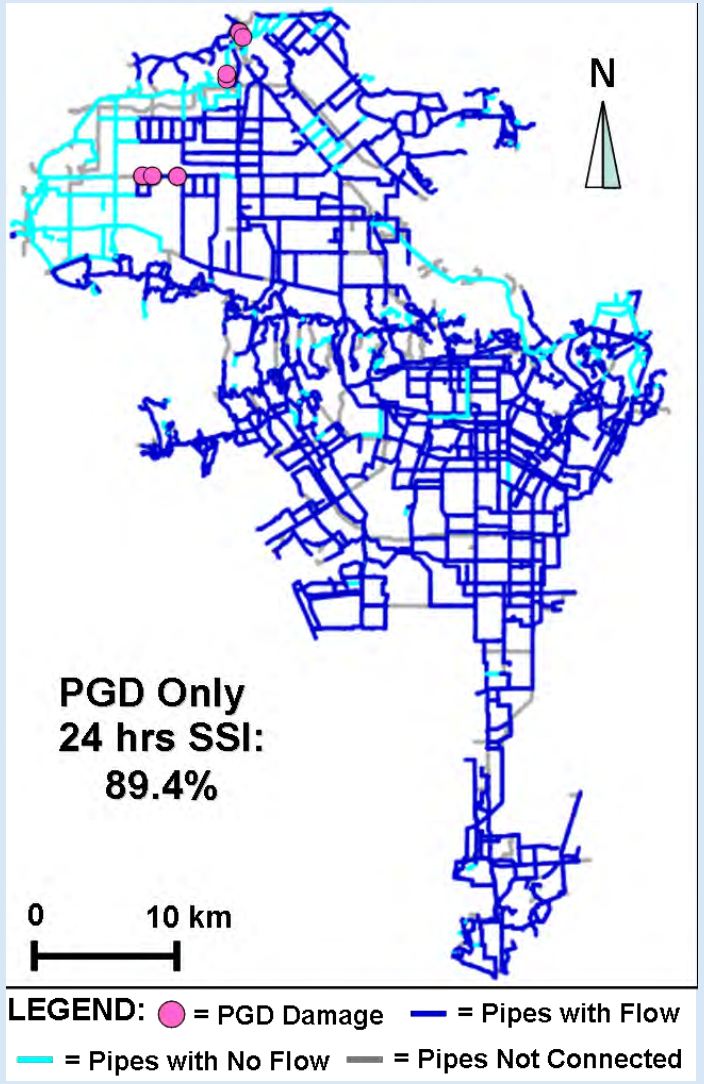


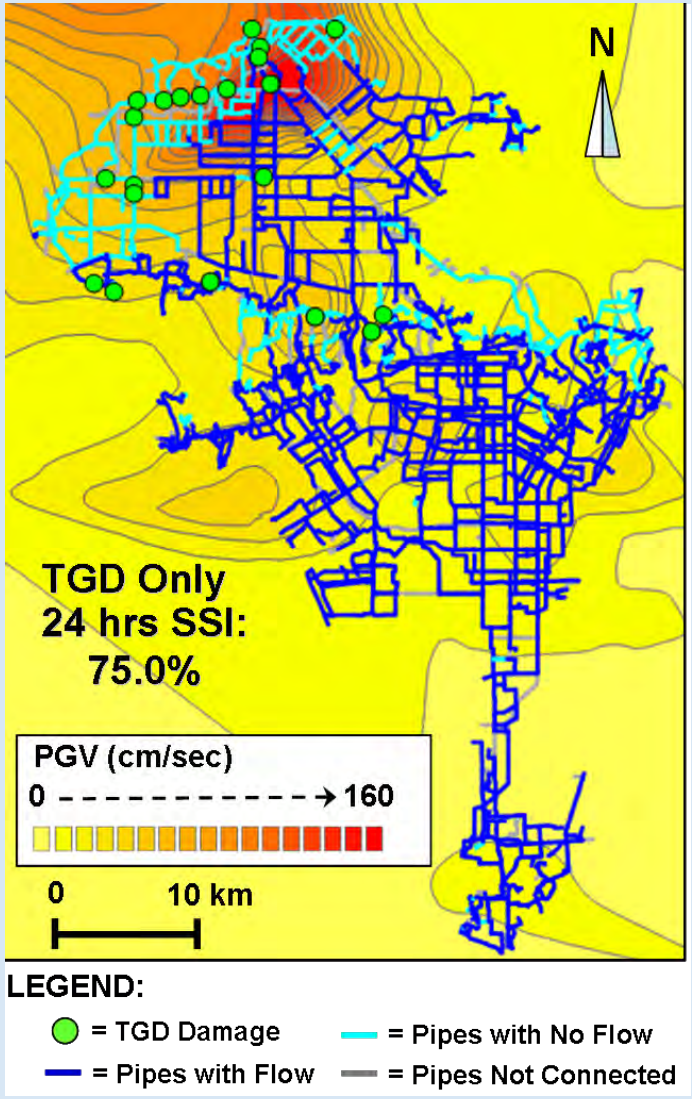
Simulation for Ground Failure, Accidents, Human Threats

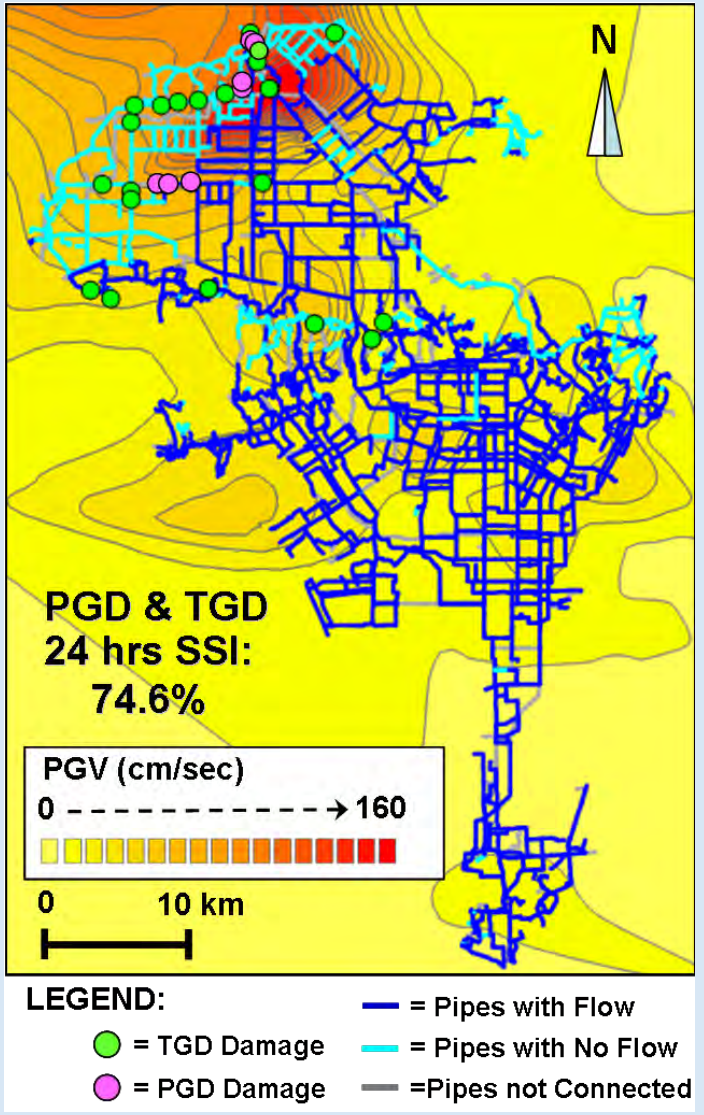
Probabilistic Simulation for System-wide Seismic Wave Effects

Combined Simulation for Permanent Ground Deformation & Seismic Wave Effects

LADWP NORTHRIDGE EQ SYSTEM RESPONSE





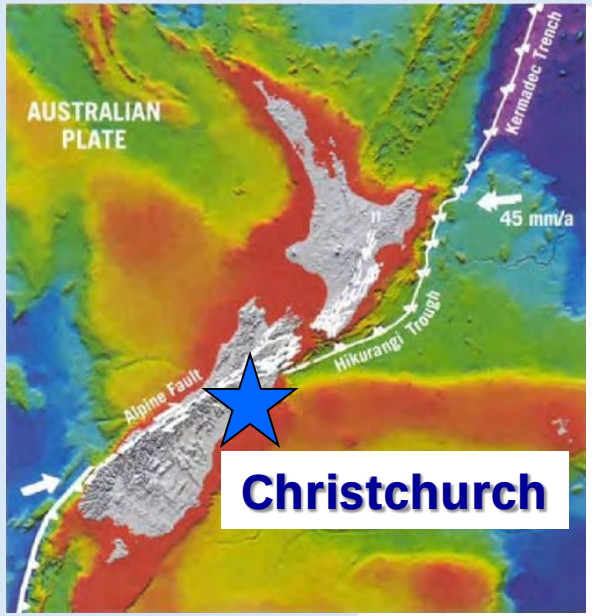


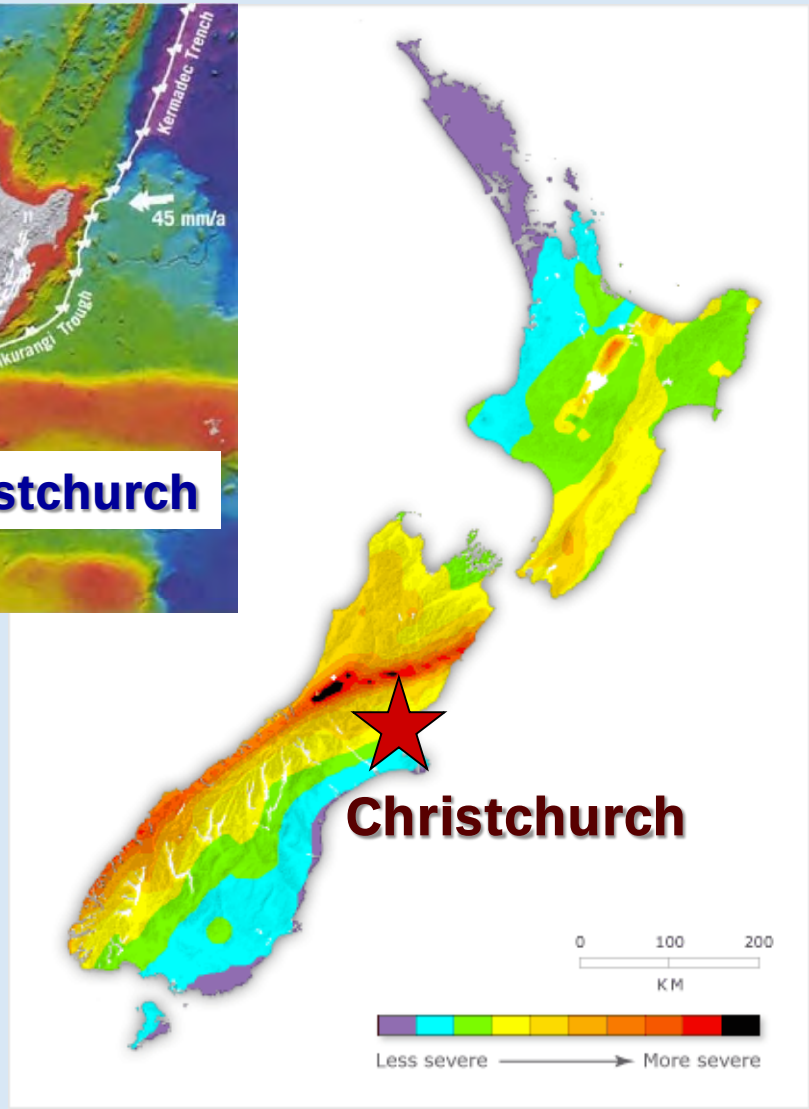
LOS ANGELES RESILIENCE

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

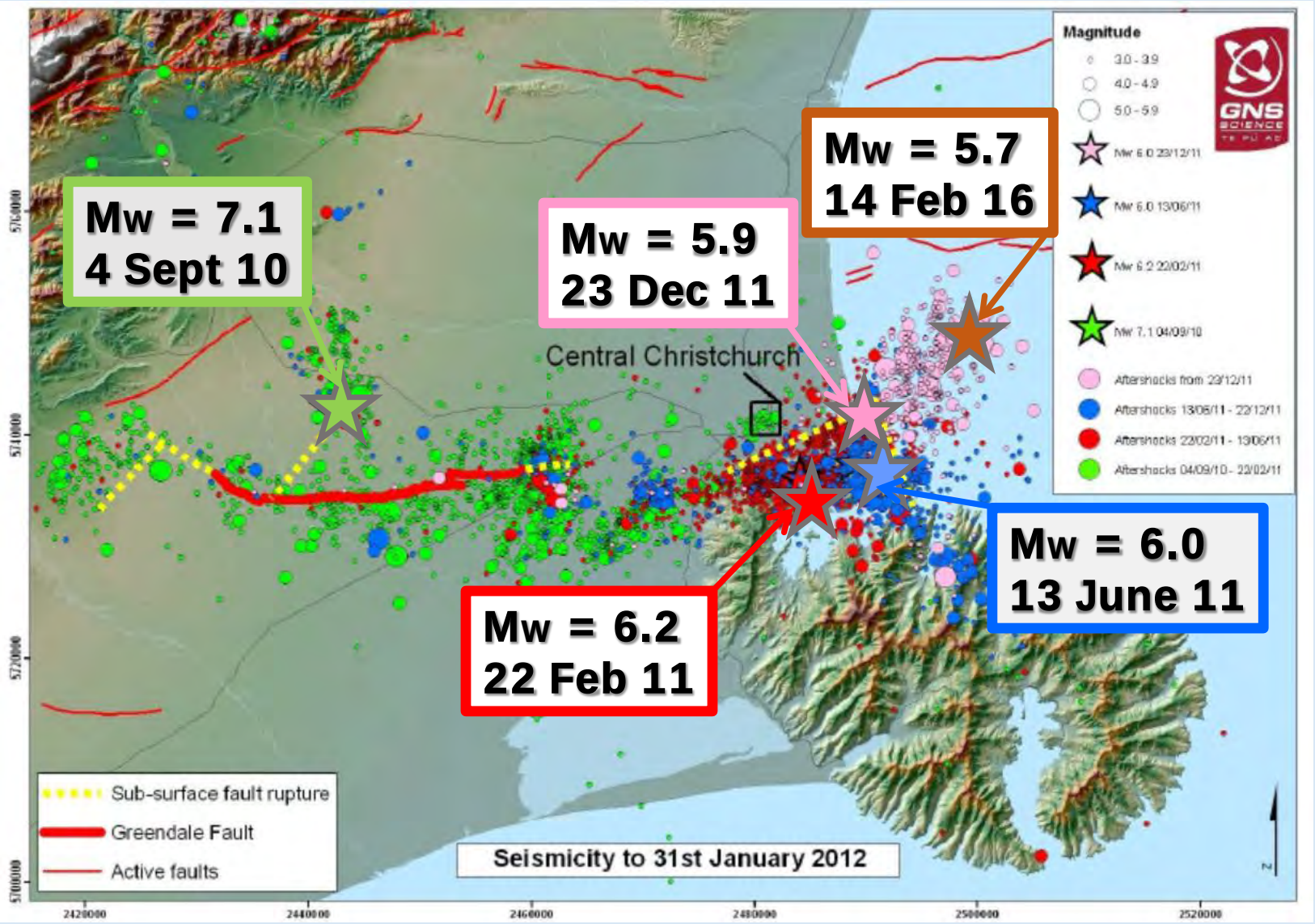
CANTERBURY EARTHQUAKE SEQUENCE

- ~ 185 Deaths
- CBD Destroyed
  - ~ 1800 CBD Bldgs. Demolished
  - ~ 55,000 Residences Damaged
- > $30(US) B Direct Losses ≈ 20 % GDP
- Massive Liquefaction& Infrastructure Damage

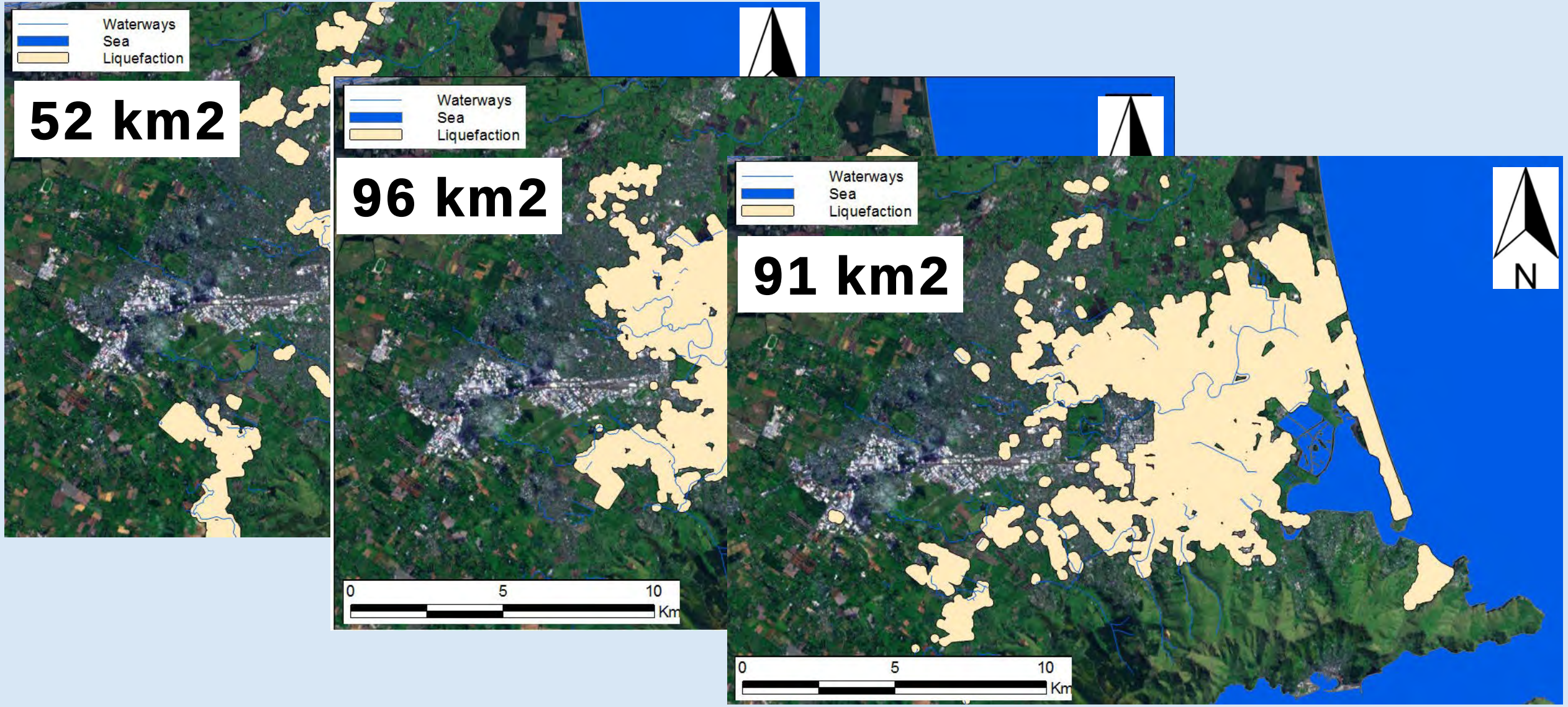




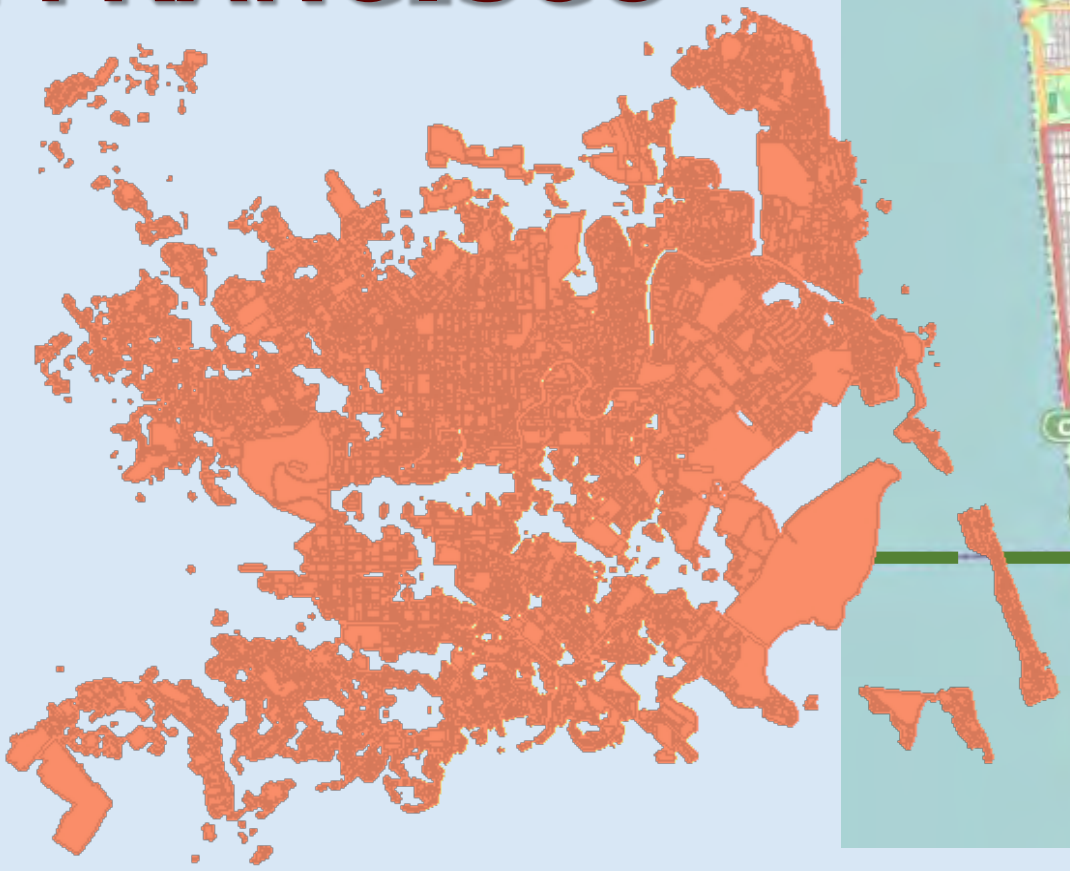
CANTERBURY EARTHQUAKE SEQUENCE



CHRISTCHURCH LIQUEFACTION



CHRISTCHURCH LIQUEFACTION IN SAN FRANCISCO



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SEISMIC RESILIENT PIPELINES

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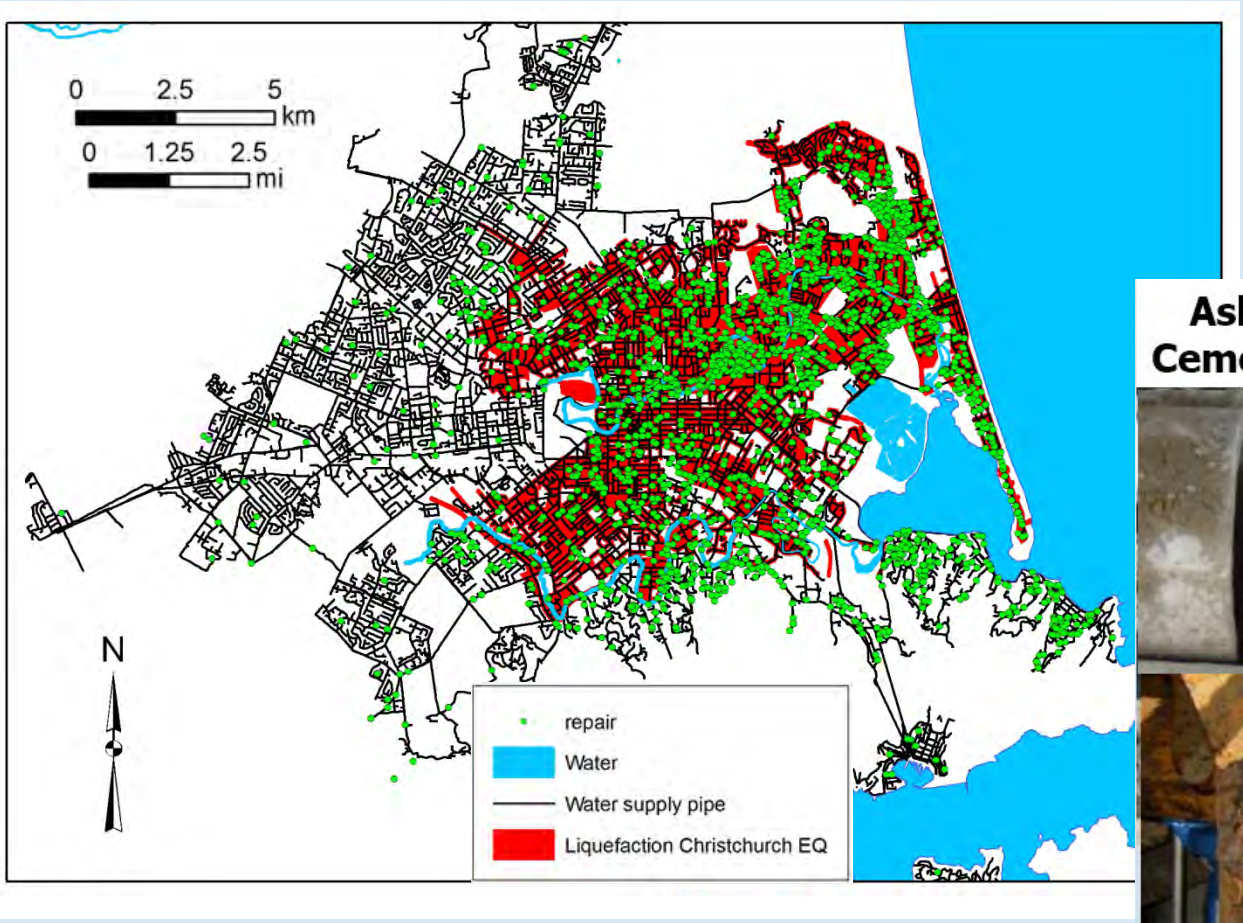
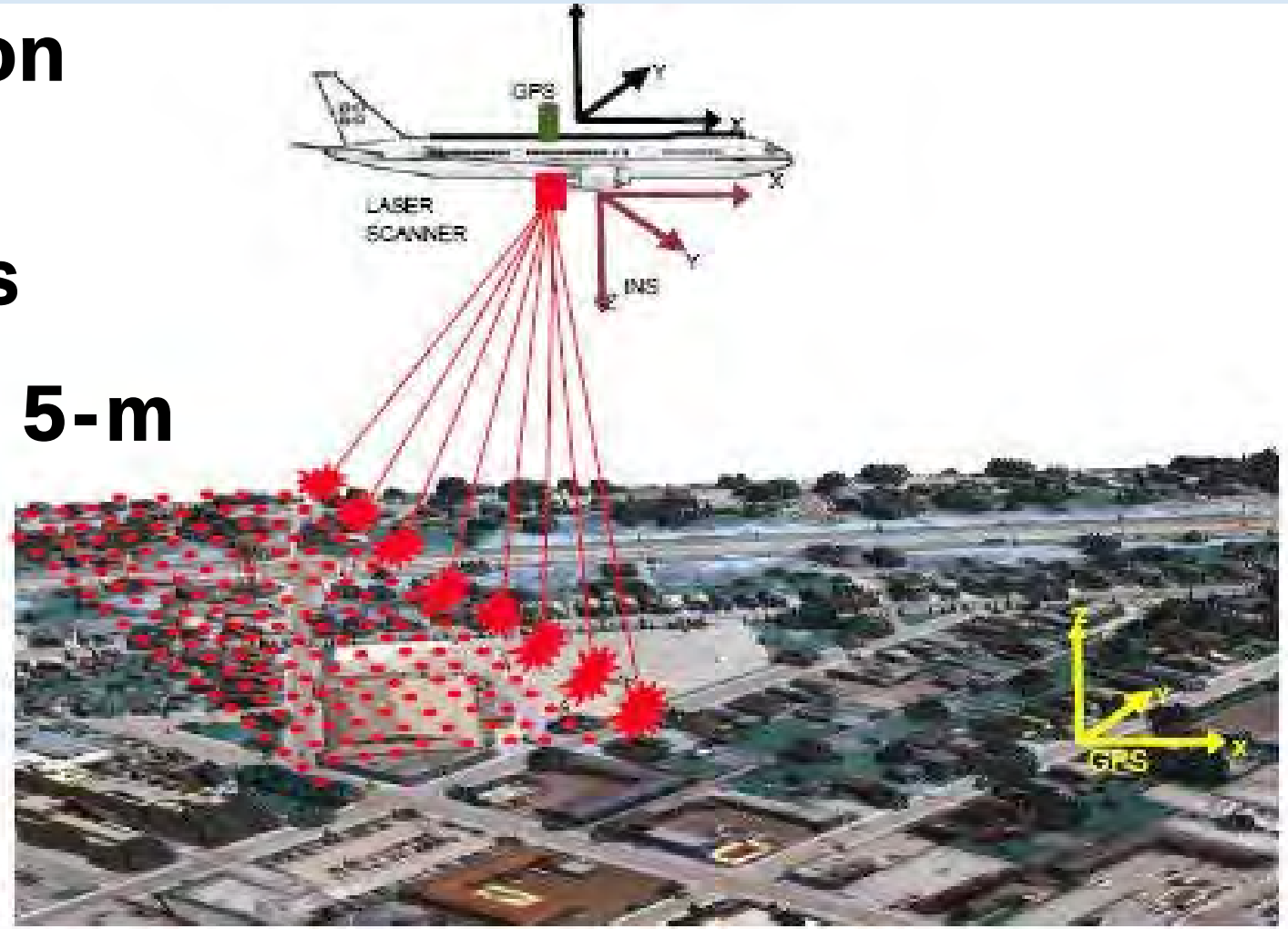
WATER DISTRIBUTION SYSTEM

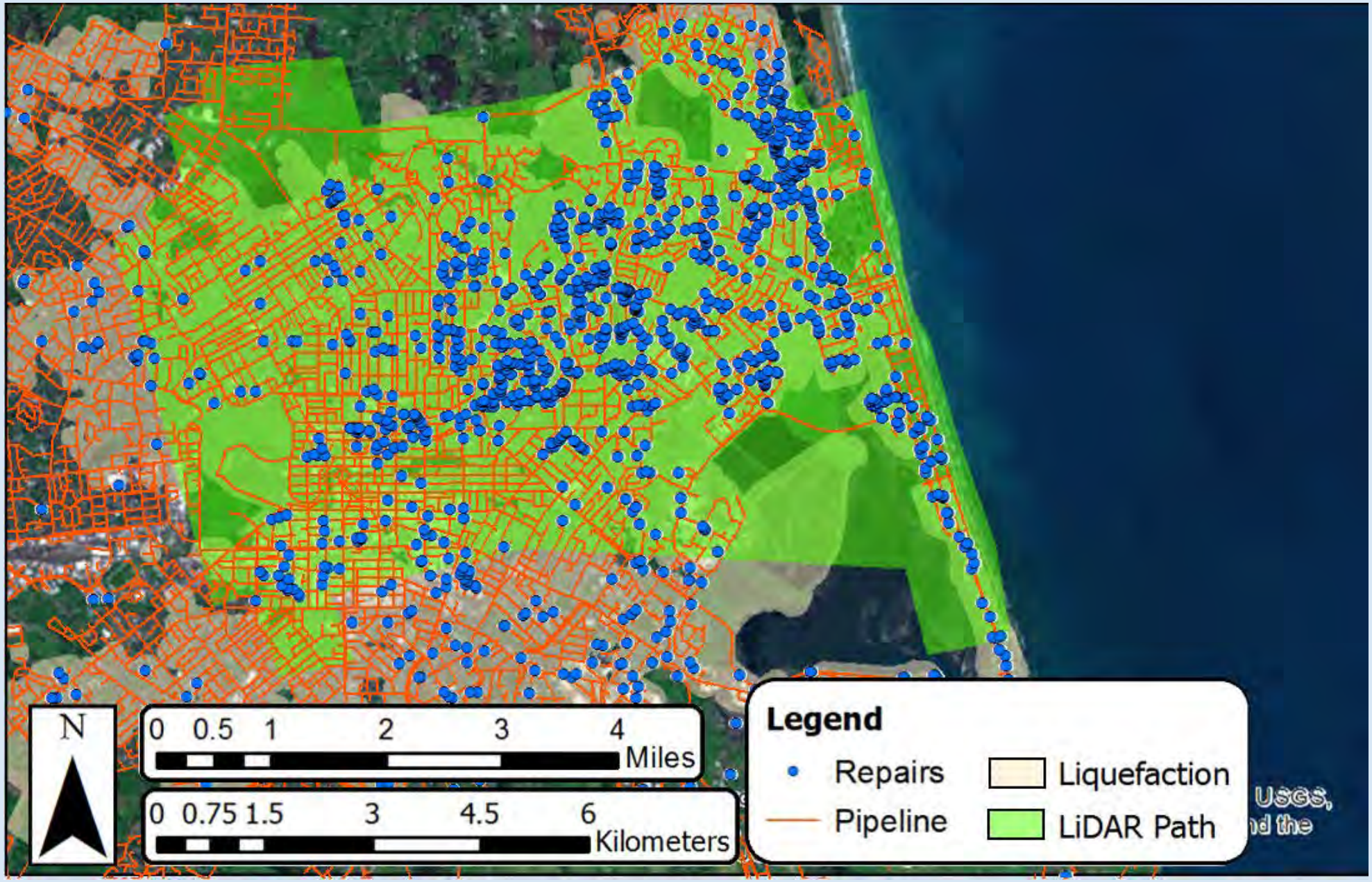


1700 km of Distribution Pipelines
1700 Repairs

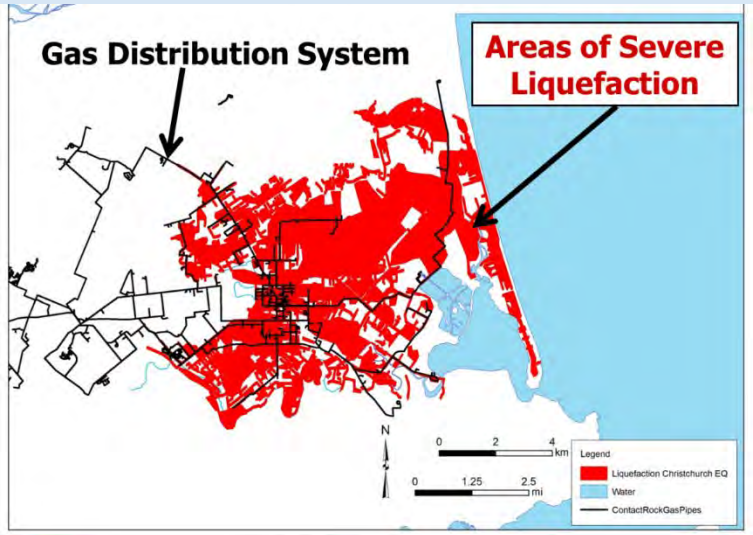
LIGHT DETECTION & RANGING (LiDAR)

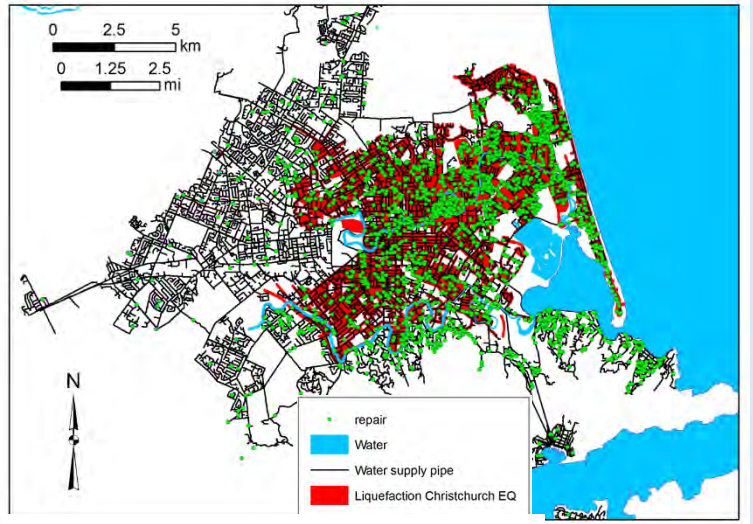
- **High Resolution LiDAR Measurements**
- **Settlement on 5-m**
- **Lateral Movement on 4 & 56-m**



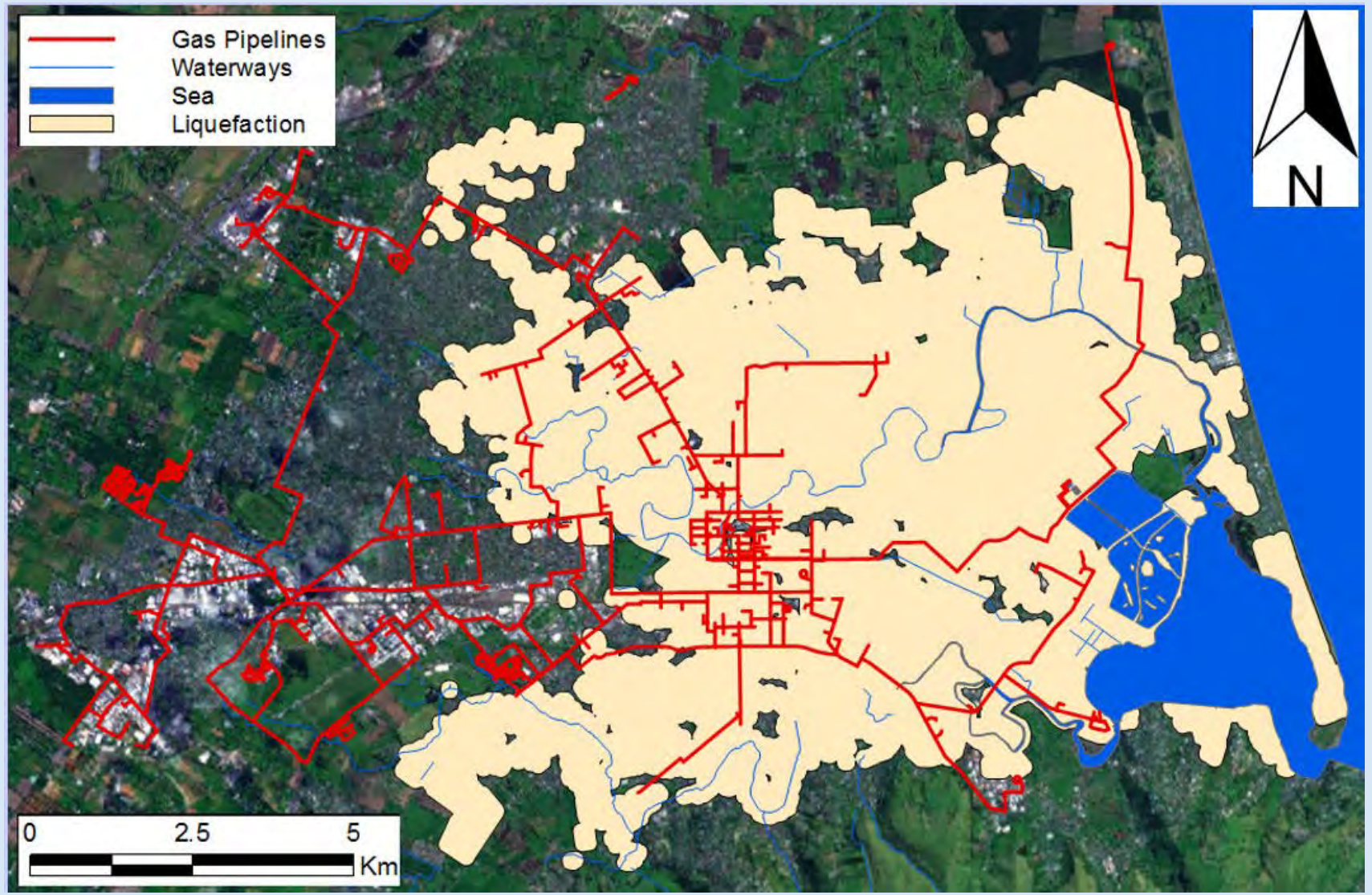

N
0 0.5 1 2 3 4
Miles
0 0.75 1.5 3 4.5 6
Kilometers
Legend
Repairs
Pipeline
Liquefaction
LiDAR Path
USGS,
nd the

GAS DISTRIBUTION SYSTEM





Water Distribution System



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SEISMIC RESILIENT PIPELINES

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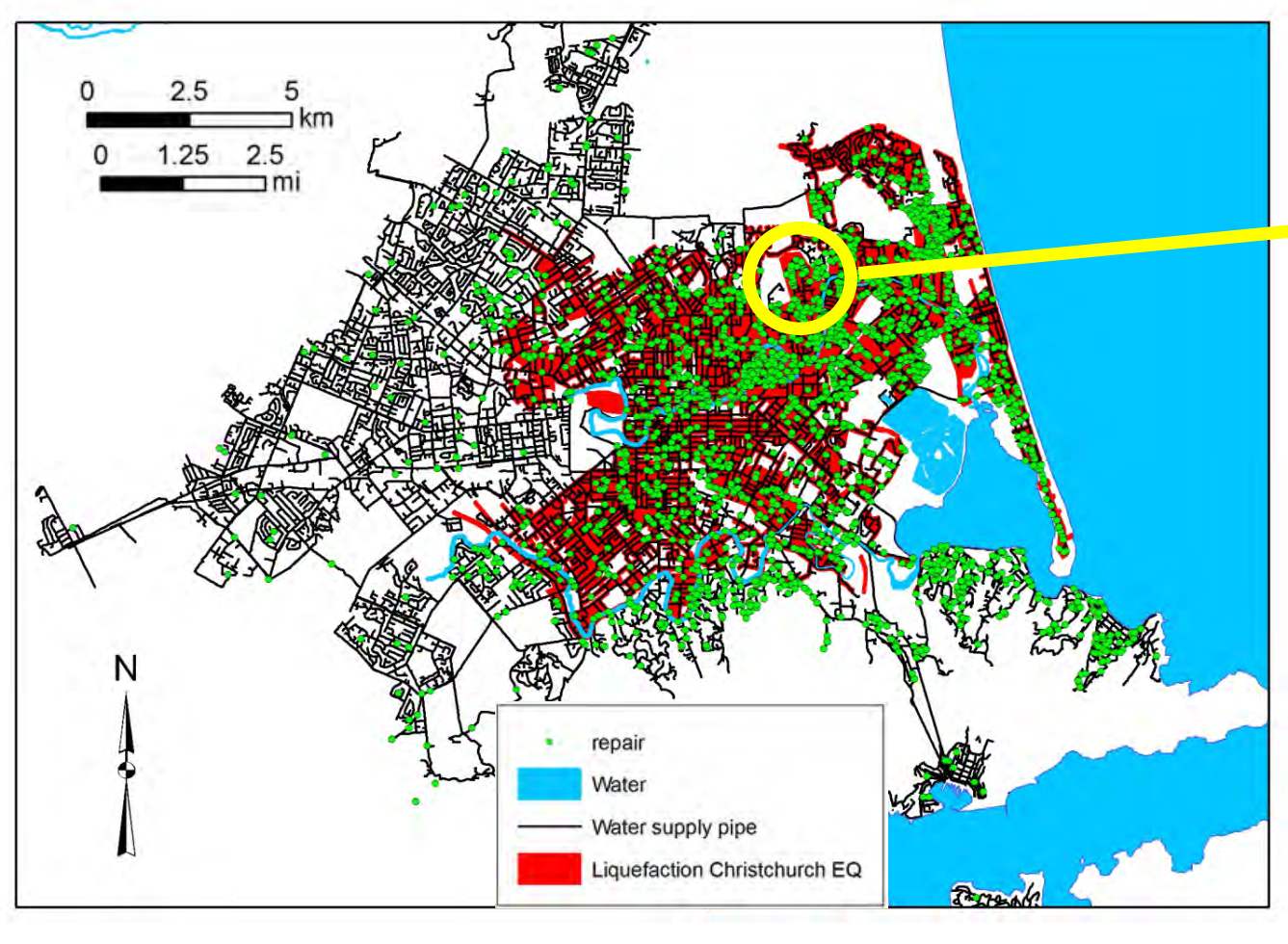
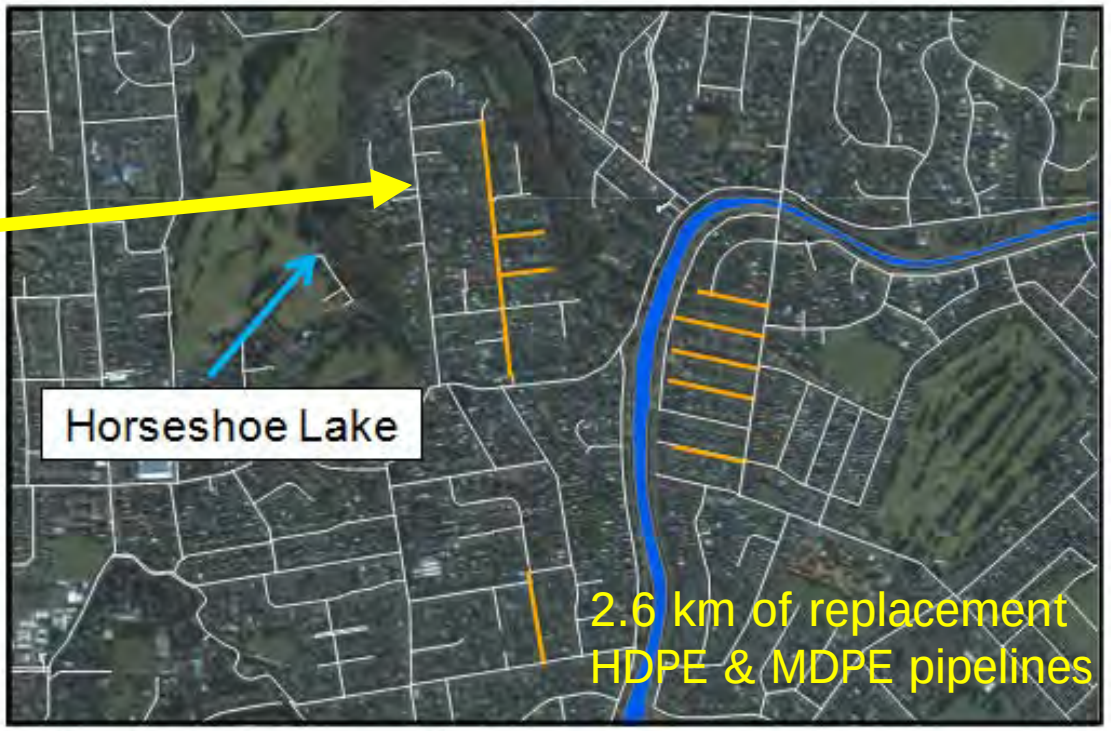
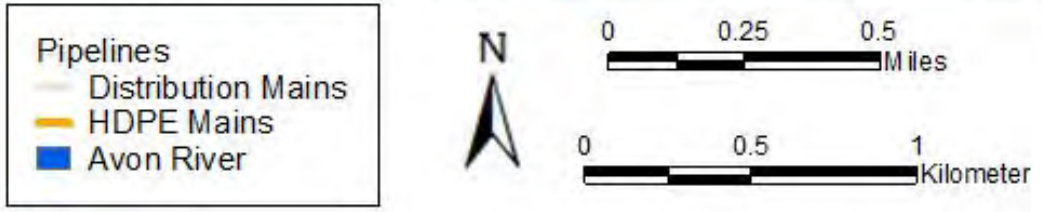
PE PIPELINES AFTER 4 SEPTEMBER 2010 EQ

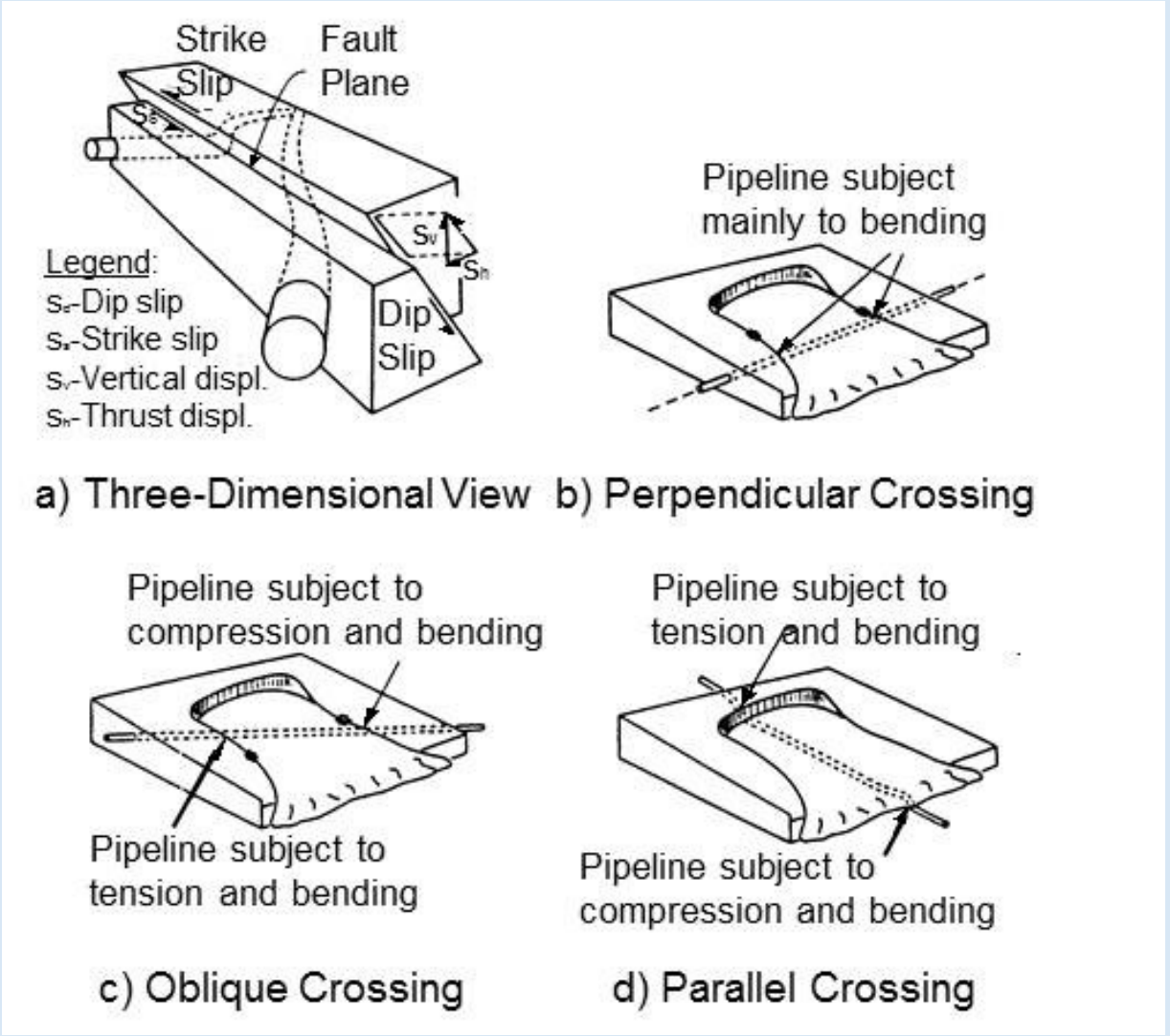






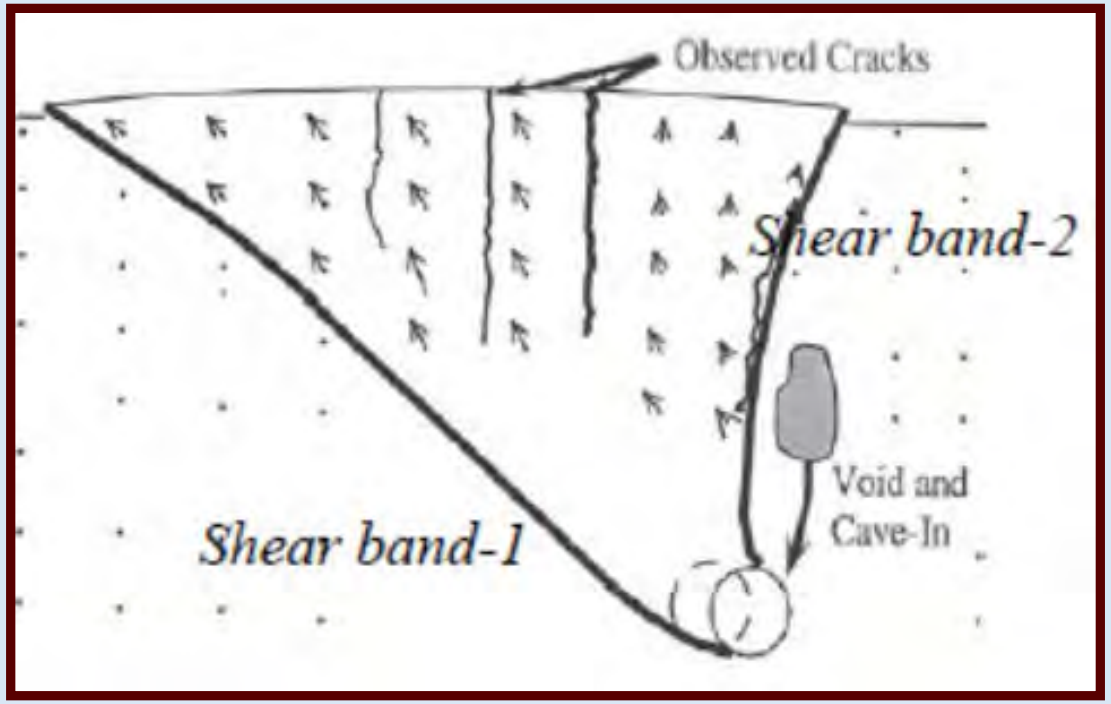
Earthquake Induced Ground Deformation

- Seismic Waves
- Fault Rupture
- Liquefaction
  - Lateral Spreading
  - Flow Failure
  - Settlement
  - Consolidation
  - Buoyancy Effects
- Landslides
- Unsaturated Soil Settlement



EXTREME SOIL-PIPELINE INTERACTION

Soil Material & Geometric Nonlinearities

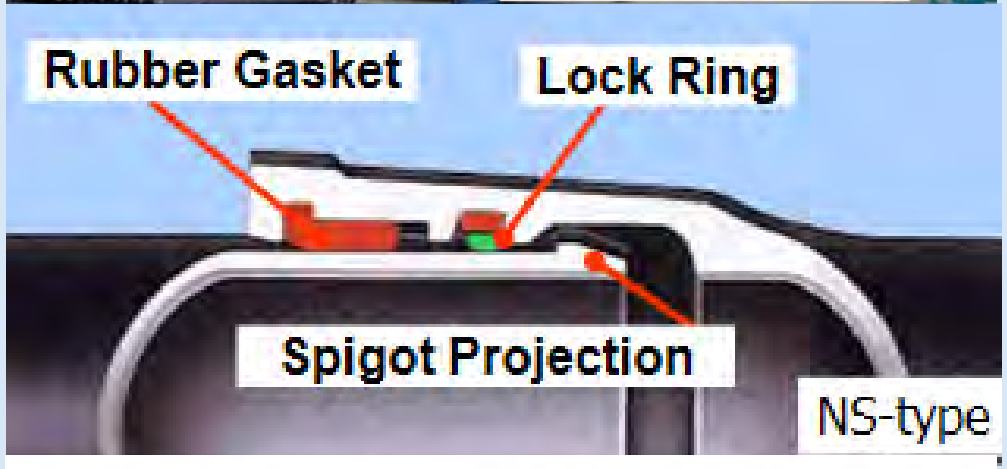


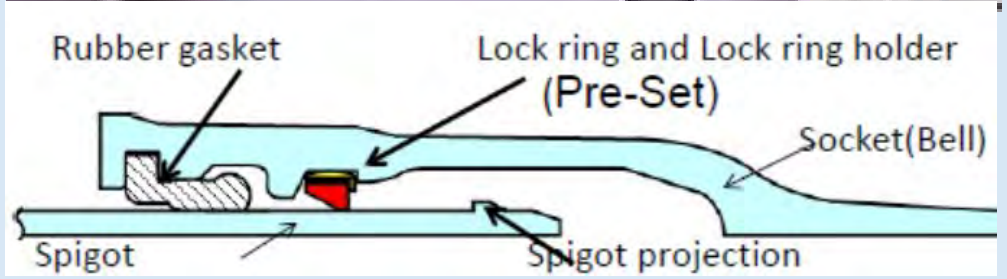
Pipeline Material & Geometric Nonlinearities

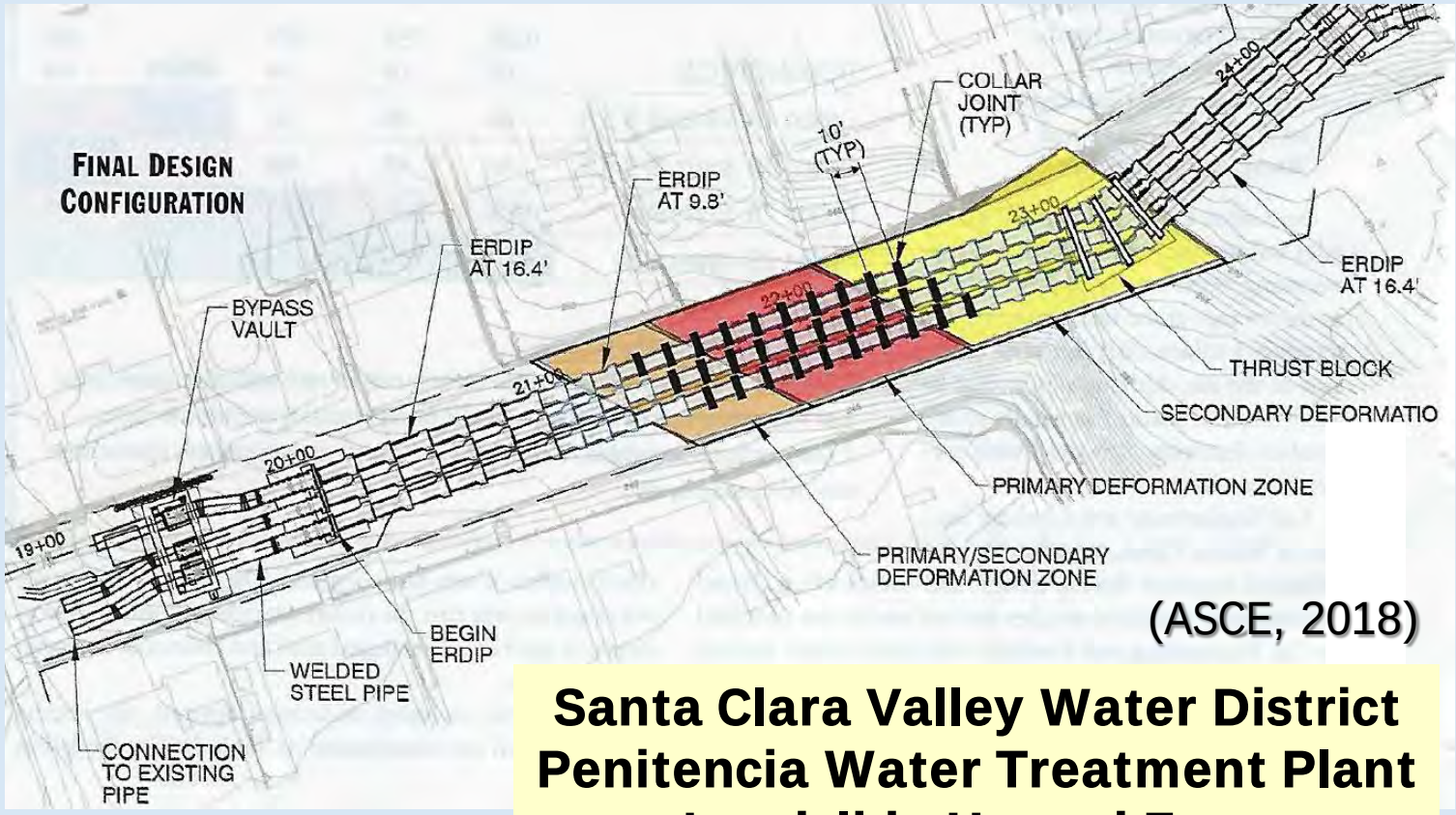
TOPIC

- **Next Generation Hazard Resilient Pipelines**

NEXT GENERATION HAZARD-RESILIENT PIPELINES



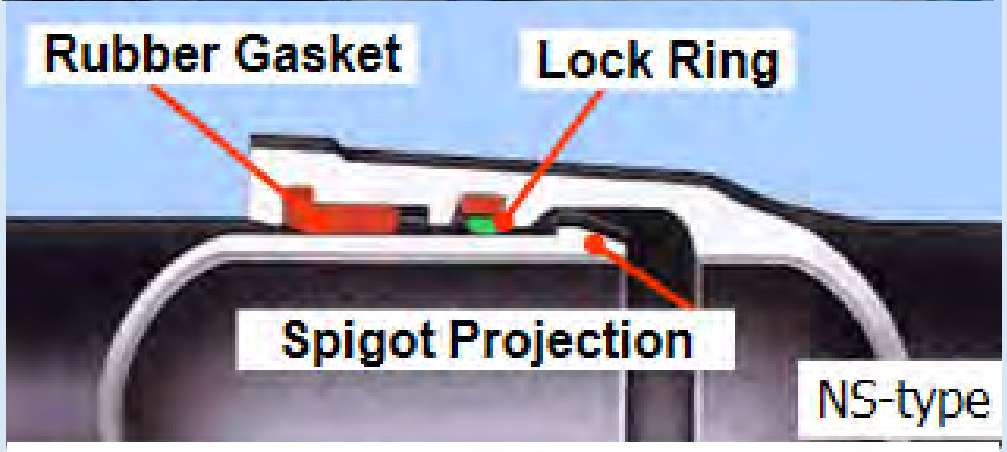


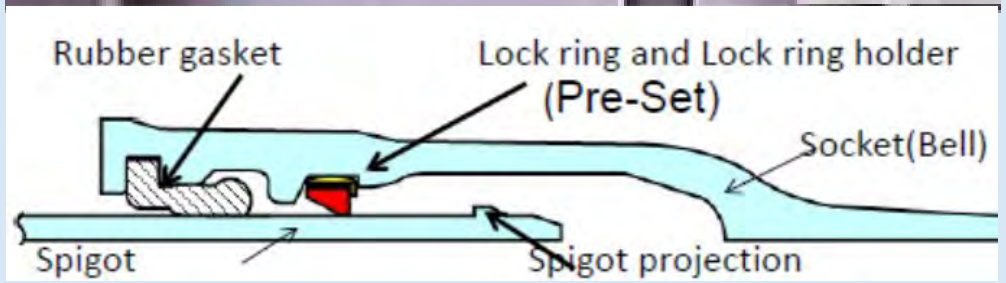


(ASCE, 2018)

Santa Clara Valley Water District
Penitencia Water Treatment Plant
Landslide Hazard Zone
72-in.-Diameter ERDIP

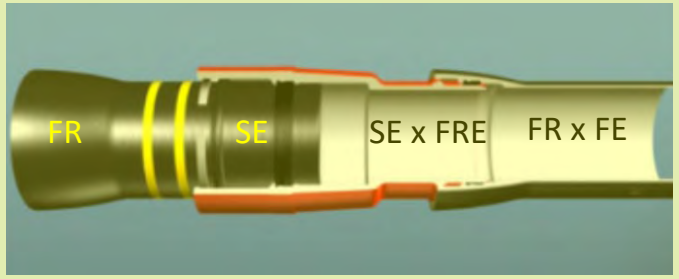
NEXT GENERATION HAZARD-RESILIENT PIPELINES



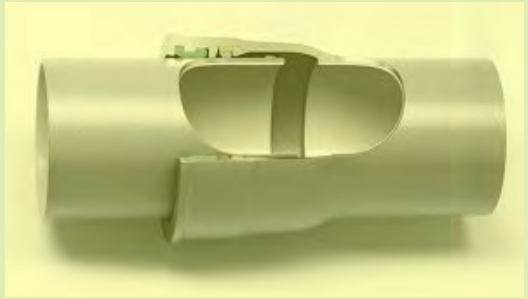


NEXT GENERATION HAZARD-RESILIENT PIPELINES

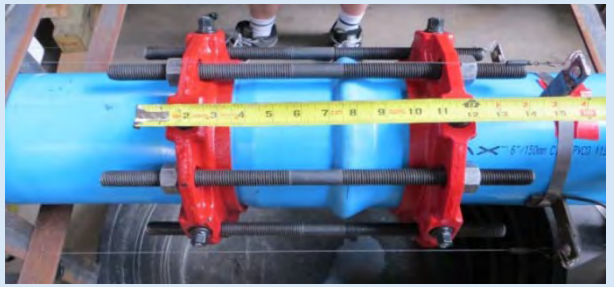
AMERICAN CAST IRON PIPE COMPANY



Kubota

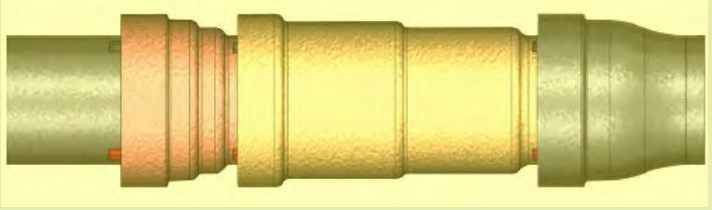


IPEX

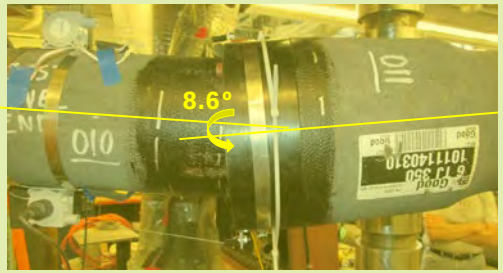


JFE

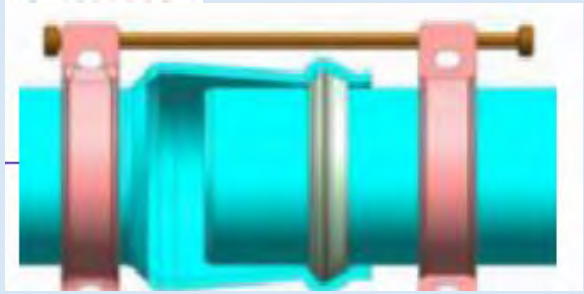
McWANE DUCTILE IRON STRONG



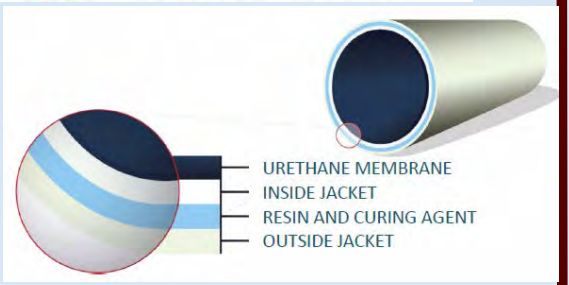
US PIPE



PPI SYSTEM



aquapipe
WATER MAIN REHABILITATION



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SEISMIC RESILIENT PIPELINES

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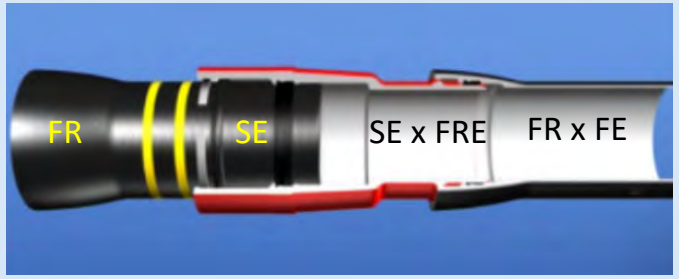
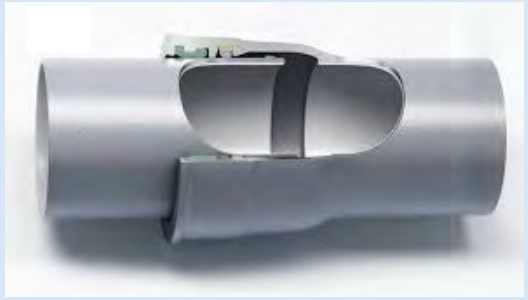
NEXT GENERATION HAZARD-RESILIENT PIPELINES

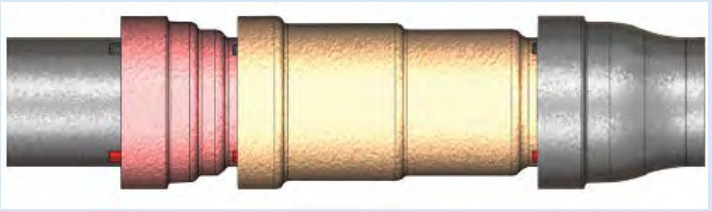
AMERICAN CAST IRON PIPE COMPANY



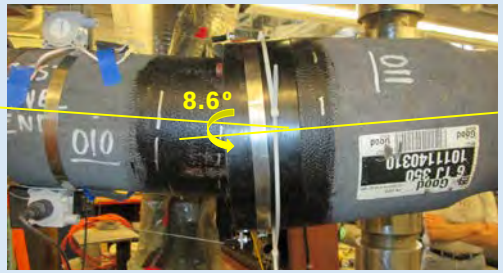
Kubota

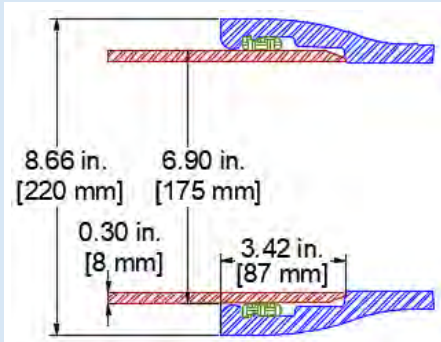


McWANE DUCTILE IRON STRONG

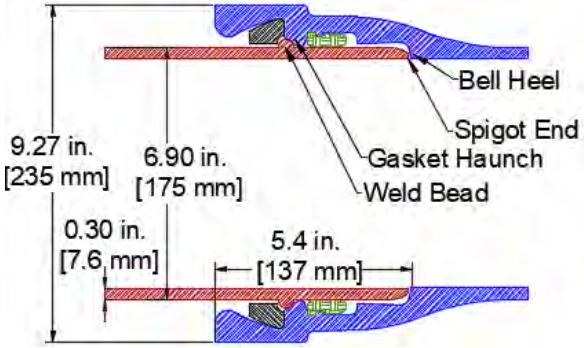


US PIPE

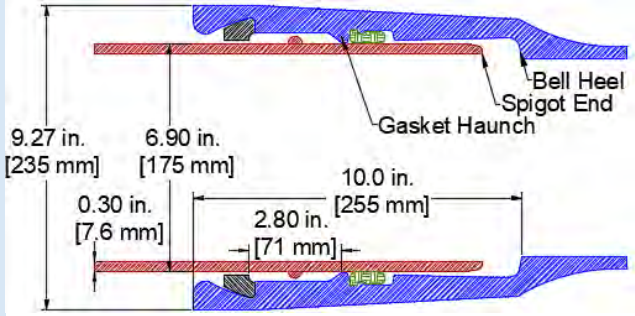




(a) Push-On Joint



(b) Restrained Joint



(c) Restrained Axial Slip Joint

US PIPE

CORNELL UNIVERSITY

SEISMIC RESILIENT PIPELINES

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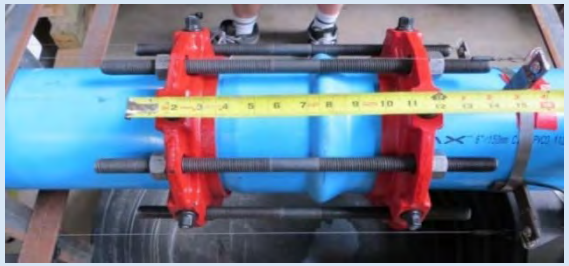
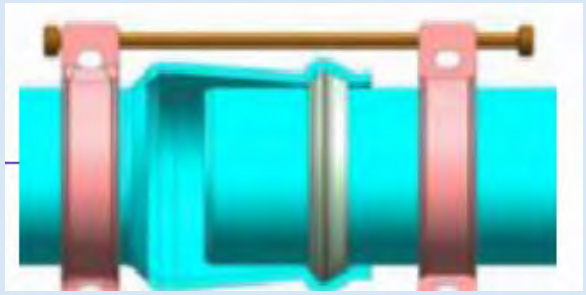
ORIENTED POLYVINYL CHLORIDE (PVCO) JOINTS

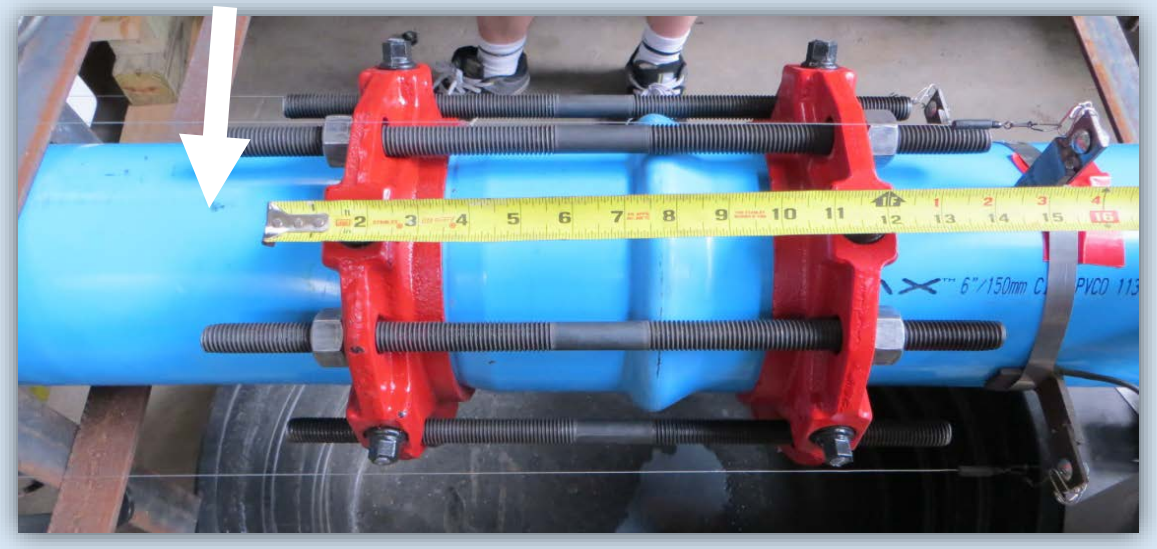
IPEX

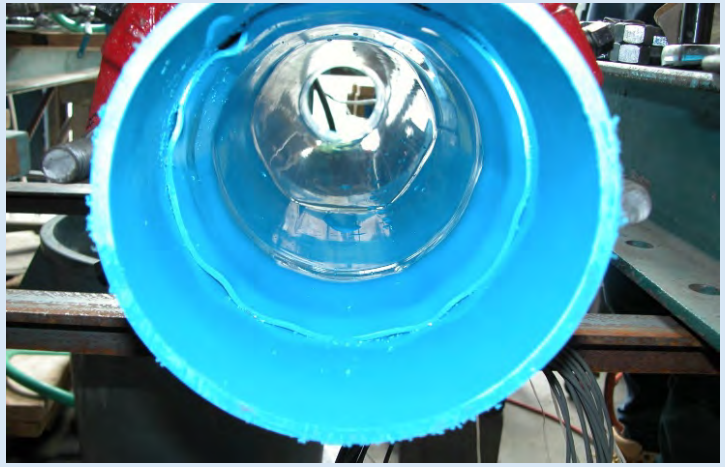


Spigot Compressed into Bell

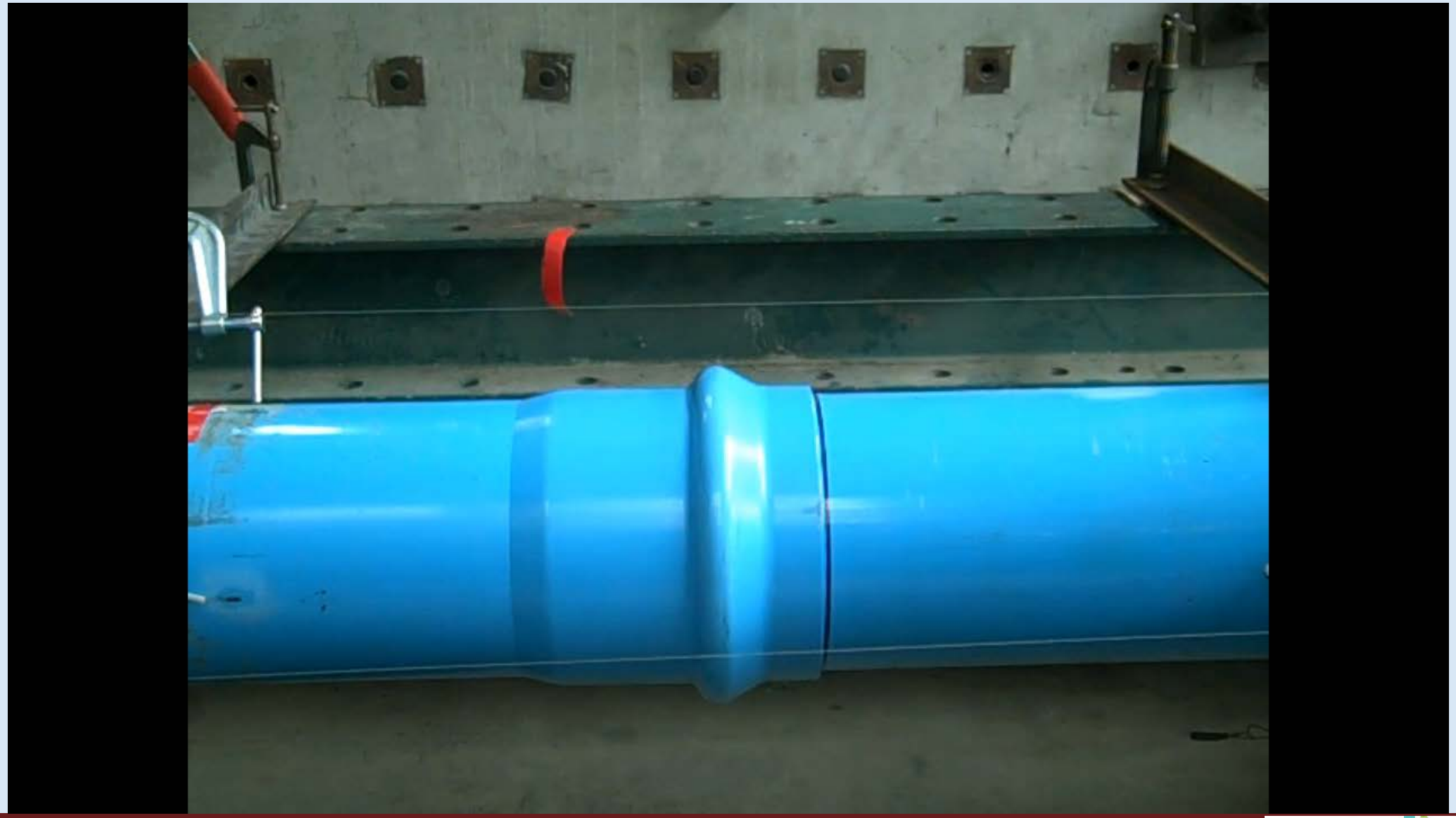
PPI SYSTEM



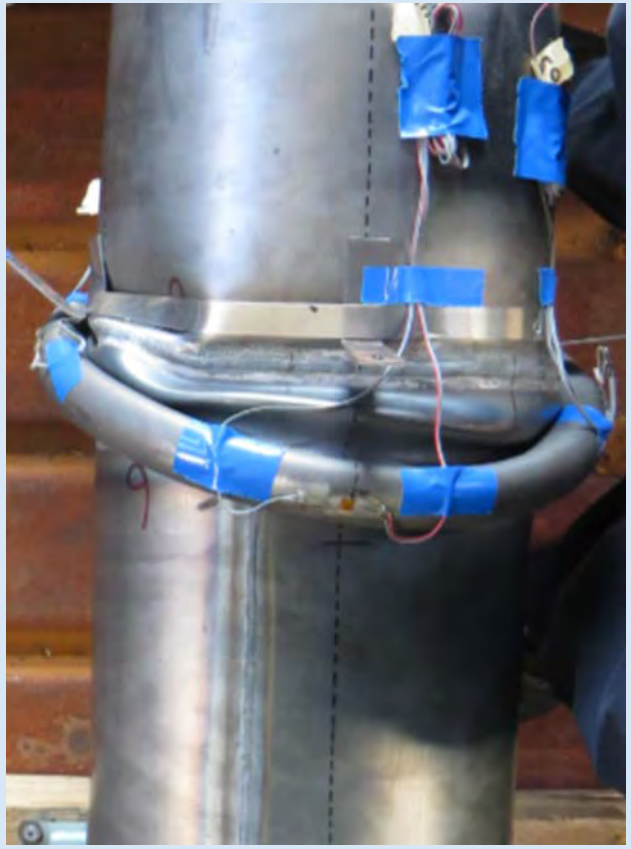


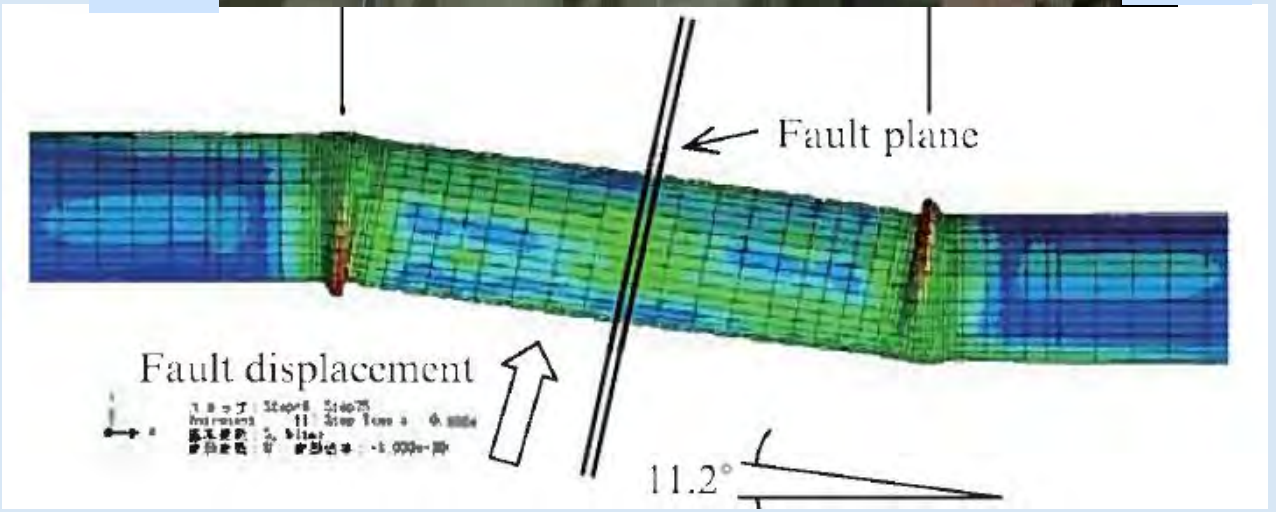


ORIENTED POLYVINYL CHLORIDE (PVCO) JOINTS

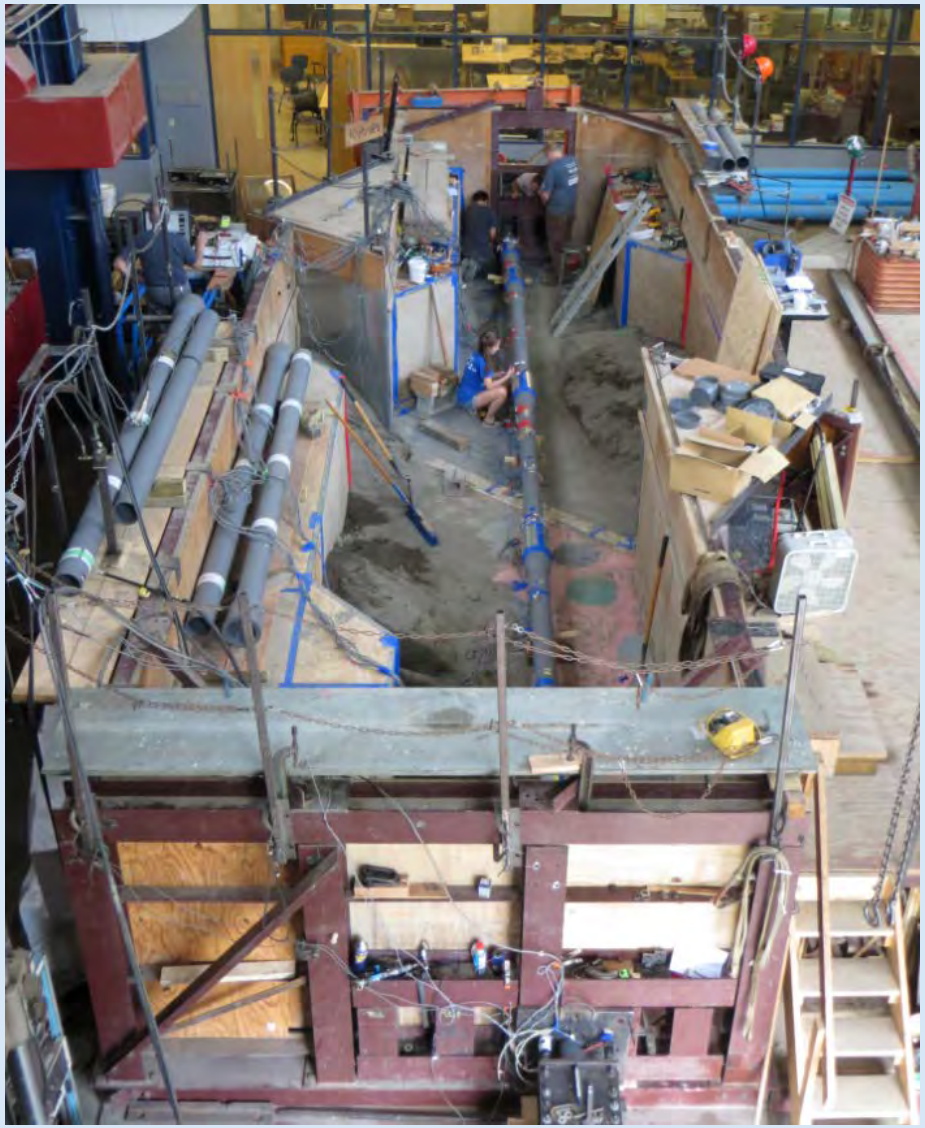


CONTROLLED BUCKLING

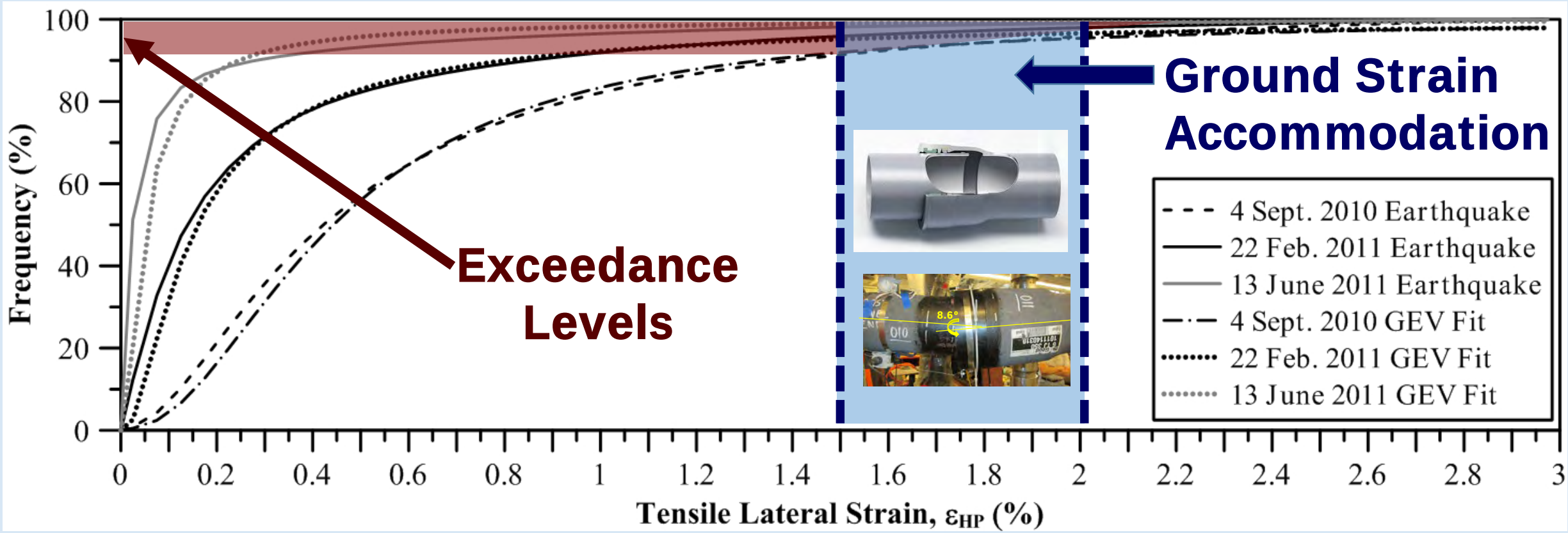




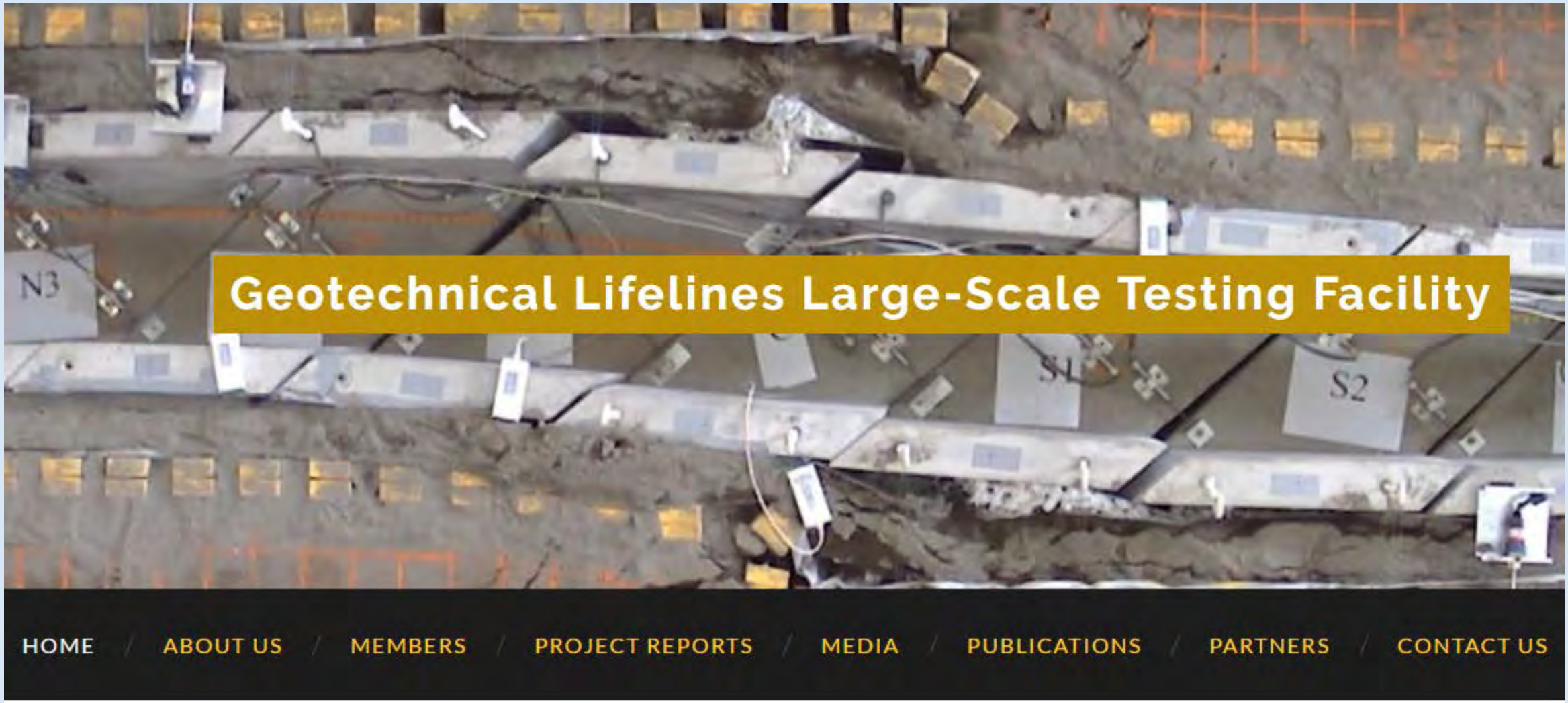
LARGE-SCALE TESTING: NEXT GENERATION INFASTRUCTURE



CUMULATIVE DISTRIBUTION OF TENSILE LATERAL GROUND STRAINS



CORNELL LAB WEB SITE https://lifelines.cee.cornell.edu/



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**

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

CSIC Cambridge Centre for Smart Infrastructure & Construction

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- **Paradigm Shift in Pipeline Technology**
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- **Can't Have Resilience Unless You Have a *Intelligence***
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