Earthquake Effects on Critical Infrastructure

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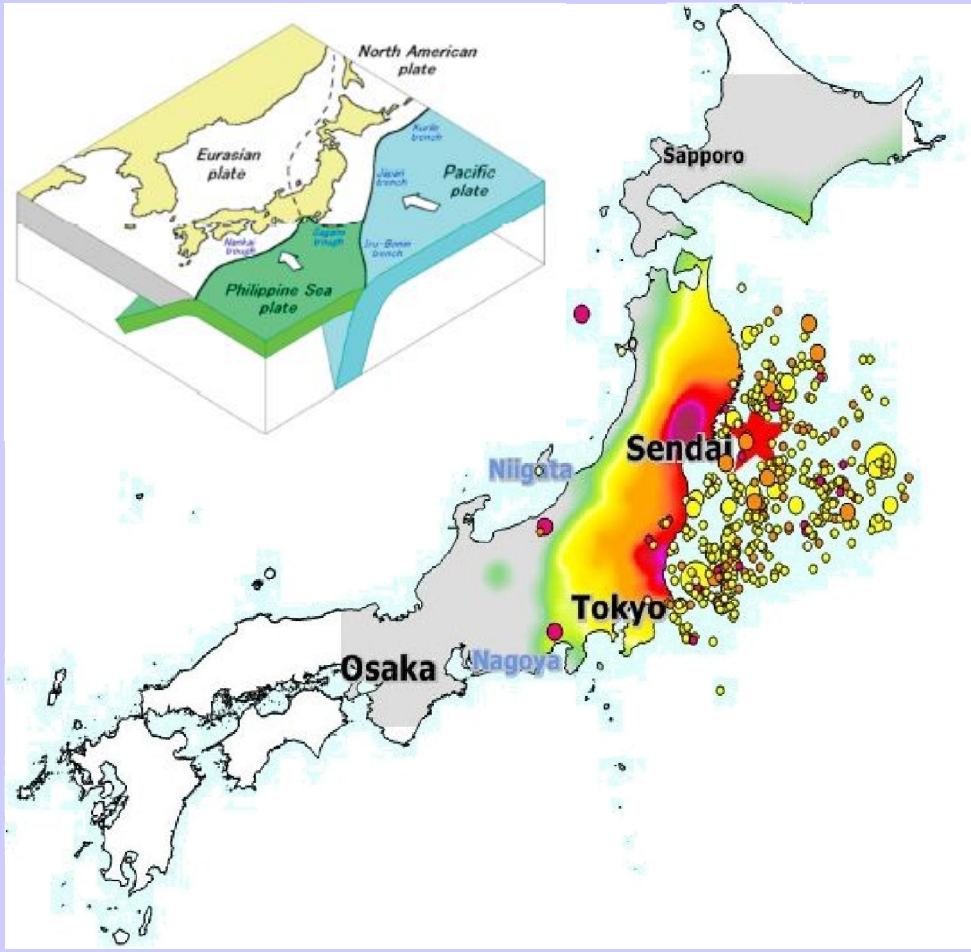
TOPICS

- Tohoku Earthquake
- Canterbury EQ Sequence
- San Francisco
- Los Angeles
- Concluding Remarks

TOHOKU EARTHQUAKE

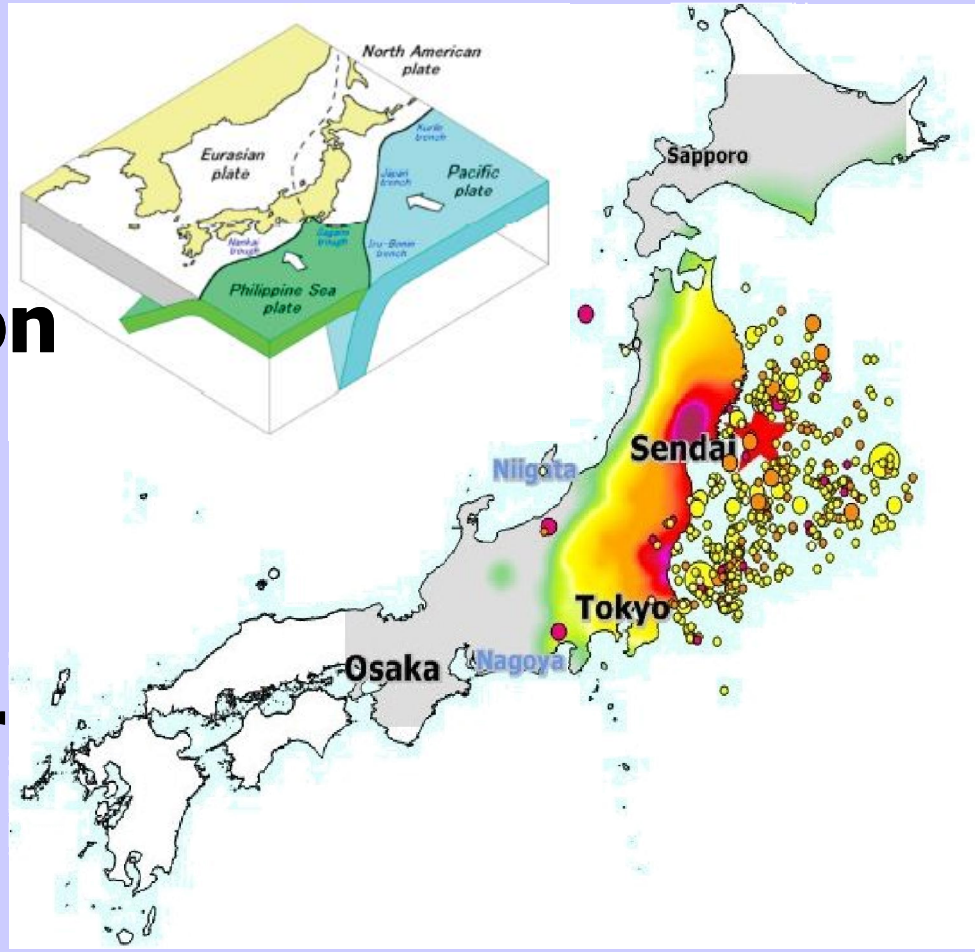
- 9.0 Mw (~ 4th Largest EQ Measured)

- 25 cm Shift in Earth's Axis
- 1000 x more power than 1995 Kobe EQ
- 600 million x more power than Hiroshima bomb



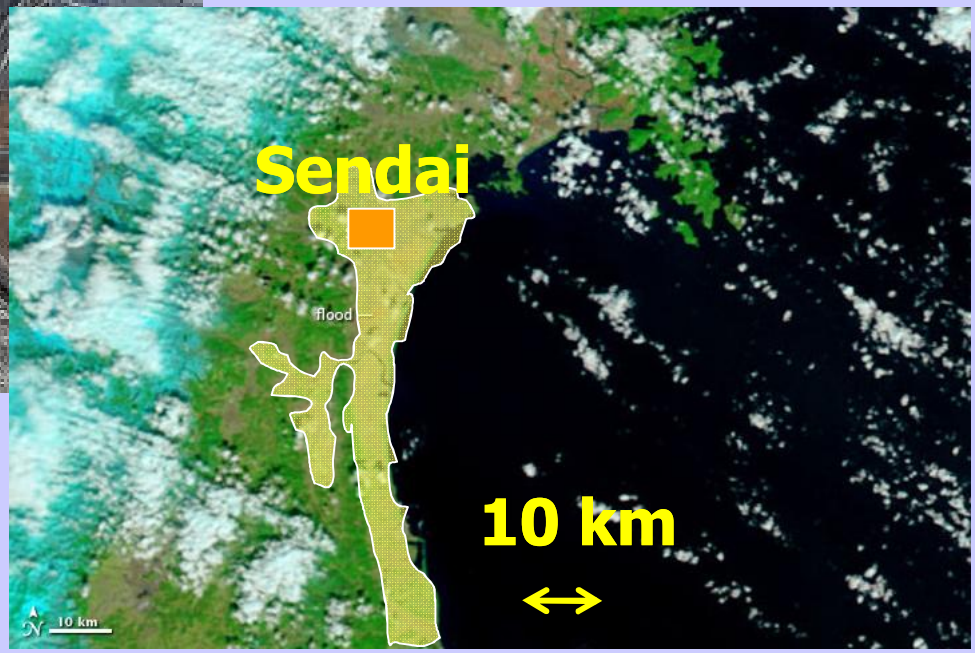
TOHOKU EARTHQUAKE

- 15,870 Deaths
- 2,814 Missing
- 129,225 Buildings Destroyed; > 1 Million Heavily Damaged
- $235 B Direct Losses
- ~ $620 B for Nuclear Decontamination & Decommissioning



TOHOKU TSUNAMI

- Inundation = 561 km2
- Tsunami Heights = 3 to 7.3 m
- 50 km Run-up on Kitakami River

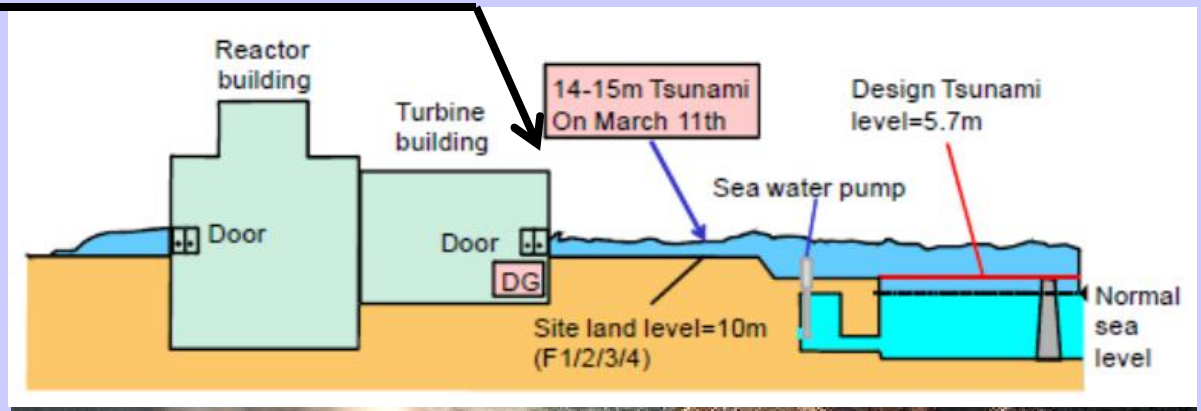


- 190 of 300 km Seawalls Heavily Damaged

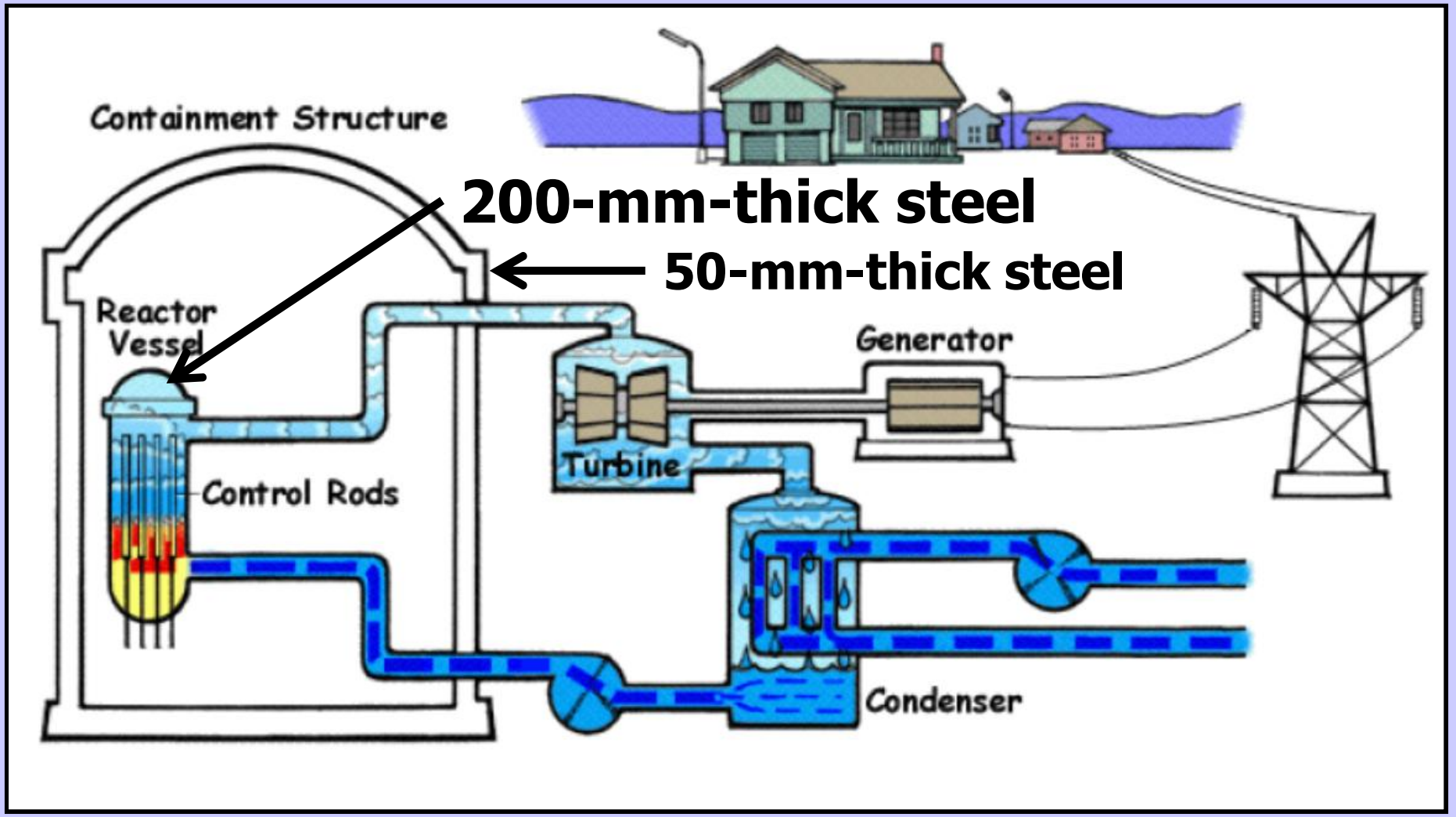
ONAGAWA TSUNAMI

FUKUSHIMA DAIICHI NUCLEAR PLANT

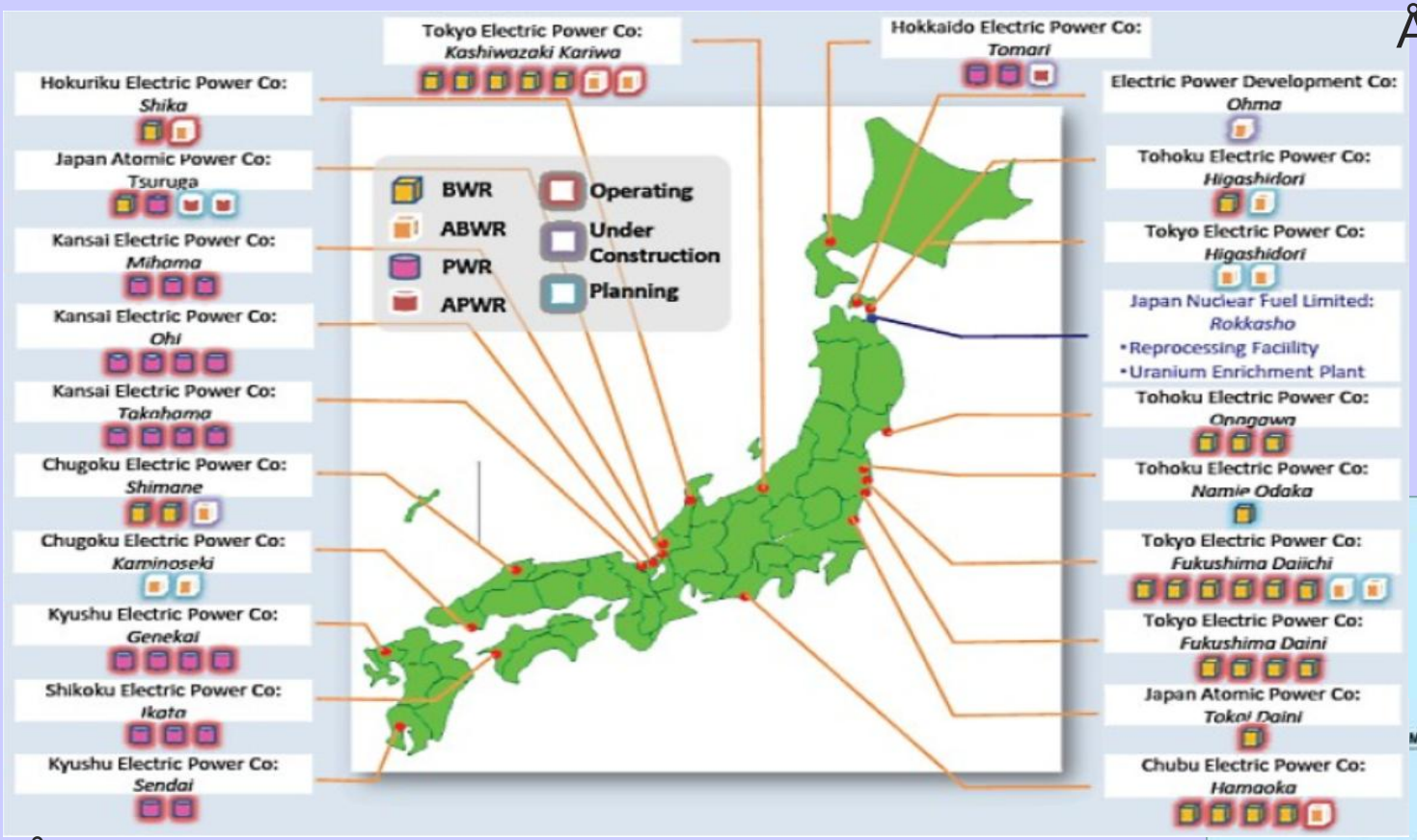
46-m-high splash



BOILING WATER REACTOR



JAPAN'S NUCLEAR POWER PLANTS



- On 5 May 12 all 54 nuclear reactors down working, or 0 % of total nuclear; only 2 reactors on line now

- Japan imports 84% of energy
- Nuclear reactors supplied ~ 30% electricity
- Japan planned to increase to 40% by 2017
- Nuclear was part of C02 reduction strategy

WORLDWIDE EFFECTS: NUCLEAR POWER

The New York Times

May 27, 2011

Officials in Germany Support Closing 7 Nuclear Plants

nuclear power plants in Germany that were
shima disaster in Japan are likely to be closed
ion Friday by state environment ministers.
ned, however, that without the seven plants
le coping with a failure in some part of the

orks to the limit of capacity," the Federal
ulates utilities, said in a report published

astern Germany, the state environment
he seven plants be closed. The decision
Merkel and her cabinet, which will

The New York Times

Switzerland Decides on Nuclear Phase-Out

By JAMES KANTER
Published: May 25, 2011

BRUSSELS — The Swiss government decided Wednesday to abandon plans to build new nuclear reactors, while European Union regulators agreed on a framework for stress-testing theirs, as repercussions from the disaster in Japan continue to ripple across Europe.

Enlarge This Image

Arnd Wiegmann/Reuters

The Swiss Energy Minister Doris Leuthard had suspended the approvals process for three new reactors, pending a safety review, after the accident that struck the reactors at the Fukushima Daiichi plant in Japan after the earthquake and tsunami of March 11.

- **Germany to Close Out Nuclear Power (22.4% Electricity, 2010)**
- **Switzerland to Terminate Nuclear (40% Electricity, 2008)**
- **Italy Referendum (2011): > 94% Voters Oppose Plans to Resume Nuclear Power (abandoned 1980s)**

LESSONS LEARNED FROM TOHUKU EARTHQUAKE

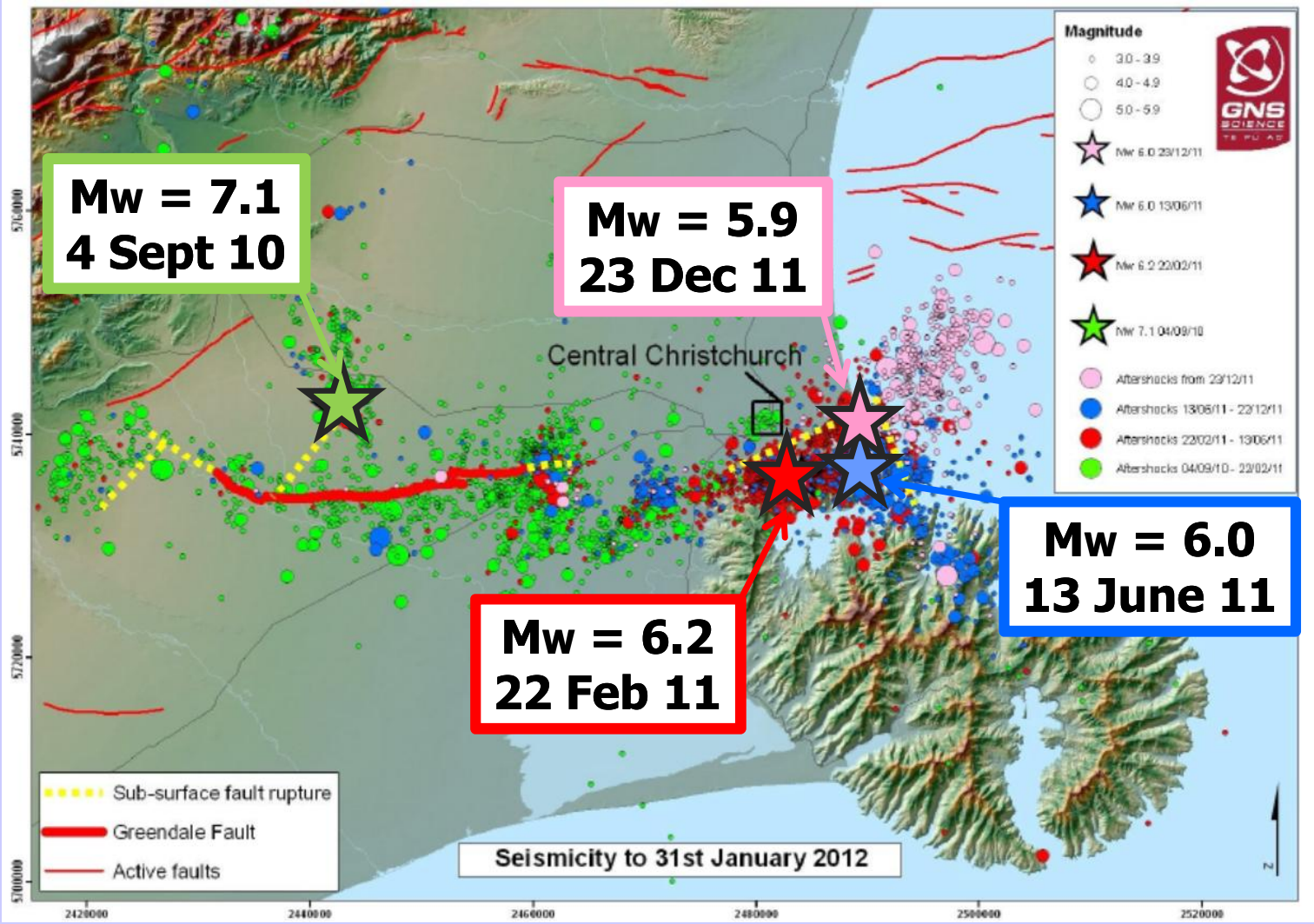
- Some Infrastructure Is Too Big to Fail
- Global Consequences of Failure
- Design for Contingencies (Consequences) As Well As Events

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

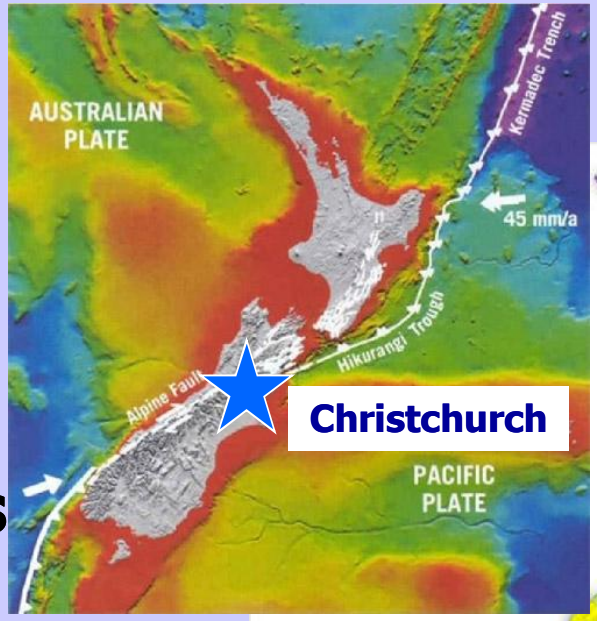

Tasman Sea
Wellington
South Island
Christchurch
Bank's Peninsula
Stwart Island

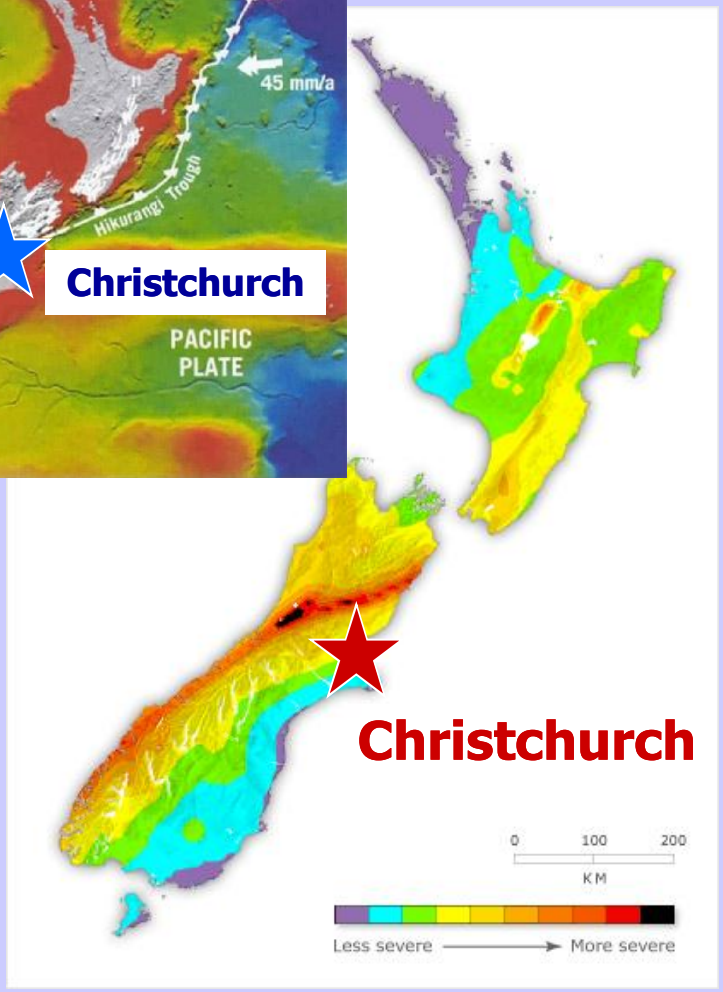
CANTERBURY EARTHQUAKE SEQUENCE



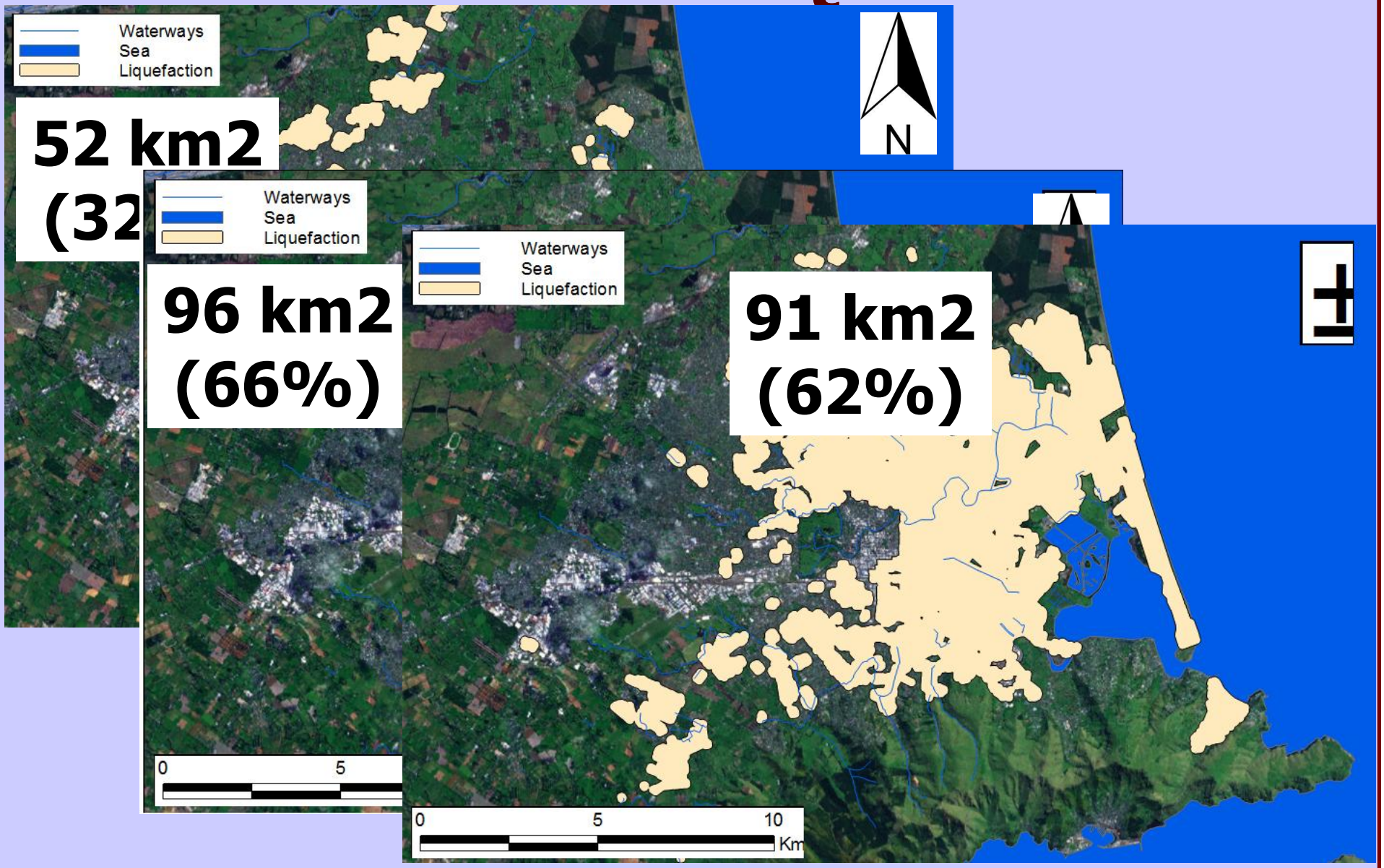
CANTERBURY EARTHQUAKE SEQUENCE

- ~ 182 Deaths
- CBD Destroyed
  - ~ 1800 CBD Bldgs. Demolished
  - ~ 55,000 Residences Damaged
- $25-30 B Direct Losses, ~25 % GDP
- Massive Liquefaction & Infrastructure Damage

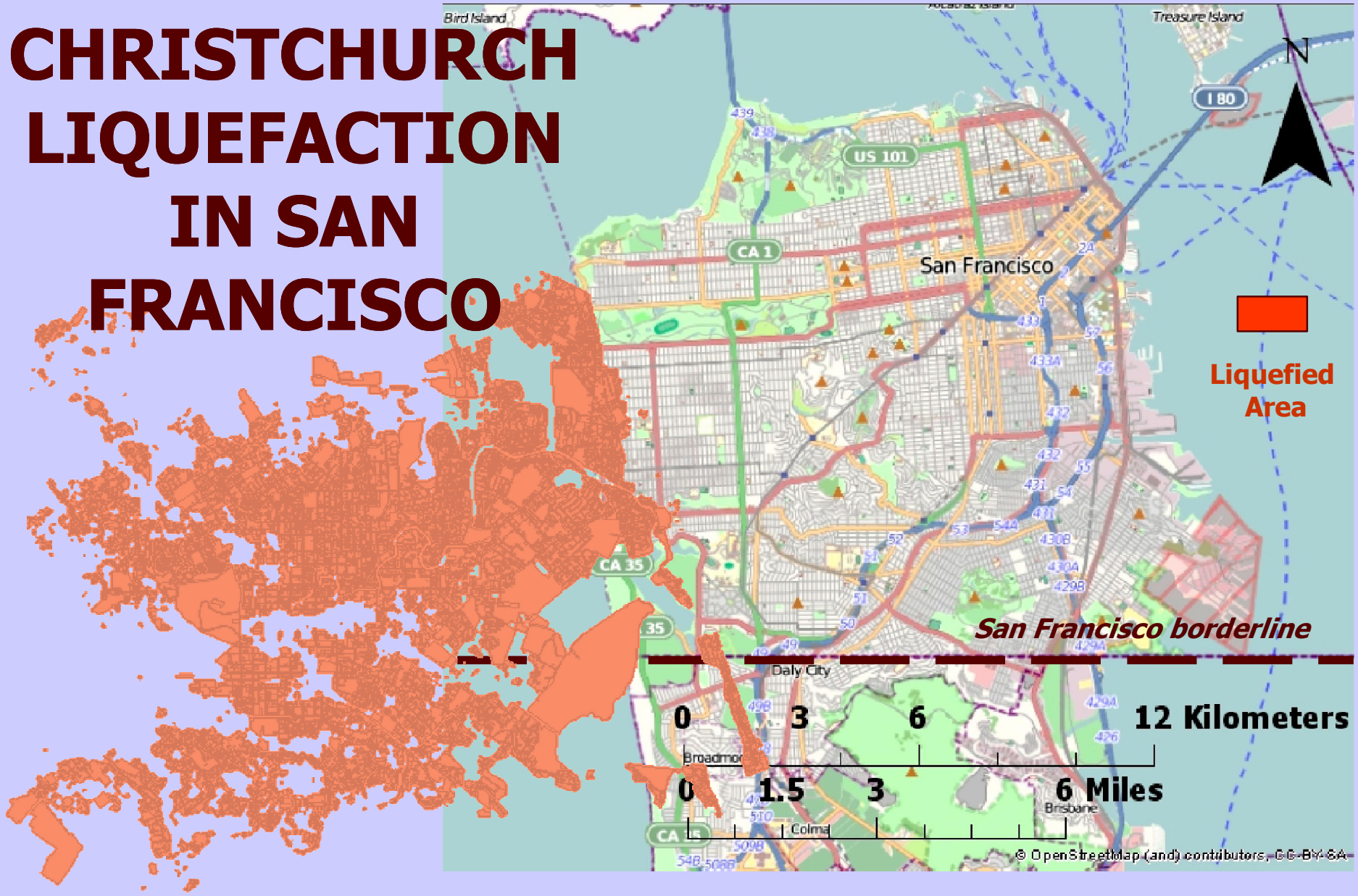




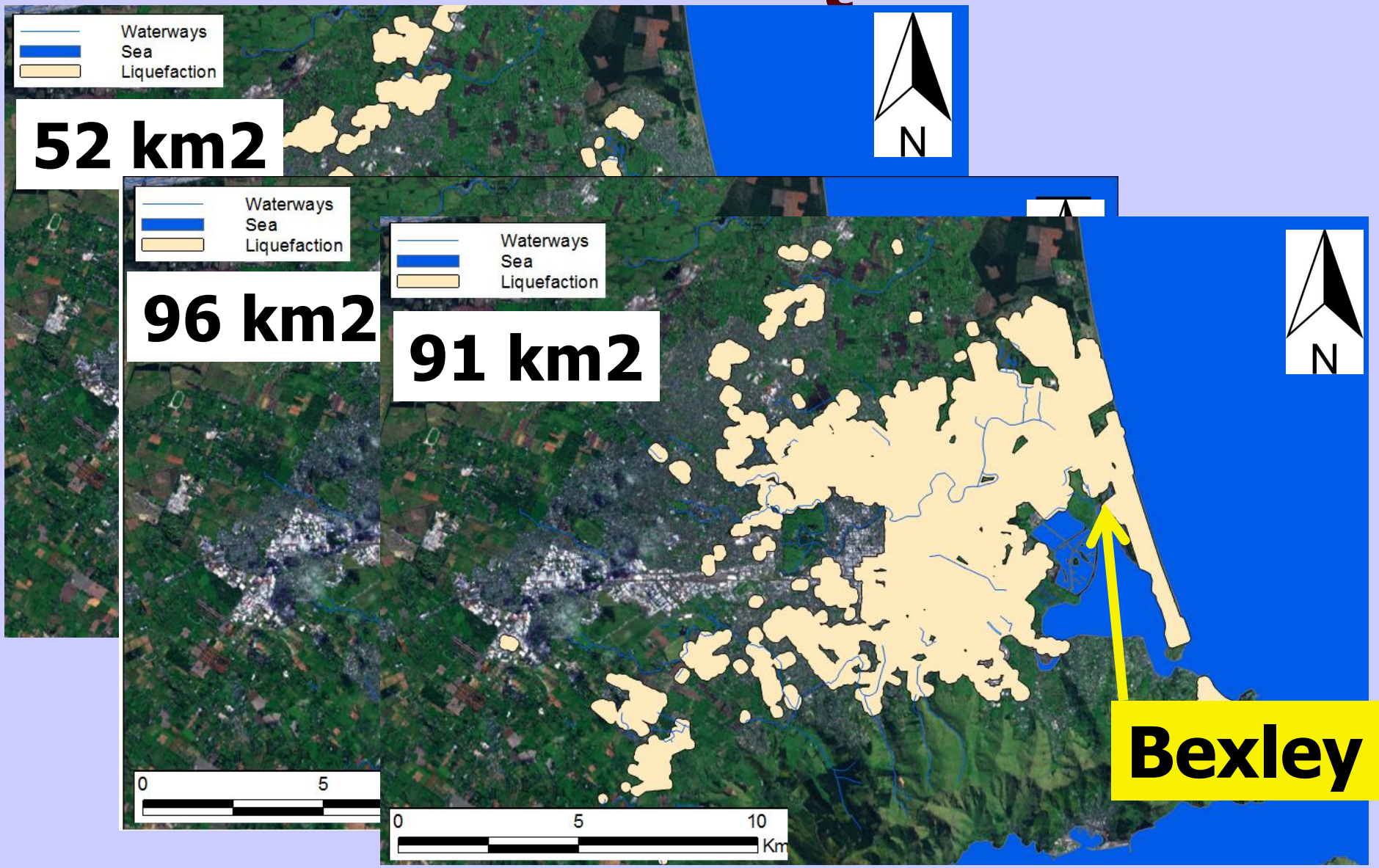
CHRISTCHURCH LIQUEFACTION



CHRISTCHURCH LIQUEFACTION IN SAN FRANCISCO

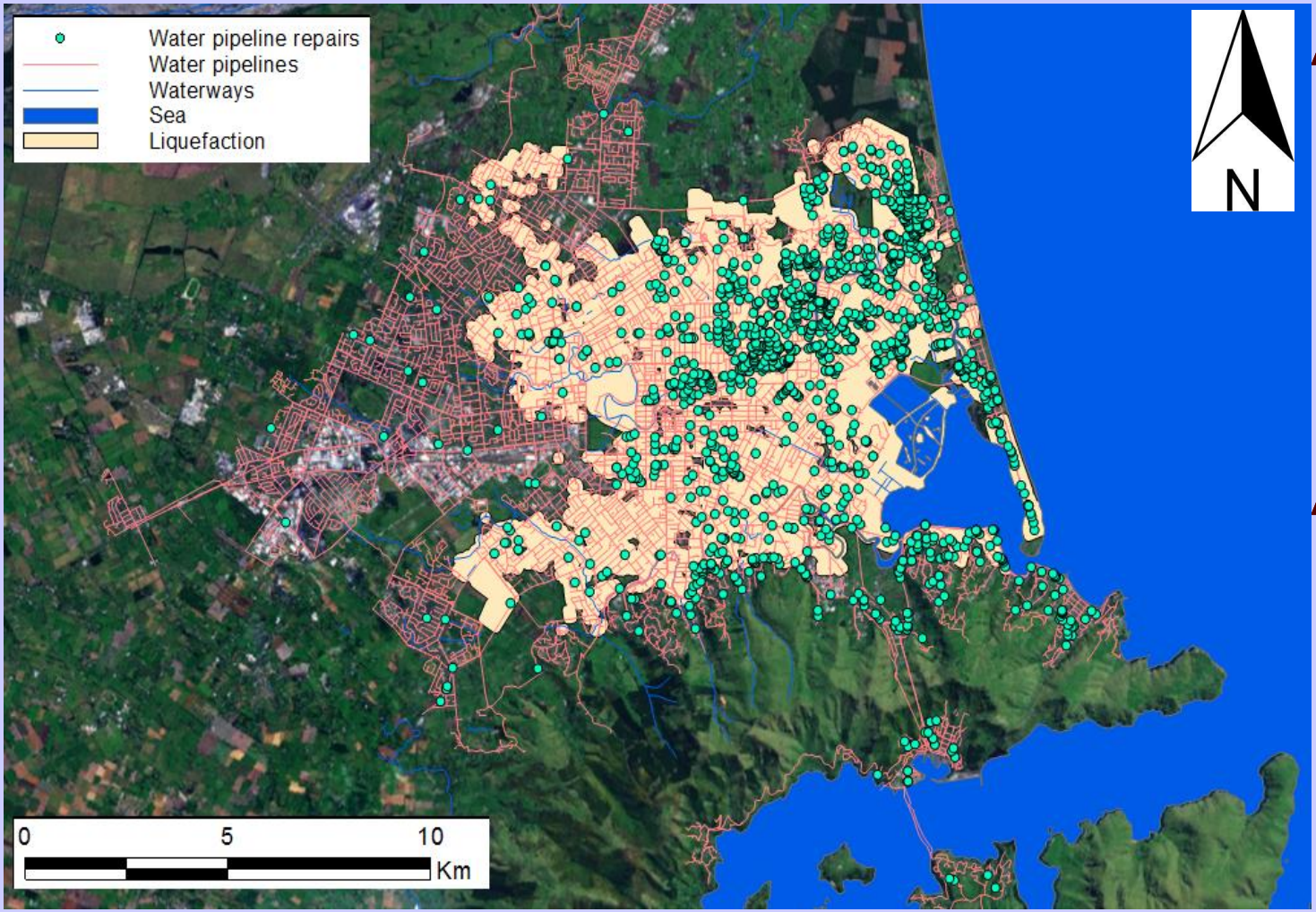


CHRISTCHURCH LIQUEFACTION



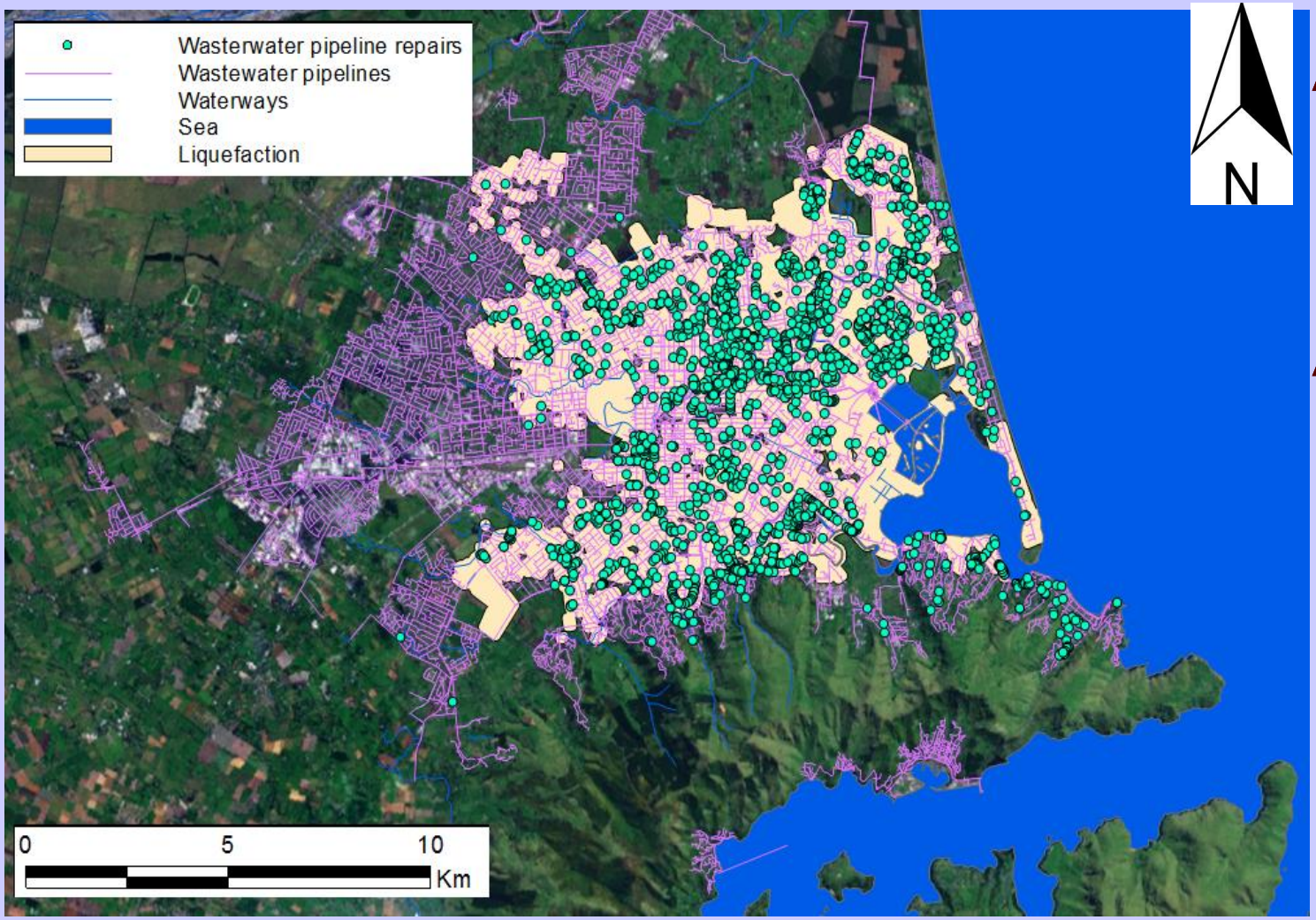
CHRISTCHURCH LIQUEFACTION

WATER MAIN REPAIRS FOR 22 FEB 2011 EARTHQUAKE



- **1645 repairs to mains & sub-mains**
- **Approx. 1700 km of pipelines**

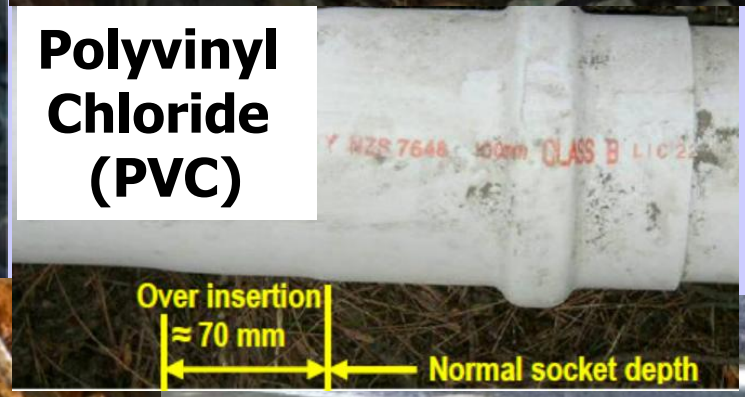
REPAIRS IN WASTEWATER SYSTEM AFTER 22 FEB 2011 EARTHQUAKE



- 1200 repairs to pipes
- Approx. 1900 km of pipes & conduits

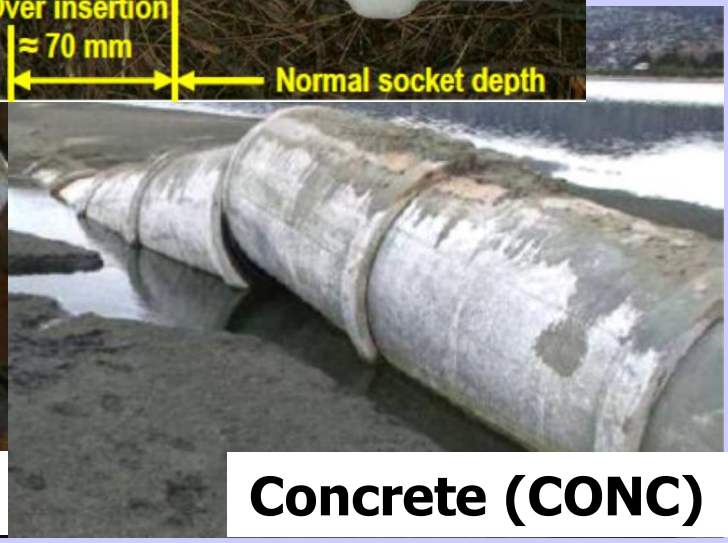
EARTHQUAKE PIPELINE DAMAGE

Asbestos Cement (AC)



Polyvinyl Chloride (PVC)

Cast Iron (CI)

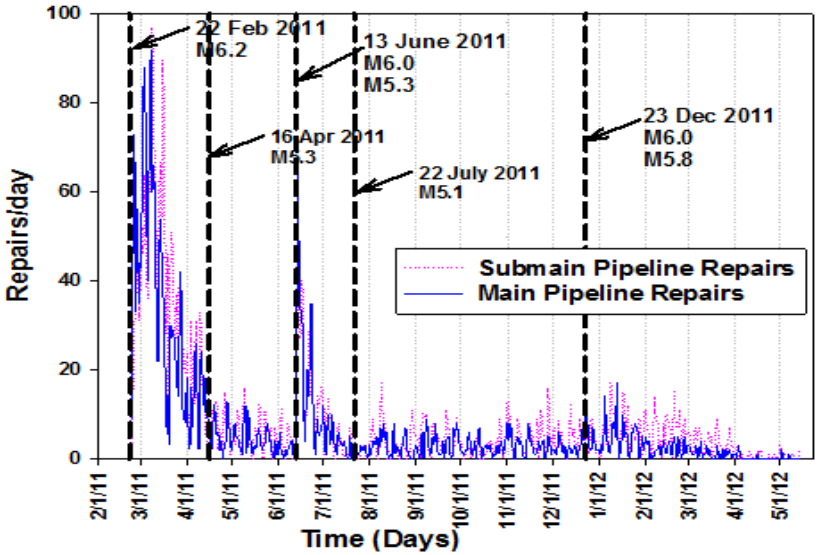


Concrete (CONC)

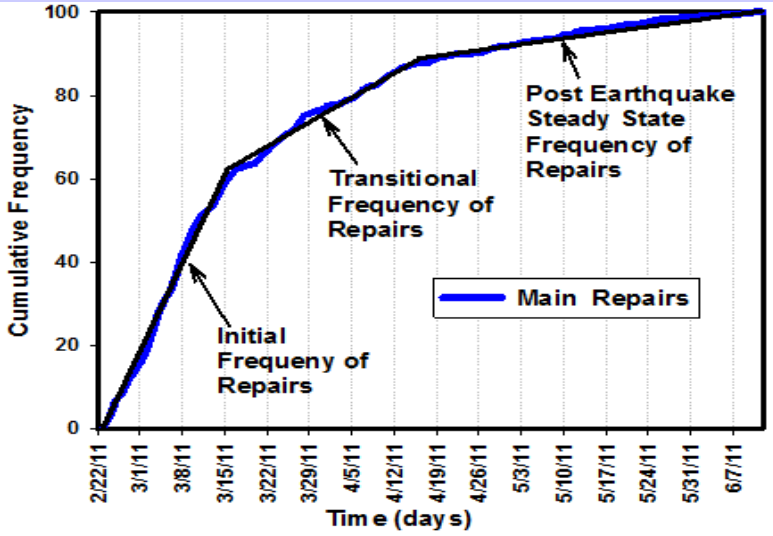
WATER MAINS & SUBMAINS

- Mains
  - Typically 75 – 600 mm diameter
  - Primary water conveyance pipelines
- Submains
  - Typically ≤ 60 mm diameter
  - Water distribution from mains to a limited number of houses

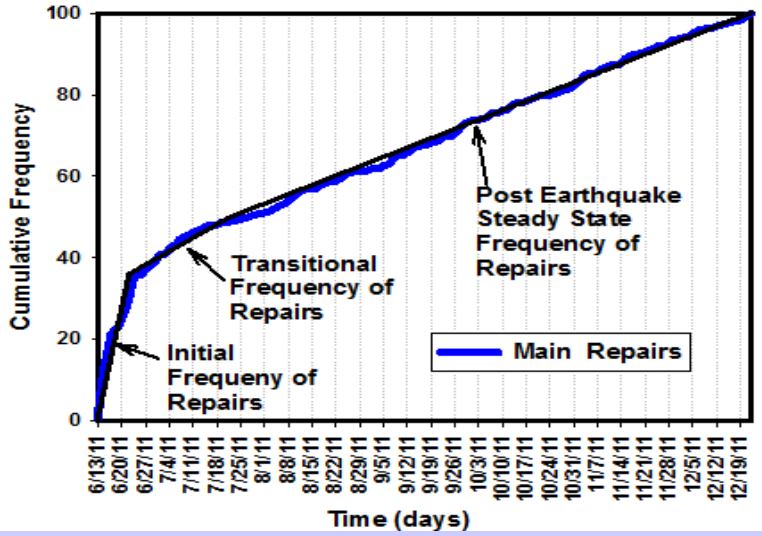
PIPELINE REPAIRS VS TIME

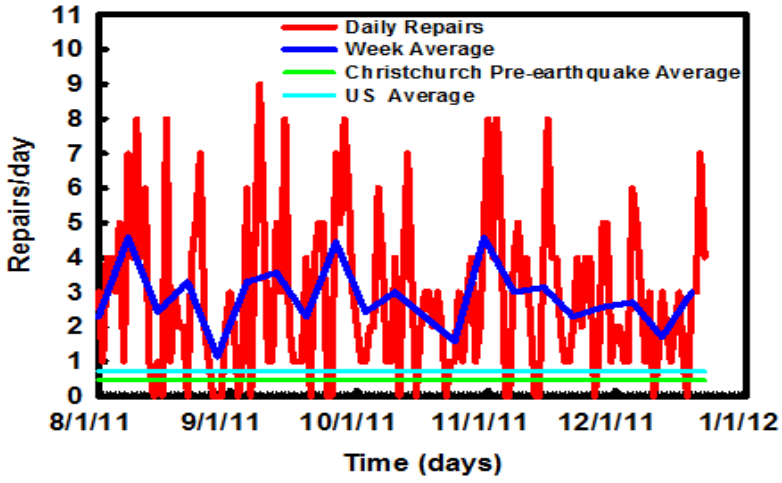


a) Daily main and submain repairs

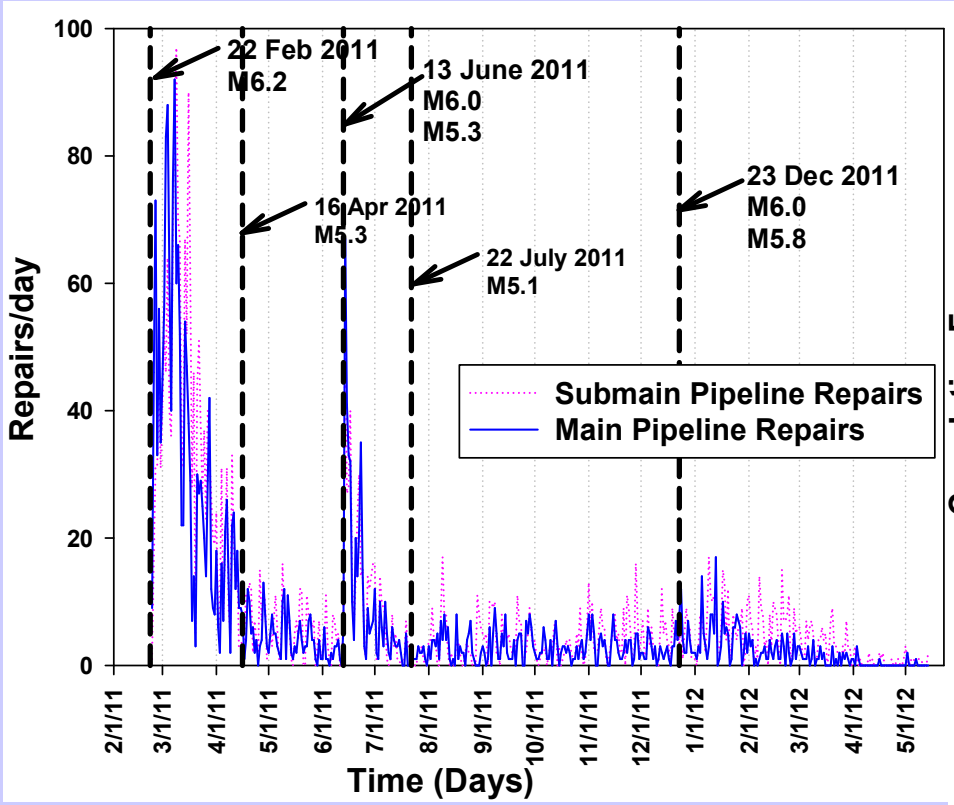


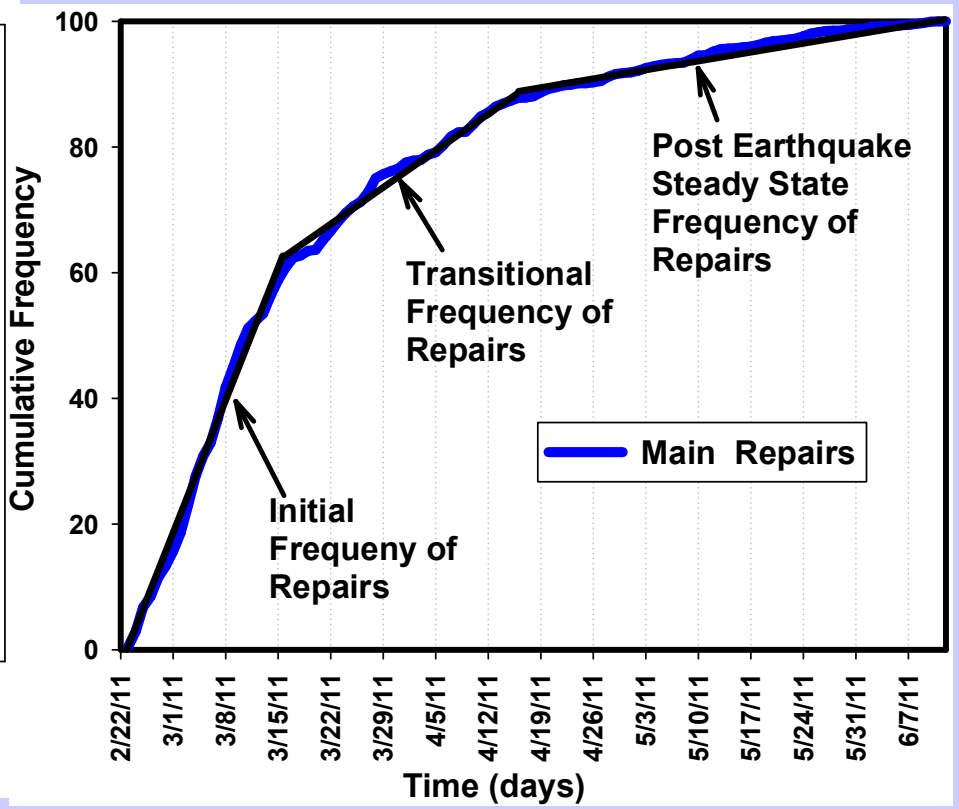
b) Cumulative frequency of repairs between 22 Feb. and 13 June 2011



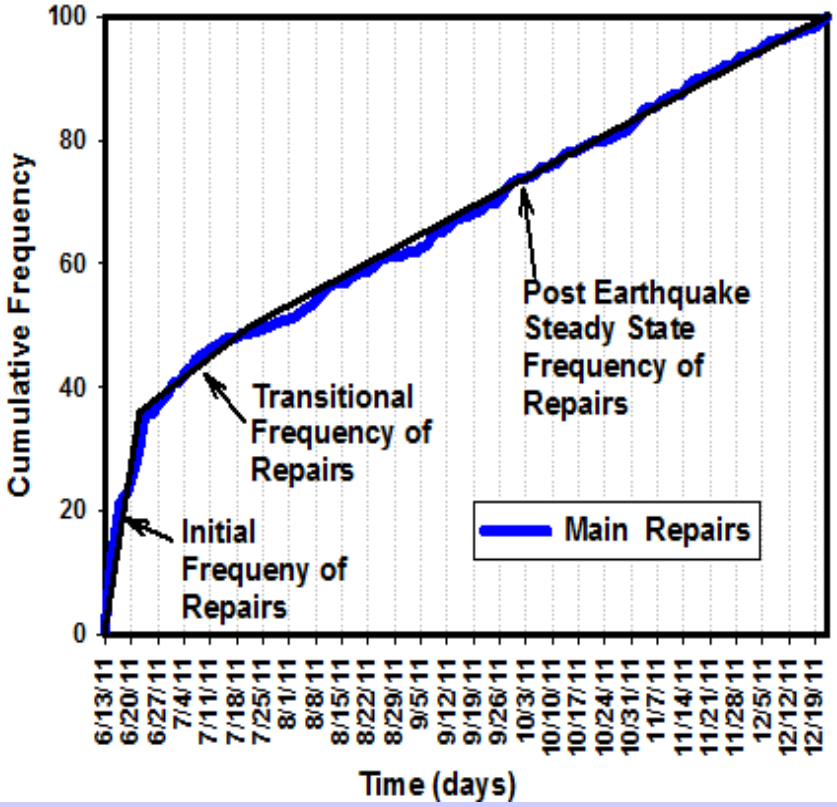


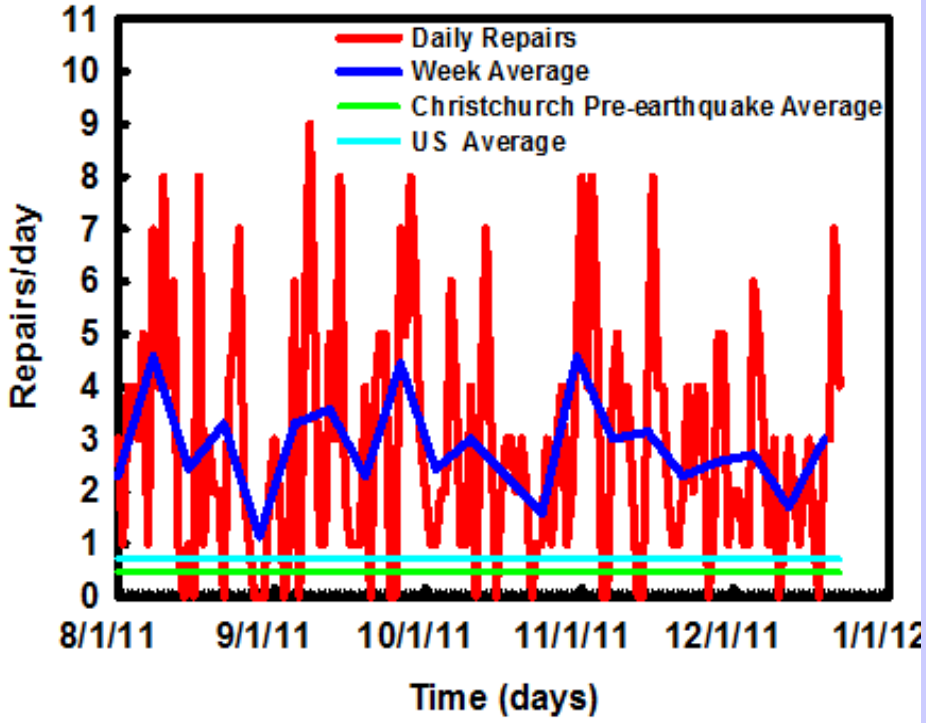
PIPELINE REPAIRS VS TIME





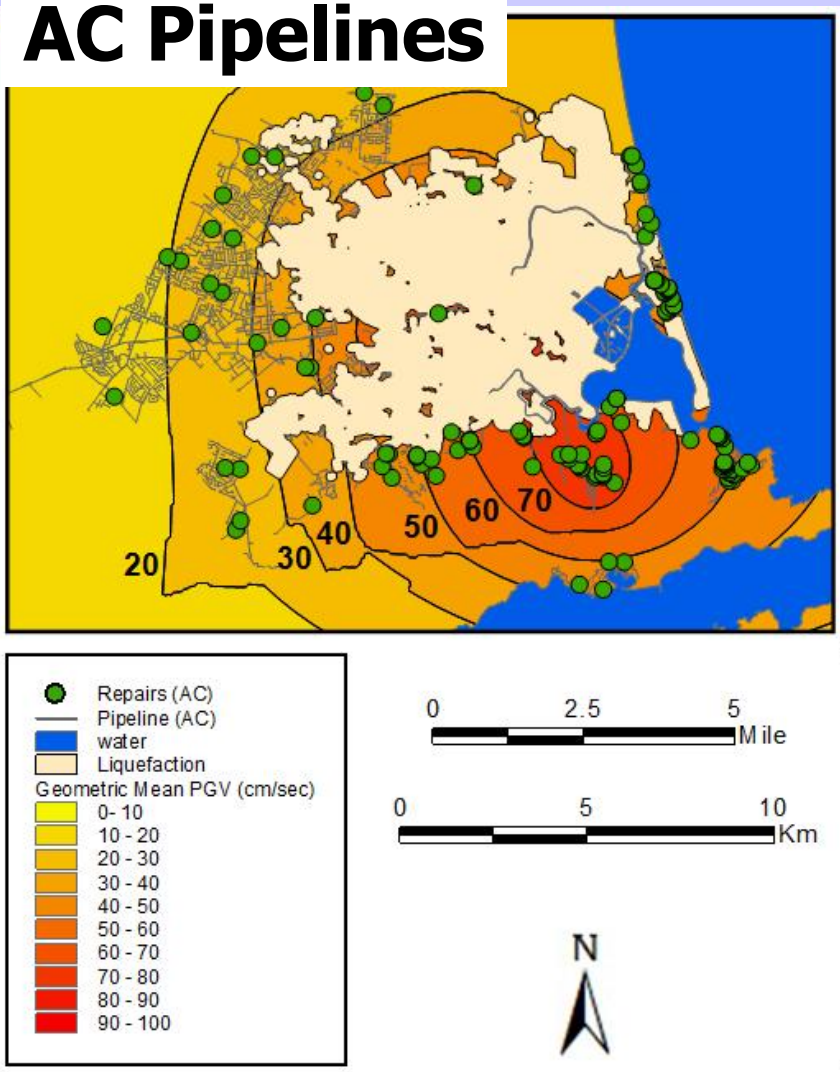
PIPELINE REPAIRS VS TIME



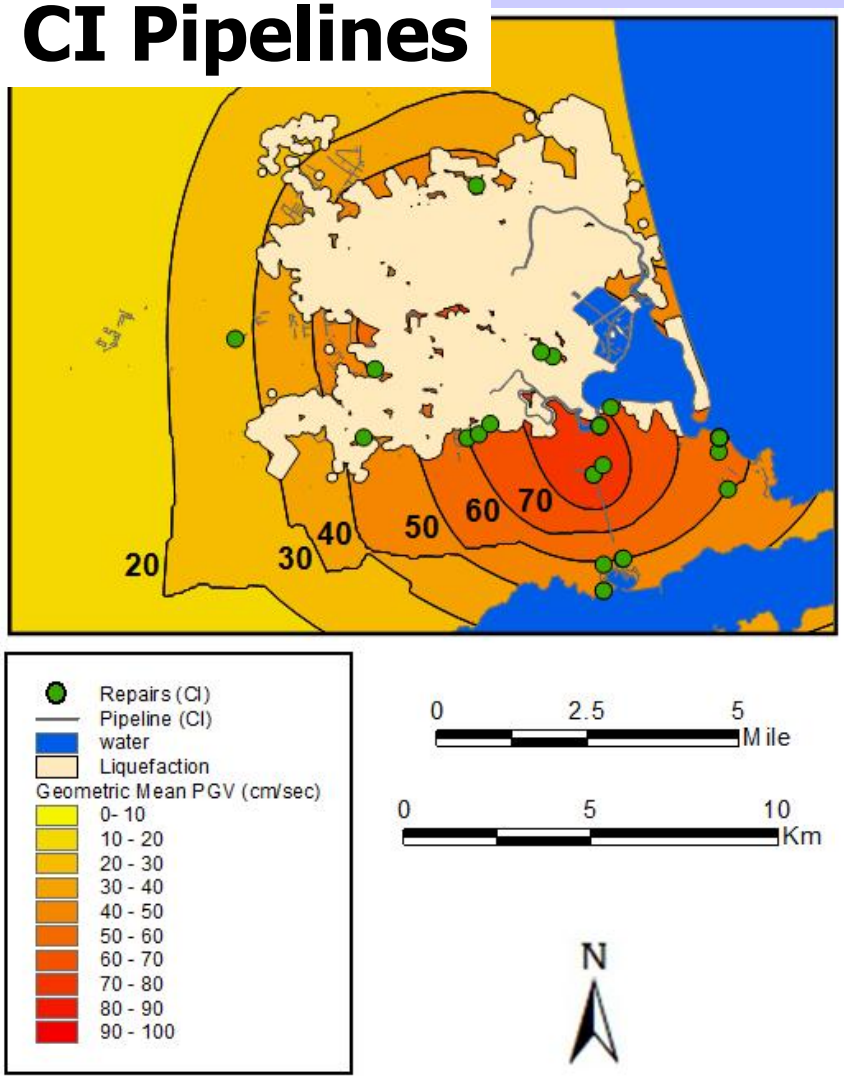


PIPELINES AFFECTED BY TRANSIENT GROUND MOTION

AC Pipelines



CI Pipelines



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]½

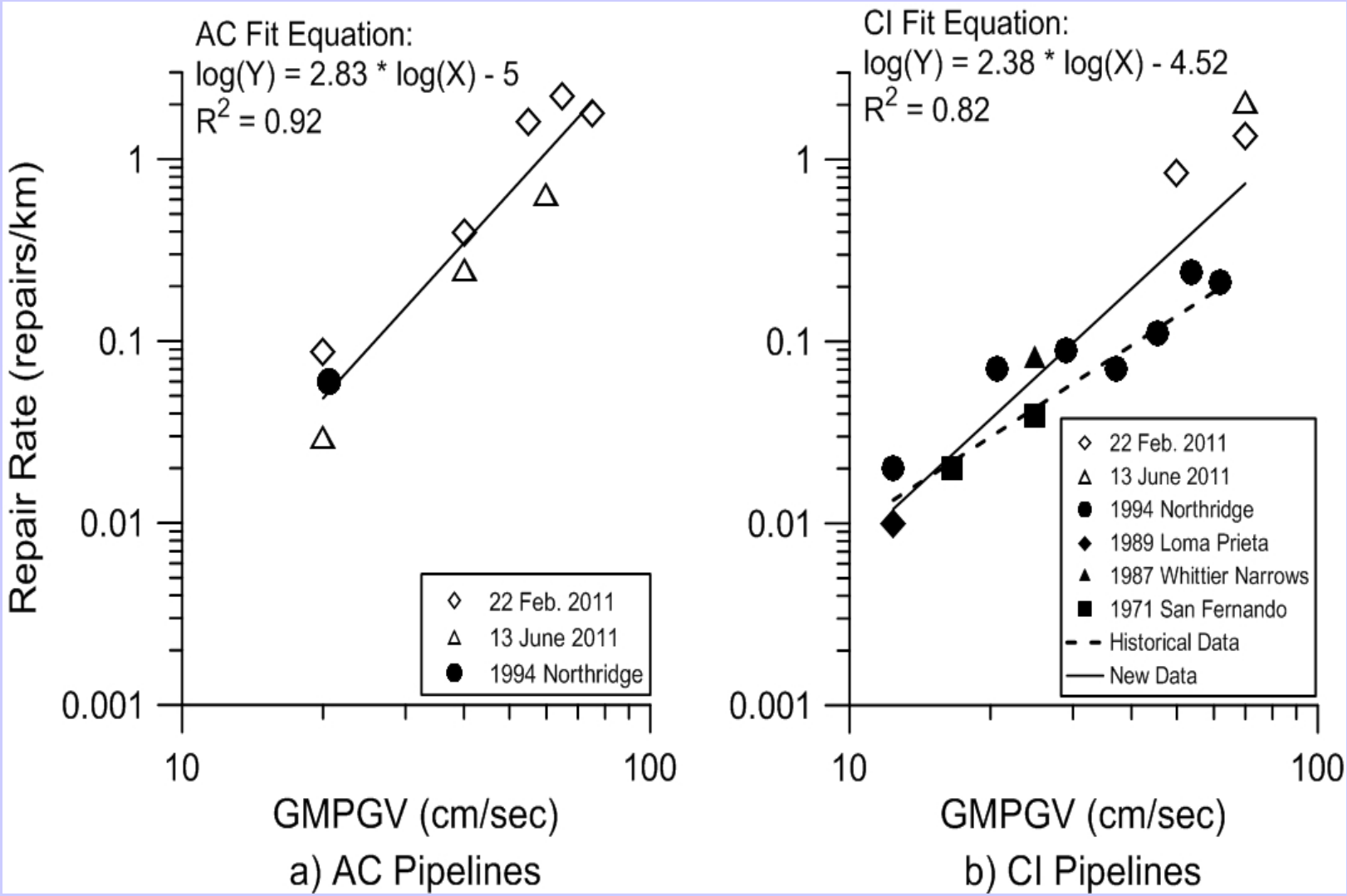
Sampled repairs follow normal distr. (central limit theorem)

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

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

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

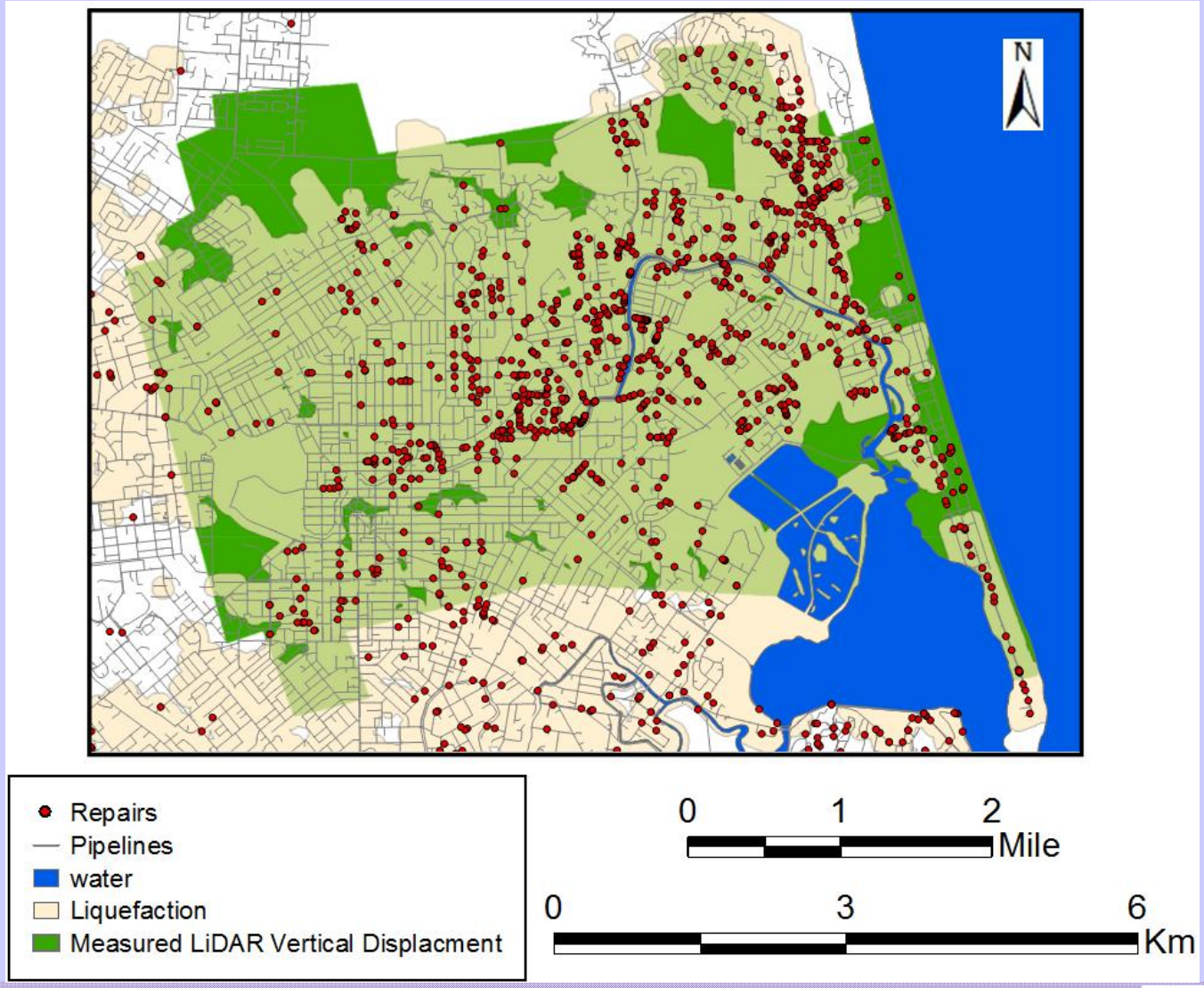
REPAIR RATE VS GMPGV



LIGHT DETECTION & RANGING

- **High Resolution LiDAR Measurements, Corrected for Tectonic Deformation**
- **Vertical Movements**
  - **5-m intervals**
  - **± 70 – 150 mm standard error**
- **Lateral Movements**
  - **56-m intervals**
  - **~± 400 mm standard error**

PIPELINE REPAIRS IN LIQUEFACTION & LiDAR AREAS

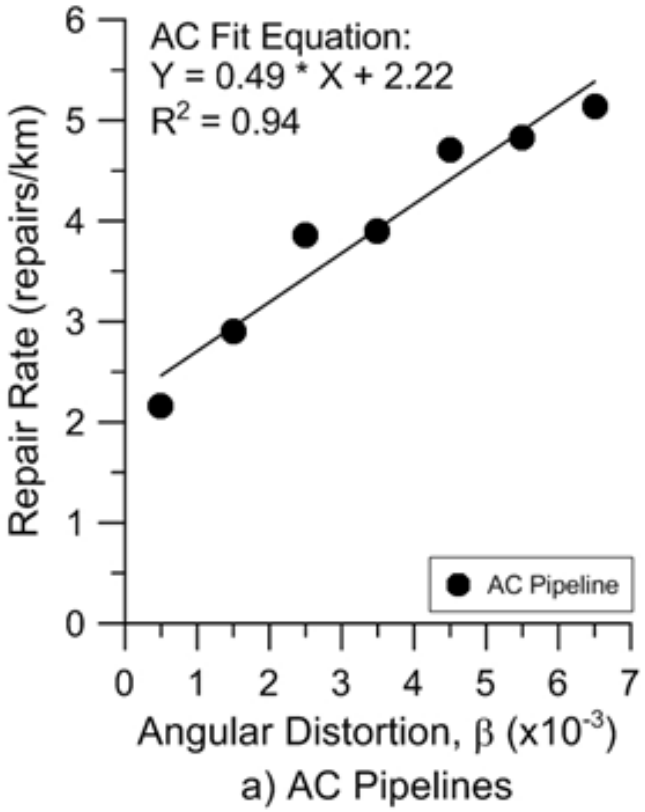


REPAIR RATE VS ANGULAR DISTORTION

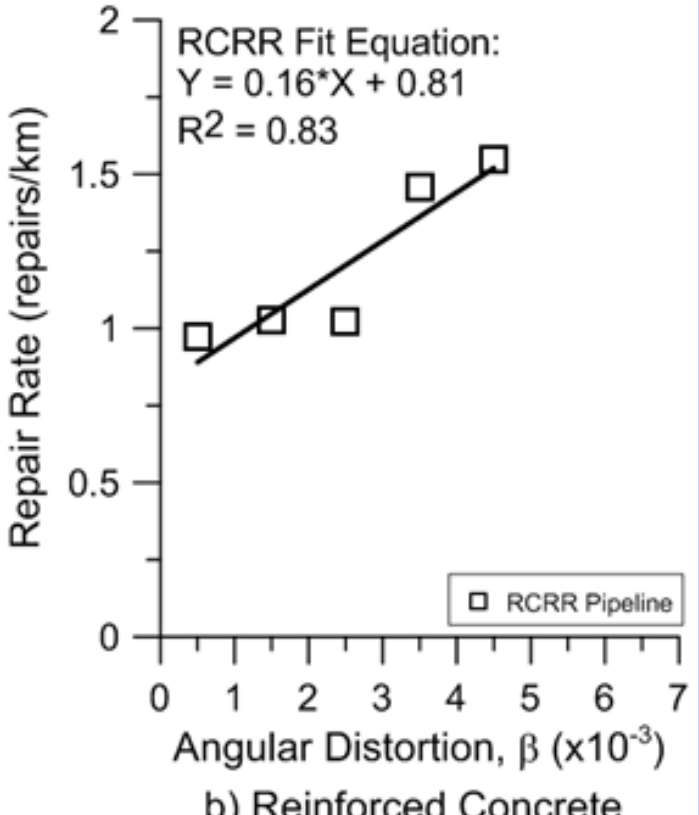
Å Angular Distortion = (dv1-dv2)/L = Δd/5m

Water Pipelines

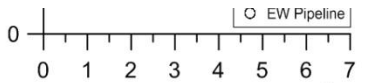
Wastewater Pipelines



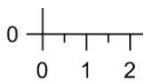
a) AC Pipelines



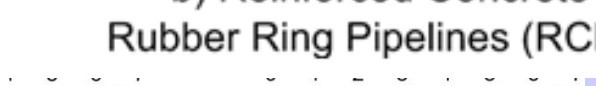
b) Reinforced Concrete Rubber Ring Pipelines (RCRR)



a) Earthenware (EW) Pipelines

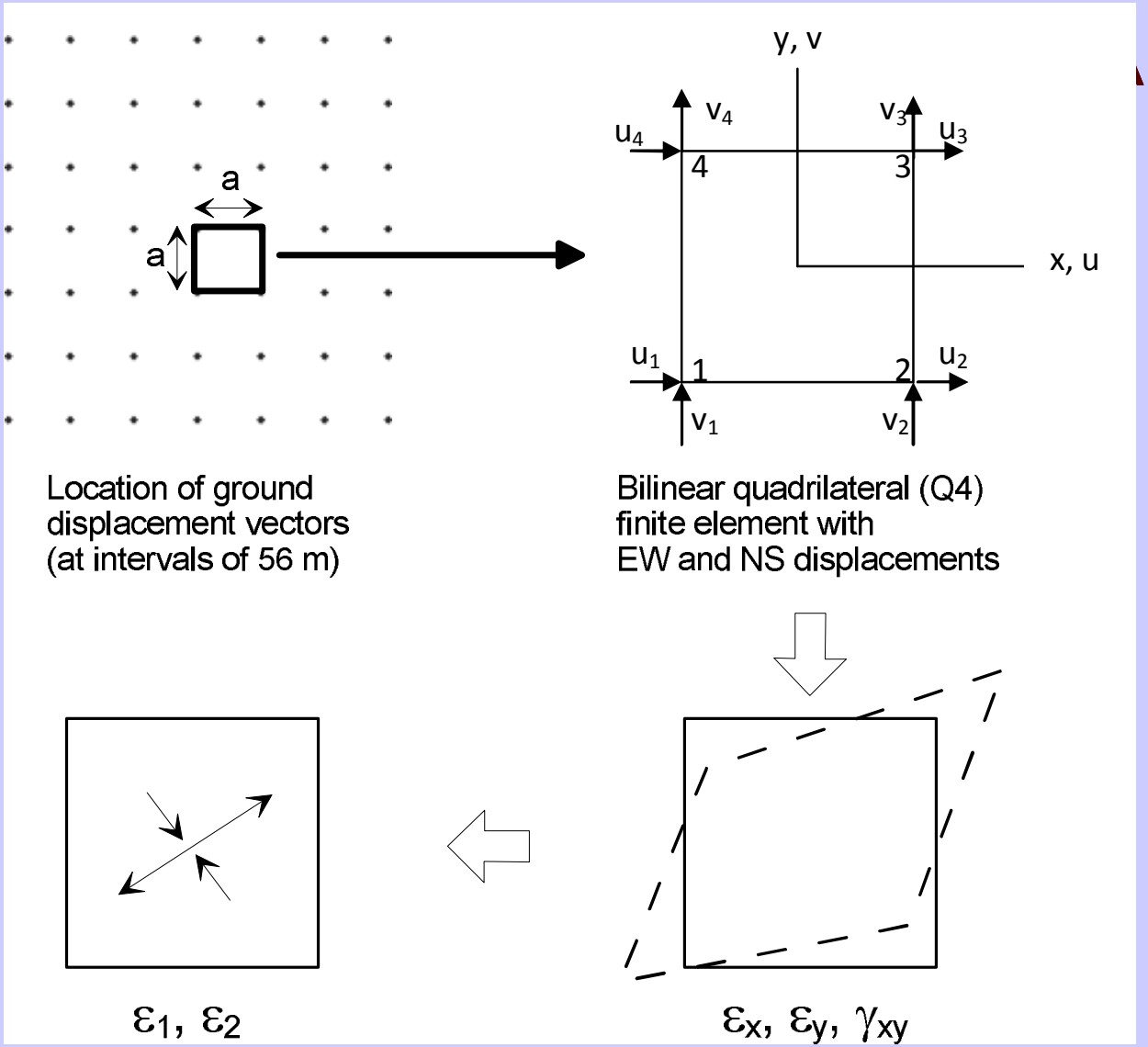


b) Reinforced Concrete Rubber Ring Pipelines (RCRR)



c) Concrete Pipelines (CONC)

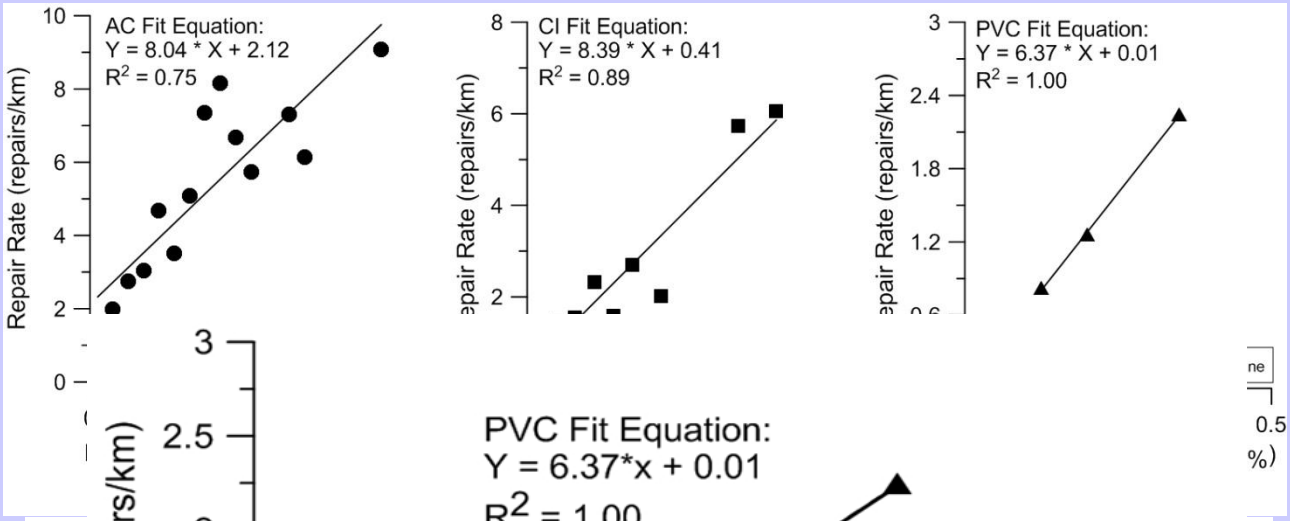
MAXIMUM PRINCIPAL LATERAL STRAIN



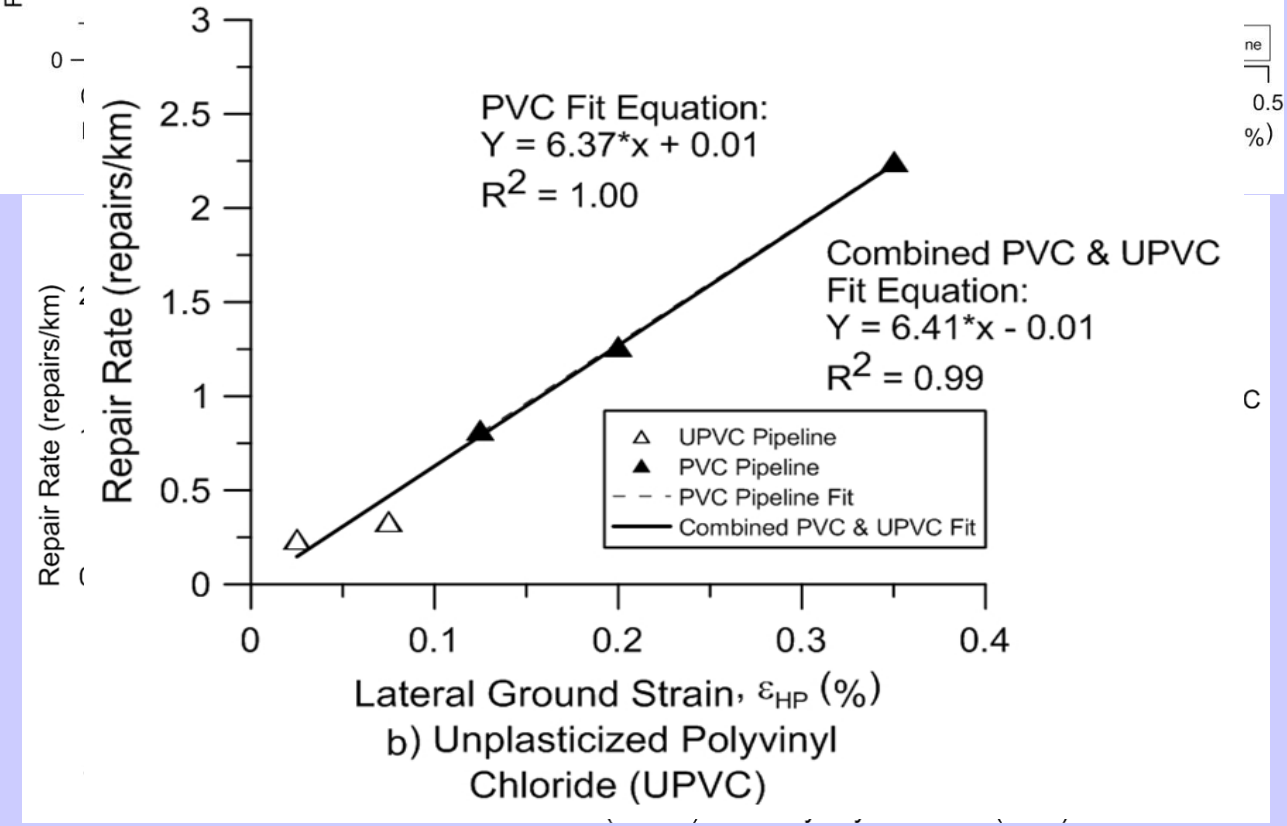
Create Bilinear Quadrilateral Finite Element from Lateral Displacements at Grid Corners to Determine Principal Strain

REPAIR RATE VS LATERAL STRAIN

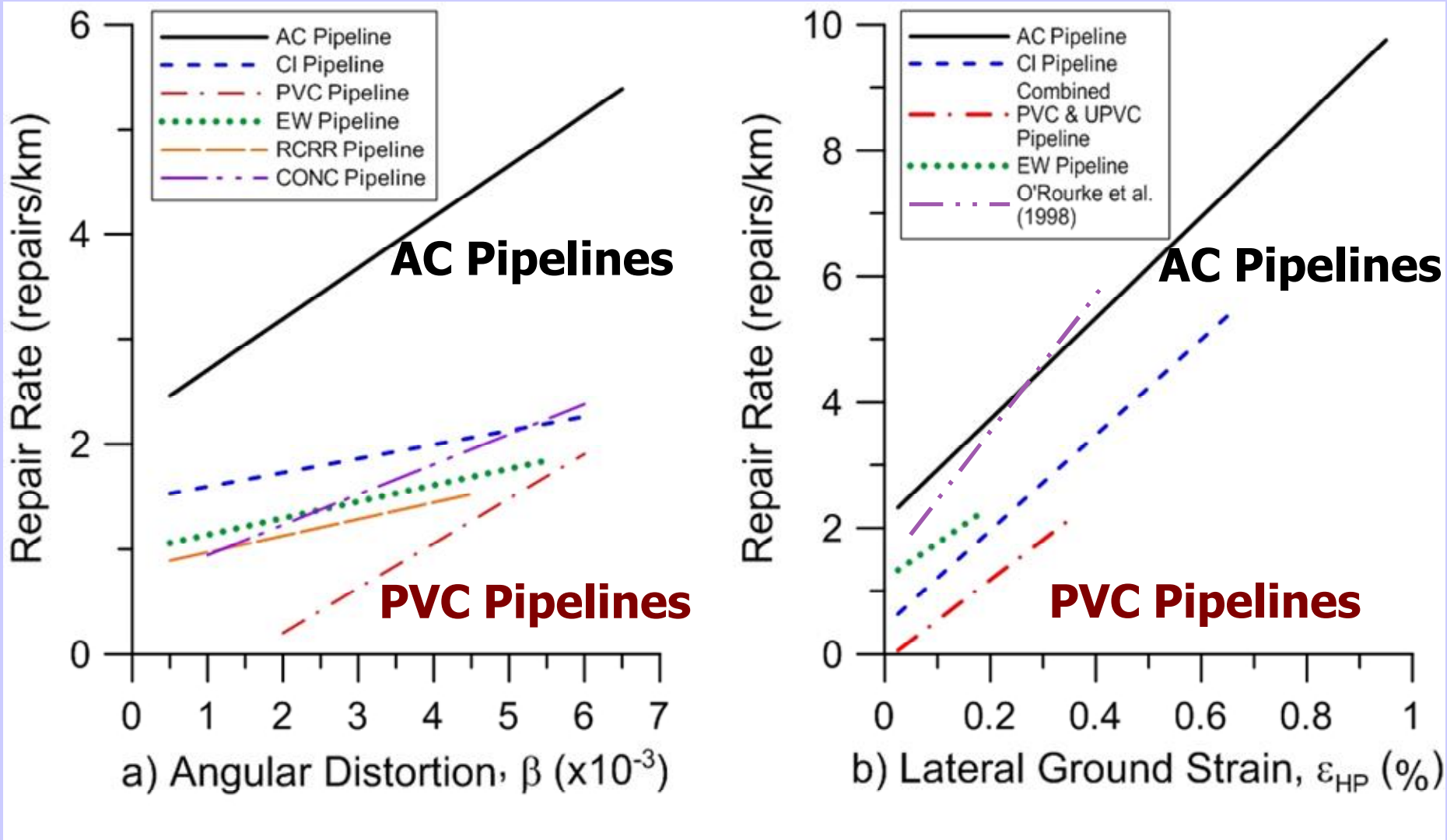
Water Pipelines



Wastewater Pipelines

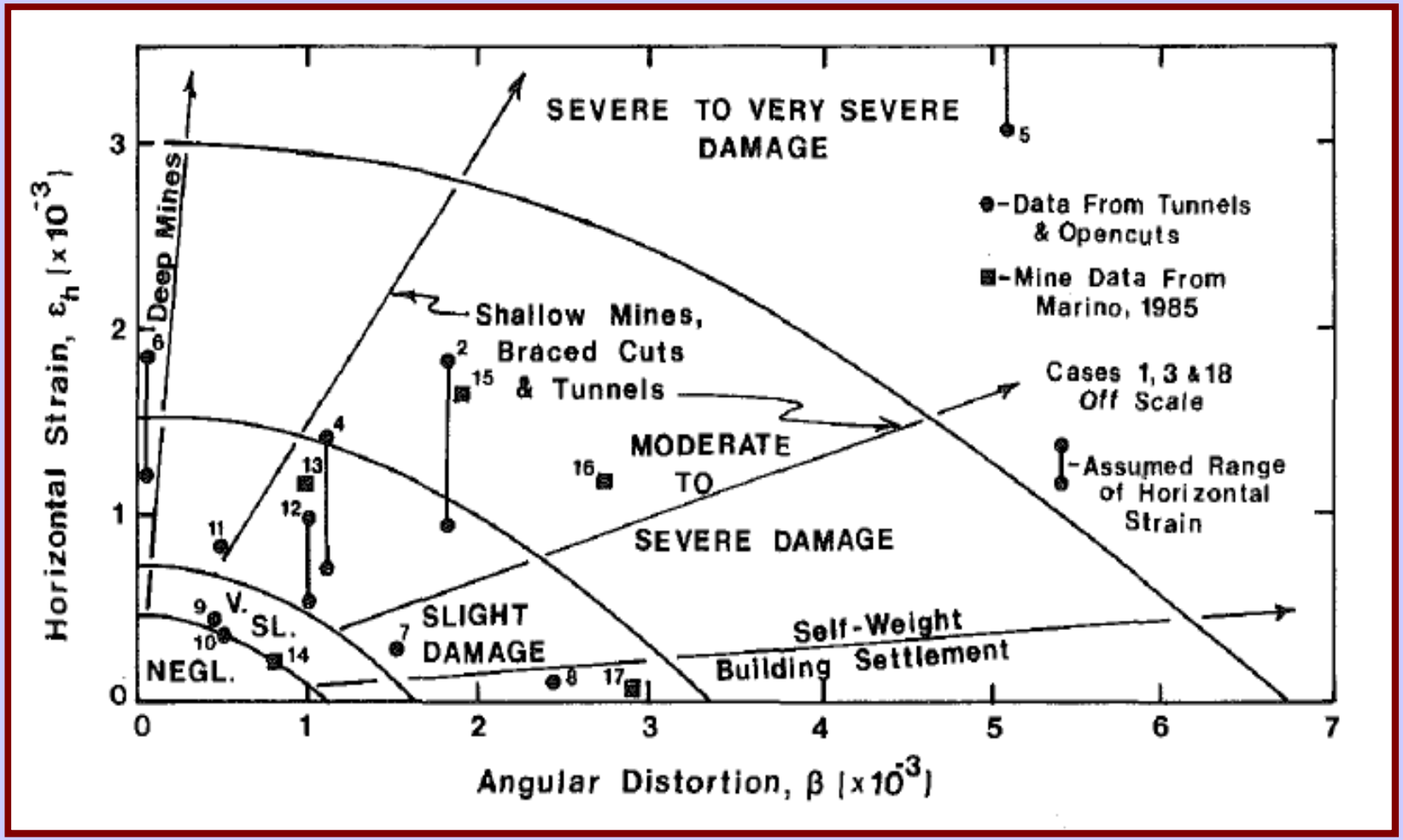


REPAIR RATE COMPARISONS

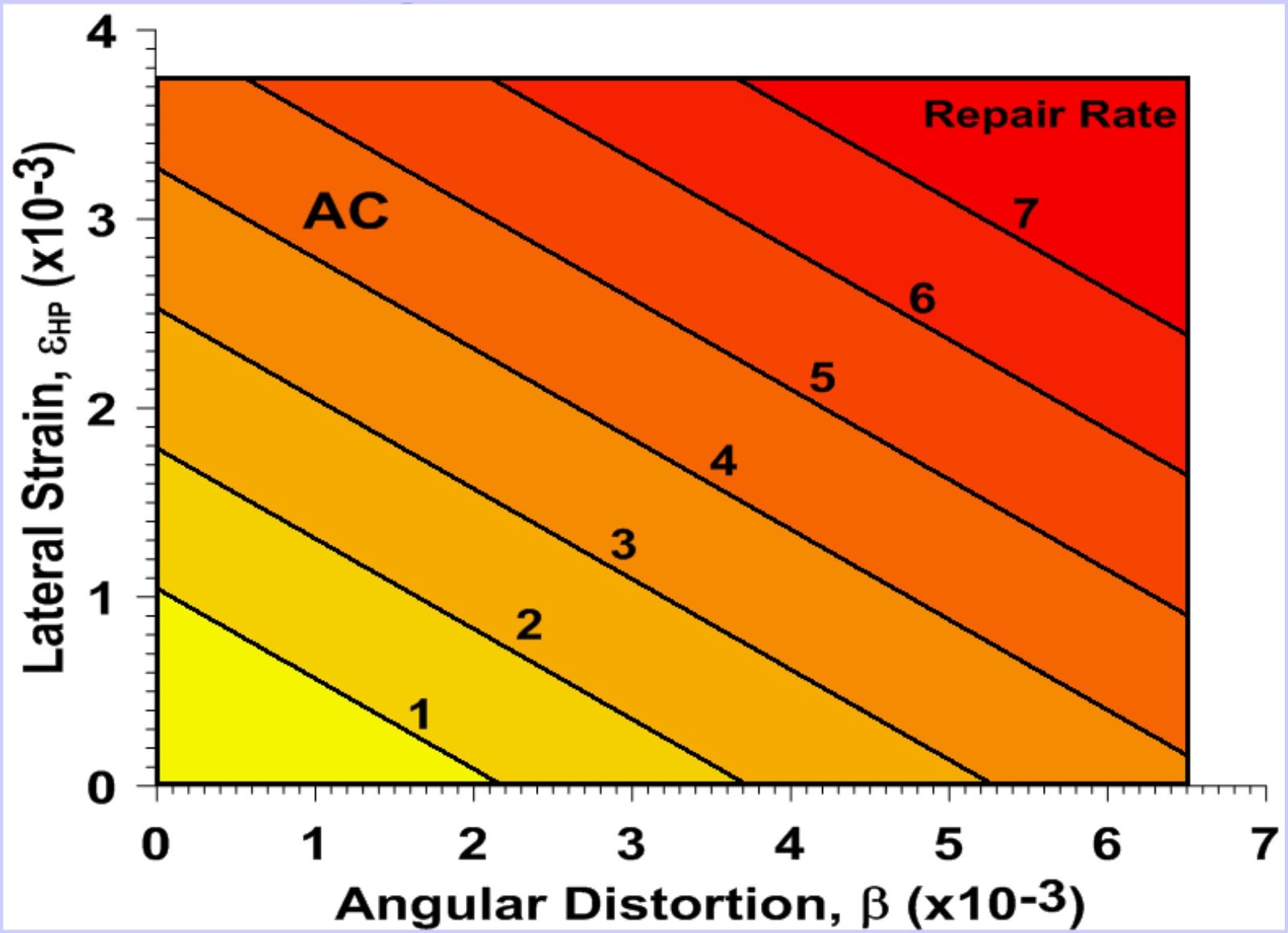


GROUND DEFORMATION METRICS

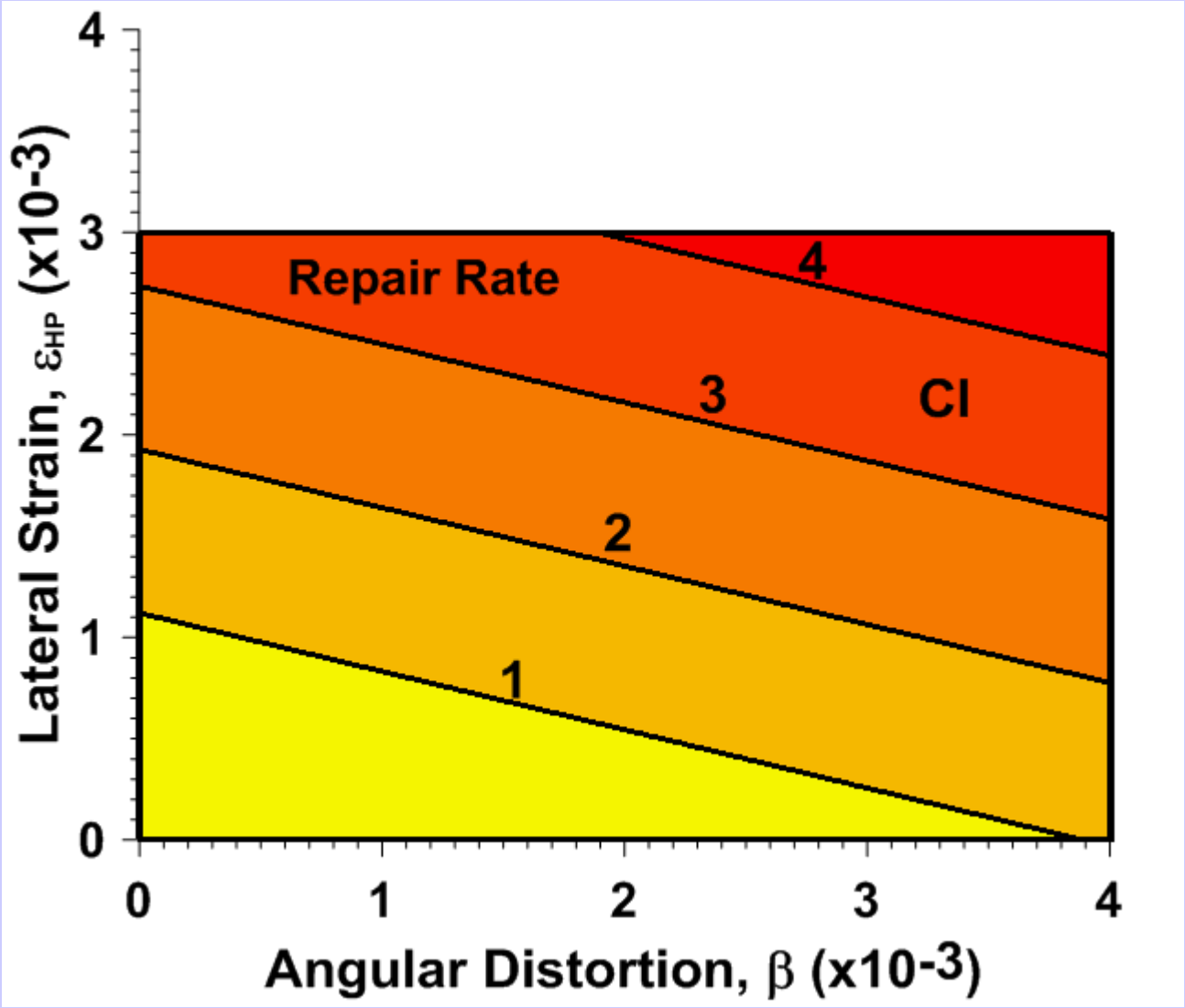
- From Boscardin & Cording (1989) for Building Damage:



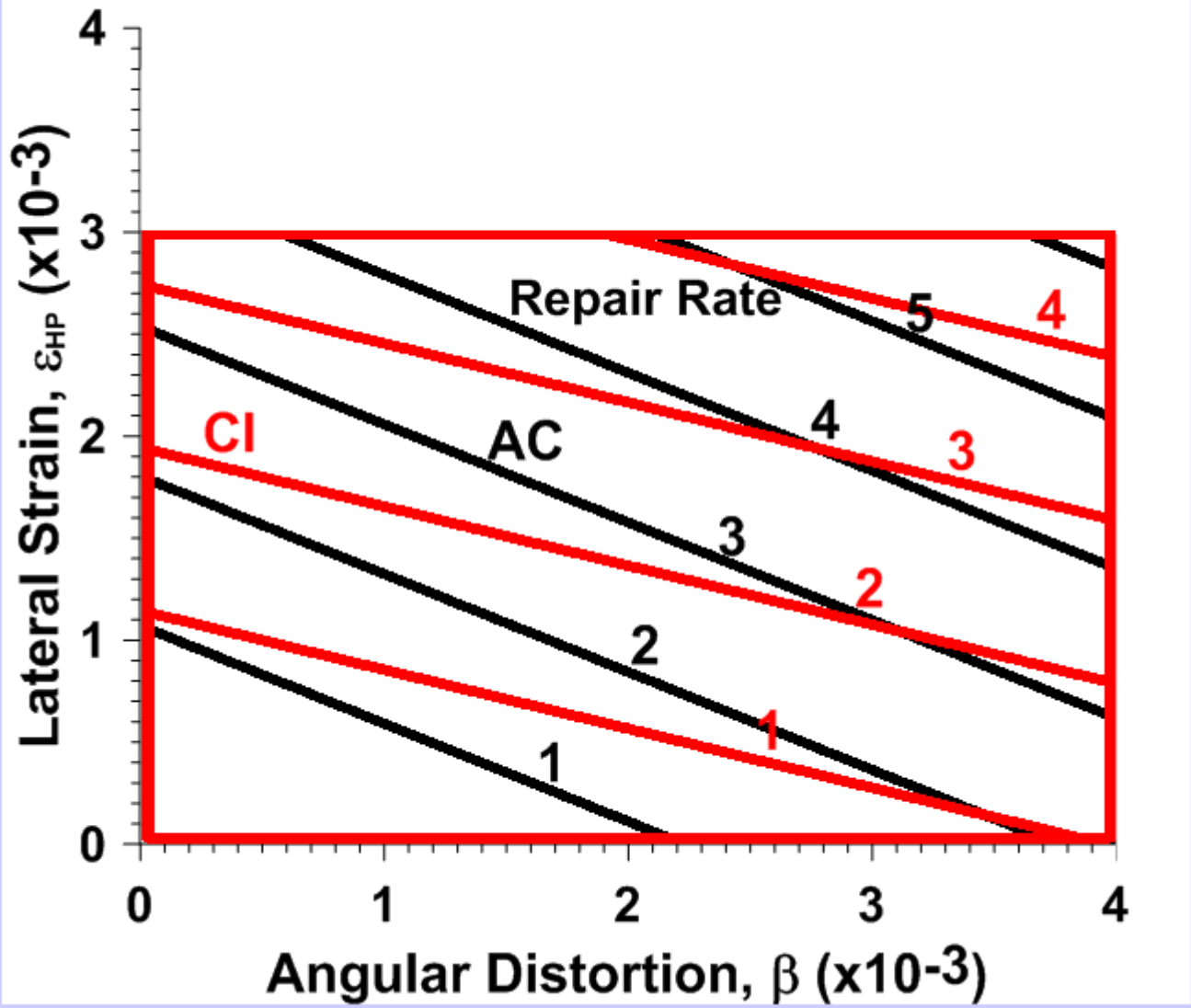
REPAIR RATE, β, AND E_{HP} FOR AC PIPELINES



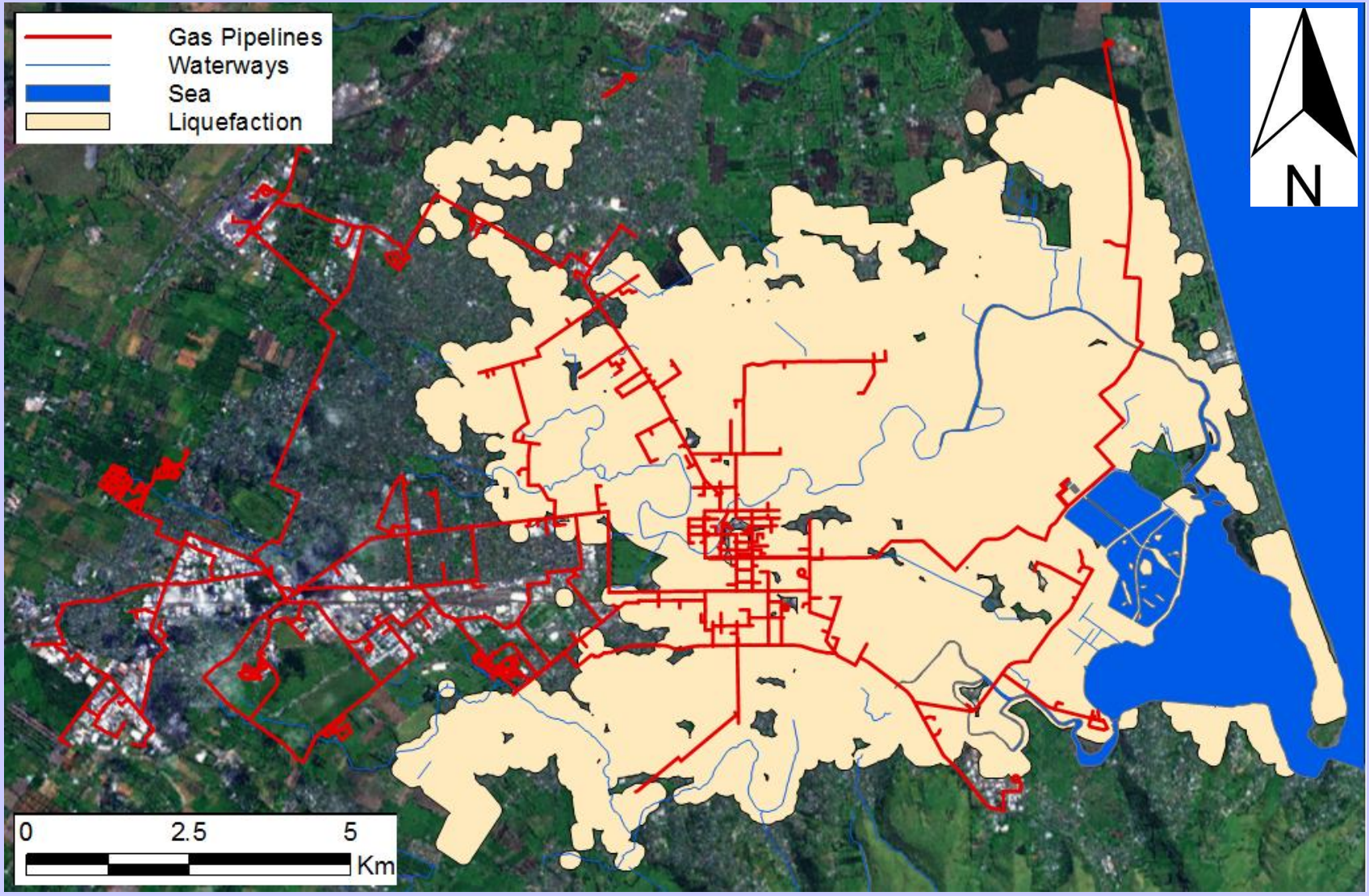
REPAIR RATE, β, AND EHP FOR CI PIPELINES

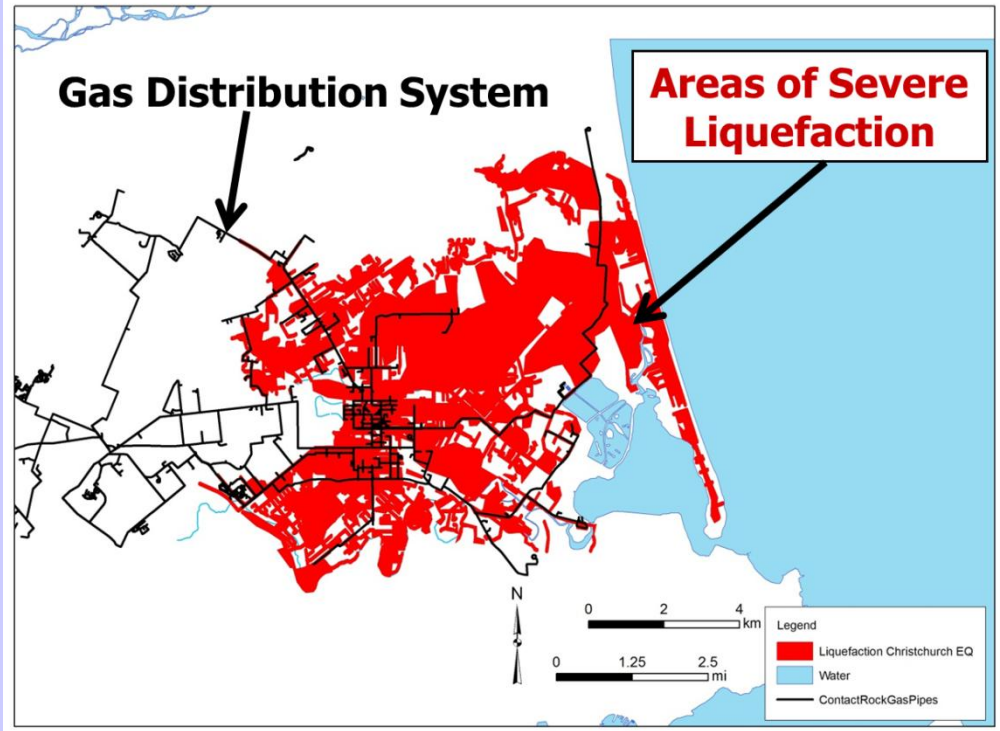


COMPARISON OF AC & CI PIPELINES

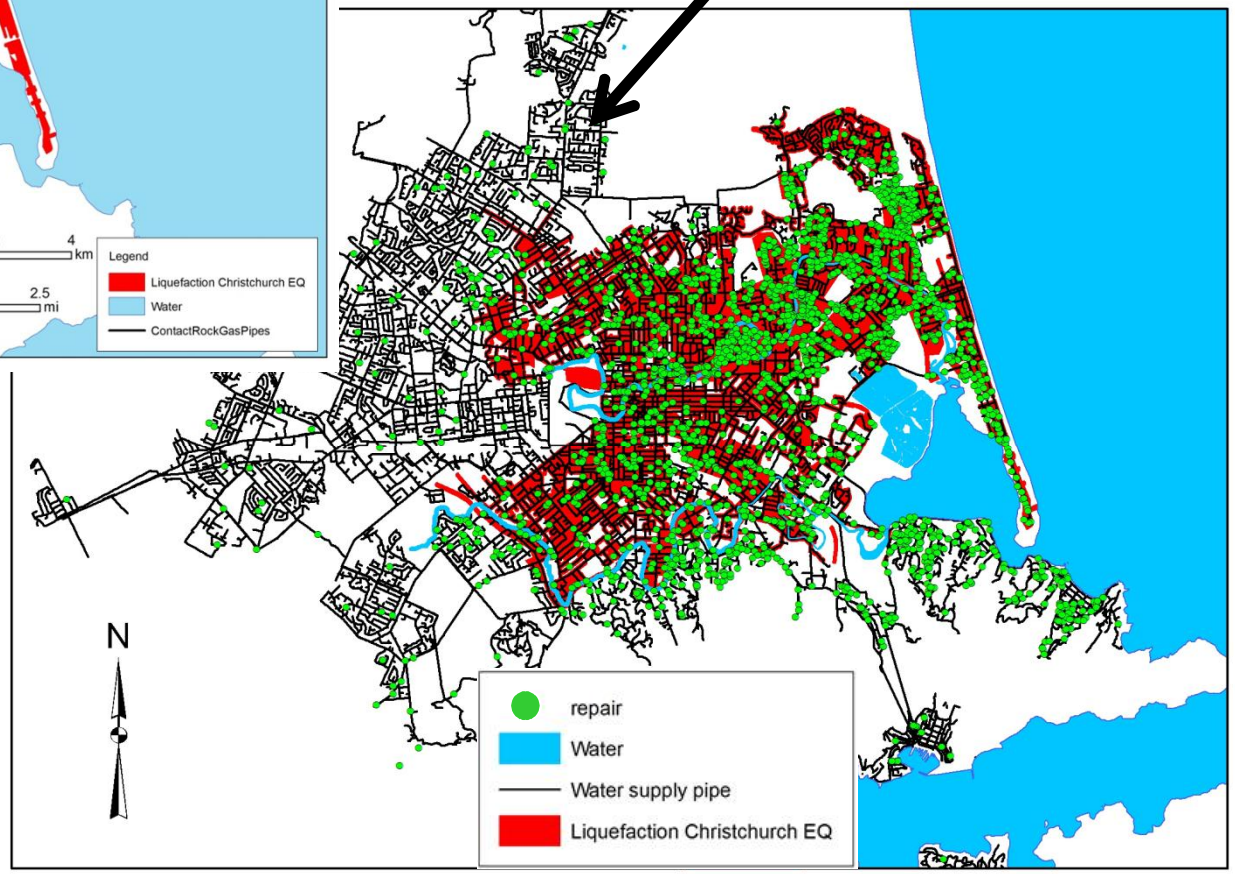


GAS DISTRIBUTION SYSTEM

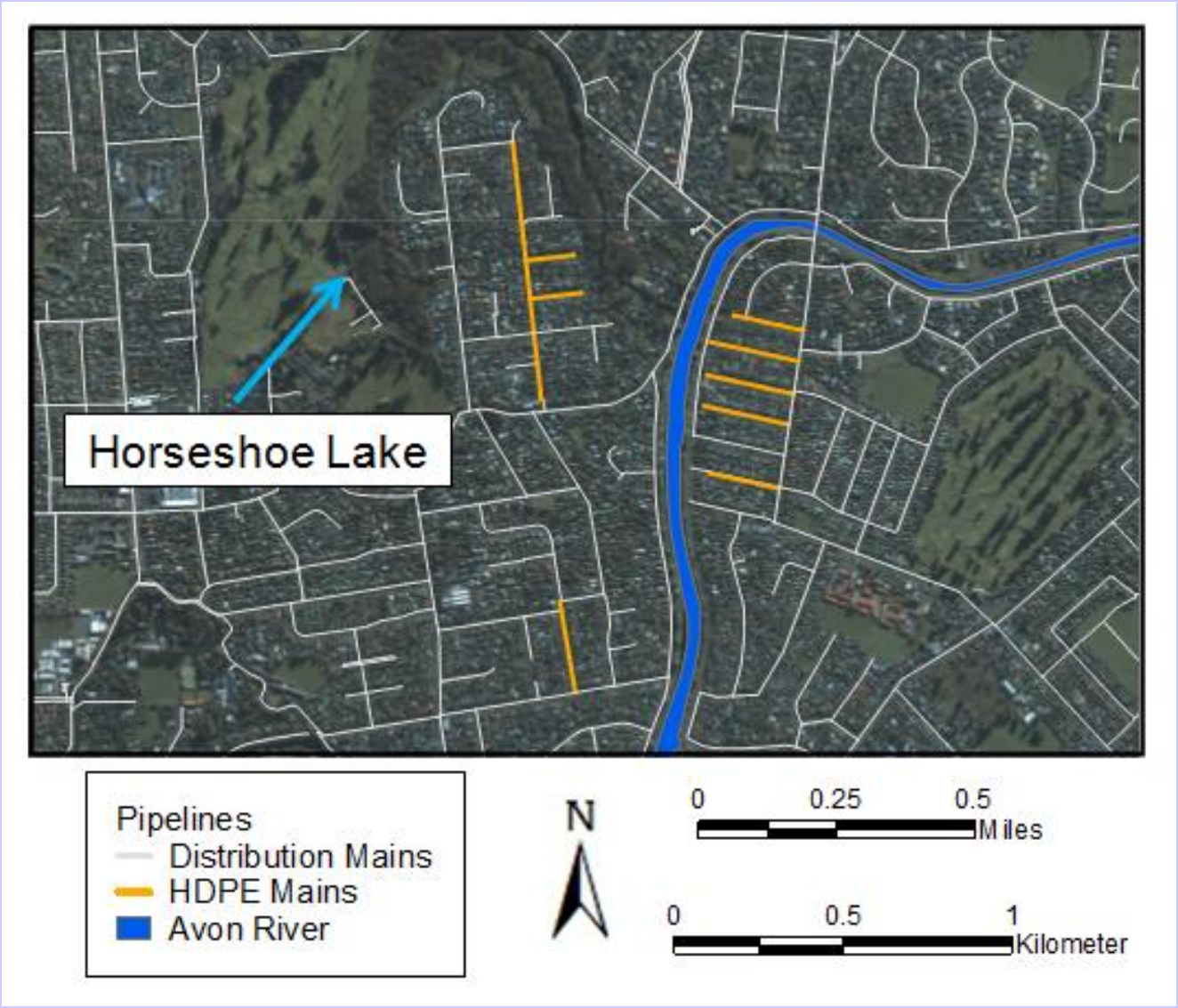




Water Distribution System



PE PIPELINES AFTER 4 Sept 2010 EQ

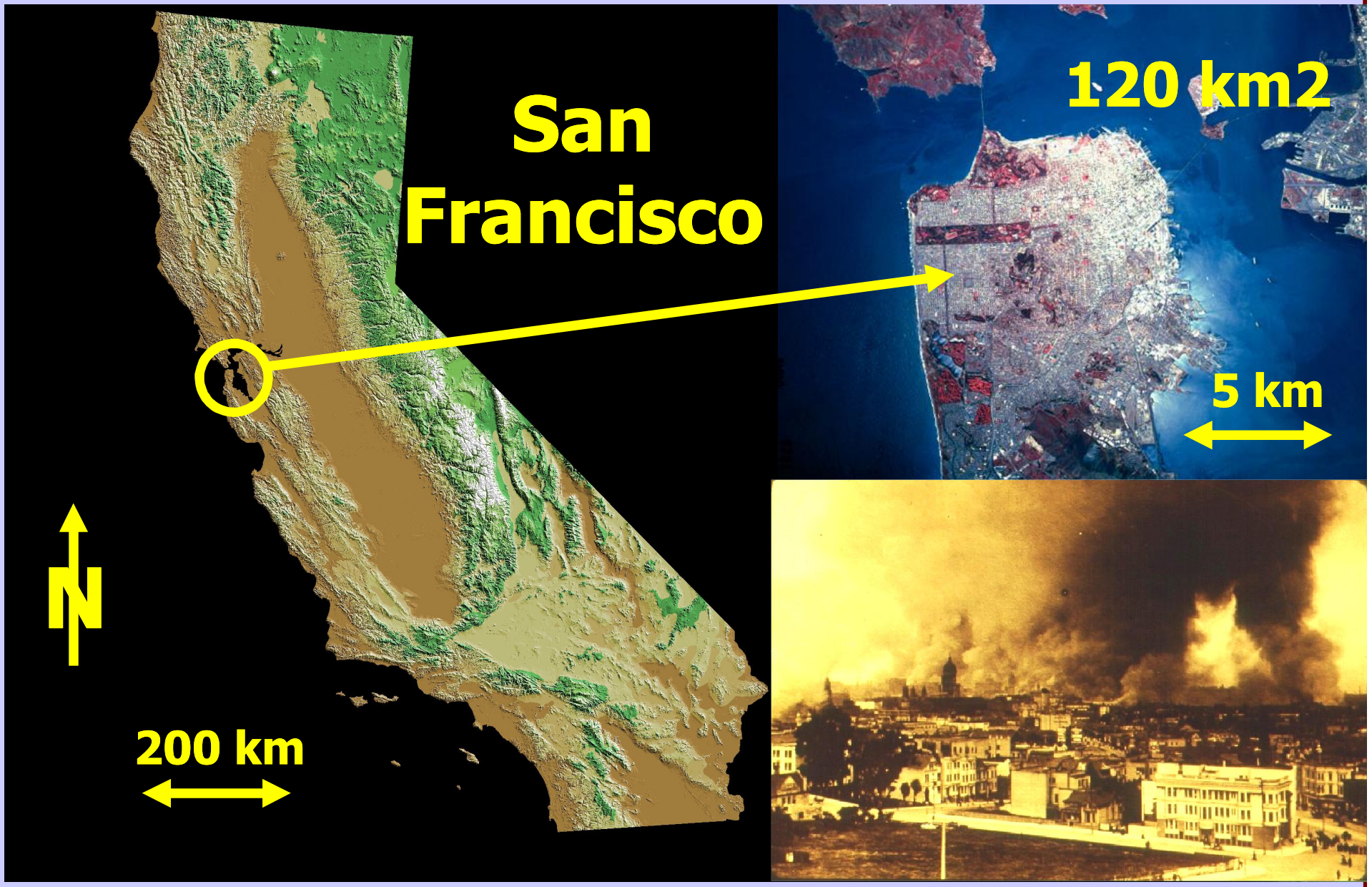


LESSONS FROM CHRISTCHURCH

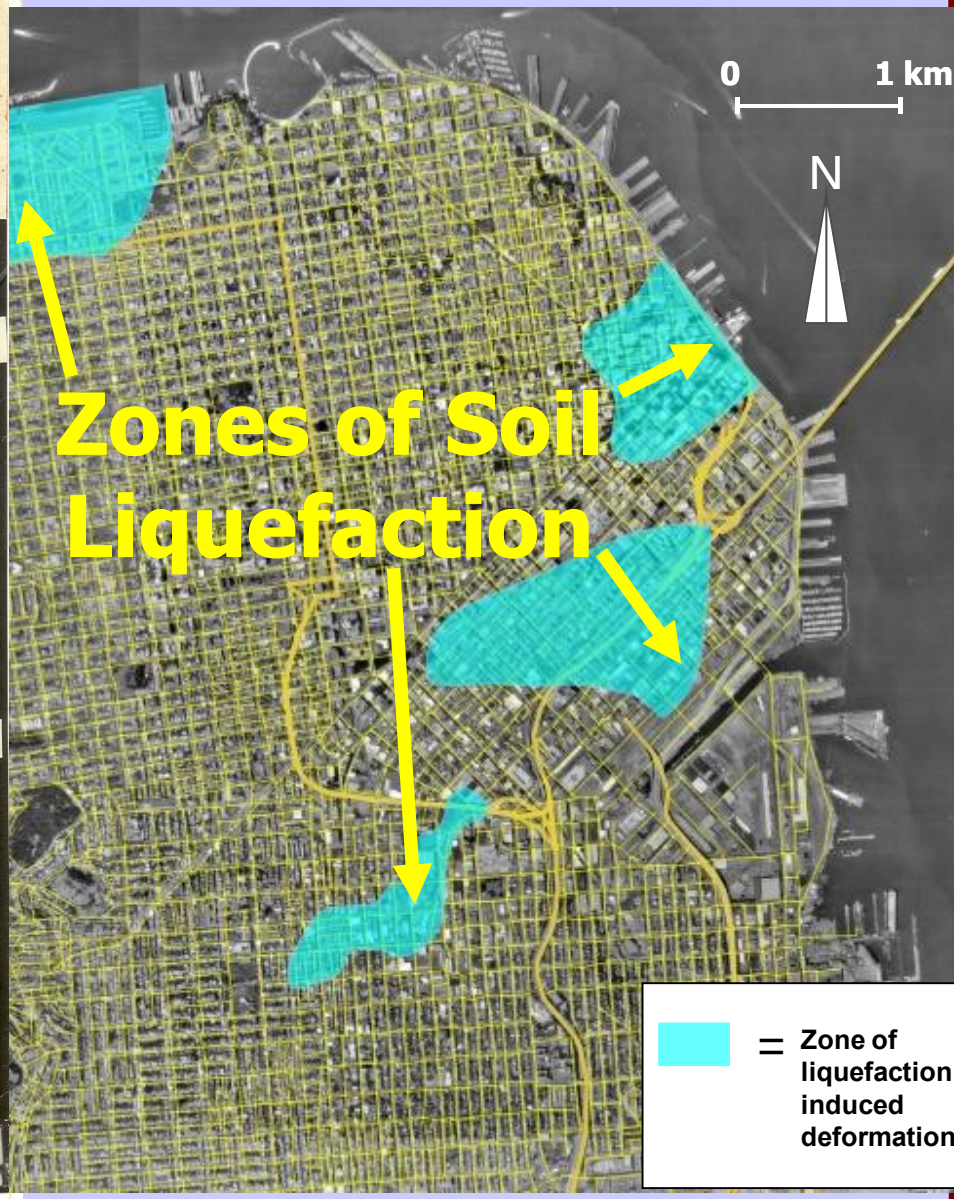
- **Extraordinary dataset: multiple EQs, dense ground motion array, massive liquefaction, high density LiDAR, geocoded repairs for thousands of km of different pipelines**
- **First time comprehensive assessment of underground lifeline response to liquefaction- induced differential vertical movement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

LESSONS FROM CHRISTCHURCH

- **Relative Performance of Most Widely Used Pipelines Quantified with Respect to Ground Deformation**
- **Statistically Significant Regressions for EQ Pipeline Damage vs Transient & Permanent Ground Deformation**
- **Unified Methodology for Building & Lifeline Damage vs Differential Vertical & Lateral Ground Movements**


San Francisco
120 km2
5 km
N
200 km


0 1000 3000 5000 feet
0 500 1000 1500 meters
N
Marina
Embarcadero
Approx. Boundary of Foot of Market Zone
Zones of Soil Liquefaction
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

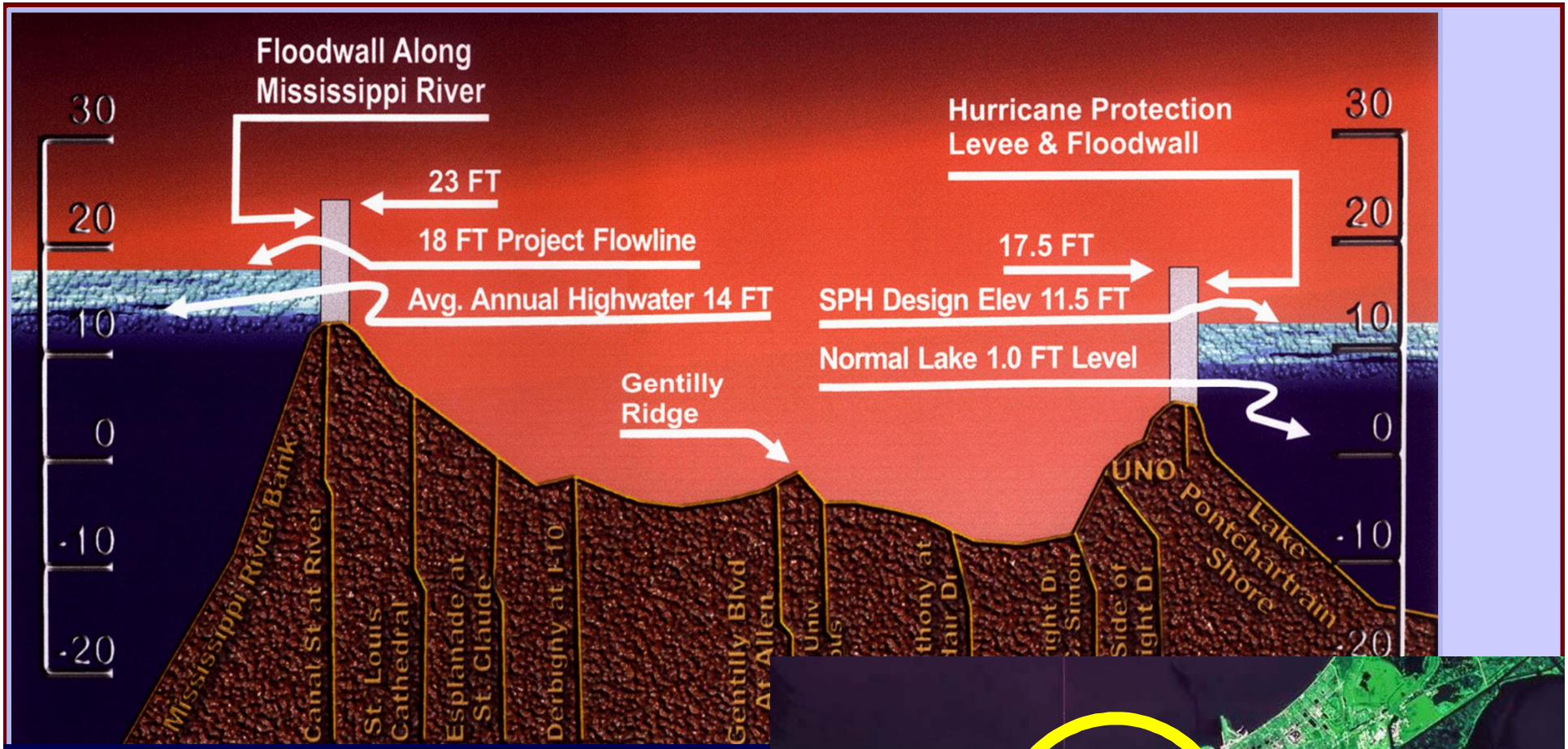

0
1 km
N
Zones of Soil Liquefaction
= Zone of liquefaction induced deformation

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**


Mississippi River
New Orleans
Mississippi
Delta
25000 km2
Most Recent
Delta



New Orleans Elevation Cross-Section

Entergy (2006)

HURRICANE KATRINA

- Greatest U.S. Disaster
- 2000 Dead & Missing
- ~ $ 160 Billion Losses
- 80% New Orleans Flooded, 53 Days to Dewater
- Impacts on Gulf Offshore Infrastructure & Energy Delivery System
- Complete Failure of Hurricane Protection System
  - Hurricane Hazard
  - Incomplete Design & Construction
  - Poor Maintenance
  - I Walls & Foundations
  - Poor Preparation
  - Inadequate Response

EVOLUTION OF CONCEPT

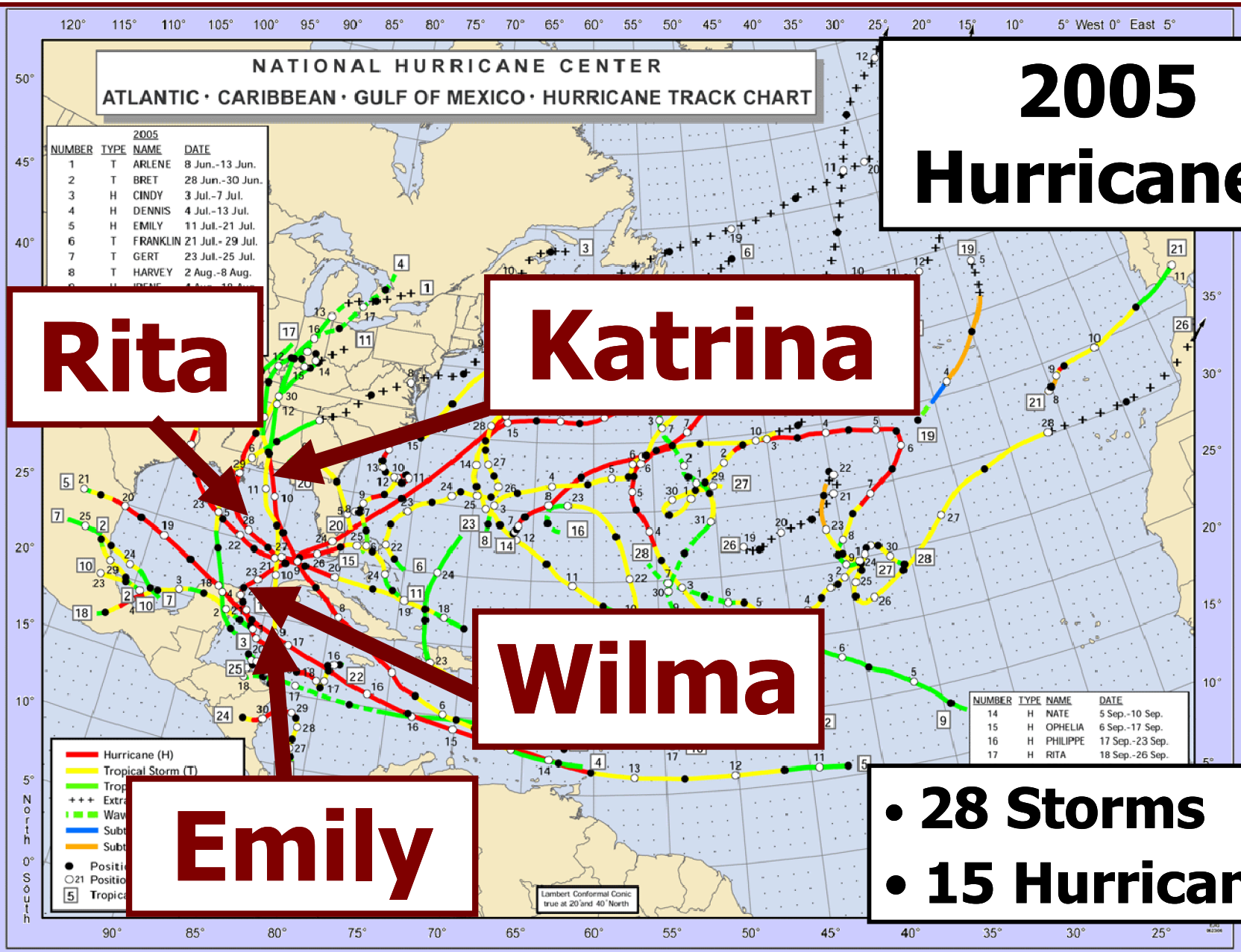
September 11:

- Protection of Critical Infrastructure

Hurricane Katrina:

- Resilient Communities

2005 Hurricanes



Rita

Katrina

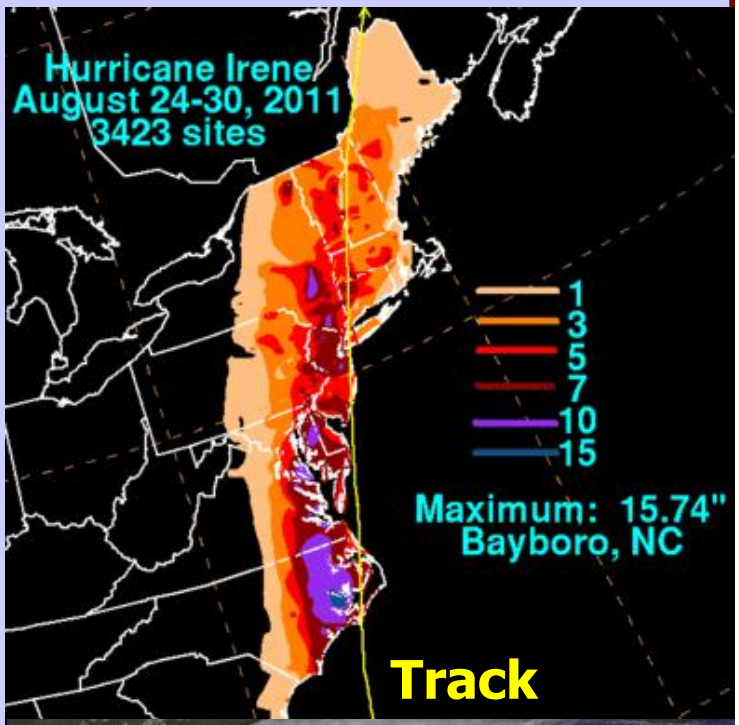
Wilma

Emily

- **28 Storms**
- **15 Hurricanes**

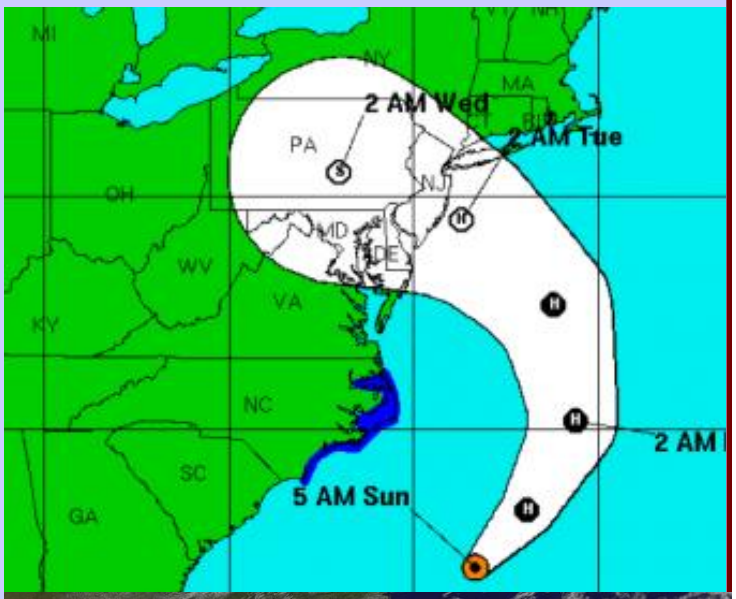
HURRICANE IRENE

- 56 Killed
- $10-15 Billion Direct Losses
- 7.4 Million Homes & Businesses Without Power
- NYC Evacuation & Shutdown of MTA & Public Transportation
- Record Flooding
- Near Miss

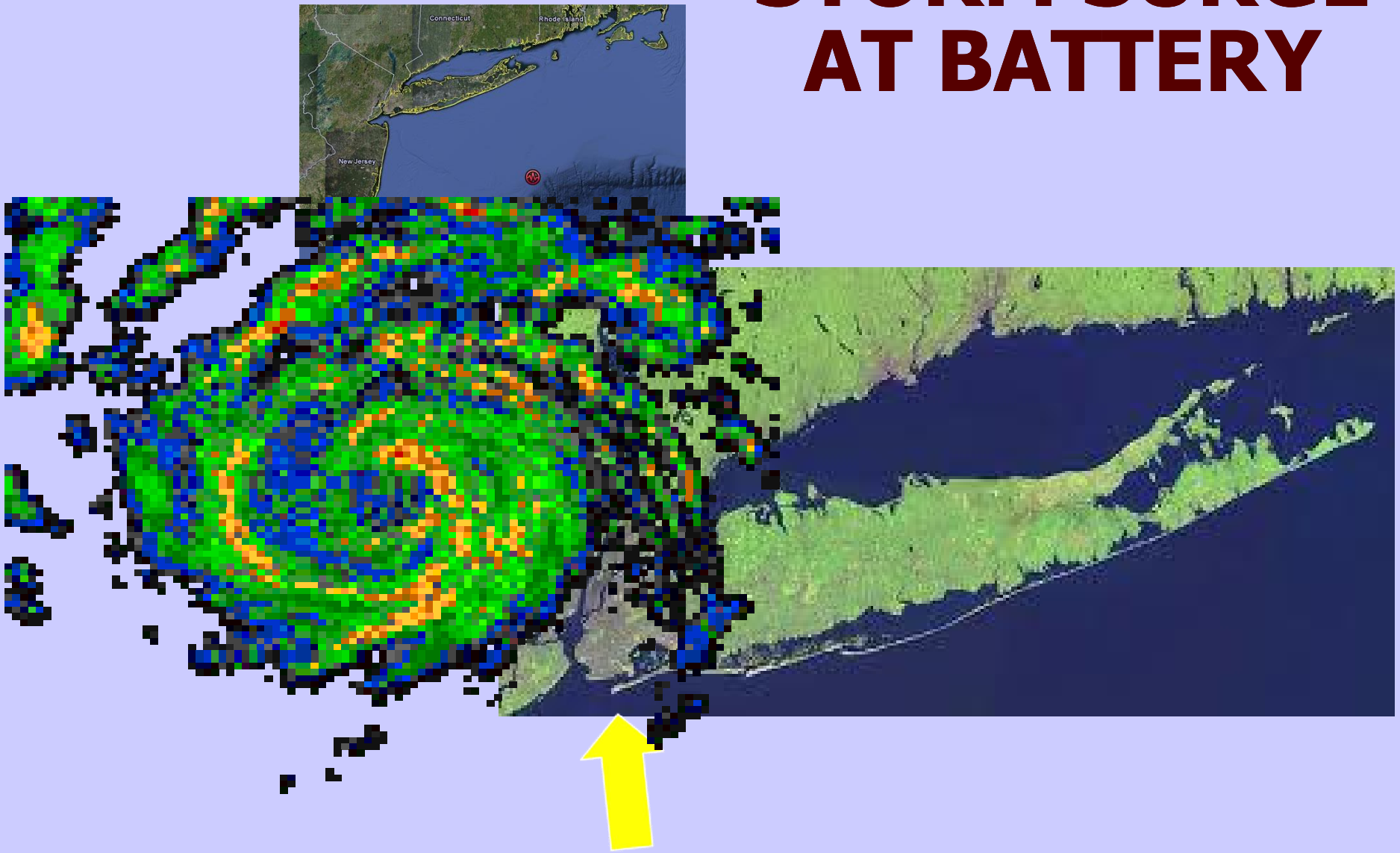


HURRICANE SANDY

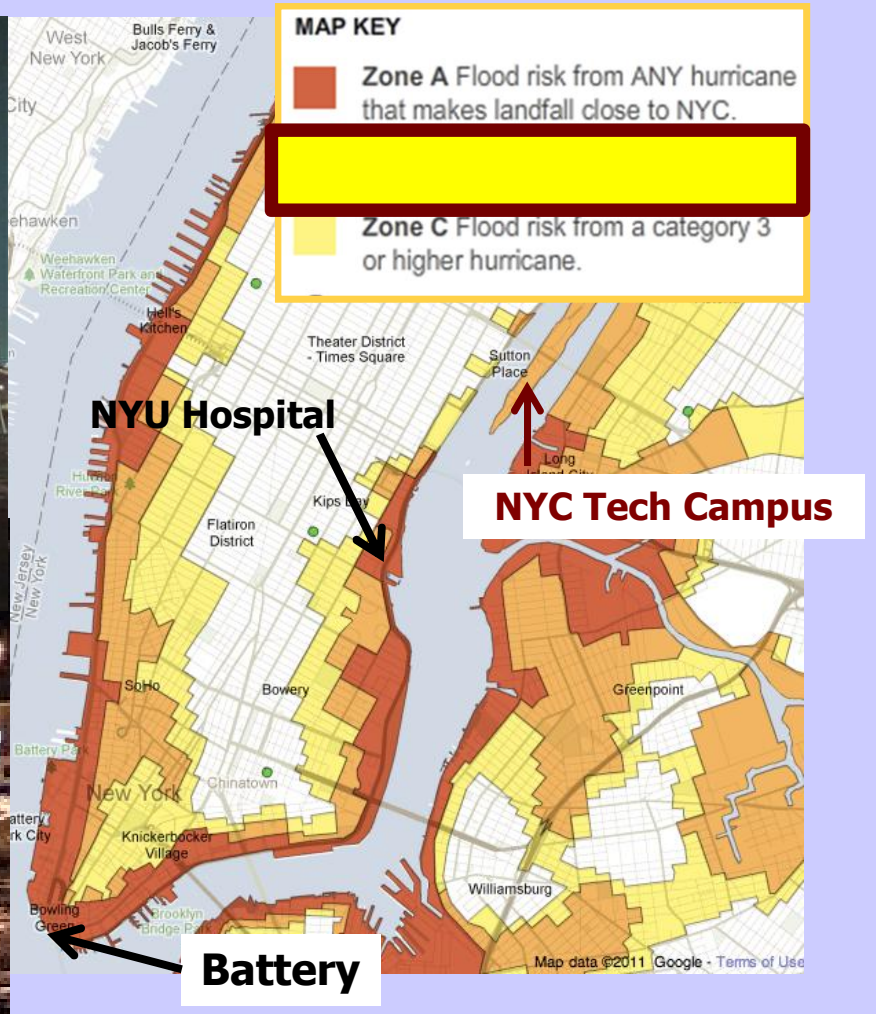
- 159 Killed in US
- $65 Billion Property and Business Losses (Sandy Task Force)
- 8.5 Million Homes & Businesses Without Power
- NYC Evacuation & Shutdown of MTA & Public Transport
- Wall Street Shut 2 Days
- Record Flooding (Surge)
- Direct Hit



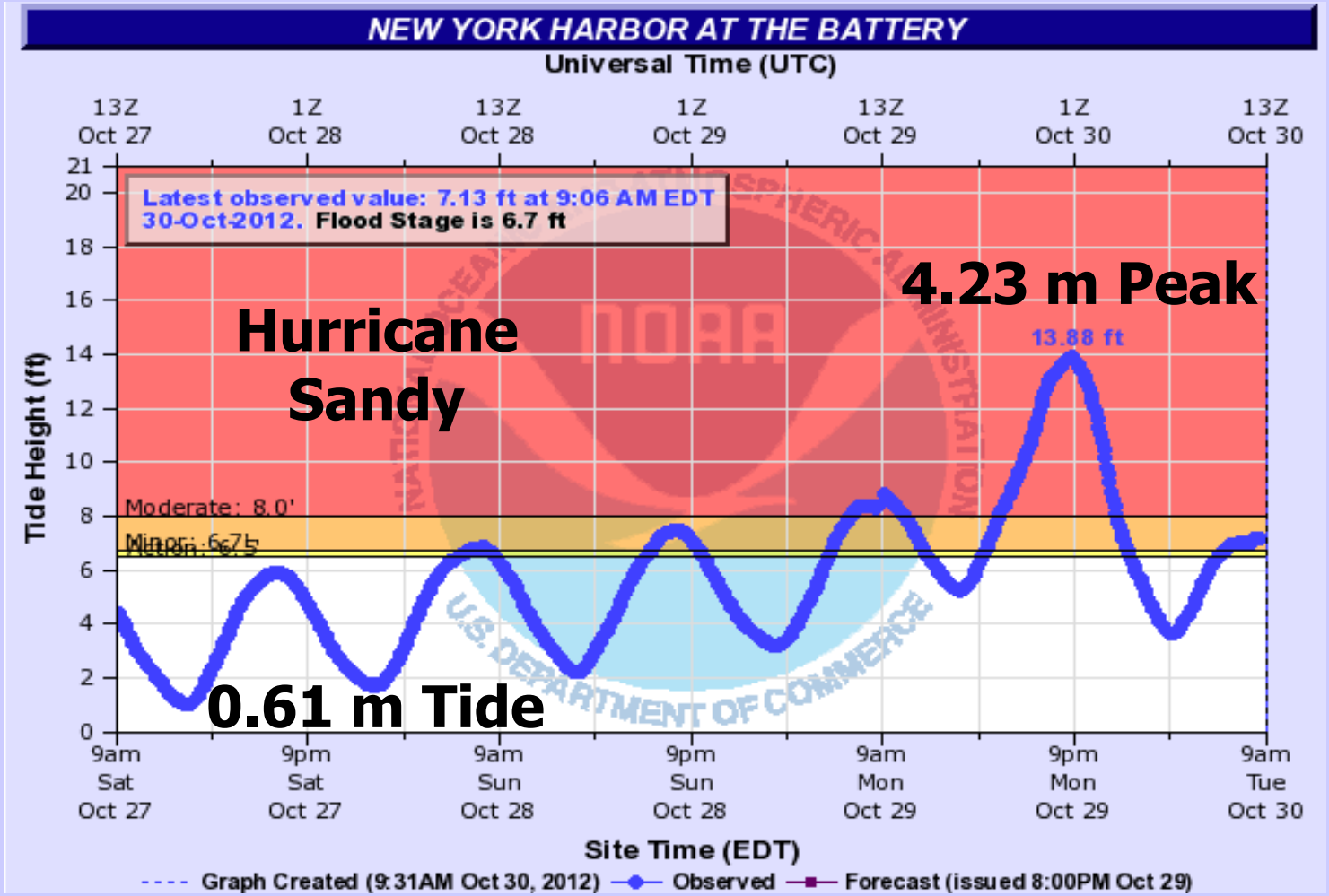
STORM SURGE AT BATTERY



NEW YORK CITY HURRICANE FLOOD ZONES

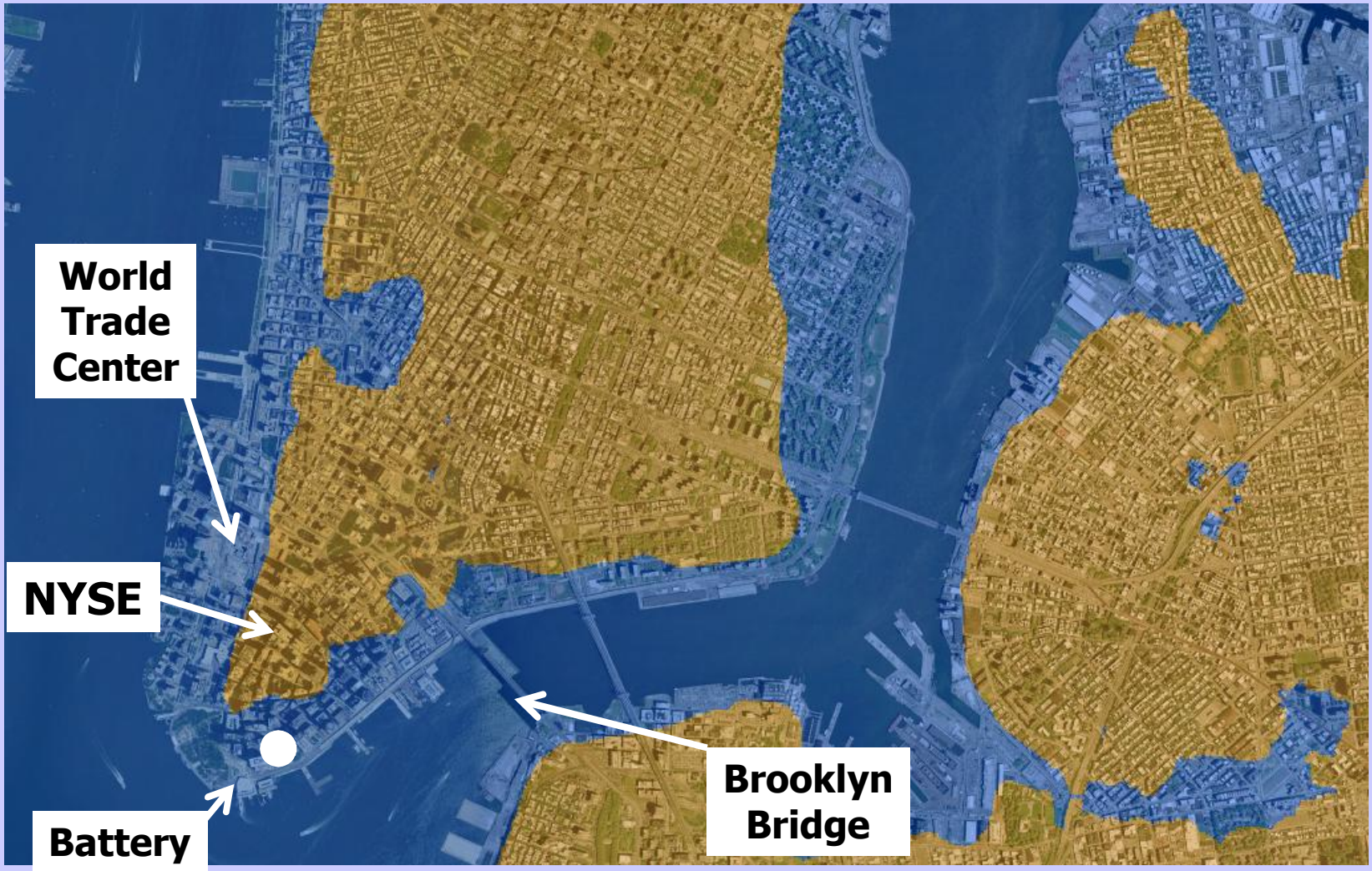


STORM WATER AT BATTERY



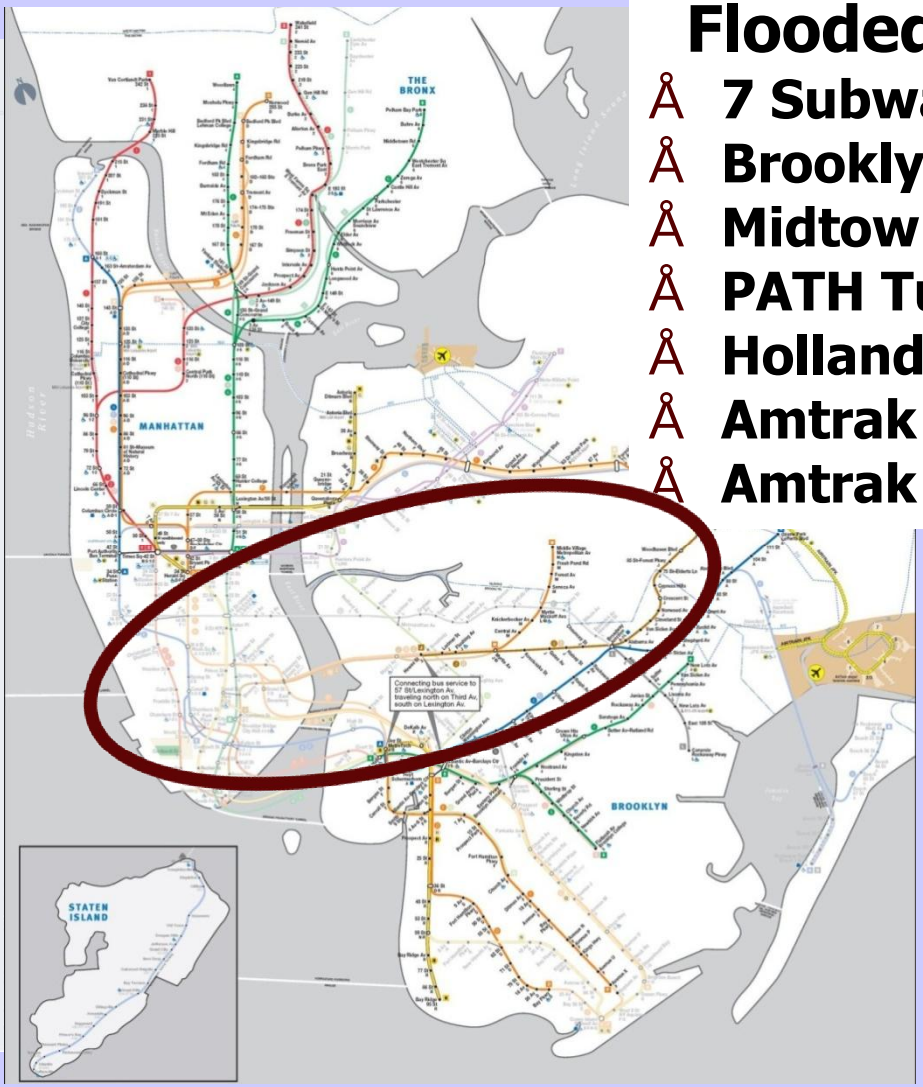
4.23 m
- 0.61 m
~ 3.62 m
Surge

HURRICANE SANDY INNUNDATION



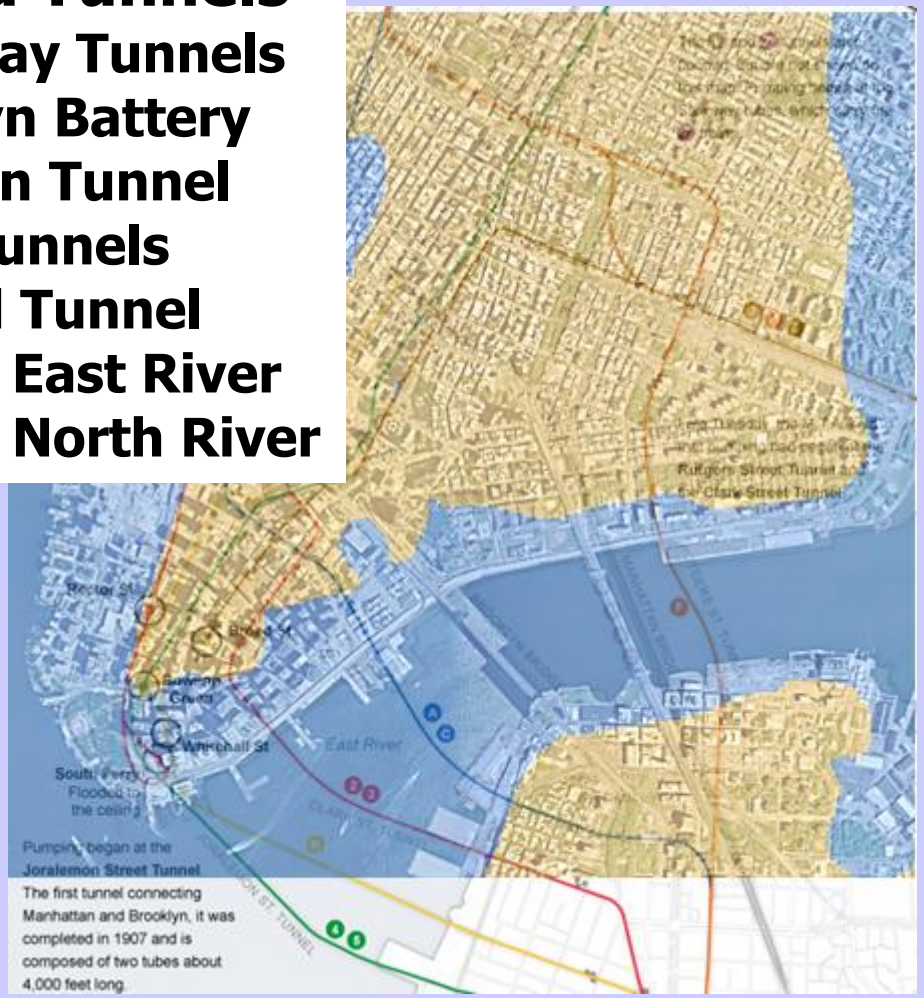
HURRICANE SANDY INNUNDATION

HURRICANE SANDY INNUNDATION

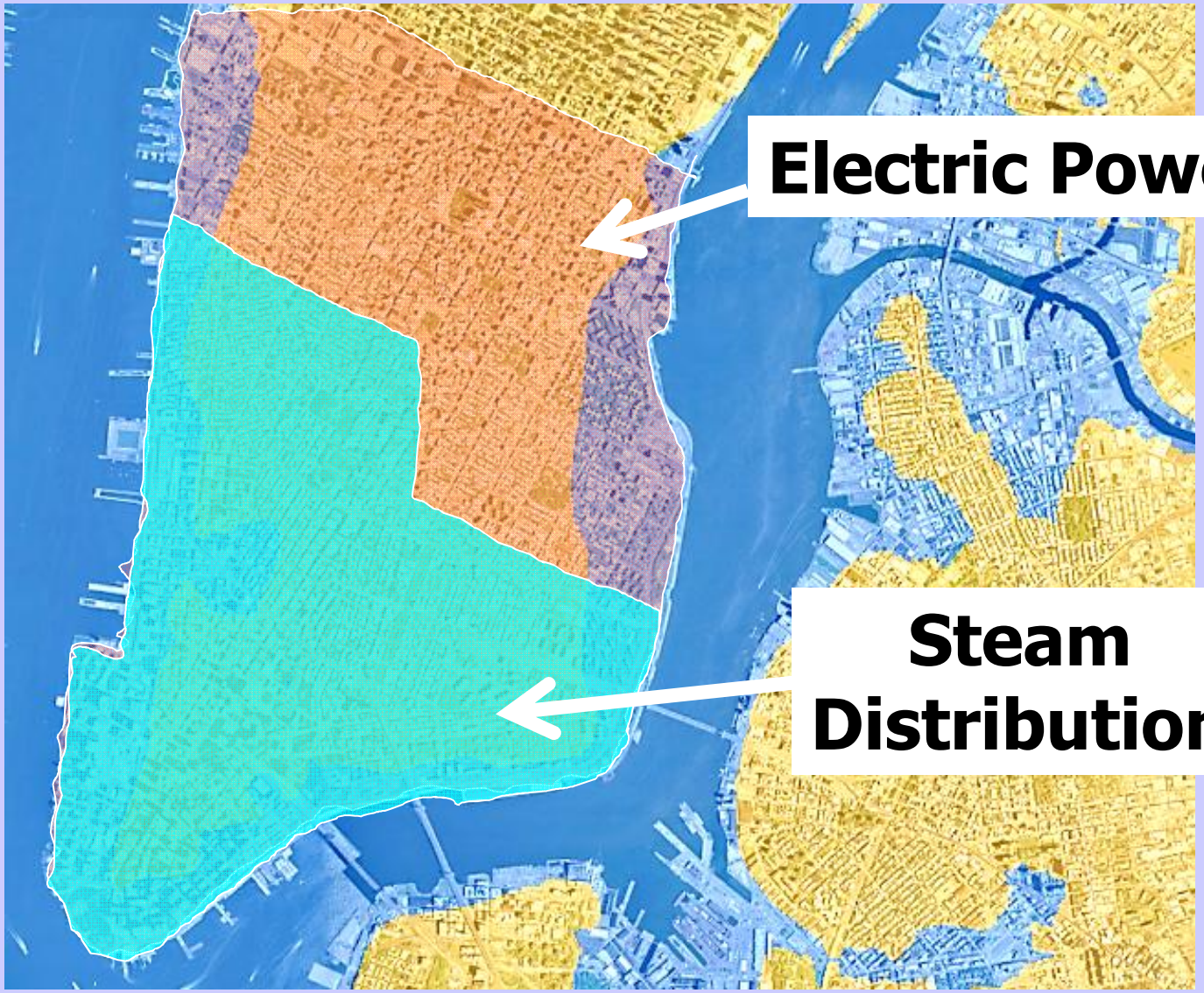


Flooded Tunnels

- 7 Subway Tunnels
- Brooklyn Battery
- Midtown Tunnel
- PATH Tunnels
- Holland Tunnel
- Amtrak East River
- Amtrak North River

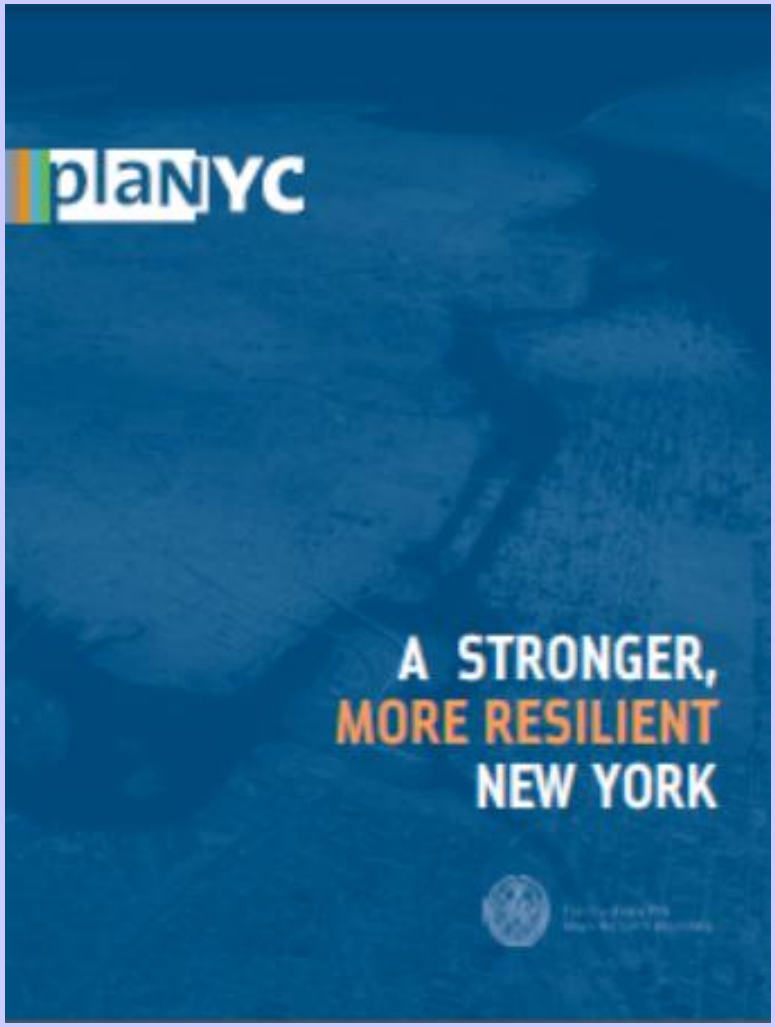


HURRICANE SANDY INNUNDATION

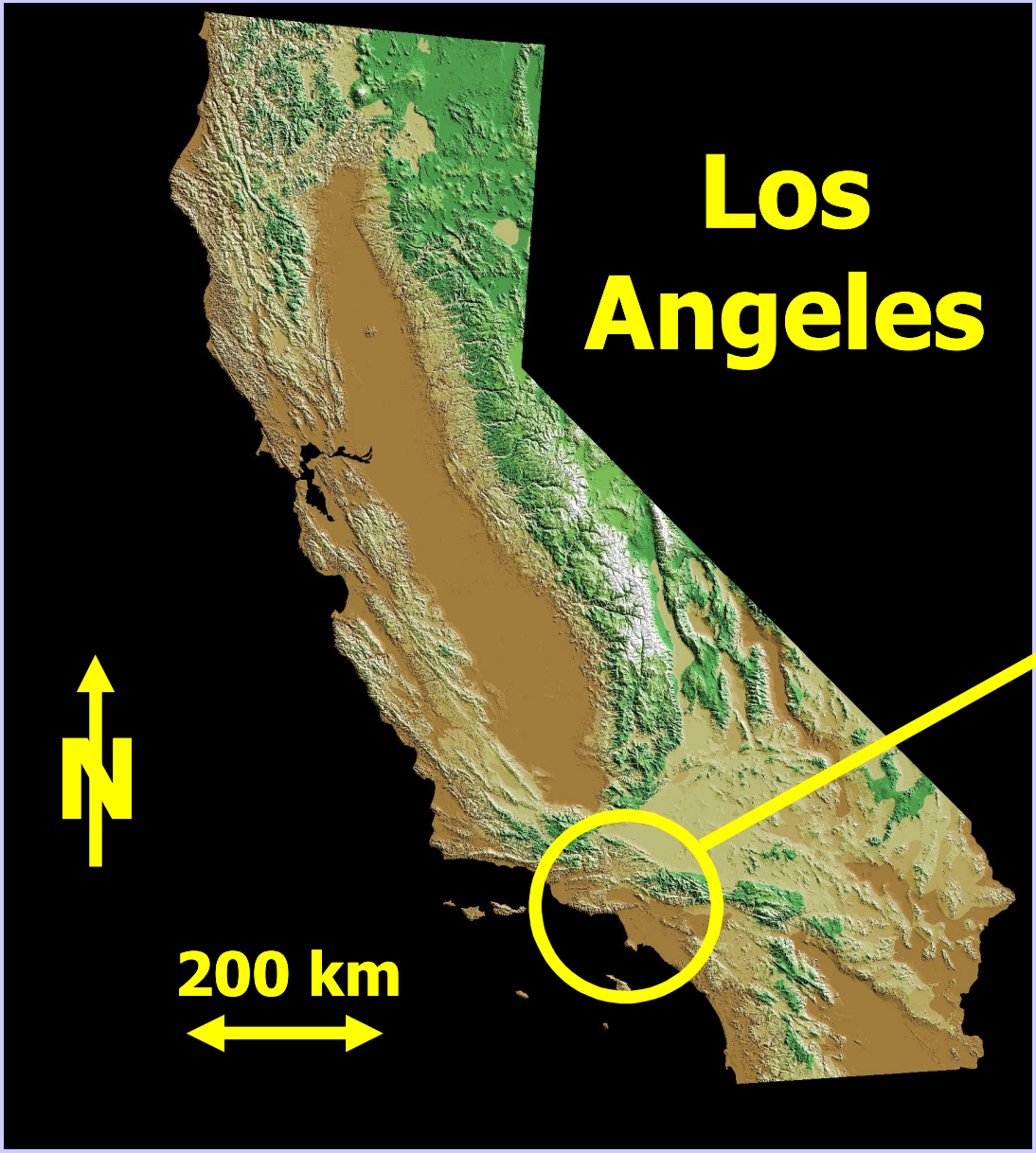


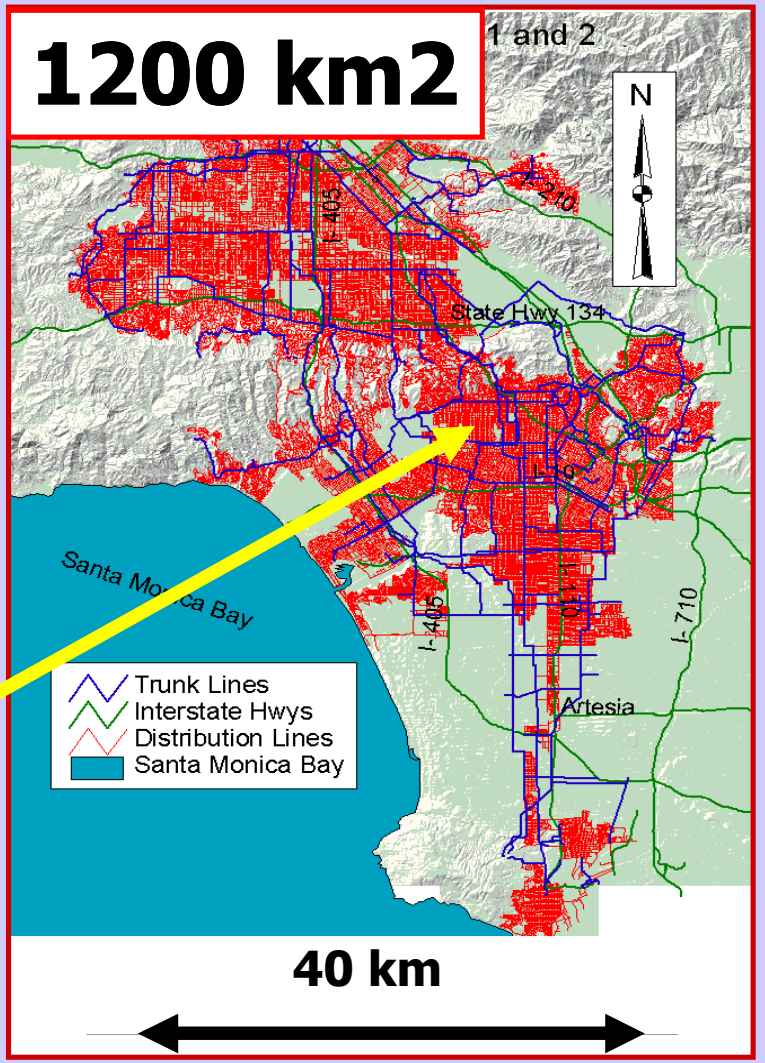
A STRONGER MORE RESILIENT NEW YORK

Mayor's Report, June, 2013



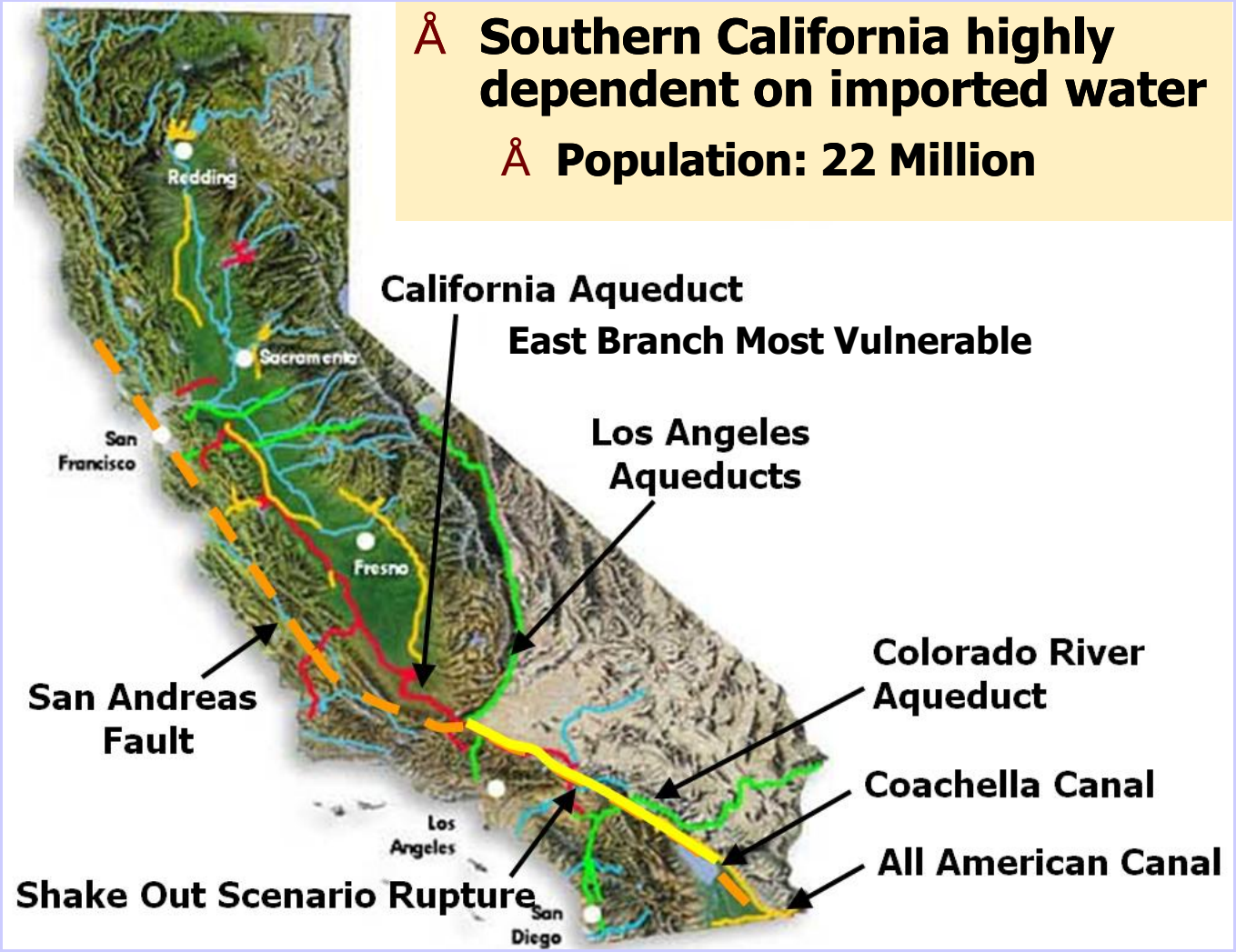
http://www.nyc.gov/html/sirr/html/report/report.shtml


Los Angeles
N
200 km


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

SOUTHERN CALIFORNIA WATER SUPPLY

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

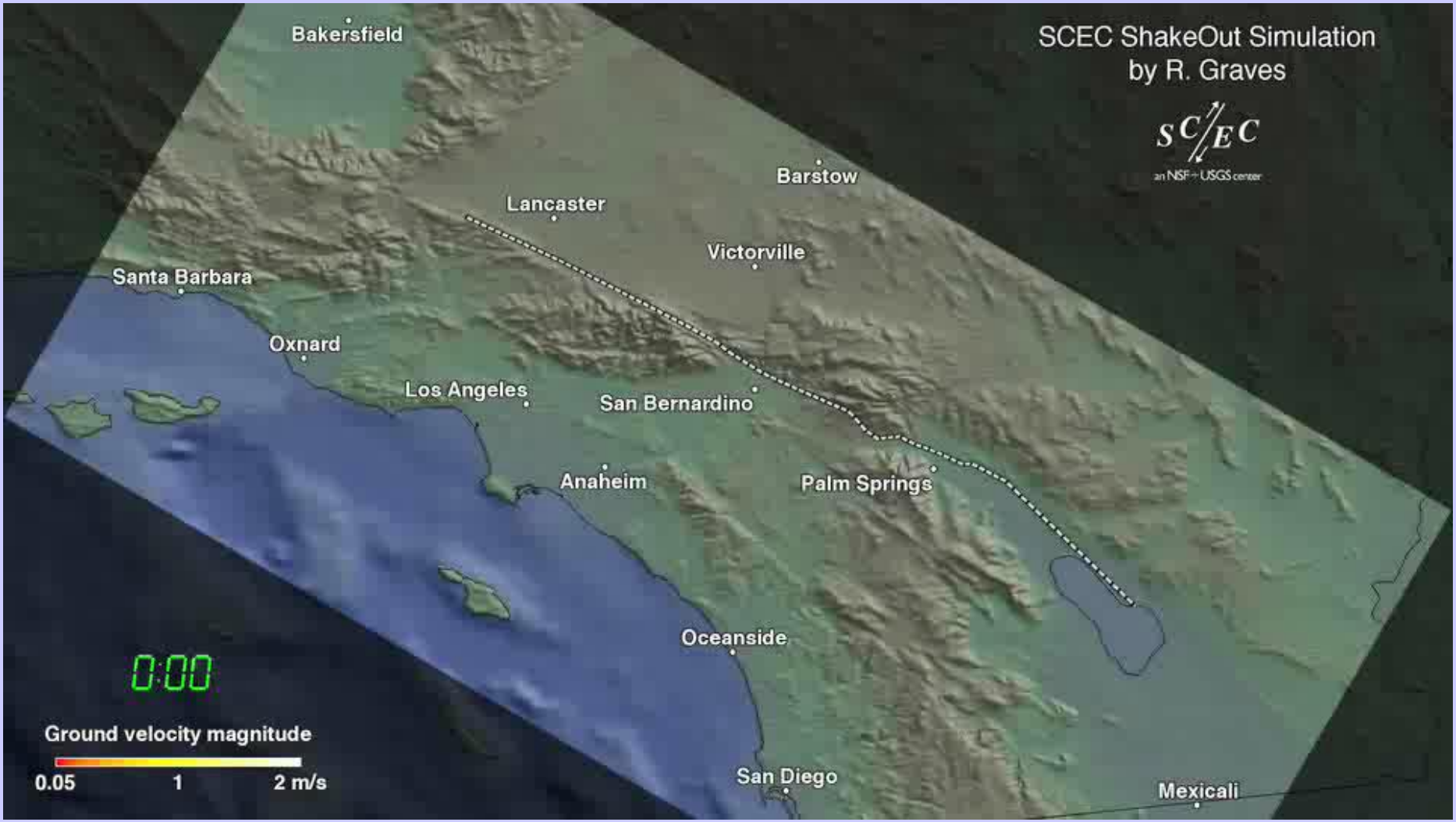


70% Imported Water:

- California Aqueduct
- Los Angeles Aqueducts
- Colorado River Aqueduct

30 % Ground Water

SHAKEOUT SCENARIO
7.8 Mw San Andreas Fault Earthquake



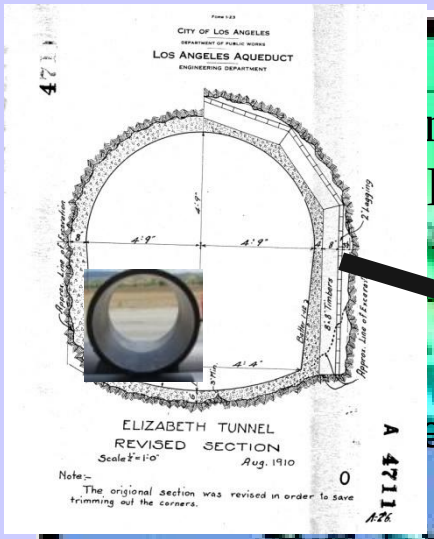
SOUTHERN CALIFORNIA WATER SUPPLY (after Davis, 2010)

- CA Aqueduct (CA DWR)
  - 49 billion m3/yr
  - Faulting Rupture in >15 places
- LA Aqueducts (LADWP)
  - 390 million m3/yr
  - Elizabeth Tunnel
- Colorado River Aqueduct (MWD)
  - 900 million m3/yr
  - Multiple fault ruptures & ~ 4 m uplift

LOS ANGELES AQUEDUCTS

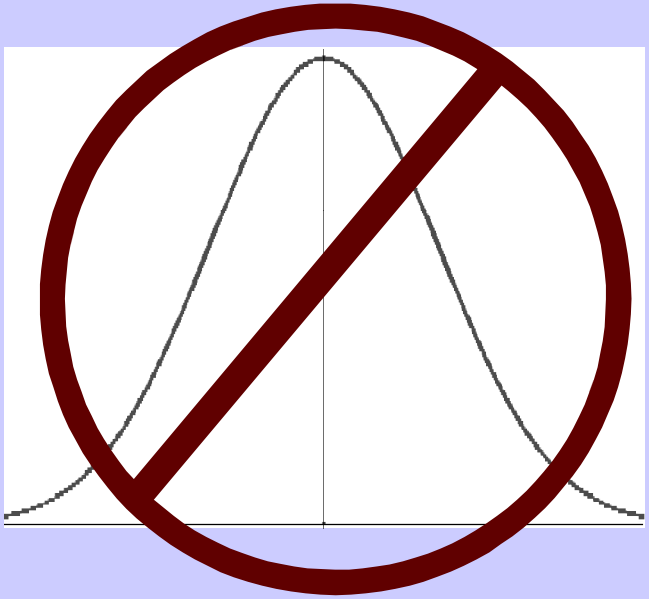
- **3.3m Horizontal Fault Displacement**
- **2.9m Wide Elizabeth Tunnel**
  - **Cuts off tunnel**

LA WATER SUPPLY CROSSES SAN ANDREAS FAULT



OBSERVATIONS

- **Anything But Normal**
  - **Target nuclear failure probability ≈ 1x 10-6/yr**
  - **5 major nuclear releases in 14,000 reactor years = 3x 10-4/yr**
  - **Probability tails control**



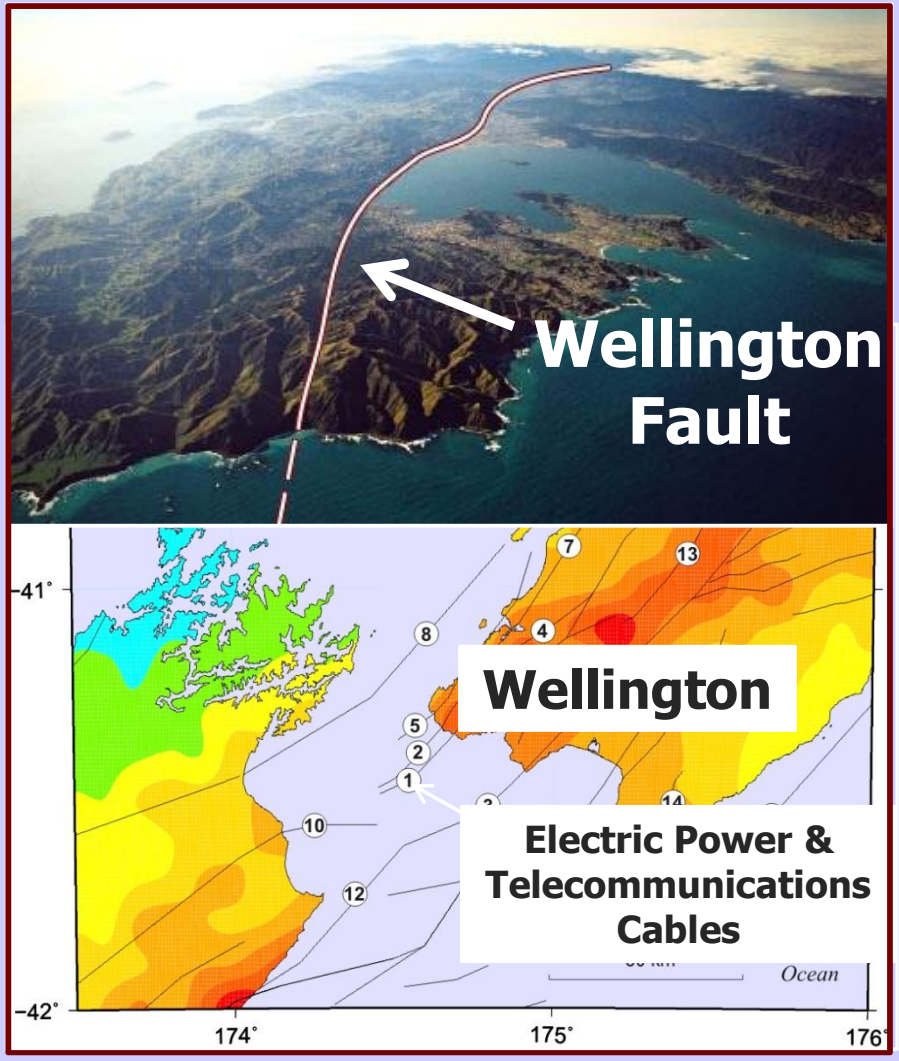
- **Problems Compounded by Institutional Constraints, Politics, Lack of Perspective, & Dysfunction**

NEW NORMAL

- Too Big To Fail
  - Reassess Risk Related to Critical Infrastructure
  - Reassess & Identify *Critical* Infrastructure
- Local Coalitions
  - Coalitions to Protect Critical Infrastructure Too Big to Fail
- Punctuated Resilience

WELLINGTON SEISMIC RISK

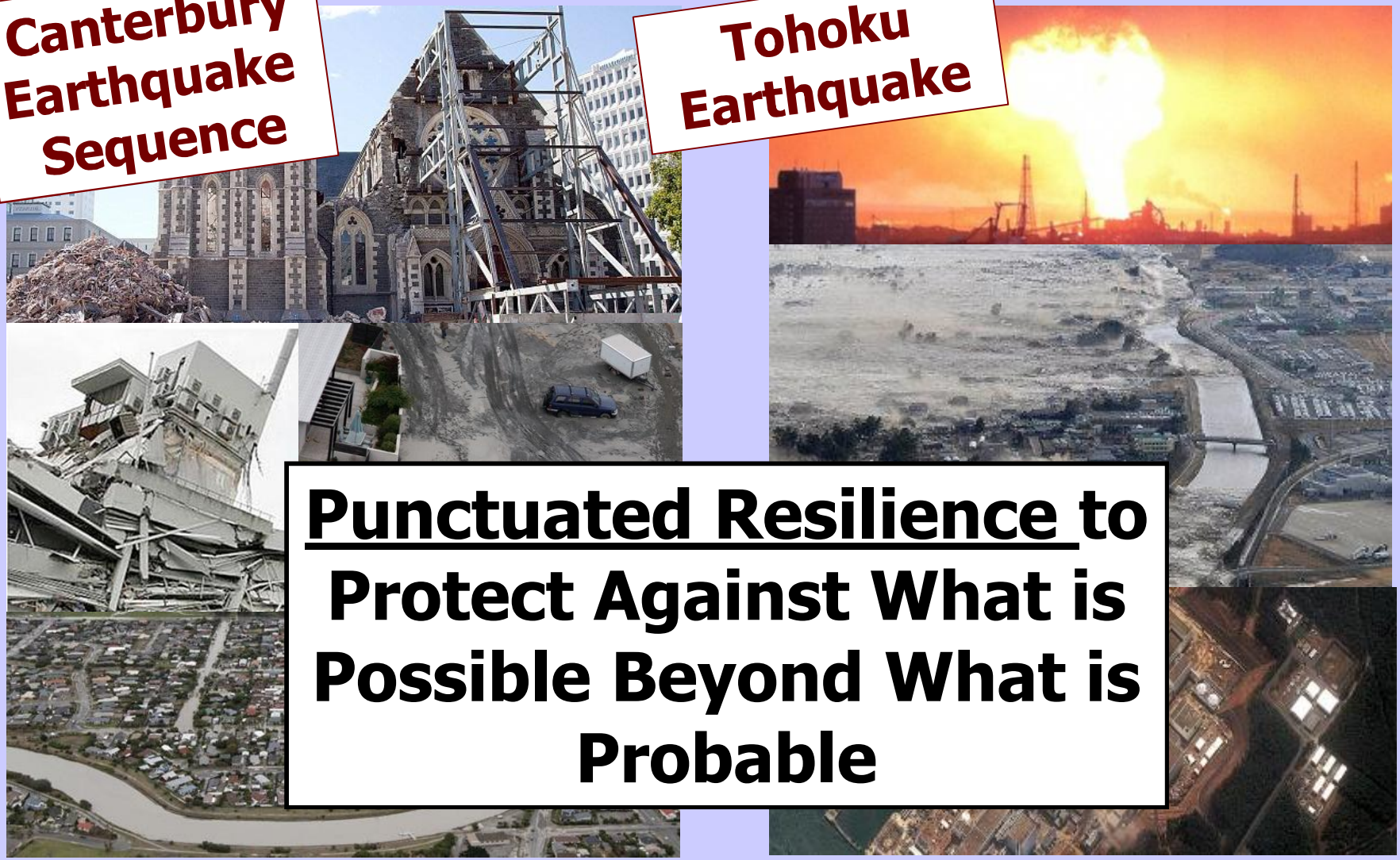
- **Urgent Need to Apply Christchurch Lessons**
  - **Harbor Facilities**
  - **Water Supply**
  - **Fire Hazards**
  - **Major Highways**
  - **Electric Power System**
  - **Telecommunications**
  - **National Government**



NEW NORMAL FOR NATURAL DISASTERS

Canterbury Earthquake Sequence

Tohoku Earthquake



Punctuated Resilience to Protect Against What is Possible Beyond What is Probable