Geo-Hazards and Critical Infrastructure

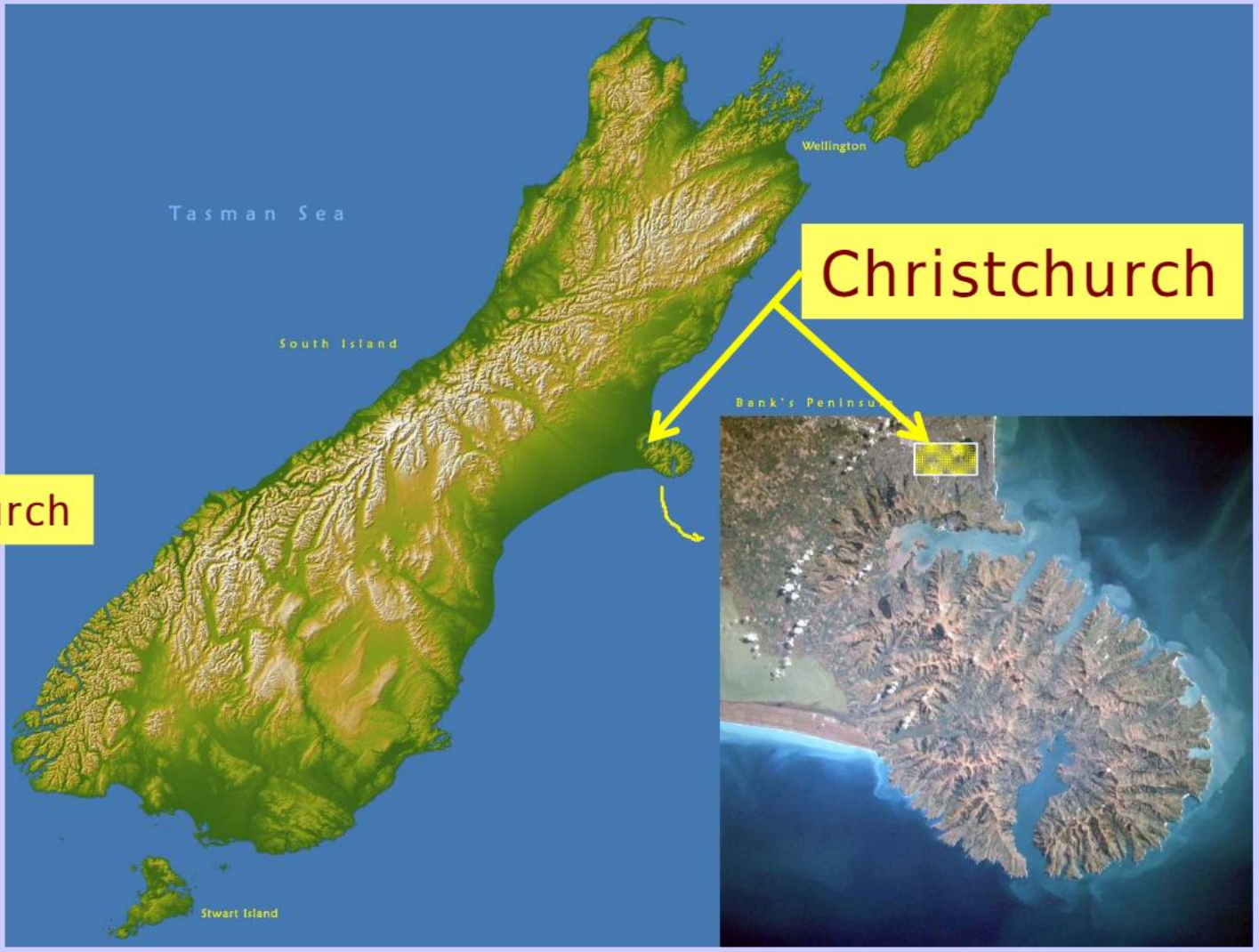
Tom O'Rourke
Thomas R. Briggs Professor of Engineering
Cornell University

TOPICS

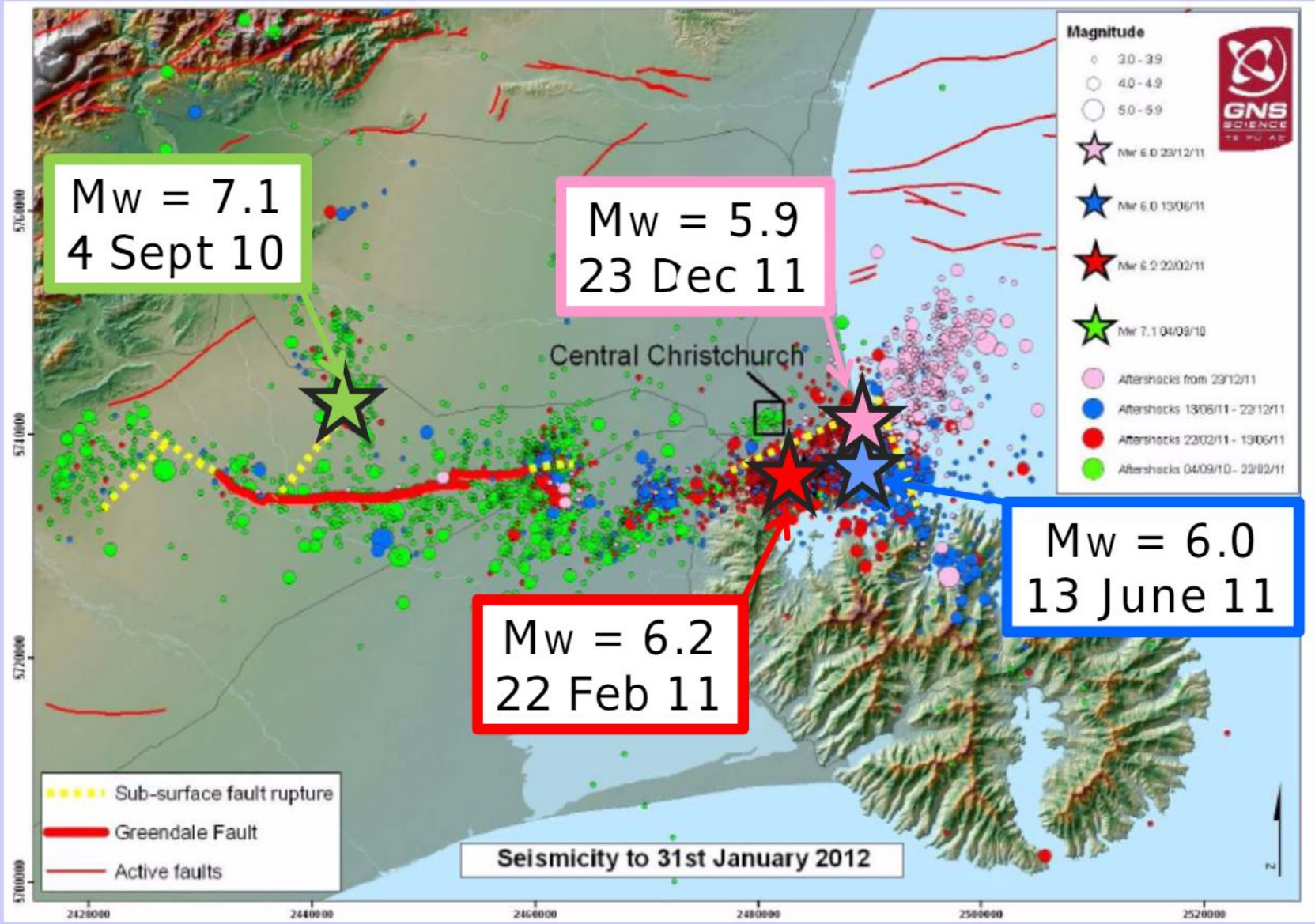
- Canterbury EQ Sequence
- San Francisco
- Los Angeles
- Critical Infrastructure

NEW ZEALAND


Chatham Islands and Kermadec Islands are not shown.
SOUTH PACIFIC OCEAN
THREE KINGS ISLANDS
Whangarei
North Island
Auckland
Hamilton
Tauranga
Tasman Sea
Napier
Palmerston North
WELLINGTON
Nelson
Cook Strait
South Island
Christchurch
Aoraki-Mount Cook
Dunedin
Invercargill
Stewart Island
SOUTH PACIFIC OCEAN
BOUNTY ISLANDS
SNARES ISLANDS
ANTIPODES ISLAND GROUP
AUCKLAND ISLANDS
Campbell Island
0 100 200 km
0 100 200 mi

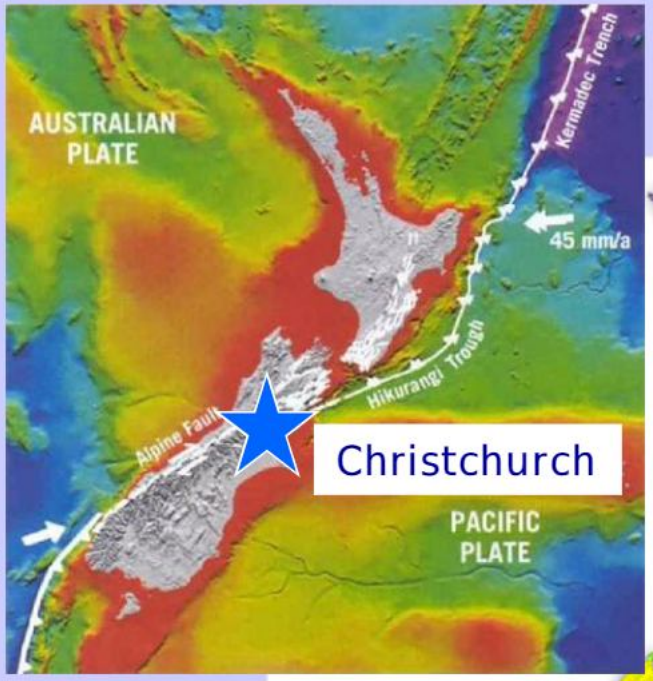

Tasman Sea
Wellington
Christchurch
South Island
Bank's Peninsula
Stwart Island

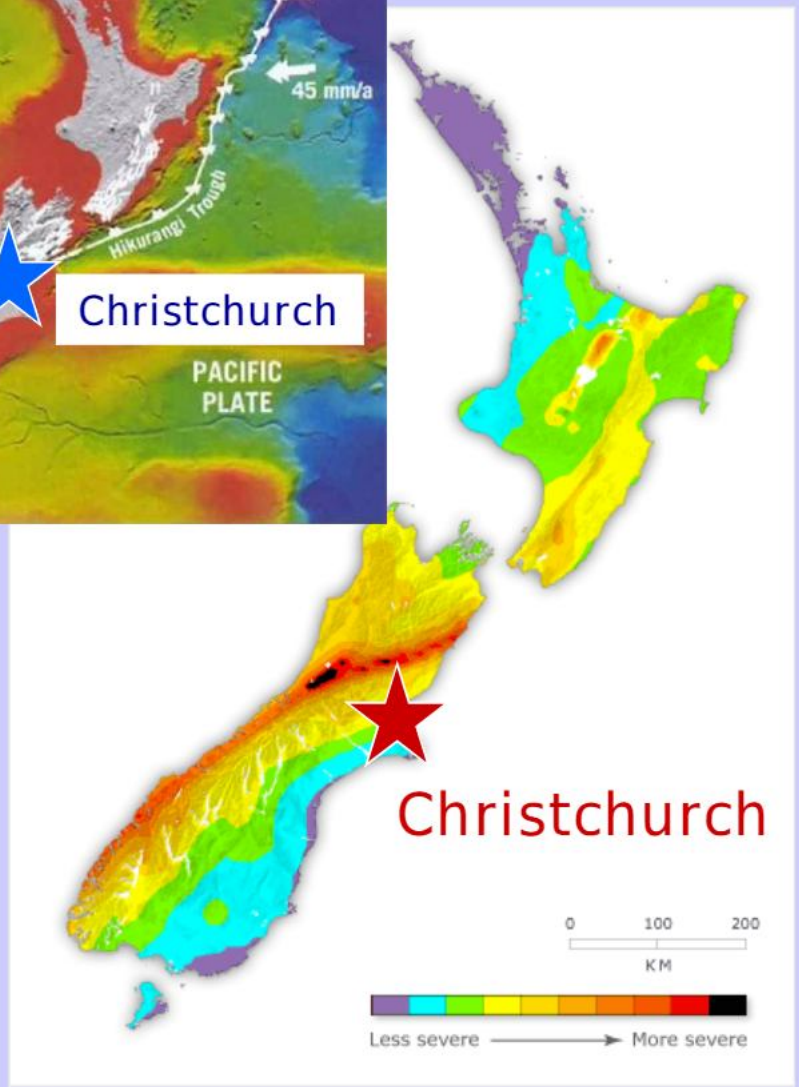
CANTERBURY EARTHQUAKE SEQUENCE



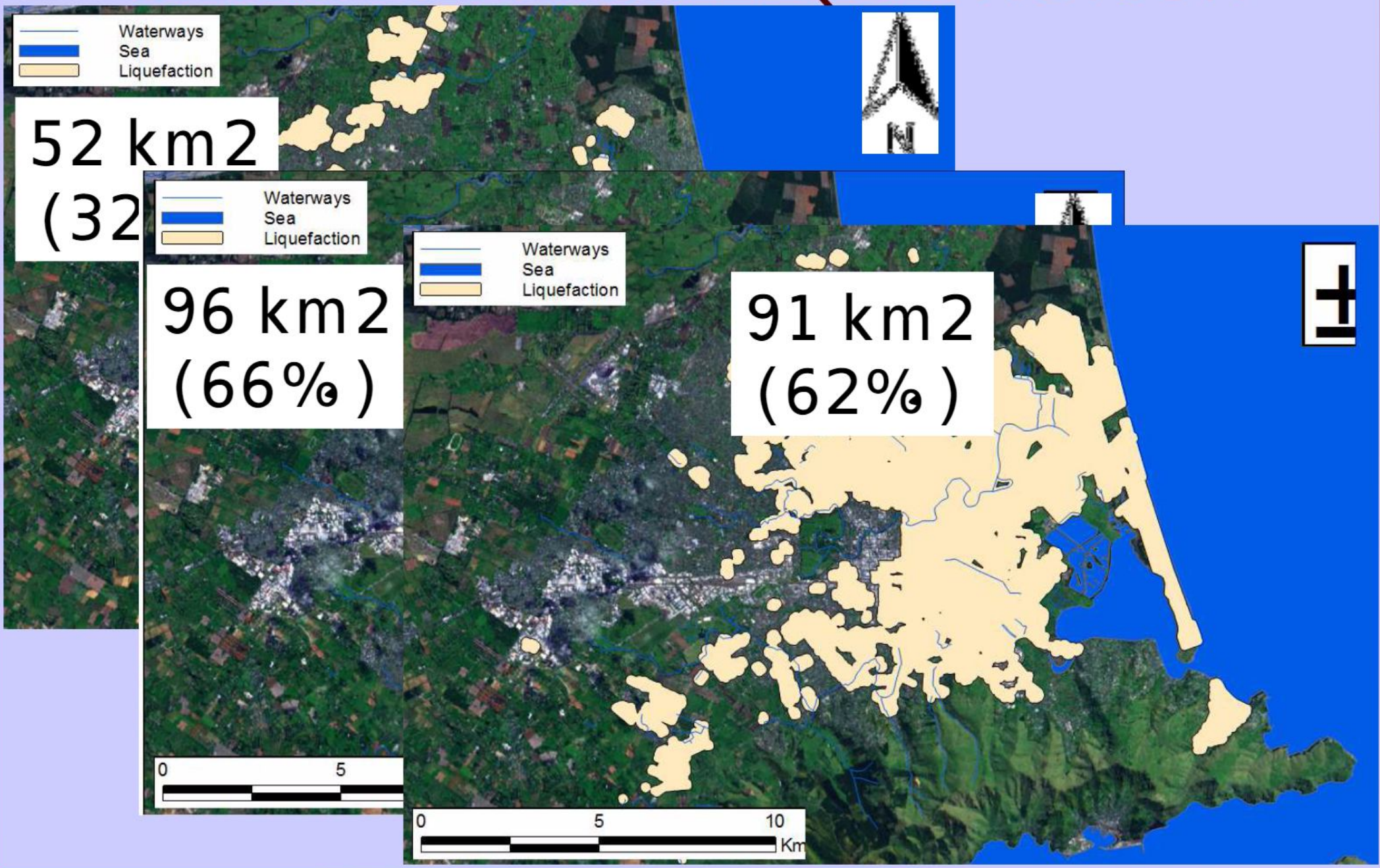
CANTERBURY EARTHQUAKE SEQUENCE

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

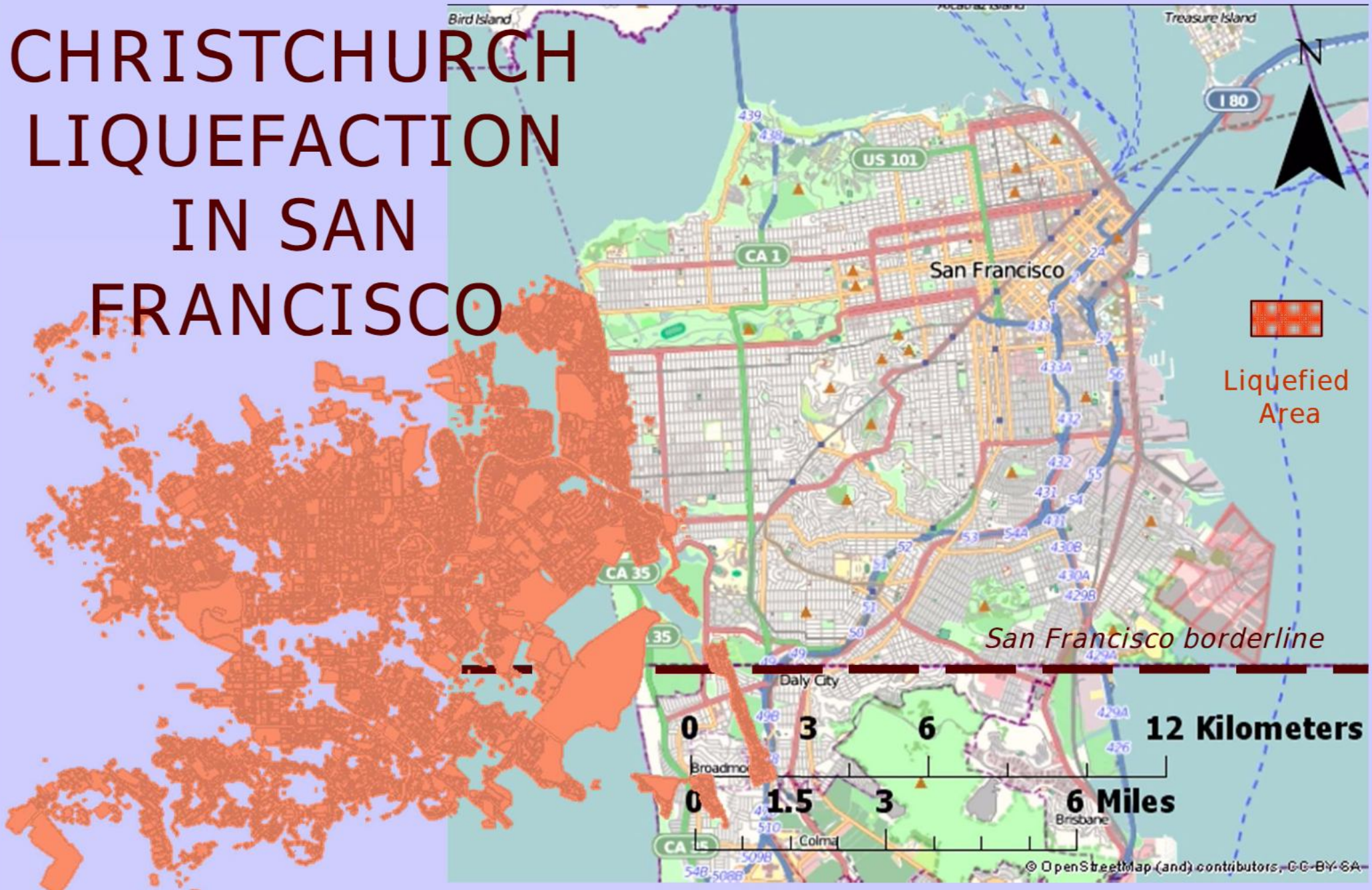




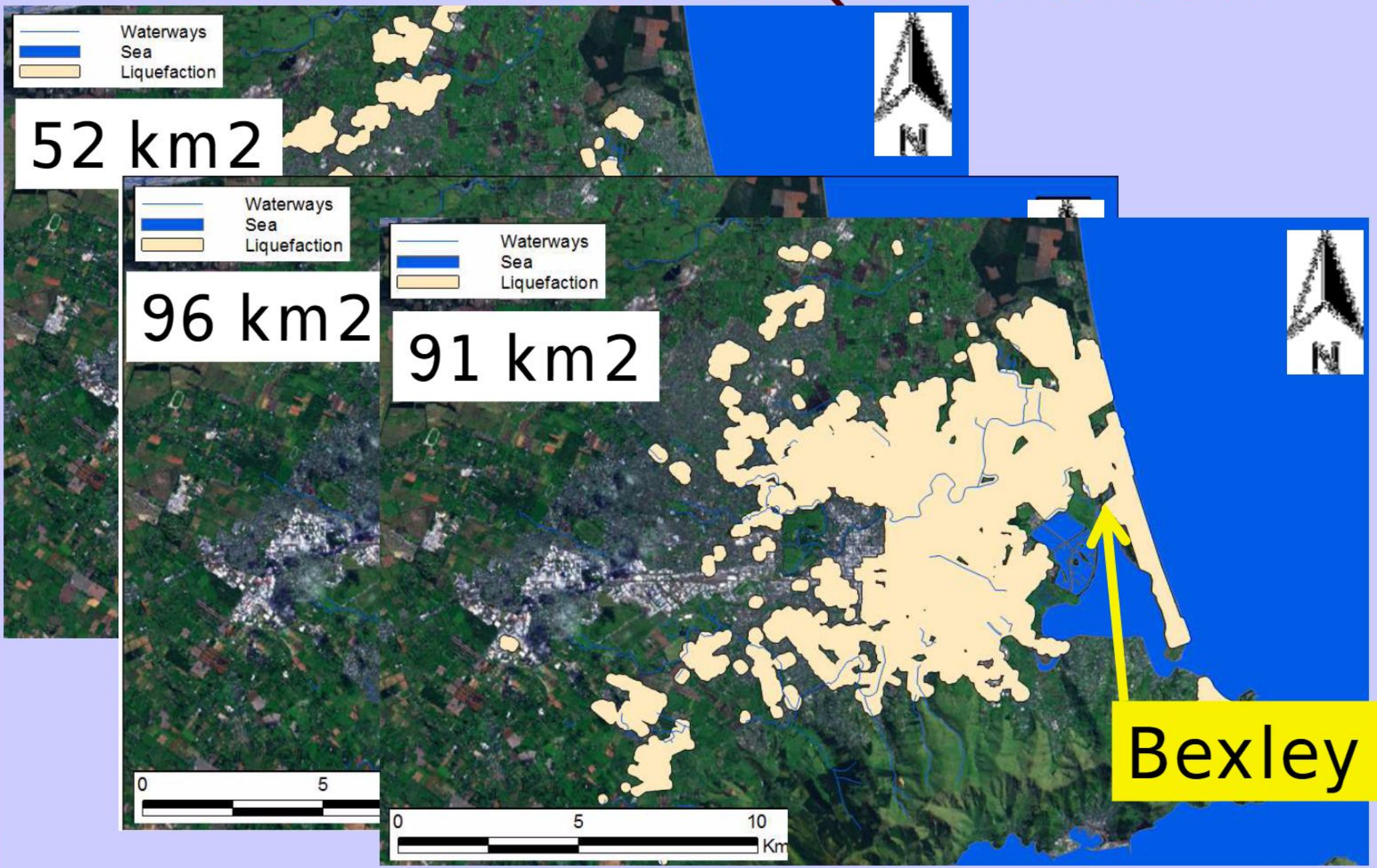
CHRISTCHURCH LIQUEFACTION



CHRISTCHURCH LIQUEFACTION IN SAN FRANCISCO



CHRISTCHURCH LIQUEFACTION



CHRISTCHURCH LIQUEFACTION

CORNELL UNIVERSITY

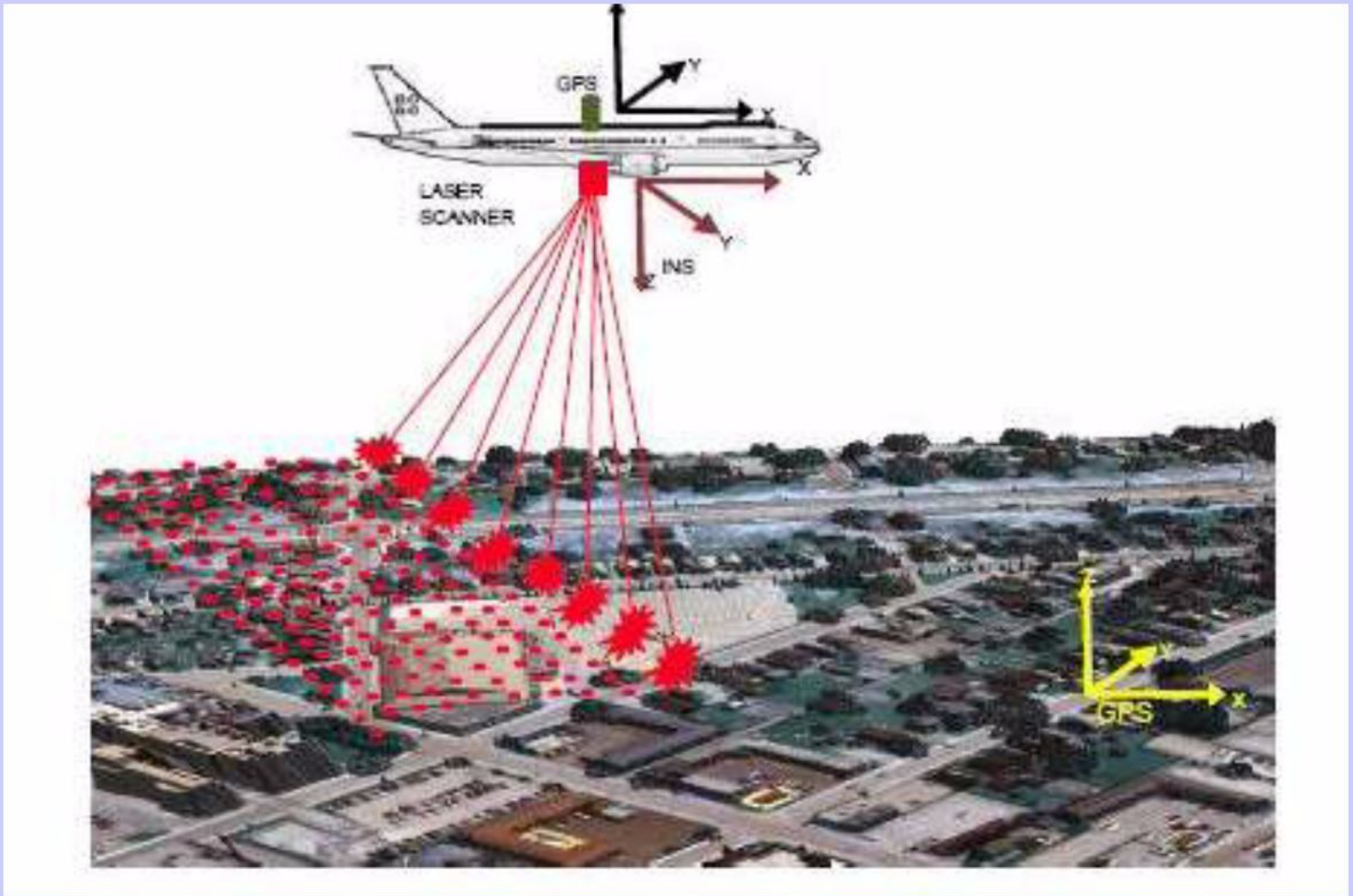
GeoHazards and Critical Infrastructure

G-I ASCE

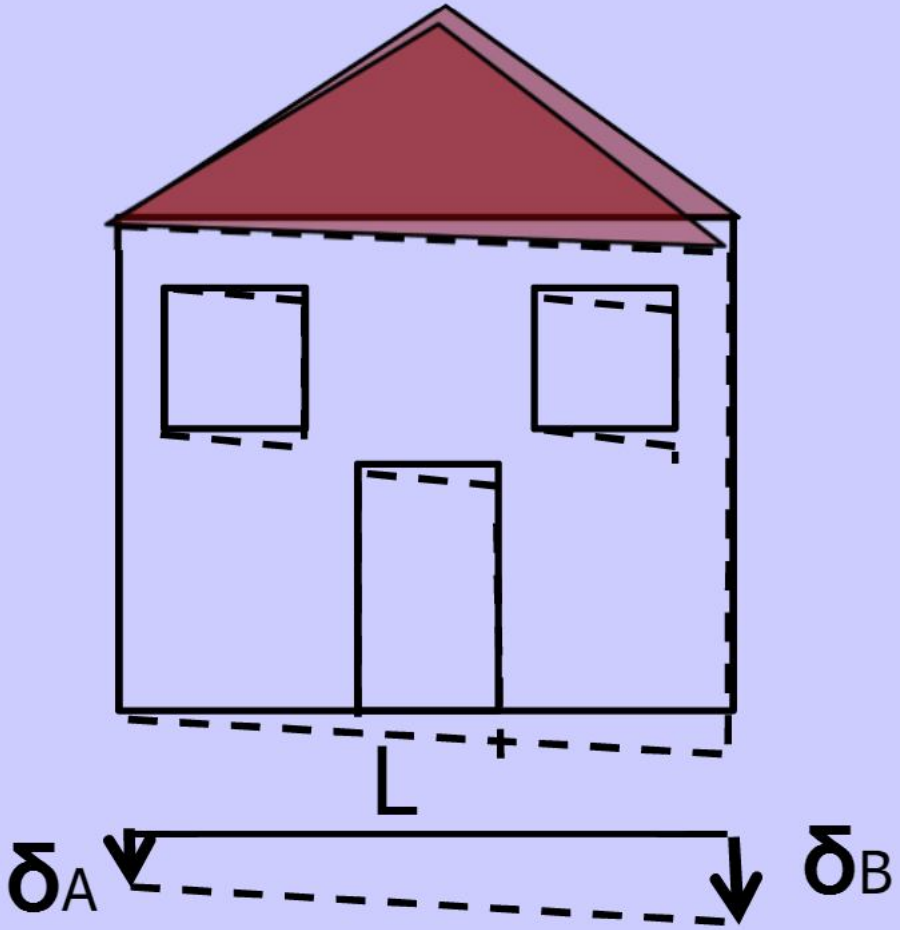
GeoVirginia 2015

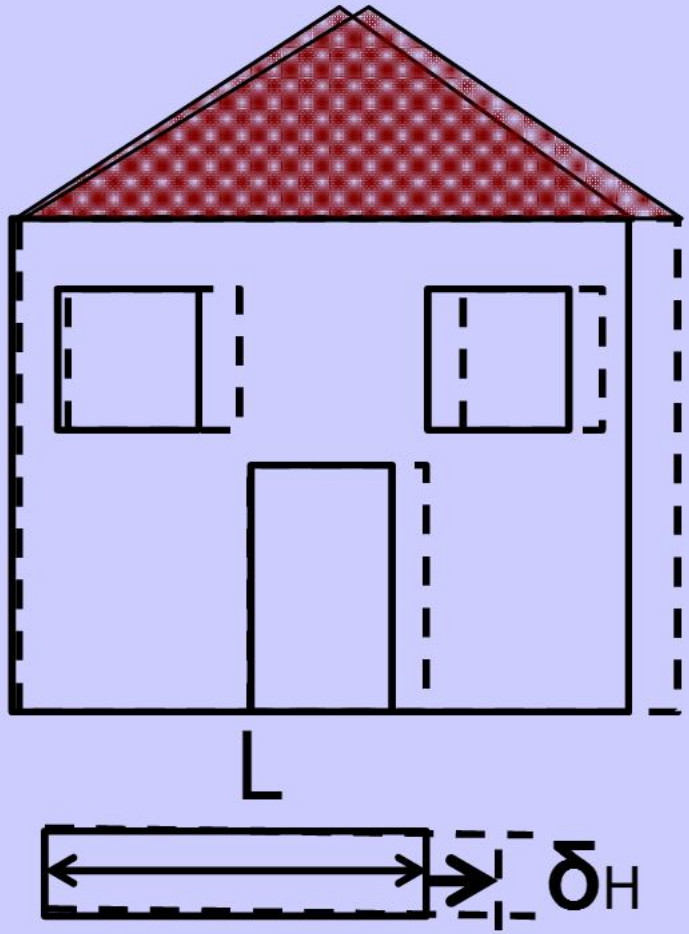
LIGHT DETECTION & RANGING

- High Resolution LiDAR Measurements, Corrected for Tectonic Deformation



ANGULAR DISTORTION AND LATERAL STRAIN



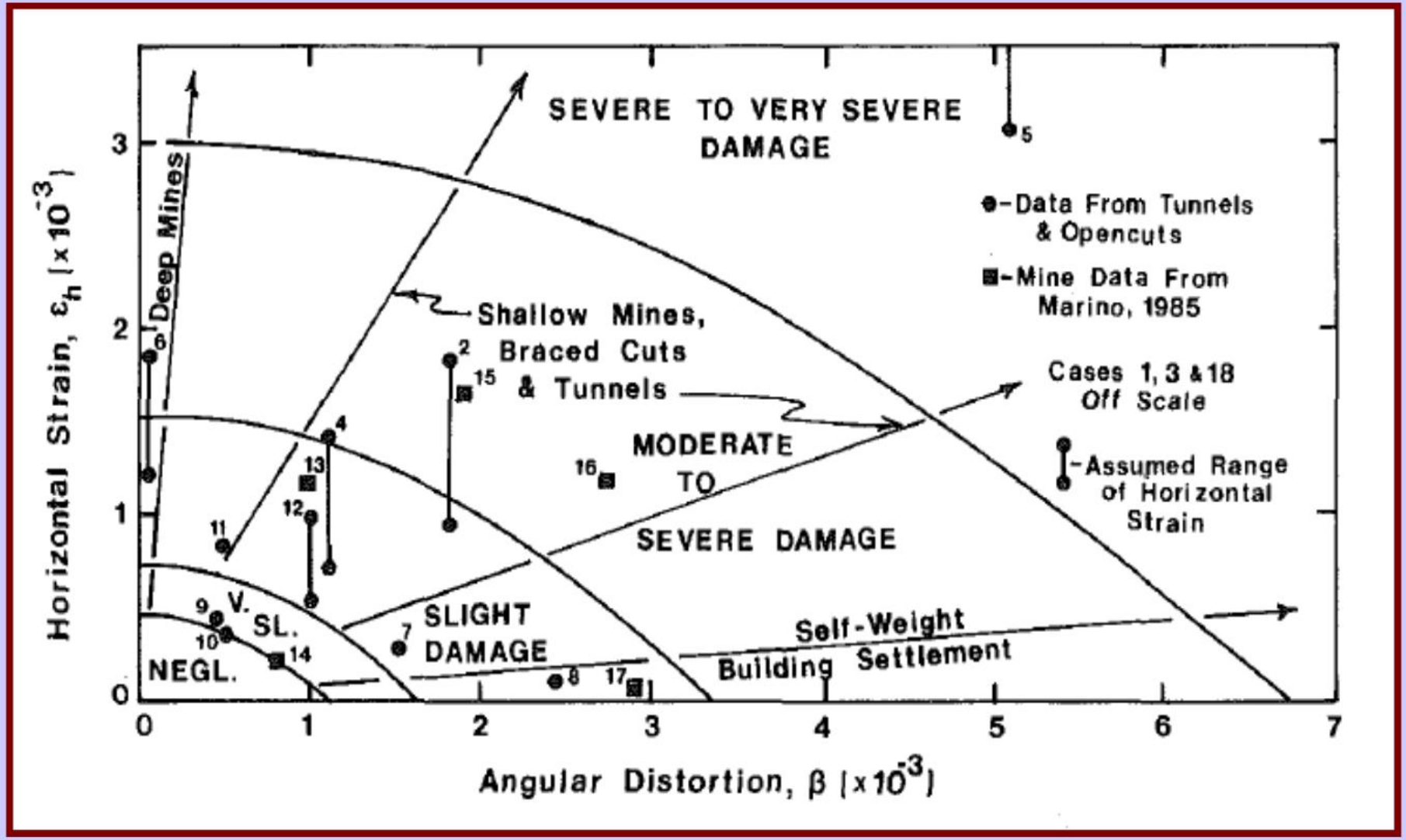


Angular Distortion = $(\delta_B - \delta_A)/L$

Lateral Strain = δ_H/L

GROUND DEFORMATION METRICS

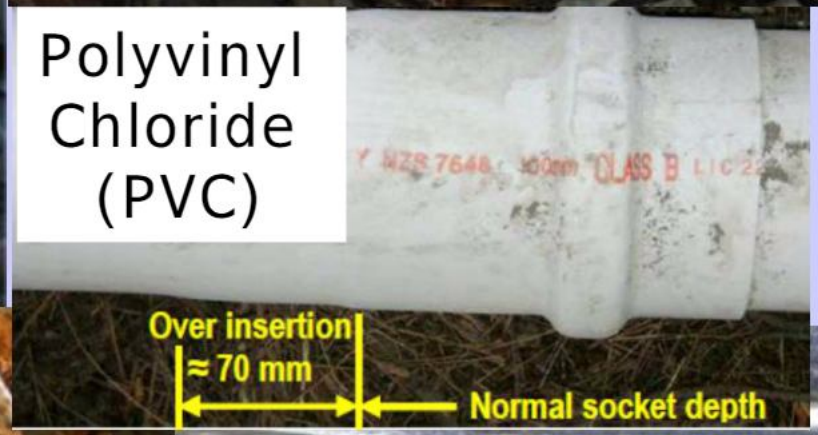
- From Boscardin & Cording (1989) for Building Damage:



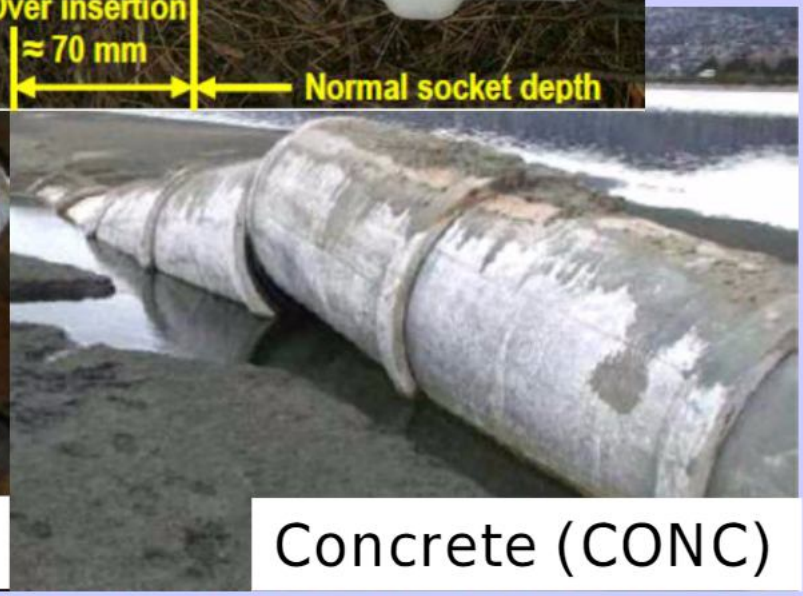
EARTHQUAKE PIPELINE DAMAGE

Asbestos Cement (AC)

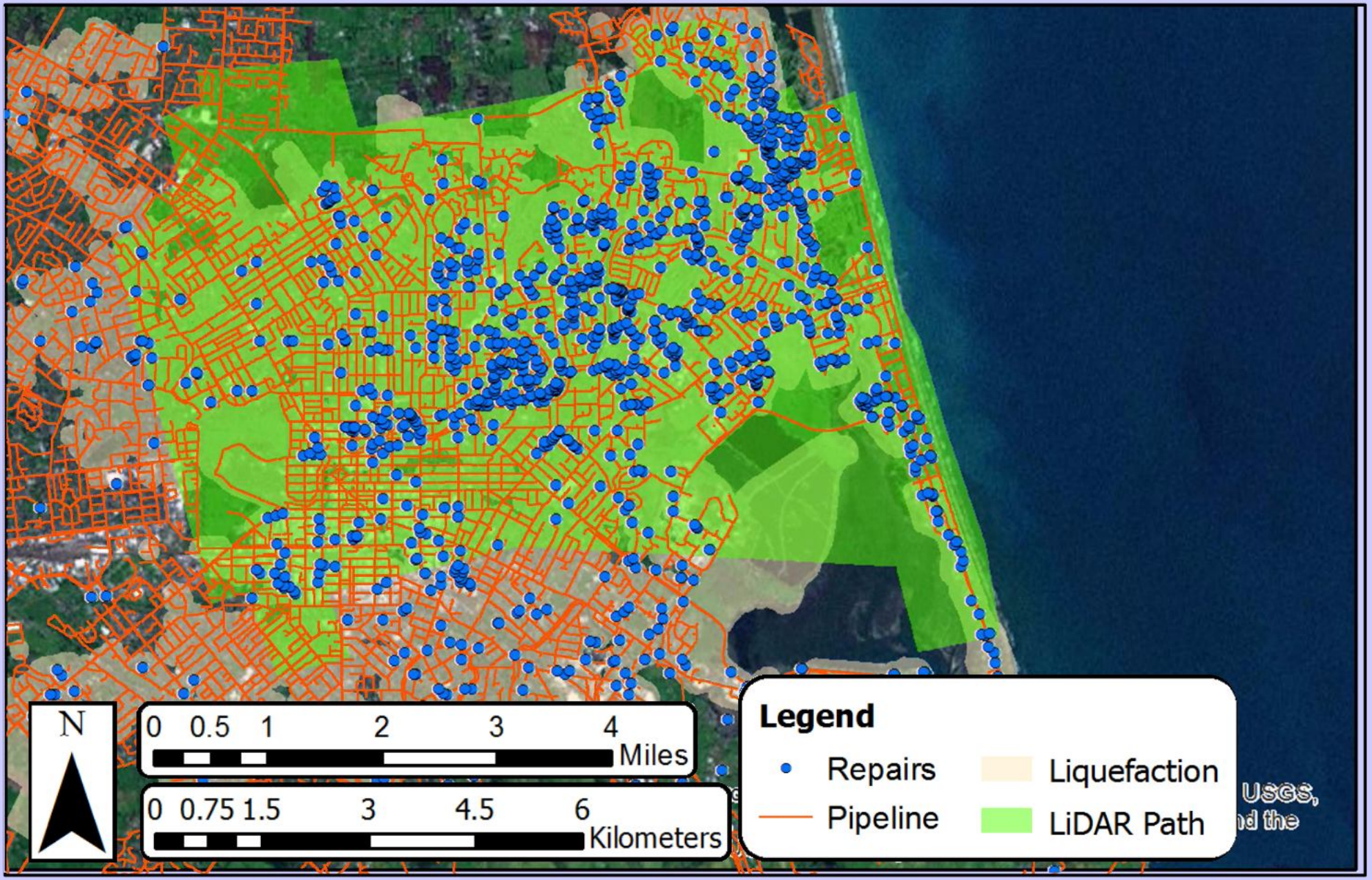
Polyvinyl Chloride (PVC)



Cast Iron (CI)



Concrete (CONC)



0 0.5 1 2 3 4
Miles

SCREENING CRITERIA

- Assume Poisson Distribution for Repairs

$$(1-\alpha)p \le (RR)x \le (1+\alpha)p$$

Poisson distribution: **μ** = (RR)x, and **σ** = [(RR)x]$^{1/2}$

Sampled repairs follow normal distr. (central limit theorem)

$$\mu + \phi^{-1}(\beta_c)\sigma = (1+\alpha)p$$

$$x \ge [\phi^{-1}(\beta_c)]^2 / \alpha^2 RR$$

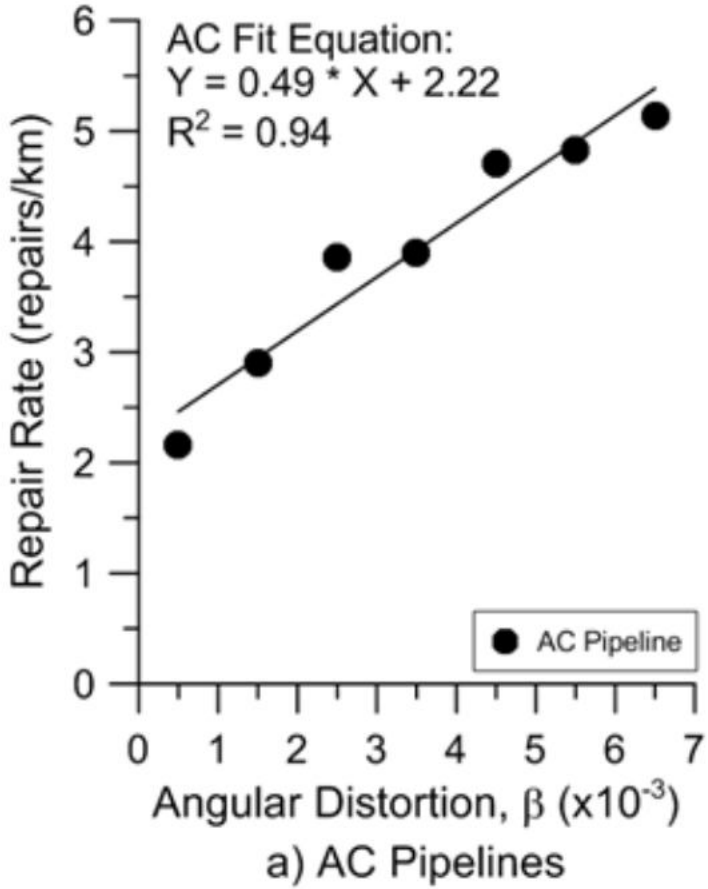
- Repair Locations Checked by GIS
- Discount Landslides/ Rockfall Areas

REPAIR RATE VS ANGULAR DISTORTION

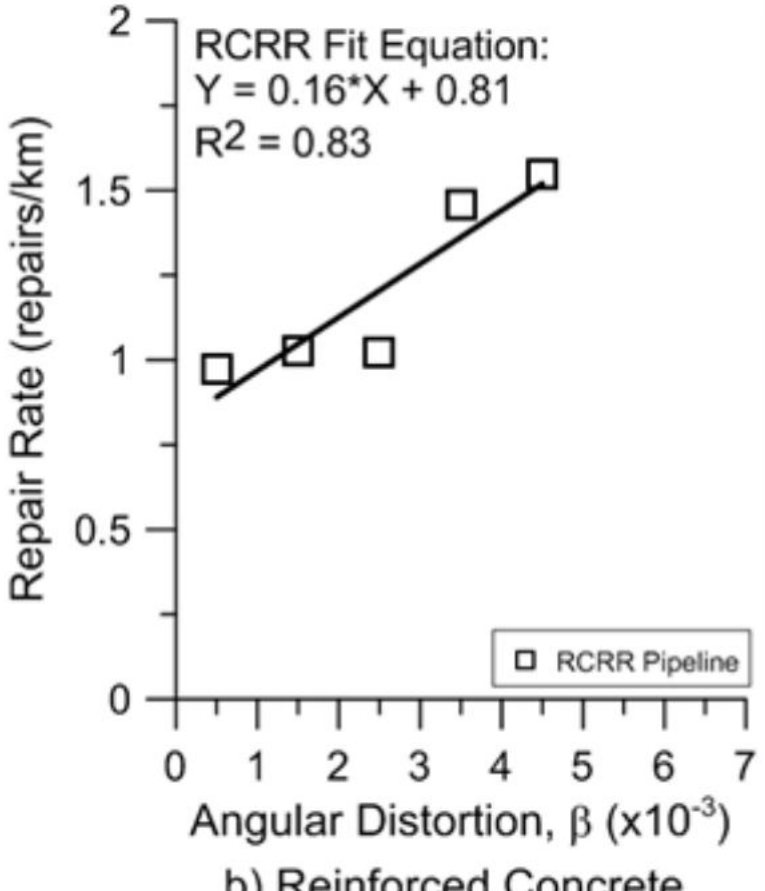
- Angular Distortion = (dv1-dv2)/L = **Δ**d/5m

Water Pipelines

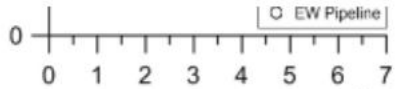
Wastewater Pipelines



a) AC Pipelines

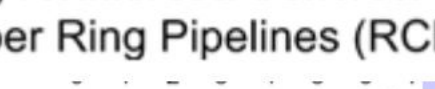


b) Reinforced Concrete Rubber Ring Pipelines (RCRR)



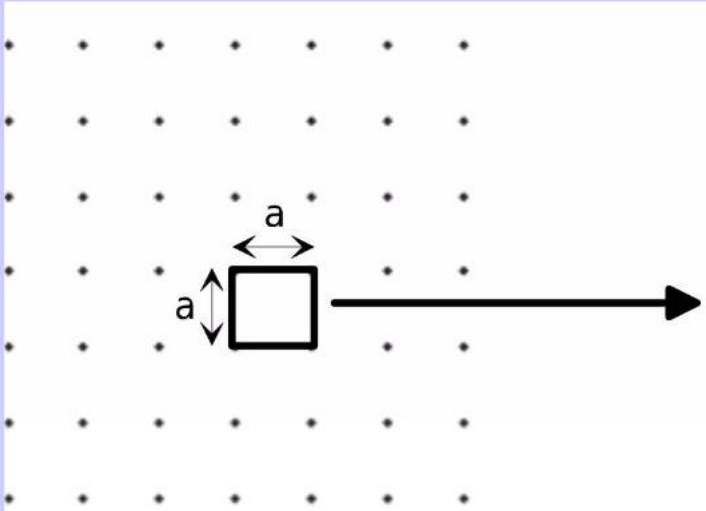
a) Earthenware (EW) Pipelines

b) Reinforced Concrete Rubber Ring Pipelines (RCRR)

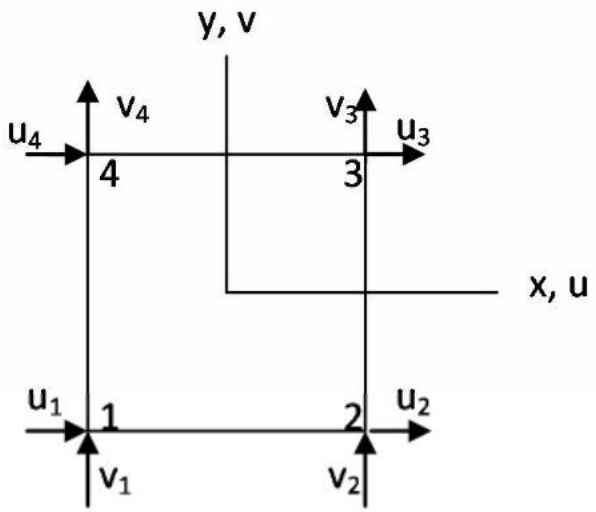


c) Concrete Pipelines (CONC)

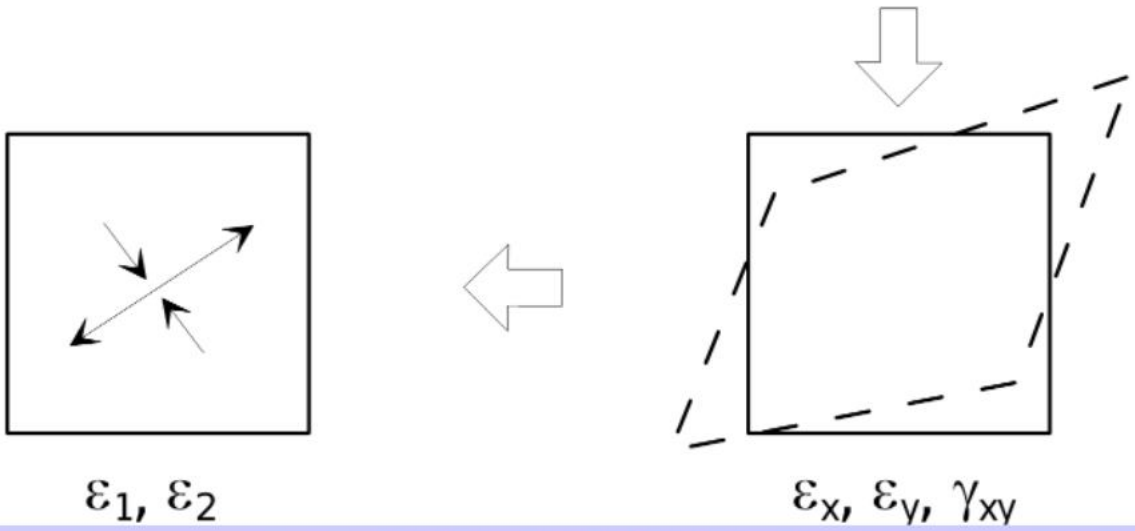
MAXIMUM PRINCIPAL LATERAL STRAIN



Location of ground displacement vectors (at intervals of 56 m)



Bilinear quadrilateral (Q4) finite element with EW and NS displacements

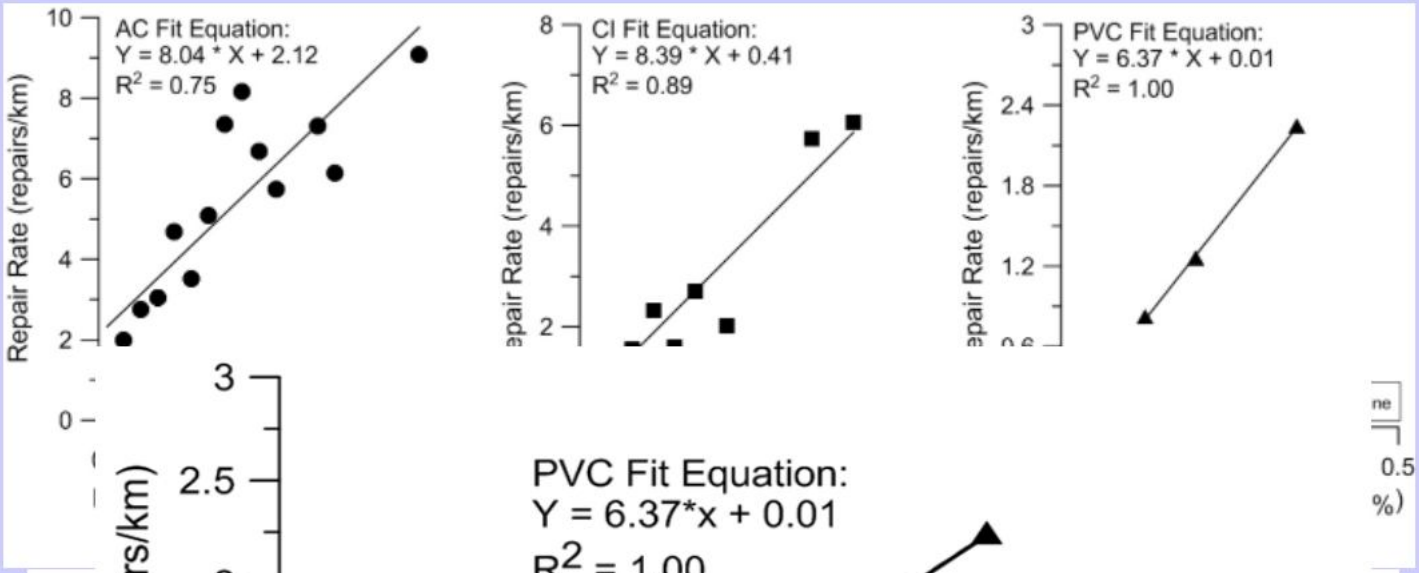


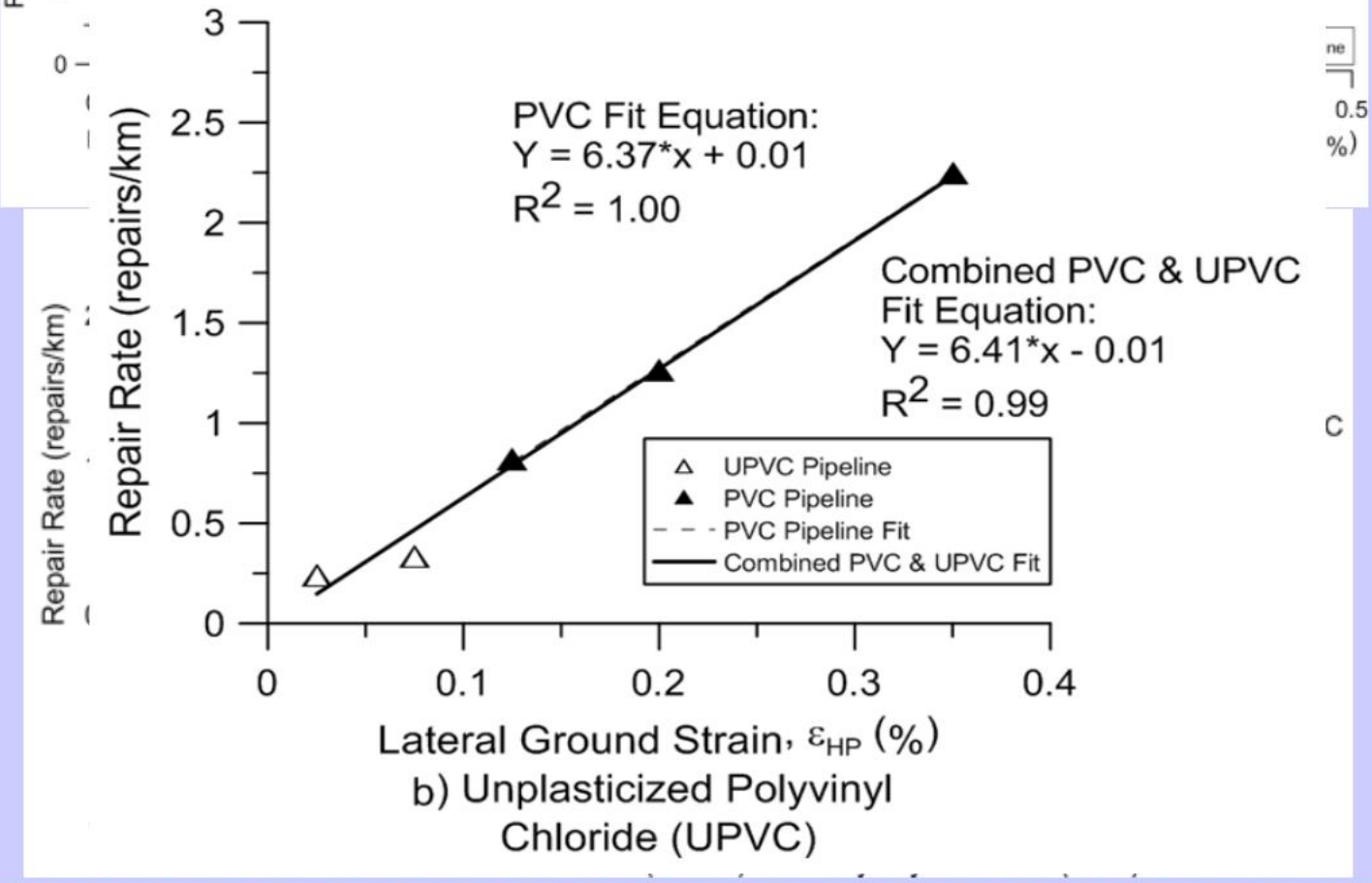
Create Bilinear Quadrilateral Finite Element from Lateral Displacements at Grid Corners to Determine Principal Strain

REPAIR RATE VS LATERAL STRAIN

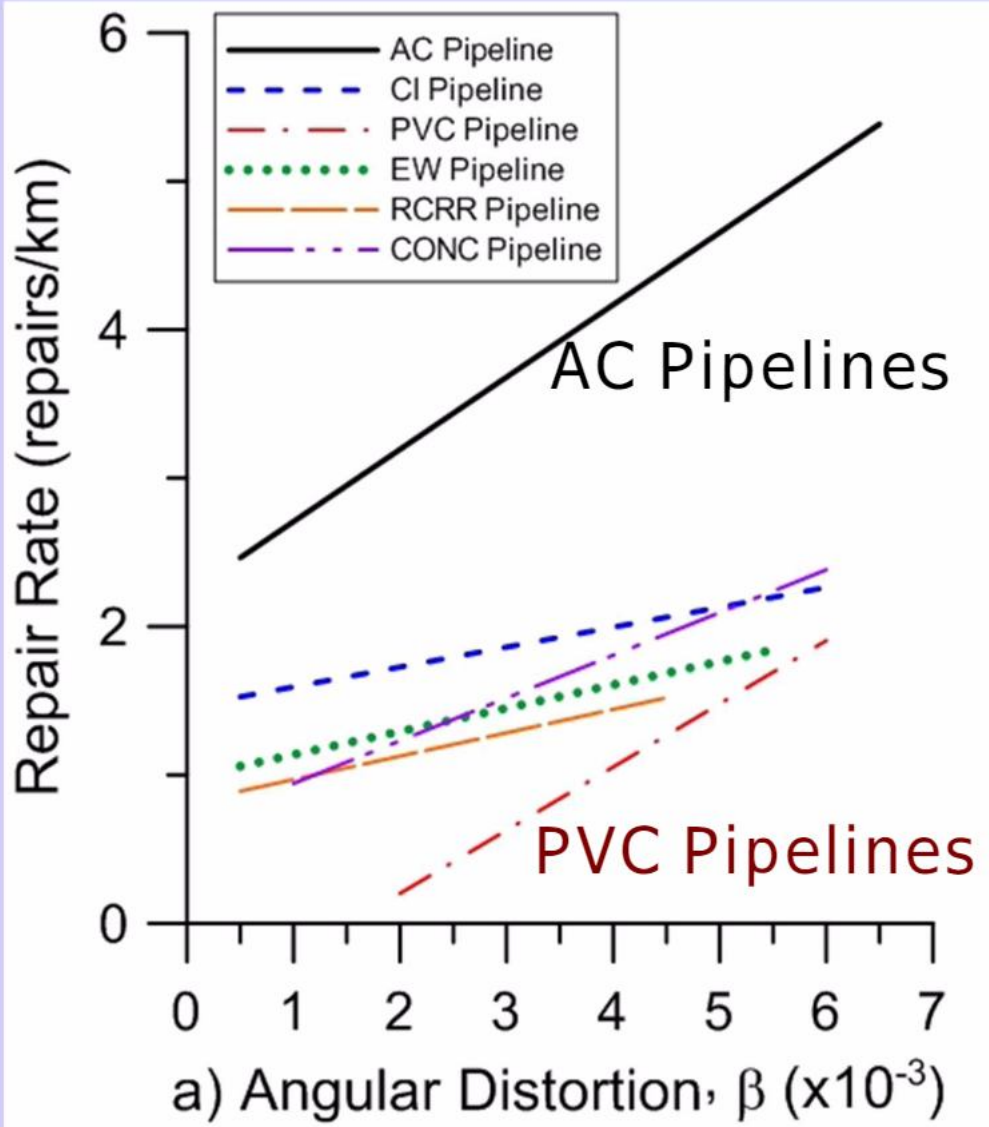
Water Pipelines

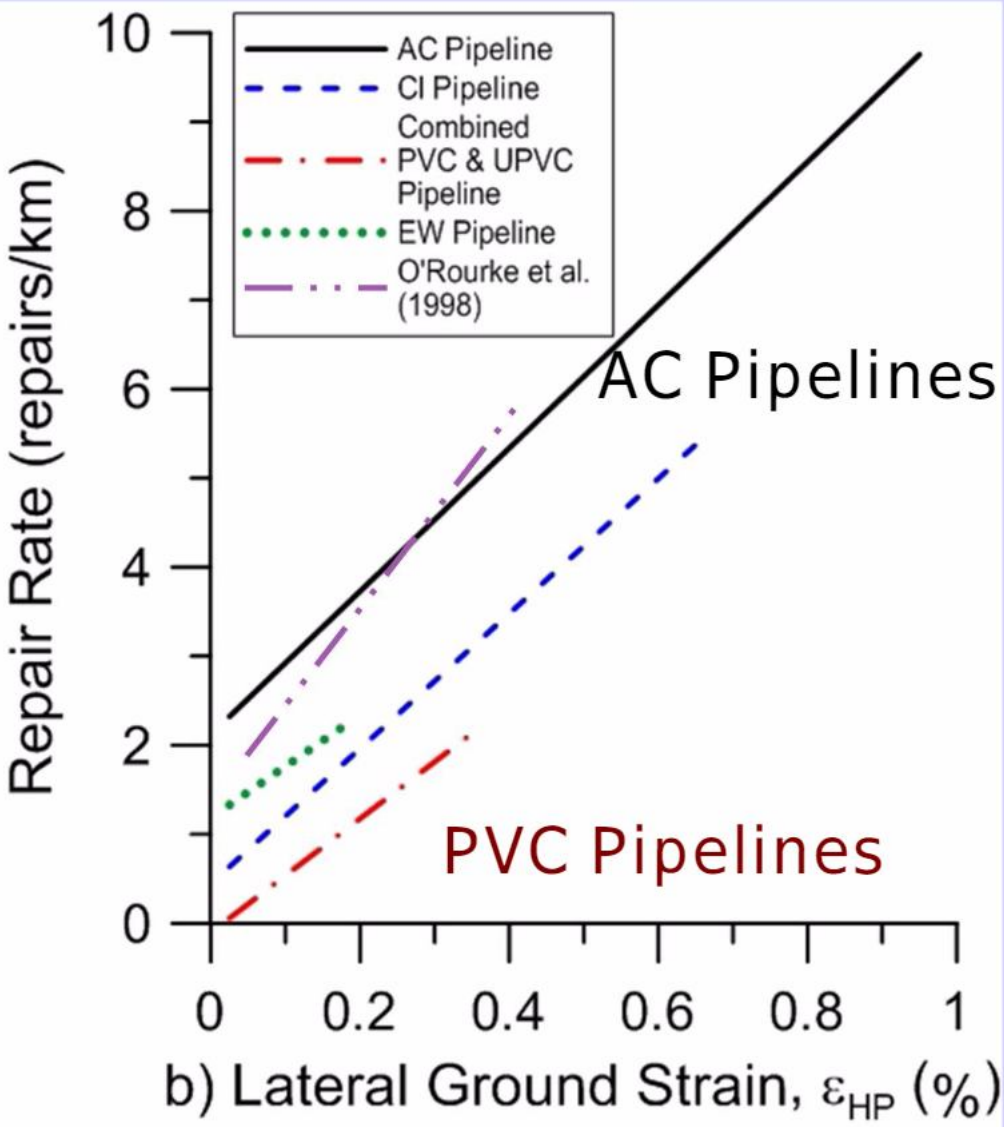
Wastewater Pipelines





REPAIR RATE COMPARISONS





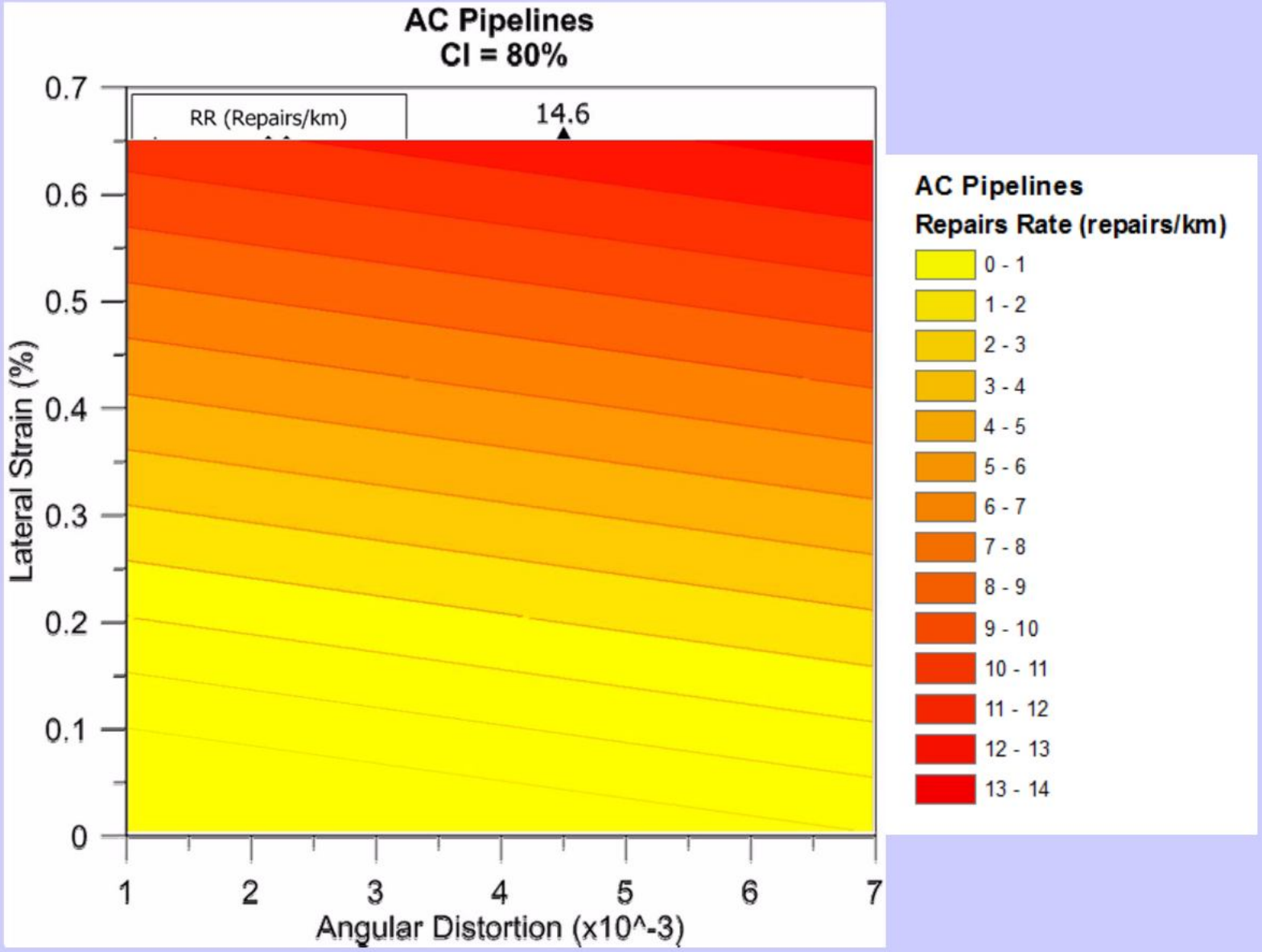
SCREENING CRITERIA

$$\mu + \phi^{-1}(\beta_c)\sigma = (1+\alpha)p$$

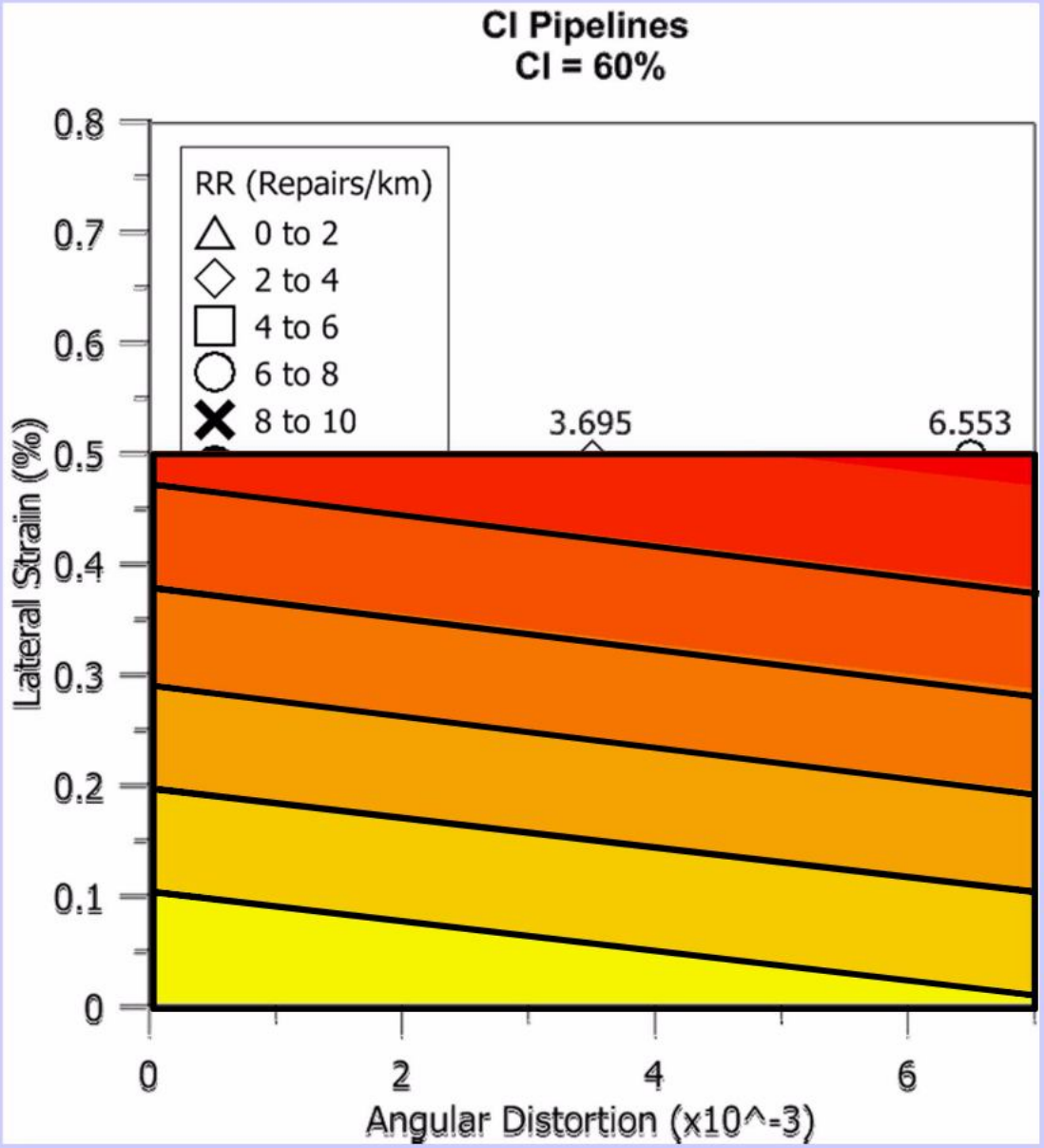
$$x \geq [\phi^{-1}(\beta_c)]^2 / \alpha^2 RR$$

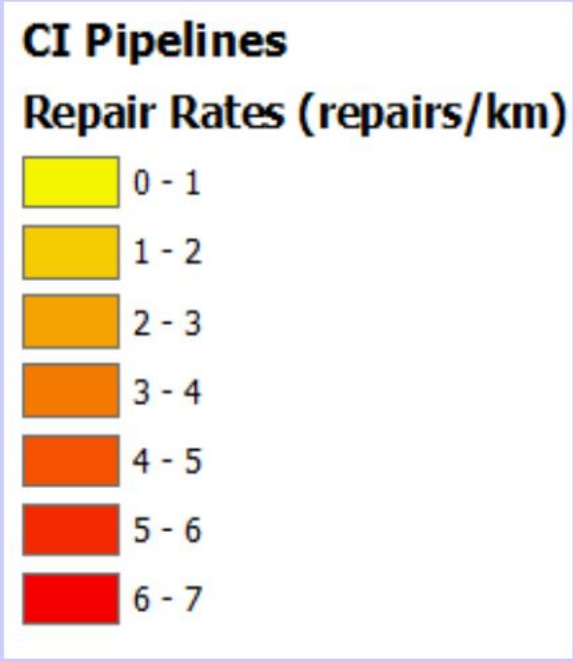
- Adjust β_C to obtain sufficient data for each lateral strain and angular distortion combination

REPAIR RATE, β, AND E_{HP} FOR AC PIPELINES

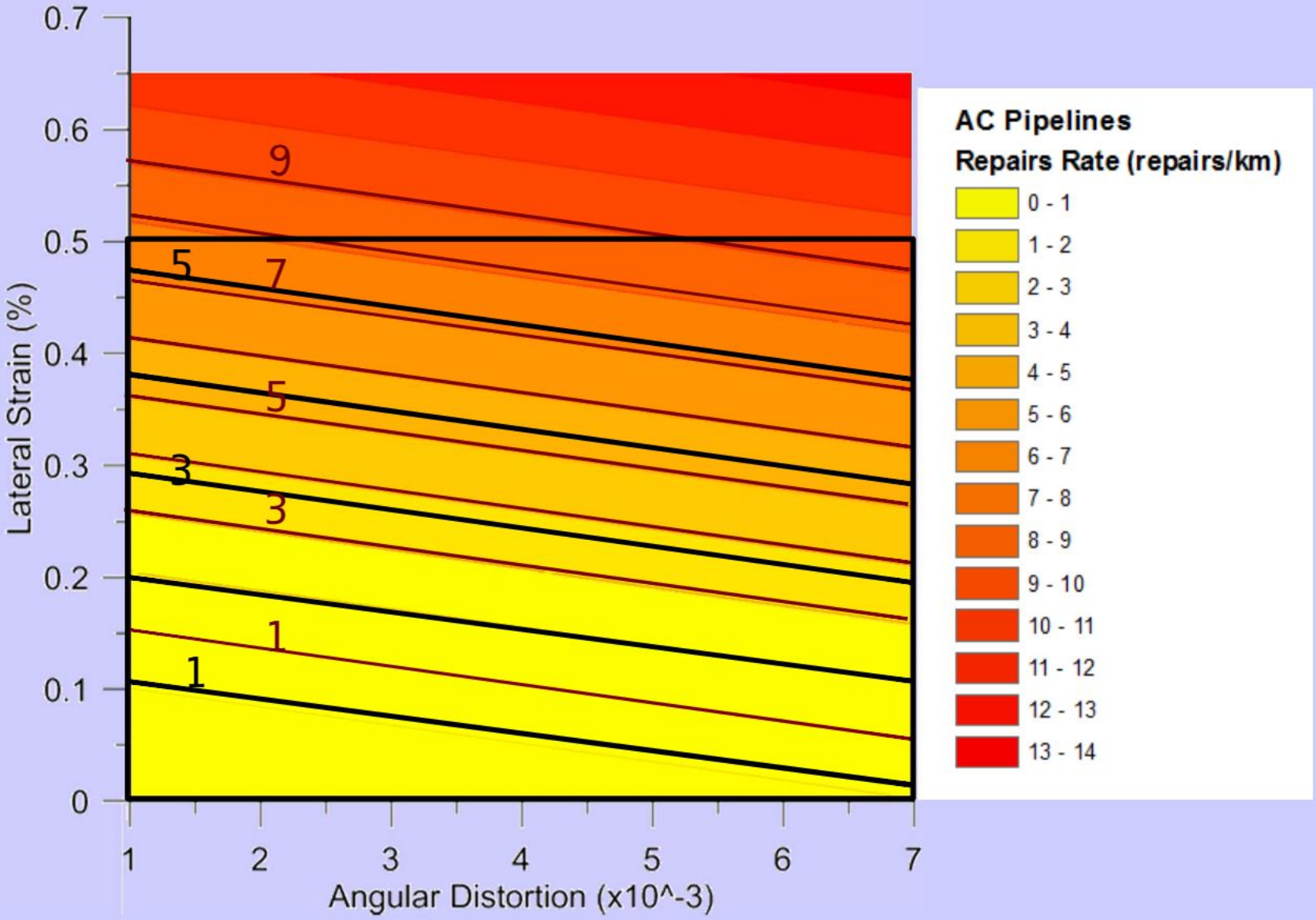


REPAIR RATE, β, AND E_{HP} FOR CI PIPELINES

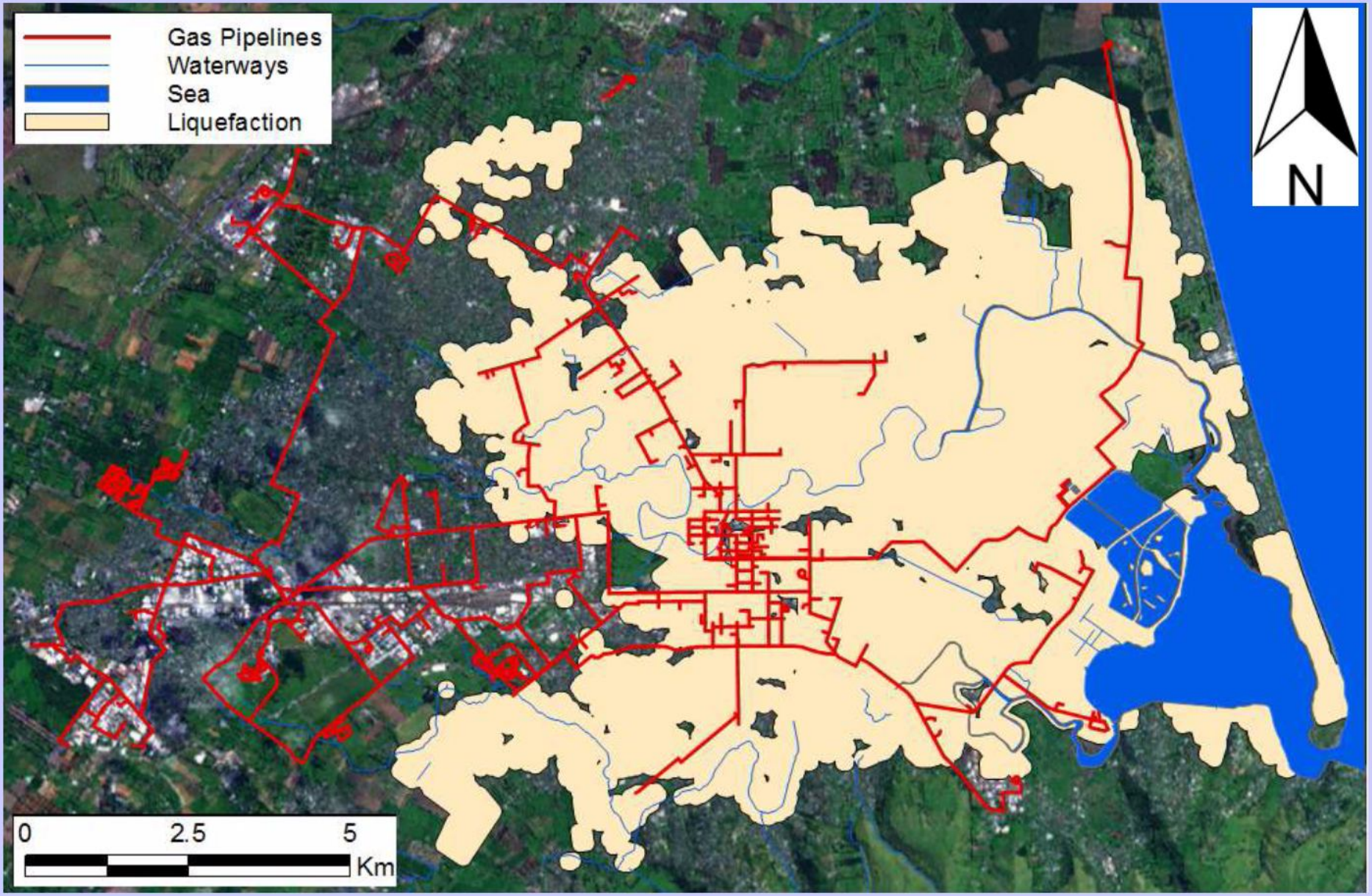


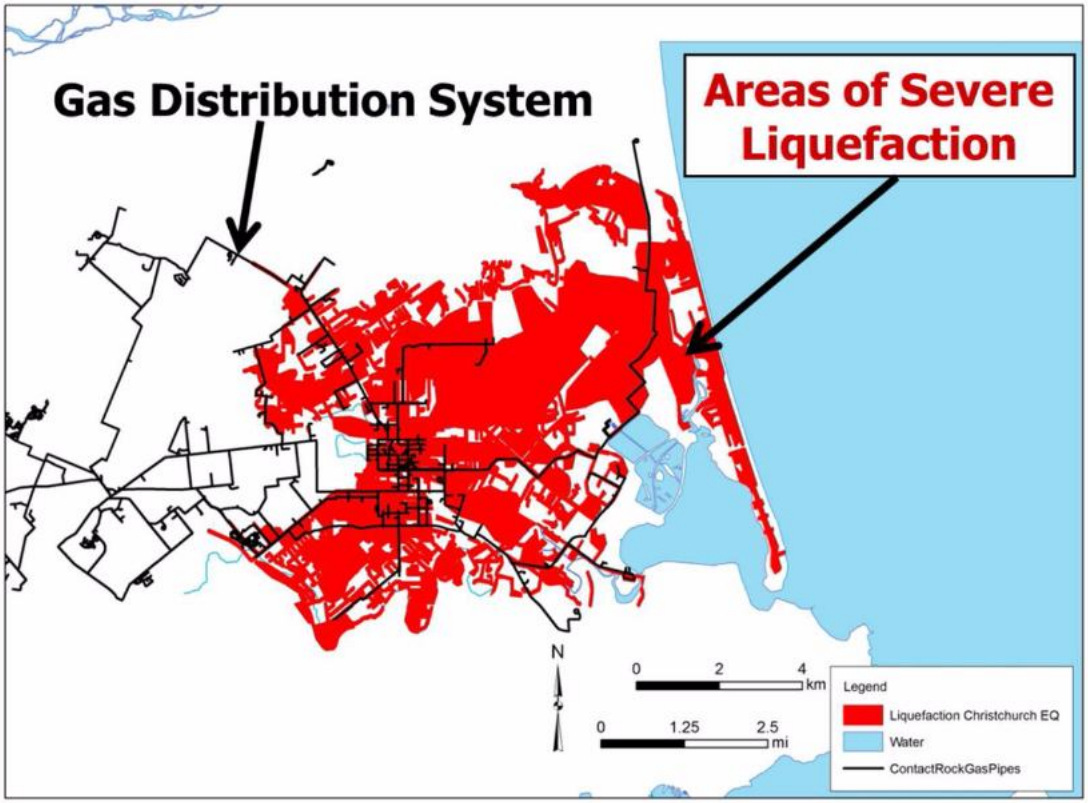


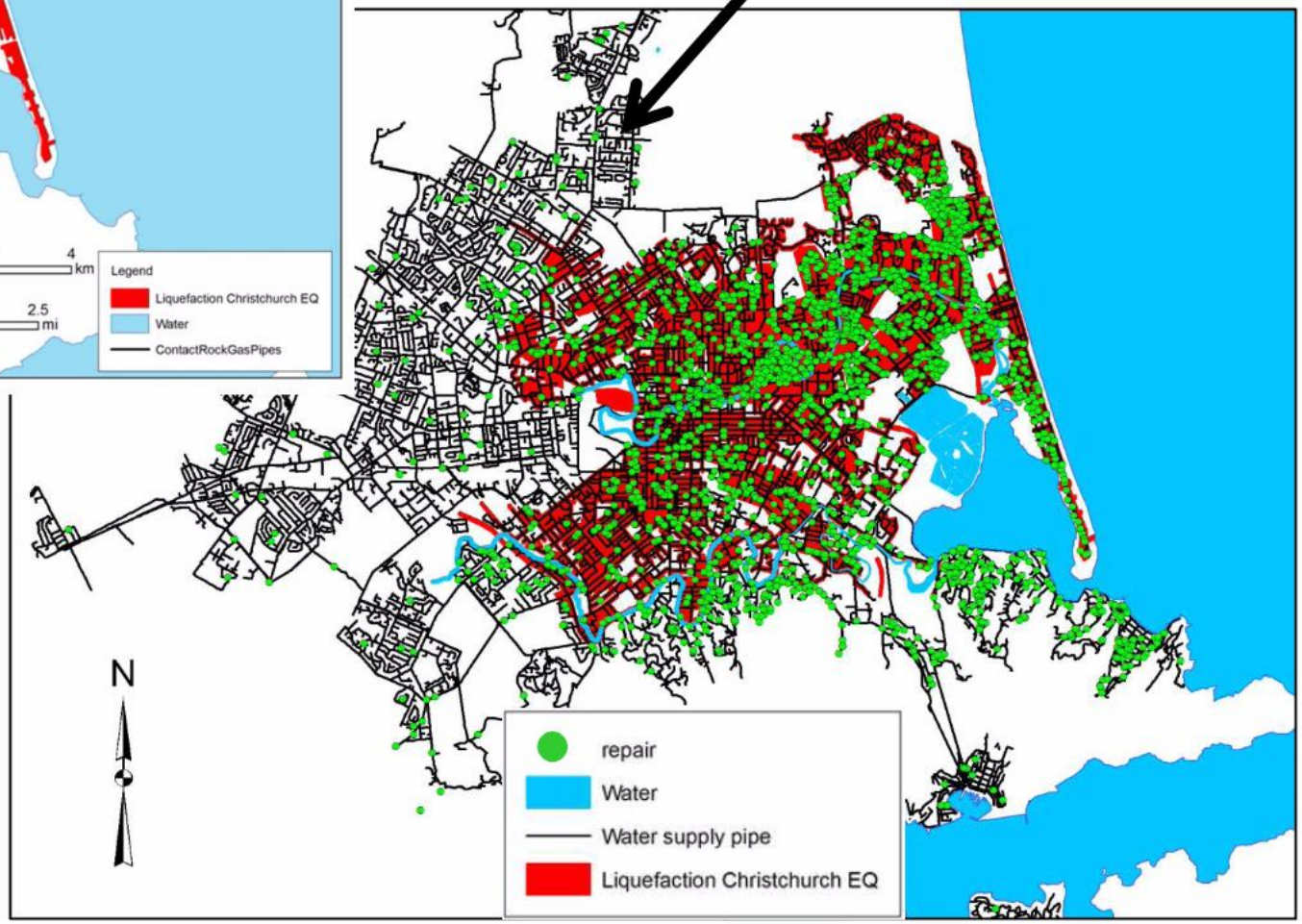
COMPARISON OF AC AND CI RELATIONSHIPS



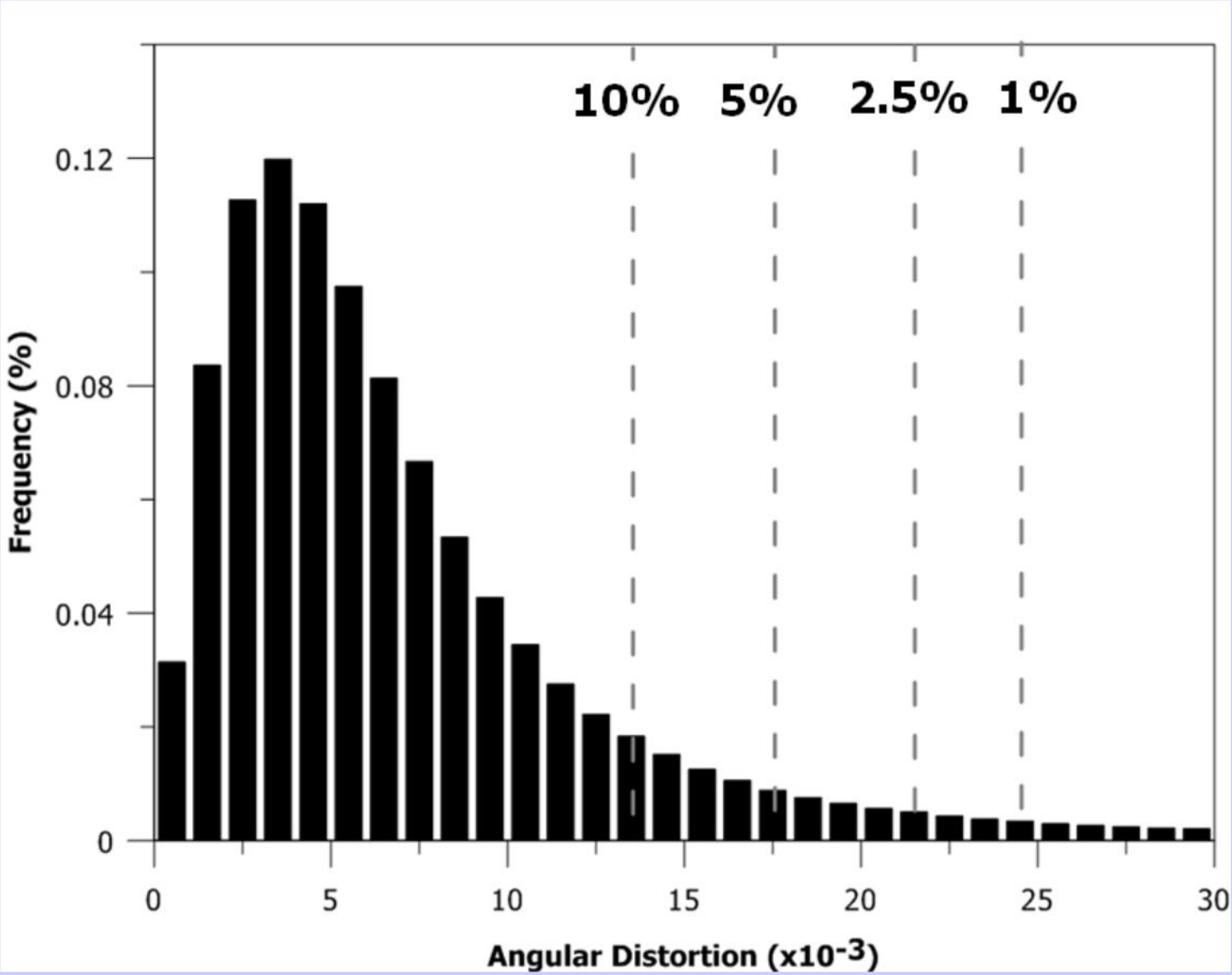
GAS DISTRIBUTION SYSTEM

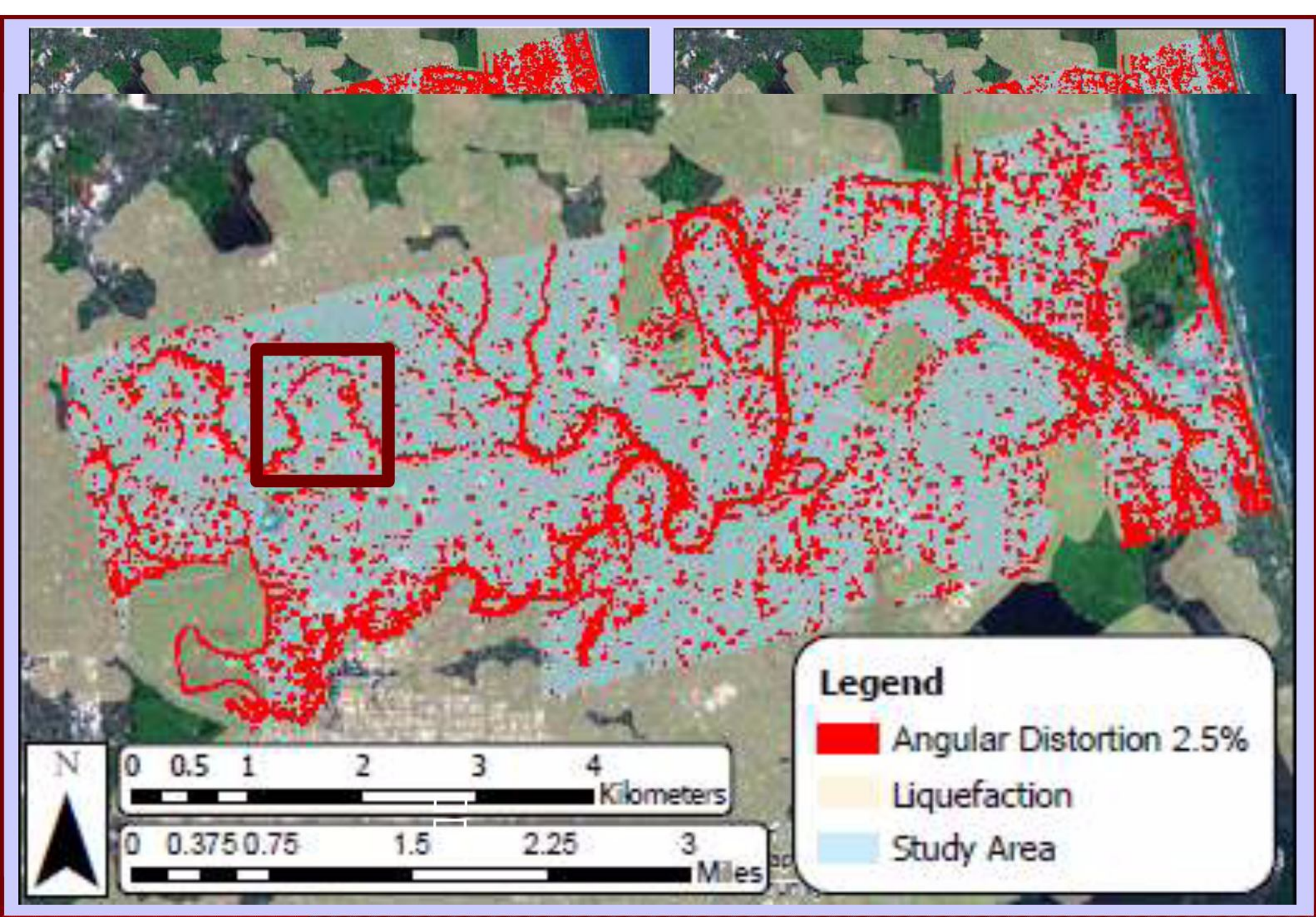



Gas Distribution System
Areas of Severe Liquefaction
N
0 2 4 km
0 1.25 2.5 mi
Legend
Liquefaction Christchurch EQ
Water
ContactRockGasPipes

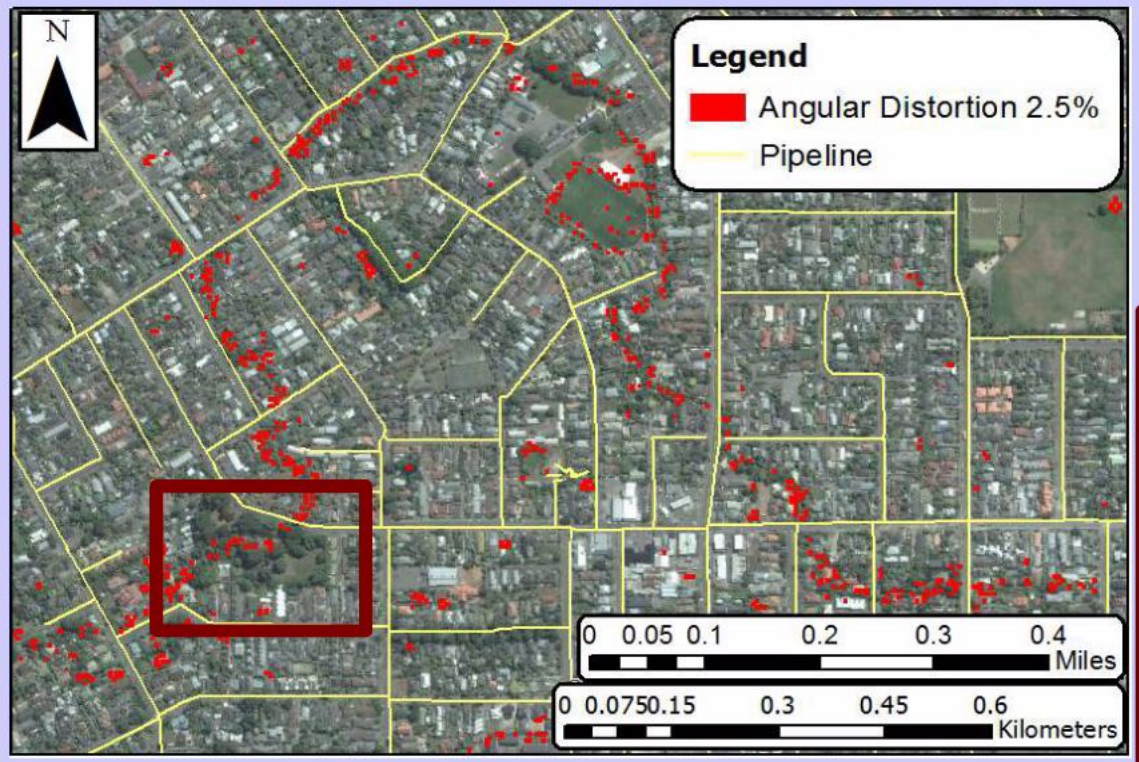

Water Distribution System
N
repair
Water
Water supply pipe
Liquefaction Christchurch EQ

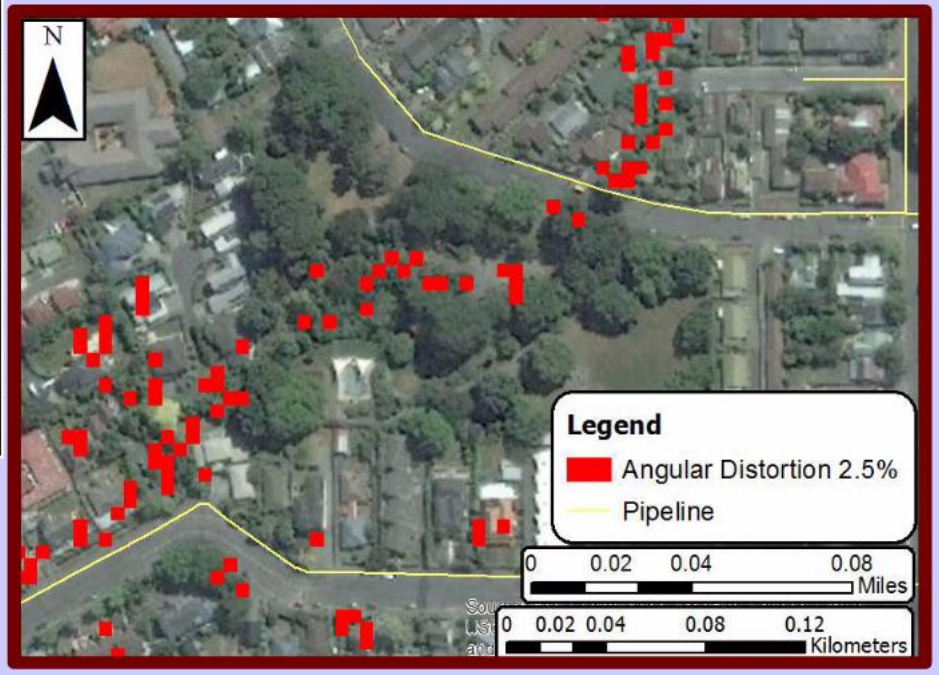
ANGULAR DISTORTION




Legend
Angular Distortion 2.5%
Liquefaction
Study Area
N
0 0.5 1 2 3 4
Kilometers
0 0.375 0.75 1.5 2.25 3
Miles

PALEO CHANNELS

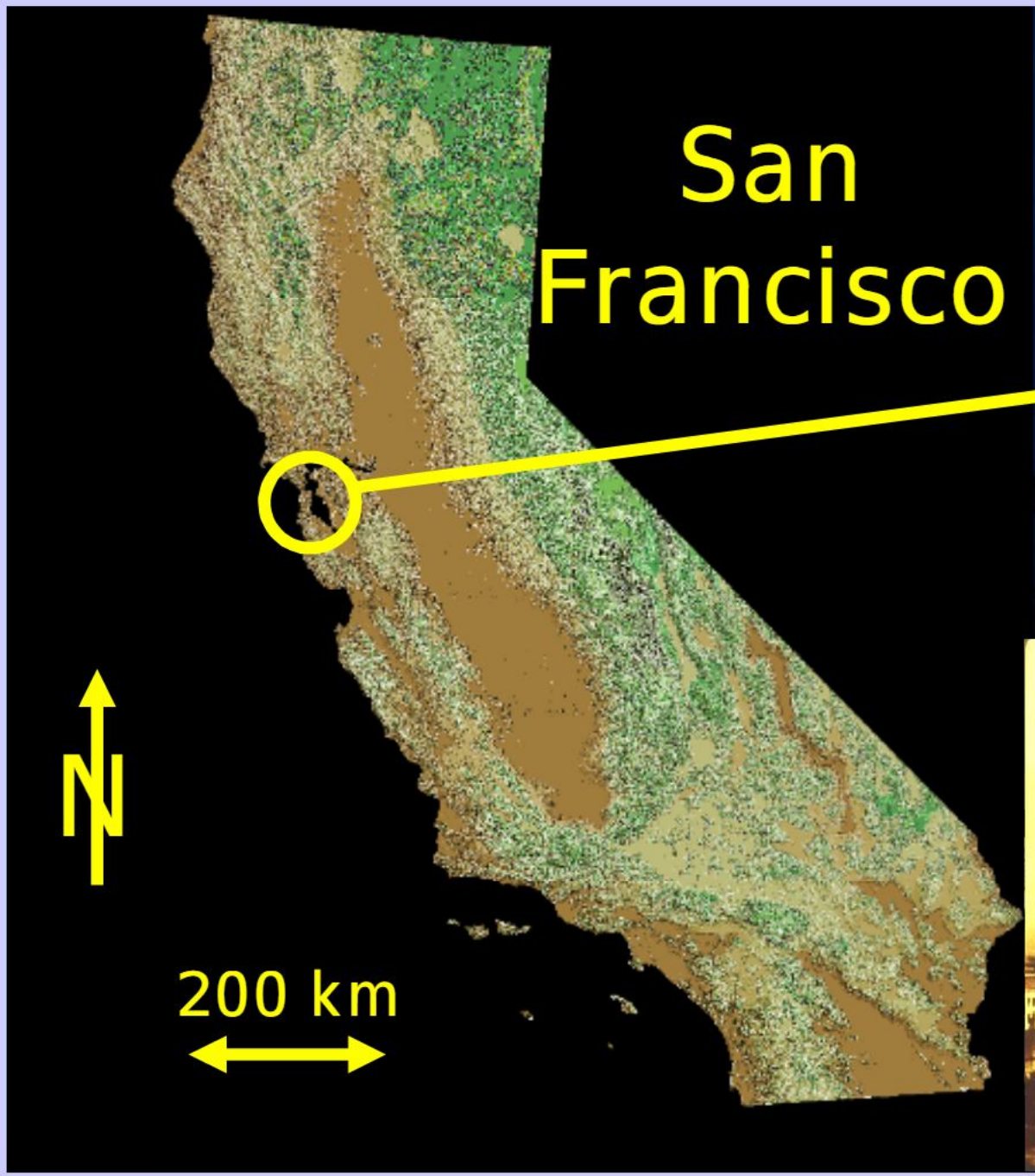


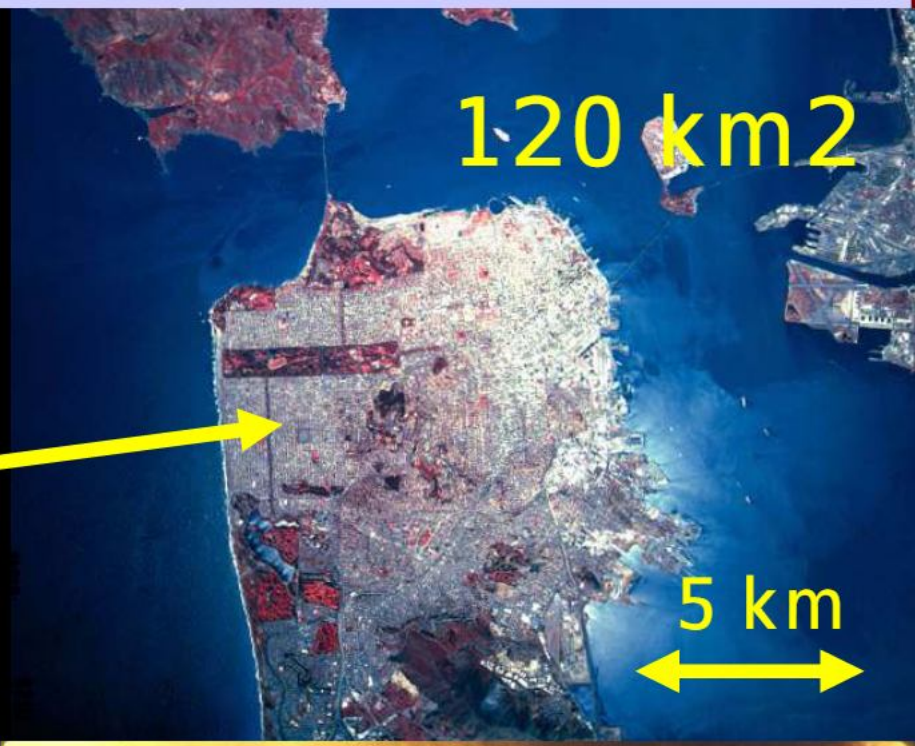


Pipeline 2.5% Exceedance

LESSONS FROM CHRISTCHURCH

- Extraordinary dataset: multiple EQs, dense ground motion array, massive liquefaction, high density LiDAR, geocoded repairs for thousands of km of different pipelines
- First time comprehensive assessment of underground lifeline response to liquefaction- induced differential vertical movement and lateral strain
- Remarkable performance of highly ductile HDPE and MDPE pipelines

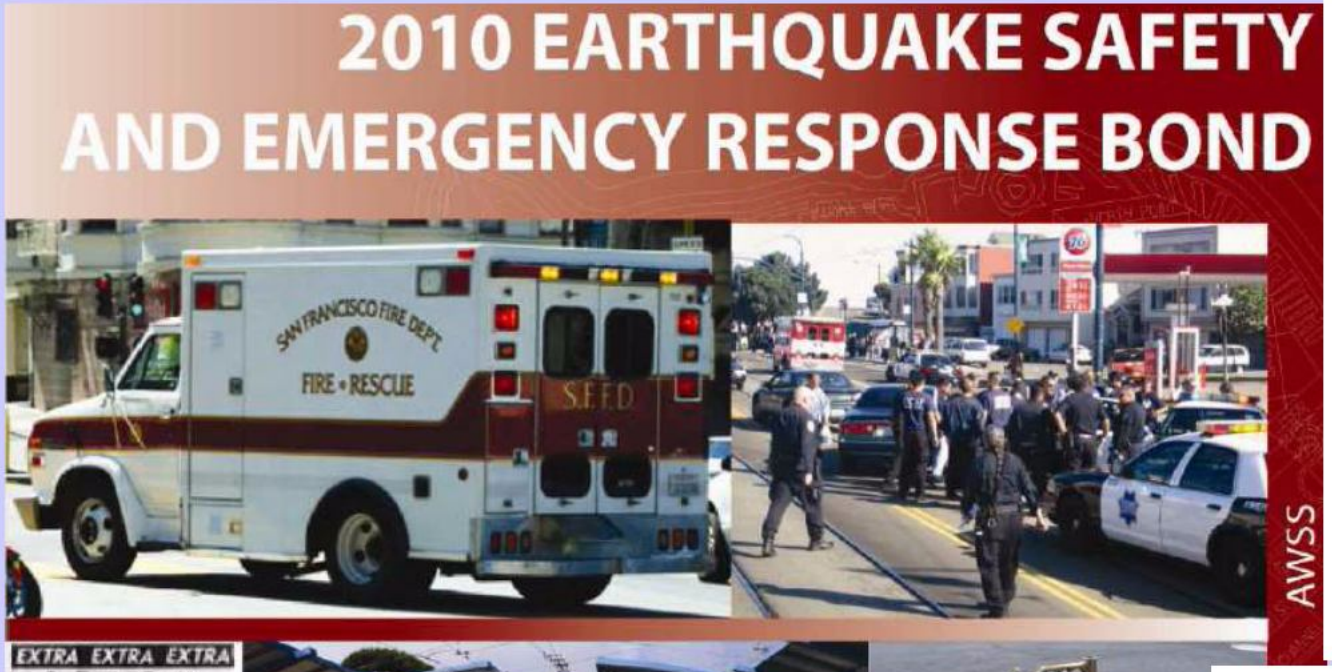

San
Francisco
N
200 km


120 km2
5 km


0 1000 3000 5000 feet
0 500 1000 1500 meters
N
Zones of Soil Liquefaction
Marina
Embarcadero
Approx. Boundary of Foot of Market Zone
U.S. Post Office
James Lick Skyway
Approx. Boundary of South of Market Zone
Market St
Old Mission Bay
Valencia St
Approx. Boundary of Mission Creek Zone
18th St
Mission St


0
1 km
N
Zones of Soil Liquefaction
= Zone of liquefaction induced deformation

EARTHQUAKE SAFETY AND EMERGENCY RESPONSE BOND

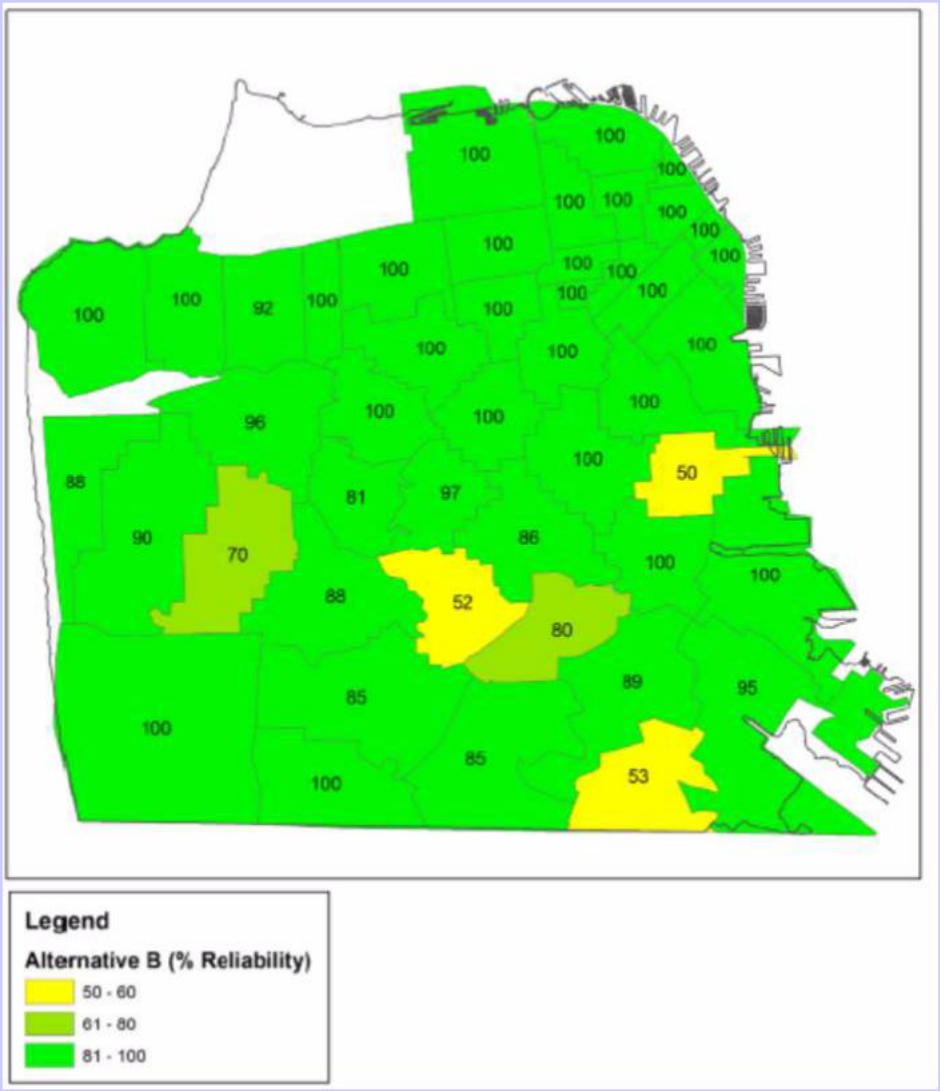


Projects and Programs	Cost (millions)
AWSS Core Facilities	$35.0
Critical Firefighting Facilities and Infrastructure	134.3
Public Safety Building	243.0
Total	**$412.3**

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

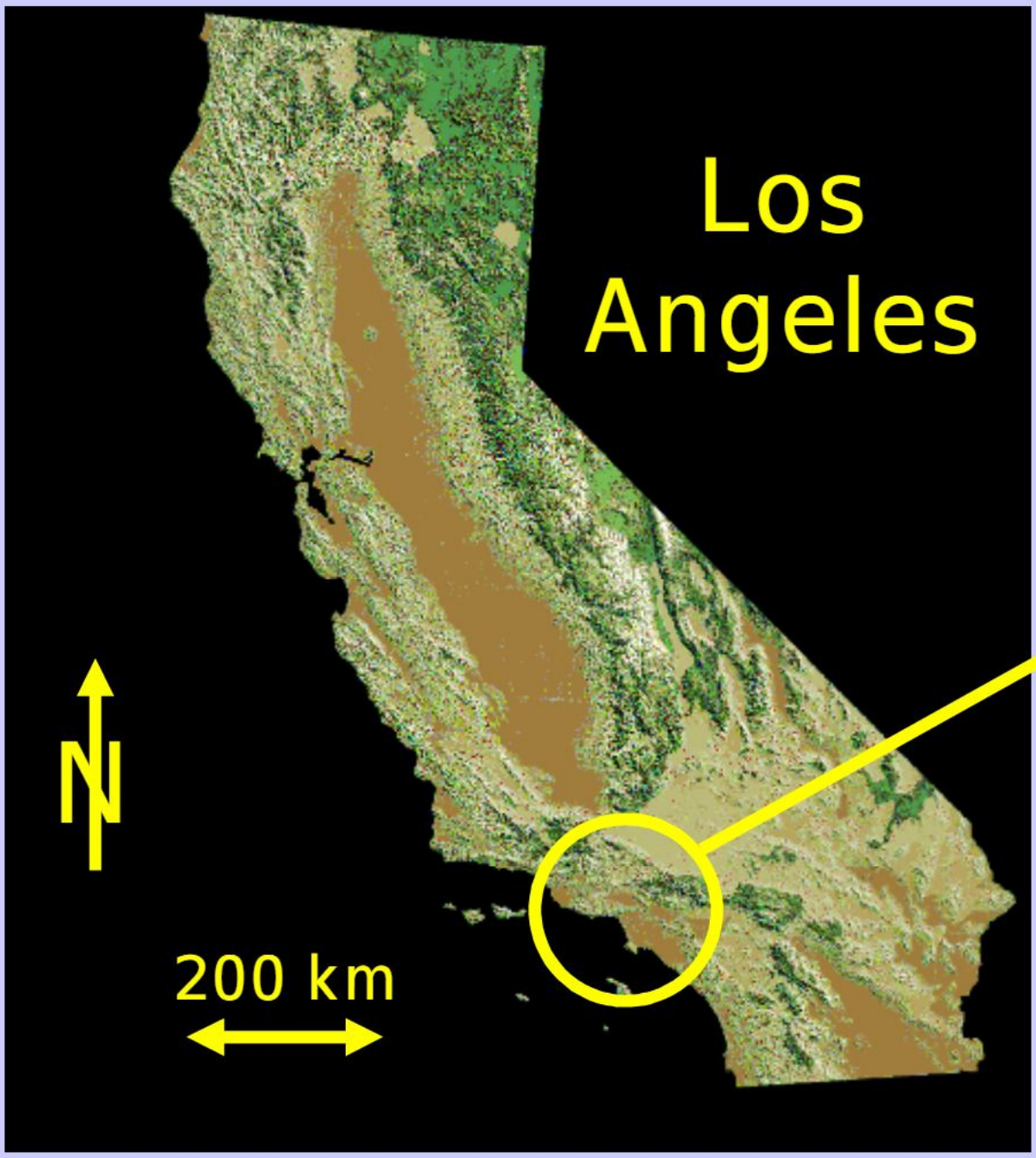
San Francisco Auxiliary Water Supply System Performance Criteria

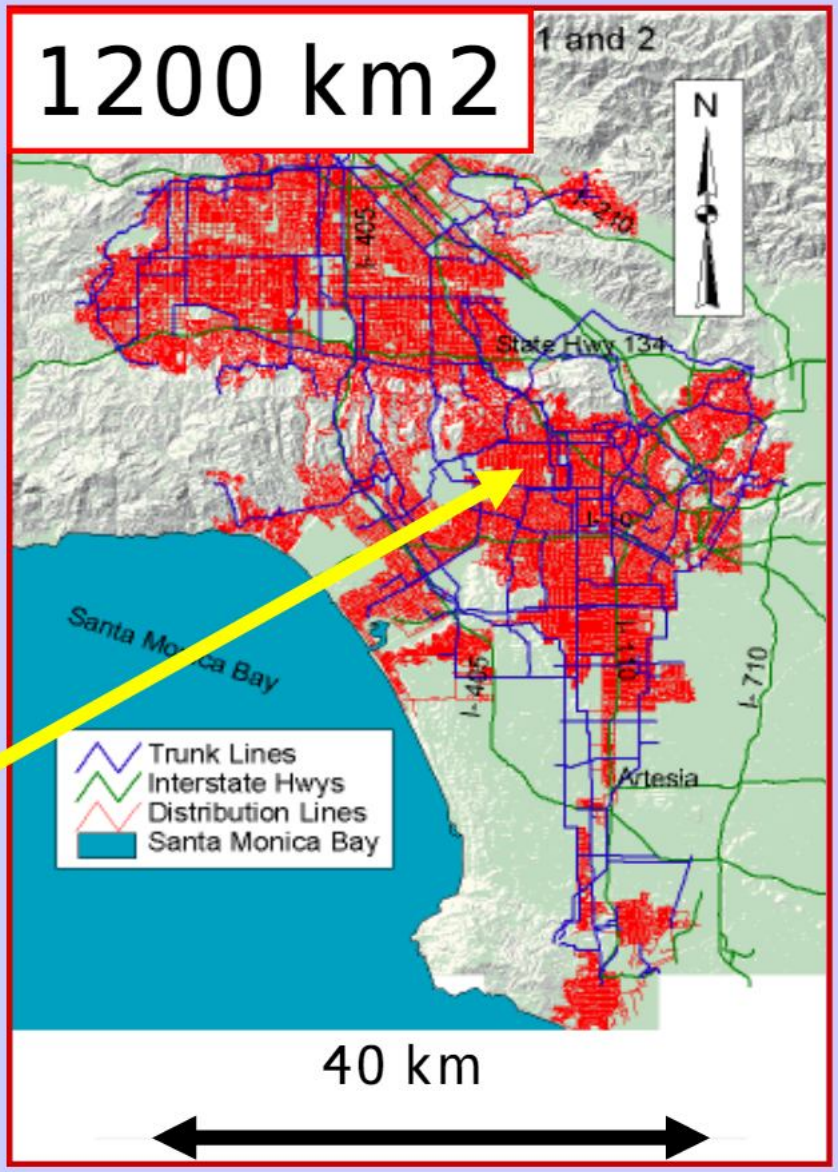
- 7.8 Mw Deterministic EQ
- Water Demands in Fire Response Areas
- Monte Carlo AWSS Network Simulations Using GIRAFFE



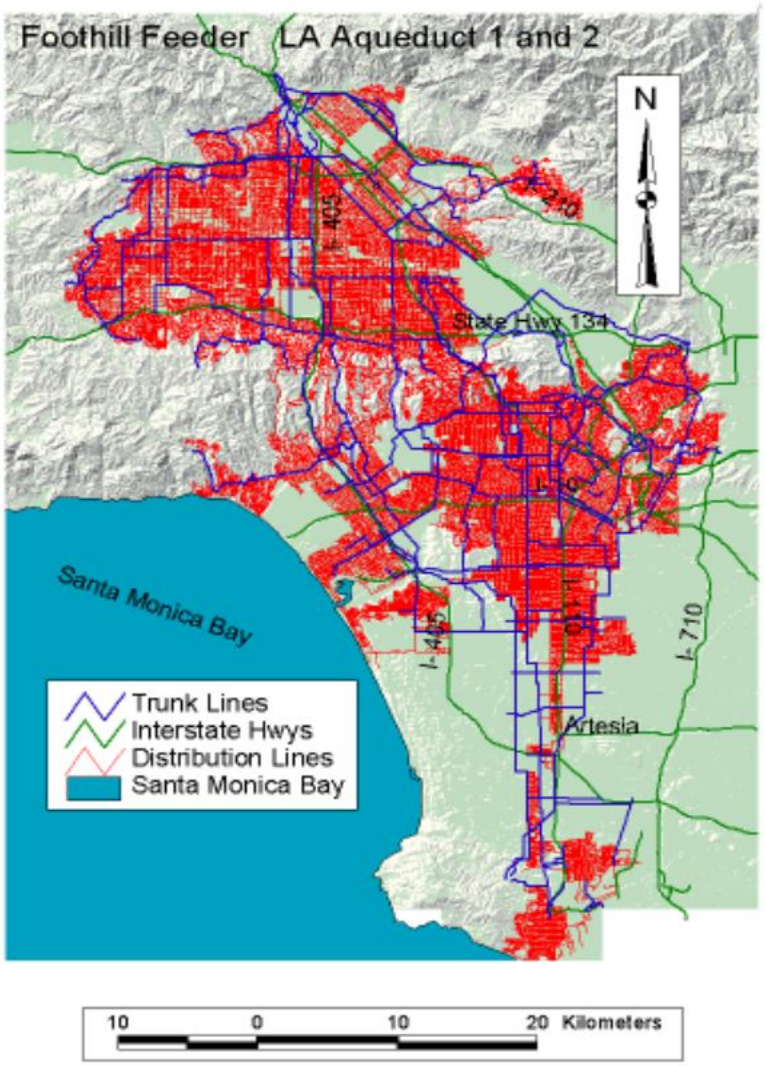
LESSONS LEARNED FROM SAN FRANCISCO

- Interdependencies of Critical Infrastructure and Geohazards
- Highly Accurate Microzonation through System-wide Characterization of Geotechnical Conditions
- Successful Use of Geotechnical and Hydraulic Network Modeling for Community Protection in Actual Earthquake


Los Angeles
N
200 km

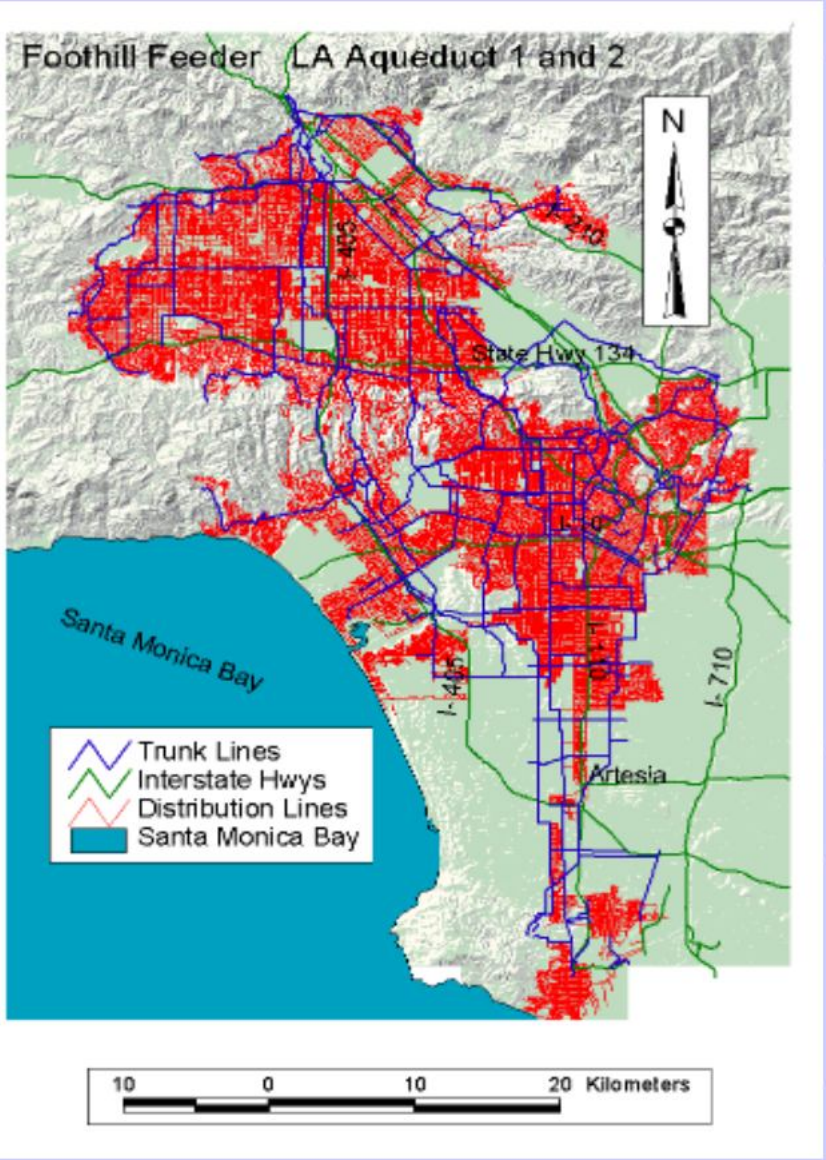

1200 km2
1 and 2
N
State Hwy 134
I-405
I-210
I-10
I-110
I-710
Santa Monica Bay
Artesia
Trunk Lines
Interstate Hwys
Distribution Lines
Santa Monica Bay
40 km

Los Angeles Department of Water and Power (LADWP)



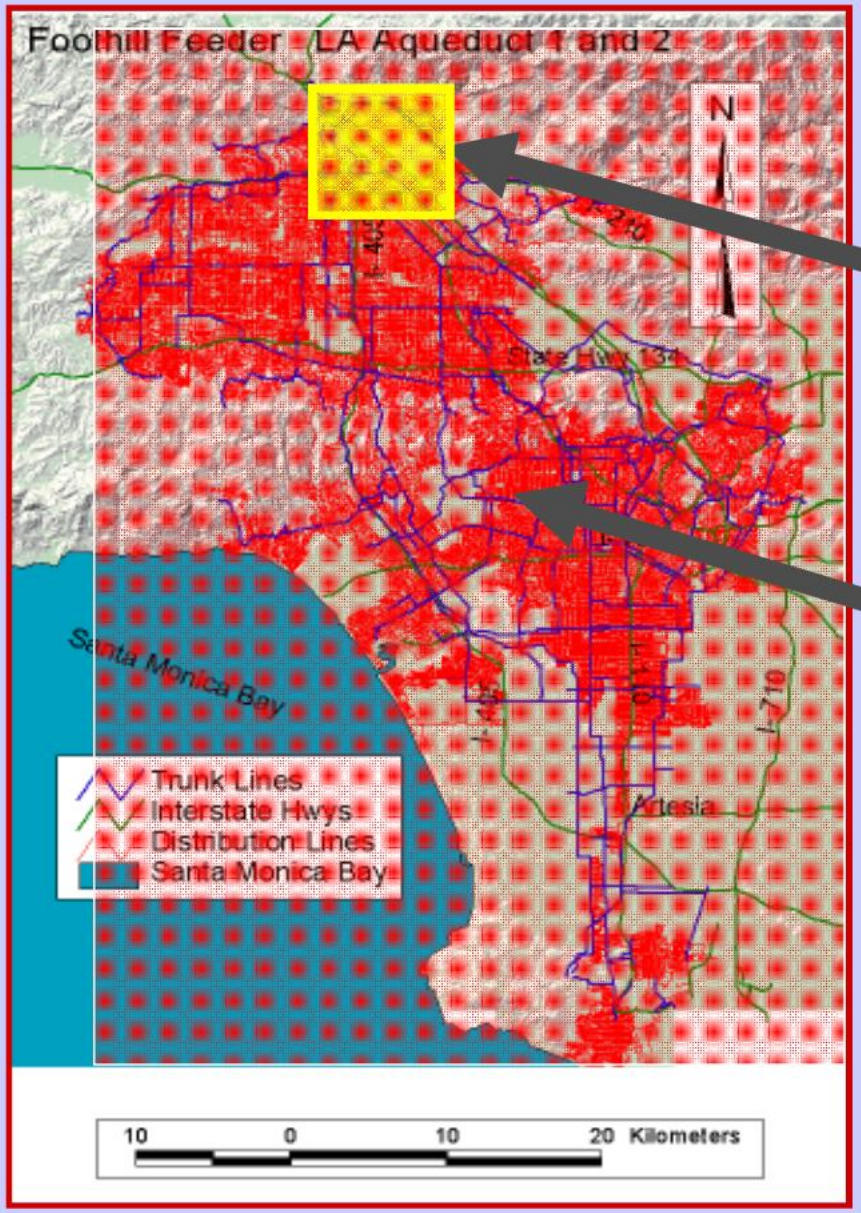
- Serves 4.1 Million People
- 12,000 km Distribution & Trunk Pipelines
- 1200 km^2

DECISION SUPPORT SYSTEM



- 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

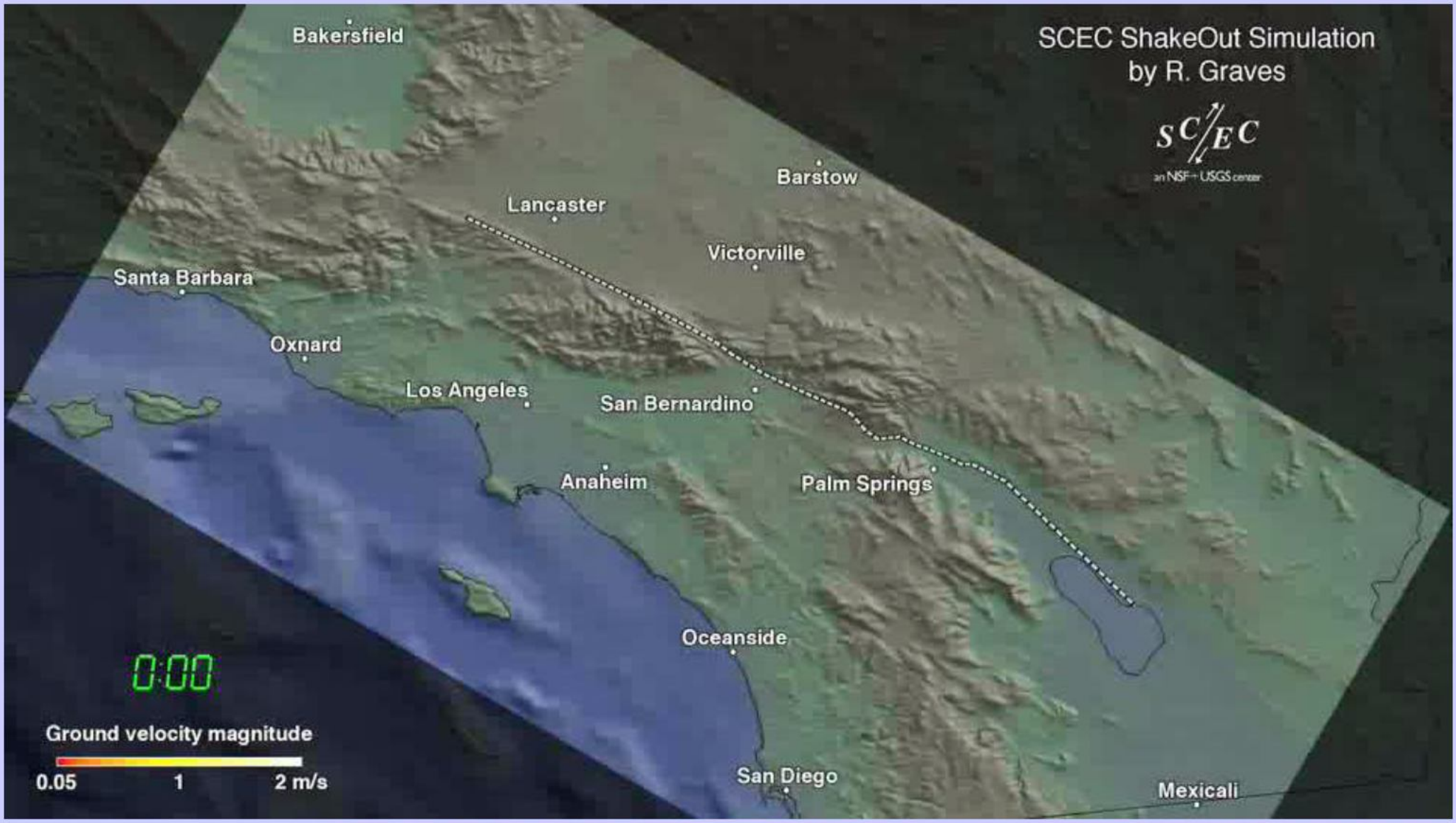
Probabilistic Simulation for System-wide Seismic Wave Effects

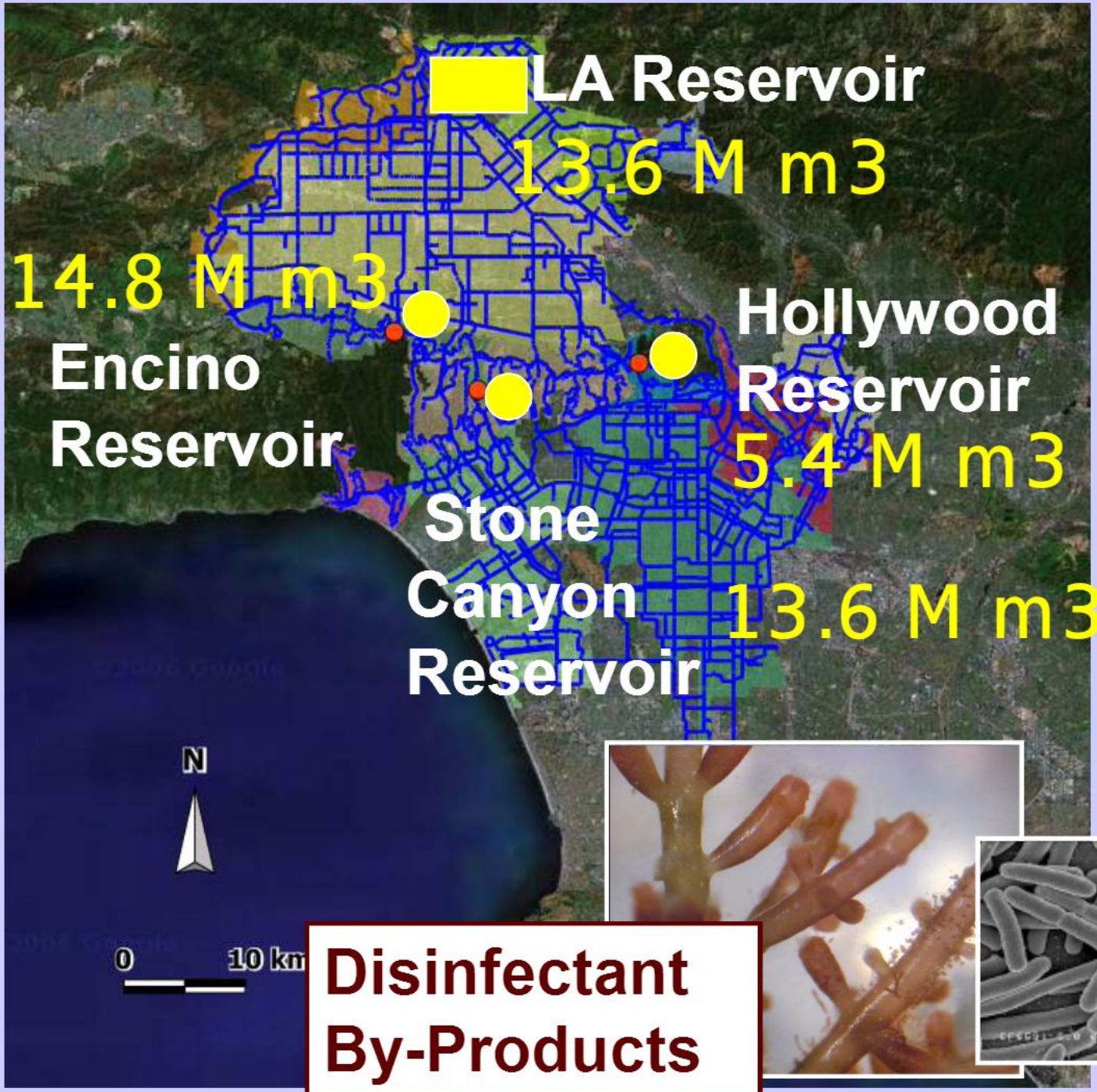
Combined Simulation for Permanent Ground Deformation & Seismic Wave Effects

VALIDATION: 1994 NORTHRIDGE EARTHQUAKE

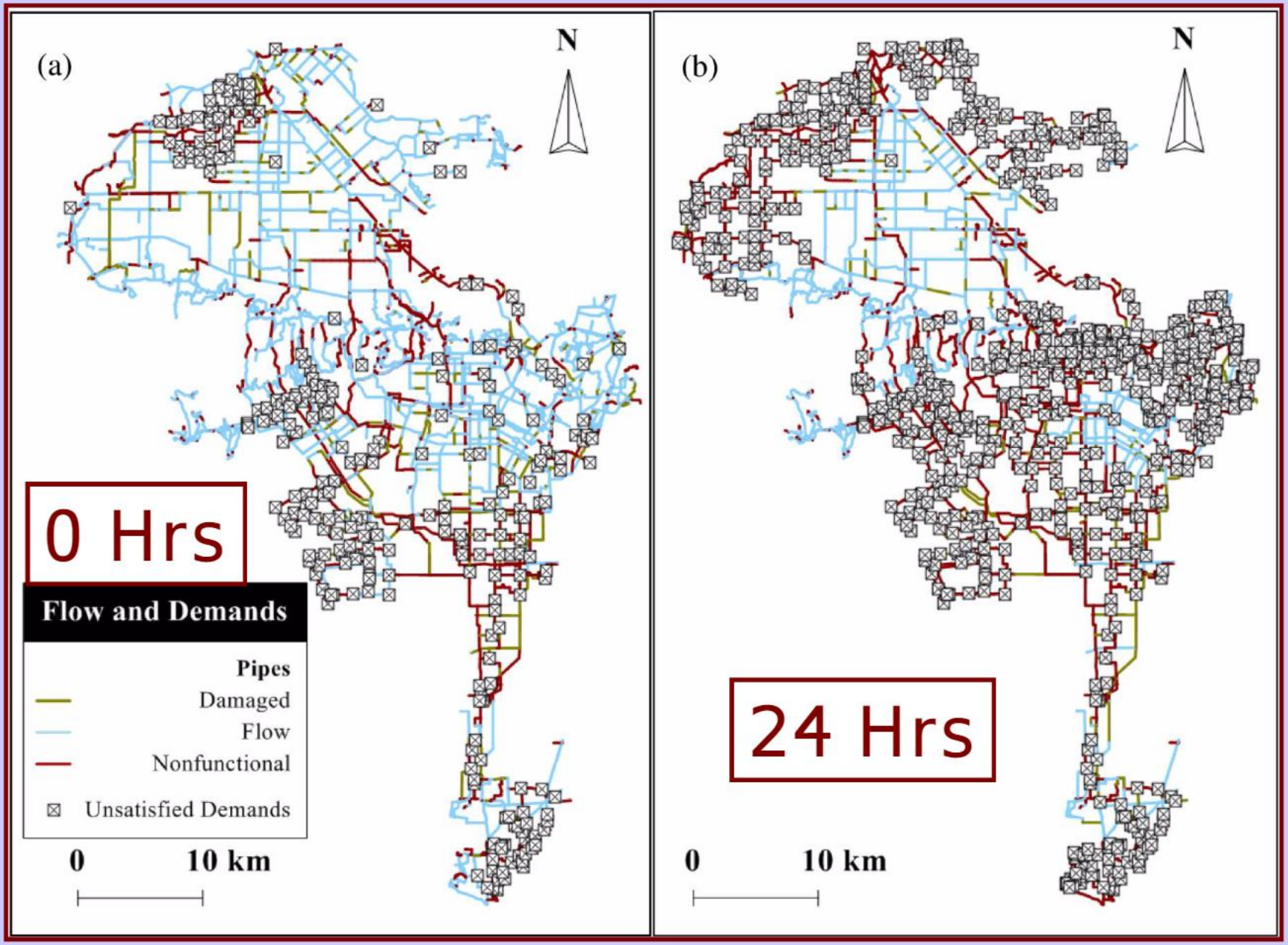
- System Serviceability
  - Results agree with LADWP records
- Geographic Distribution of Lost Water Service
  - ~90% match with actual records
- Flow at Key Locations
  - Excellent agreement with records

SHAKEOUT SCENARIO
7.8 M_W San Andreas Fault Earthquake

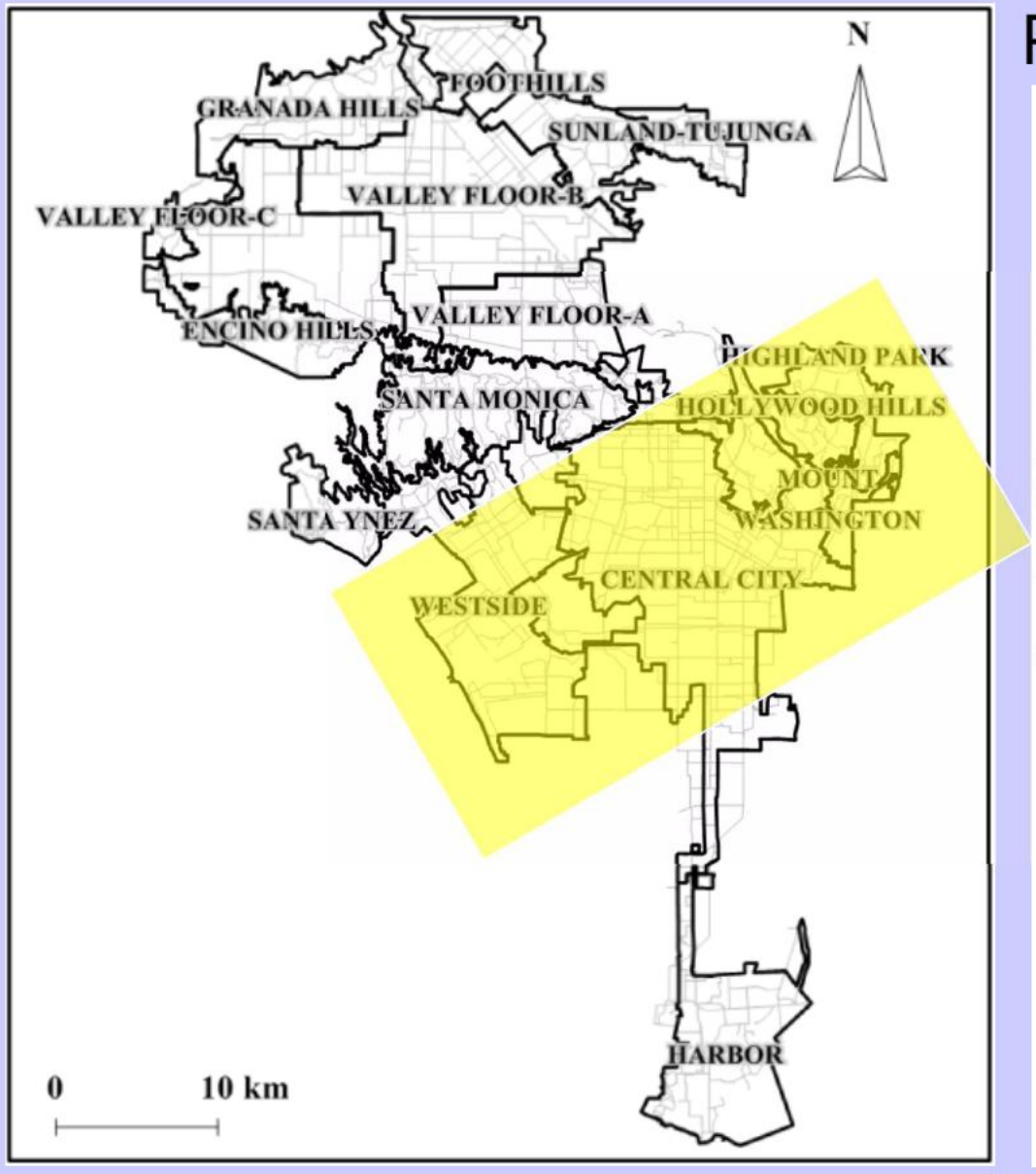



LA Reservoir
13.6 M m3
14.8 M m3
Encino
Reservoir
Hollywood
Reservoir
5.4 M m3
Stone
Canyon
Reservoir
13.6 M m3
N
0
10 km
Disinfectant
By-Products

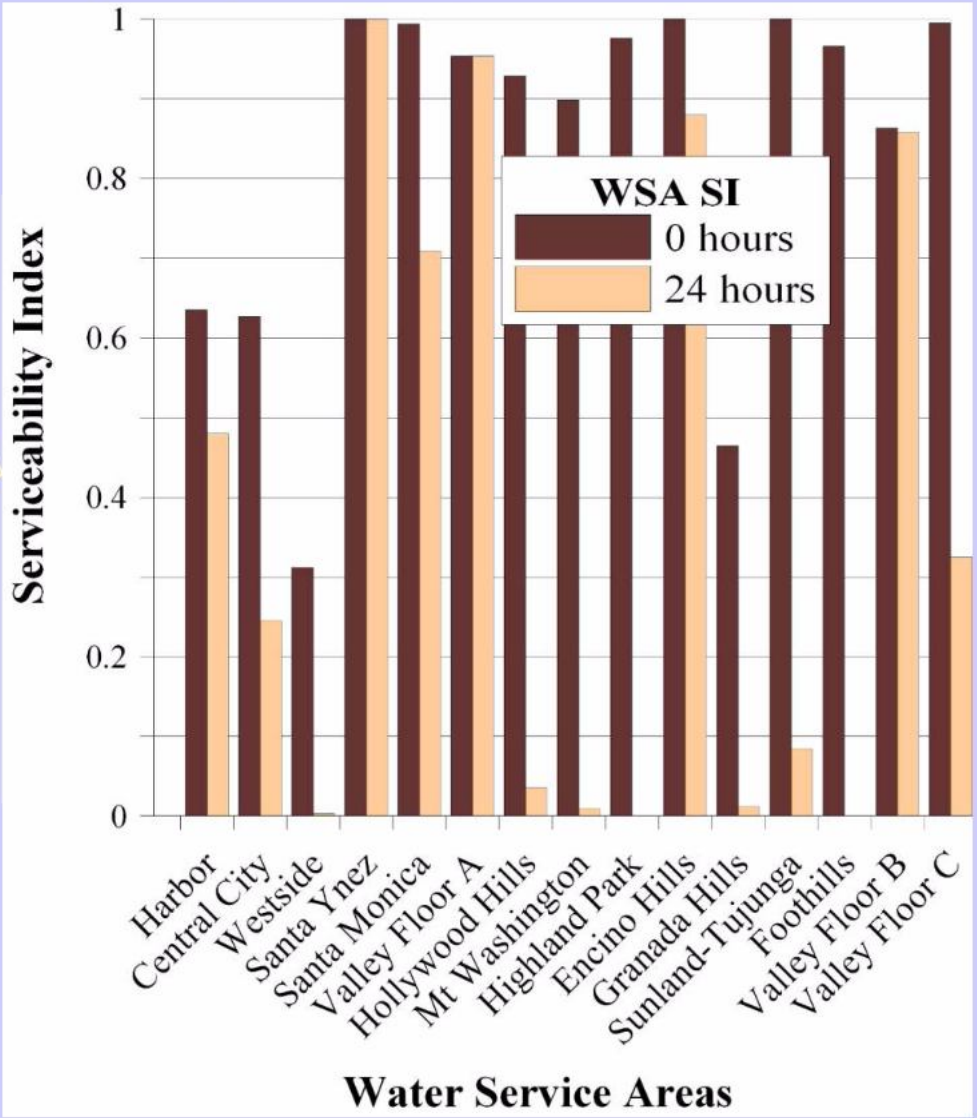
FLOW CONDITIONS



WATER SERVICE AREAS

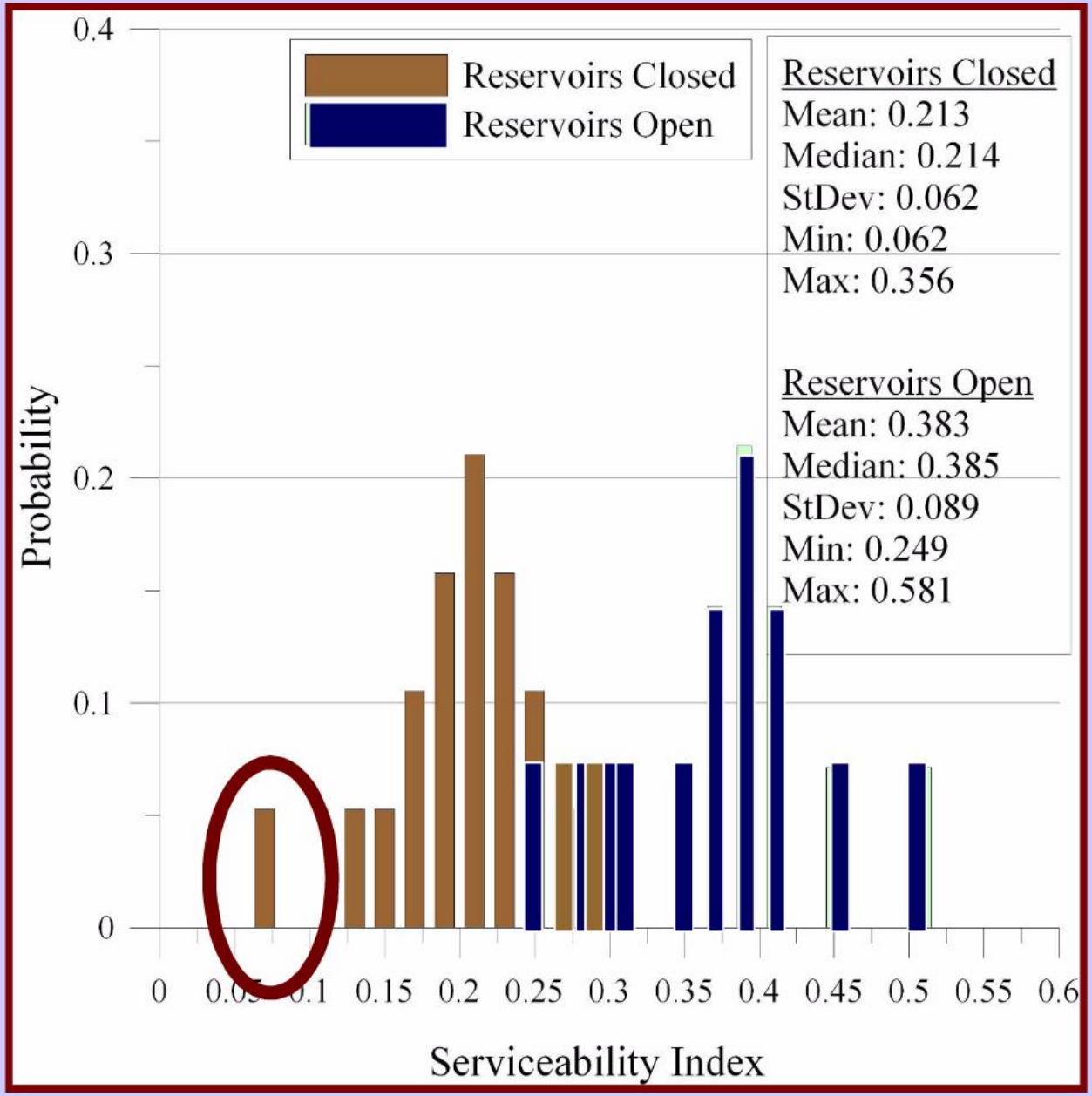


Results for 15 Service Areas



EMERGENCY USE OF RESERVOIRS

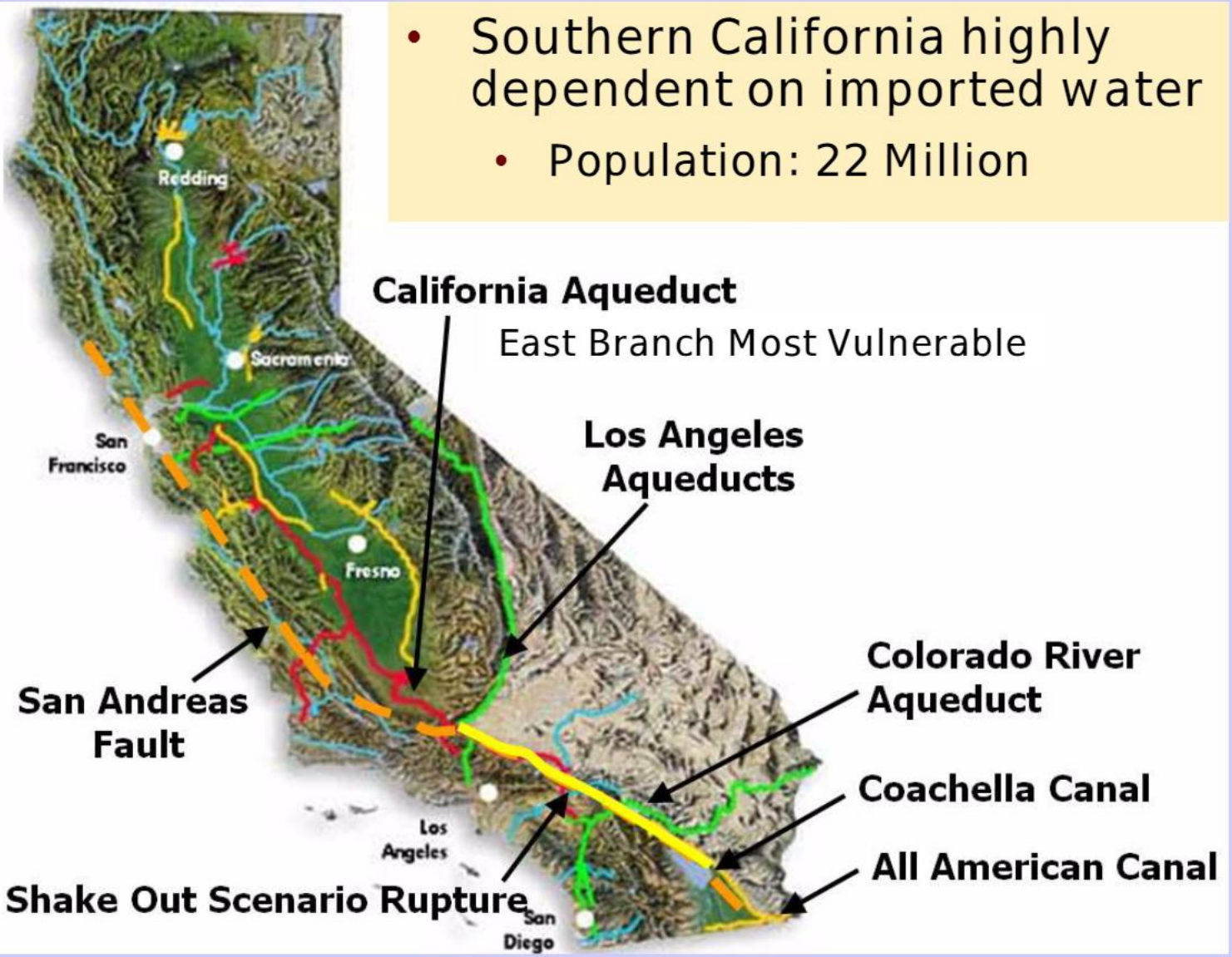
SI for most populated areas of Los Angeles (Westside, Central City, Highland Park, and Mount Washington) performance with reservoirs on and off



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

SOUTHERN CALIFORNIA WATER SUPPLY



- Southern California highly dependent on imported water
  - Population: 22 Million

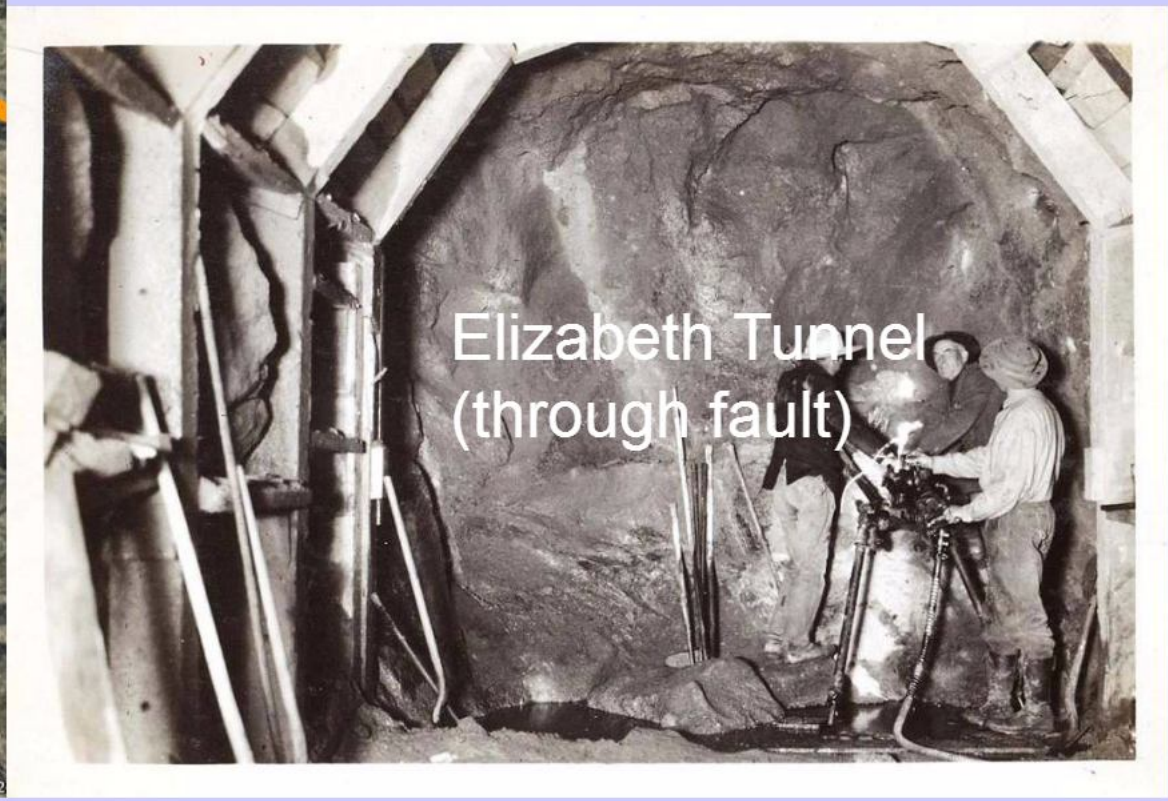
70% Imported Water:

- California Aqueduct
- Los Angeles Aqueducts
- Colorado River Aqueduct

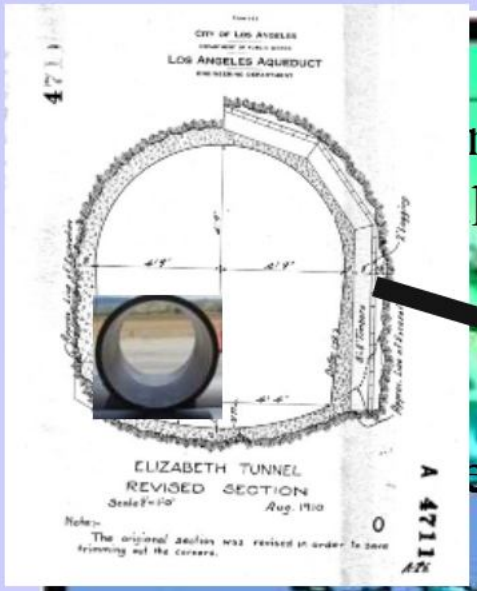
30 % Ground Water

LOS ANGELES AQUEDUCTS

- 3.3m Horizontal Fault Displacement
- 2.9m Wide Elizabeth Tunnel
  - Cuts off tunnel



LA WATER SUPPLY CROSSES SAN ANDREAS FAULT



RESILIENCE