Pipe Rehabilitation for a Seismic Resilient System

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Large Pressure Pipe Structural Rehabilitation Conference

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Contents

- Resilient Water Systems
- Seismic Resilient Pipe Network (SRPN)
- Role of Pipe Rehabilitation in a SRPN
- Resilience application

Note: Many concepts presented apply to multiple hazards and also to small diameter pipes.

Resilient Water Systems

- Resilience - what is it and how does it apply to water infrastructure?
- Resilience Definition (there are many – this one is from the white House)

  "The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents." (PPD21)

- In general, dealing with **Community Resilience** to hazard strikes (e.g. earthquake)
- Water Systems provide critical services to the communities within which they operate

Resilient Water Systems

- So then, what is a seismic resilient water system? Here is a working definition:

*“**A seismic resilient water system is designed and constructed to accommodate earthquake damage with ability to continue providing services or limit service outage times tolerable for community recovery efforts**.”*

Water System Resilience

- When considering existing water infrastructure, some key aspects need to be considered:

- We cannot prevent damage! This is too costly & takes too long
- We must modify the system to provide water to the community when they need it. Which requires knowledge of:
  - Water needs over the recovery time
  - Seismic hazards and potential impacts
- New Paradigm of **Infrastructure Resilience Management**
- **Resilience Management requires new tools** to handle large and complicated geographically distributed systems exposed to many different seismic hazards posing different risks to the loss of services and ability to restore them following an earthquake
  - Working with engineers, researchers and scientists to develop the tools

Application to LADWP System

Concepts for developing a seismic resilient pipe network will be described relative to the resilience program being implemented for LADWP Water System (mainly a built-out system)

Also applicable to new system development and expansion, but this is beyond the workshop scope

LADWP OVERVIEW

- Largest Municipal Utility in USA
- Founded 1902
- Serves 4-million people
    - 712,000 water service connections
- 1214-square kilometer (465 sq mile) service area
- 678 billion liter (179 billion gallon) annual water sales
- Receives water from:
    - 4 aqueducts
    - Local wells
- LADWP owns and operates the water and power systems

WATER SUBSYSTEMS

Water System is made up of multiple subsystems having their own characteristics

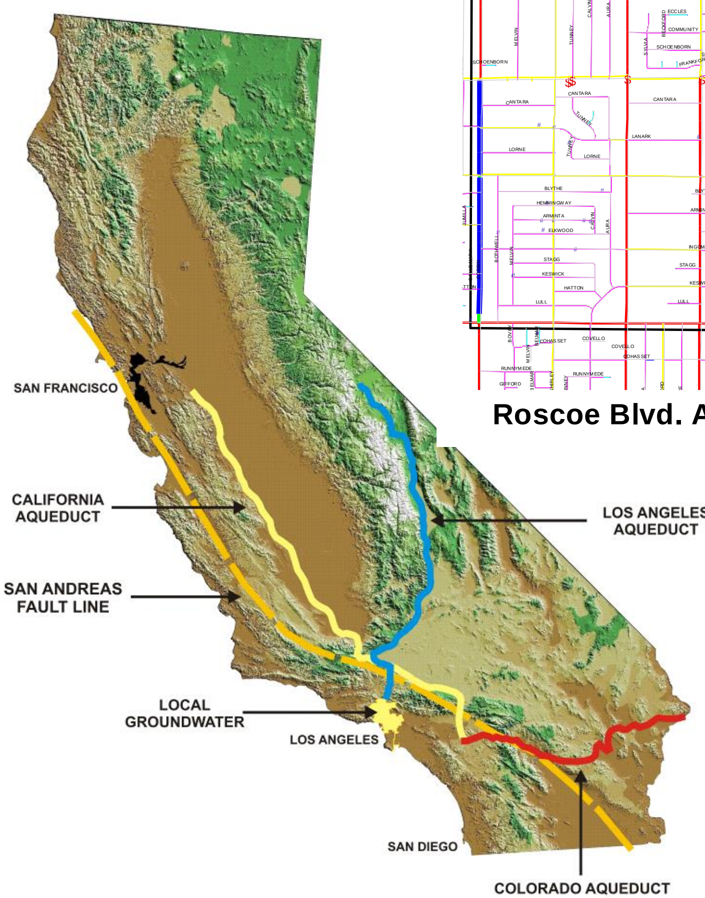
Large diameter pipes generally apply to these subsystems

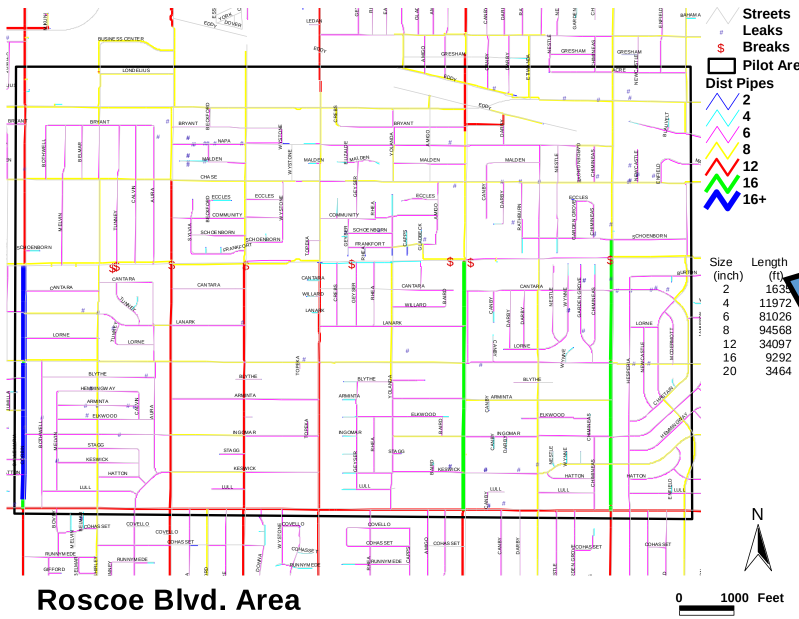
Subsystems	**Description**
Raw Water Supply Systems	Systems providing raw water for local storage or treatment including local catchment, groundwater, rivers, natural and manmade lakes and reservoirs, aqueducts.
Treatment Systems	Systems for treating and disinfecting water to make it potable for safe use by customers.
Transmission Systems	Systems for conveying raw or treated water. Raw water transmission systems convey water from a local supply or storage source to a treatment point. Treated water transmission systems, often referred to as trunk line systems, convey water from a treatment or potable storage point to a distribution area.
Distribution Systems	Networks for distributing water to domestic, commercial, business, industrial, and other customers.

Each subsystem is critical to providing services

Los Angeles Department of Water and Power

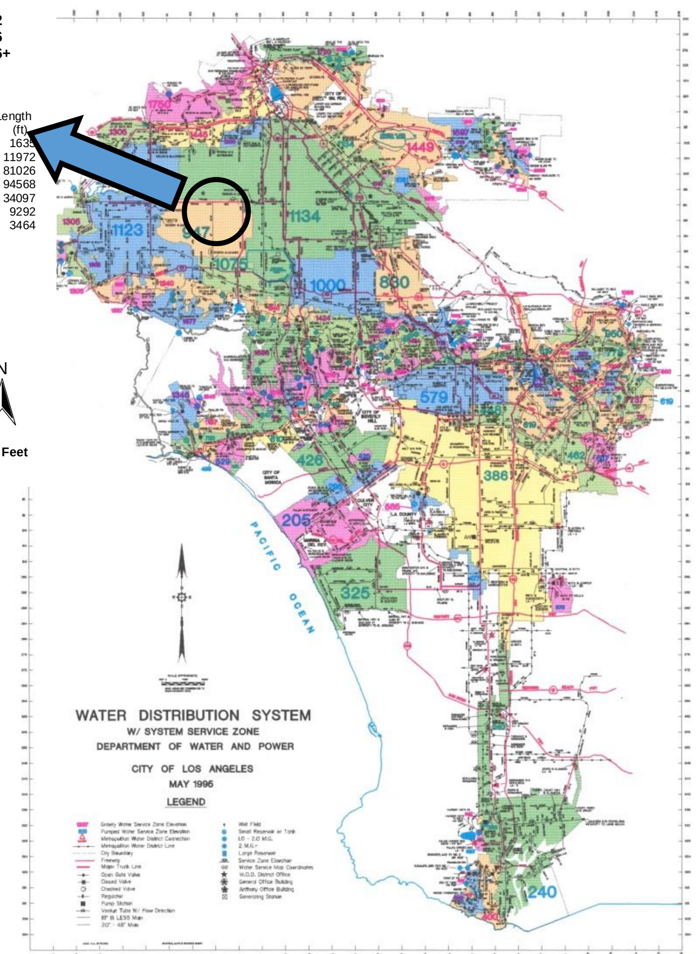
Supply





Distribution

Transmission



Seismic Resilient Pipe Network

- **Designed and constructed to accommodate damage with ability to continue providing water or limit water outage times tolerable to community recovery efforts**
- Responsibility to Community Resilience
  - Provide water to critical areas when needed by community for disaster recovery
  - Establish performance criteria
- Account for all significant seismic hazards

WATER SYSTEM SERVICE CATEGORIES

Water System resilience is dependent upon the amount of service losses suffered and time to reestablish

Service Categories	Description
Water Delivery	Able to distribute water to customers, but the water delivered may not meet water quality standards (requires water purification notice), pre-disaster volumes (requires water rationing), fire flow requirements (impacting fire fighting capabilities), or pre-disaster functionality (inhibiting system operations).
Quality	Water to customers meets health standards (water purification notices removed). This includes minimum pressure requirements.
Quantity	Water flow to customers meets pre-event volumes (water rationing removed).
Fire Protection	Able to provide pressure and flow of suitable magnitude and duration to fight fires.
Functionality	The system functions are performed at pre-event reliability, including pressure (operational constraints resulting from the disaster have been removed/resolved).

Does water come out of tap?

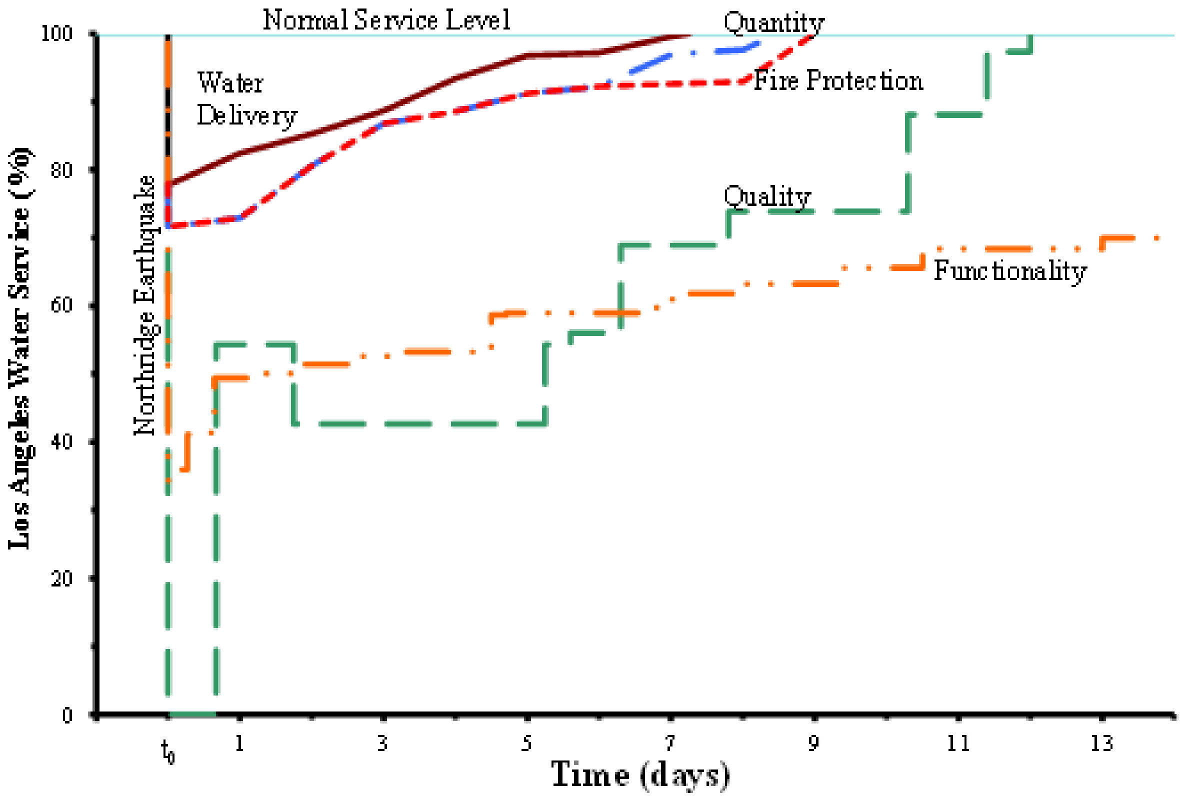
Is it safe to Drink?

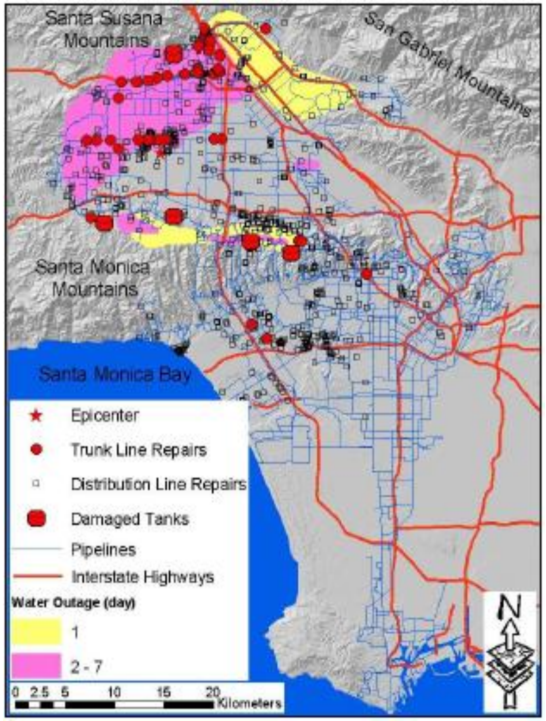
Can you get the amount you need?

Does Fire Dept. get what they need?

Is the water system in working order?

1994 NORTHRIDGE EARTHQUAKE, L.A. EXAMPLE WATER RESTORATIONS



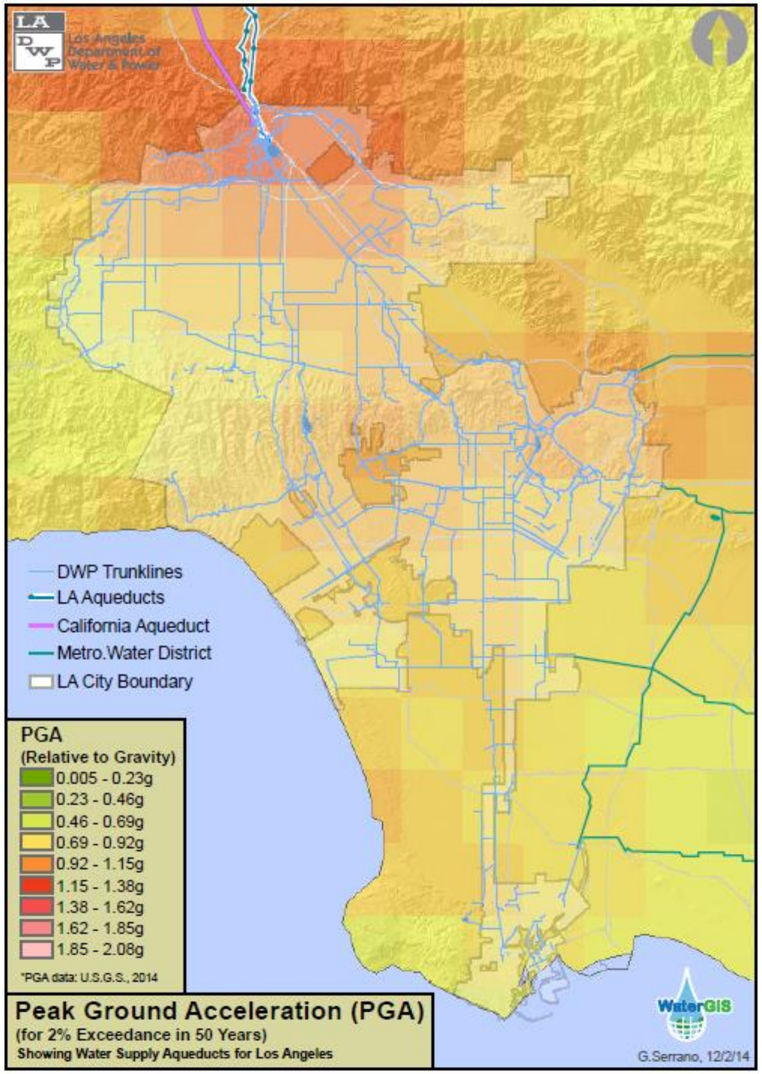


Strategies for Improving Network Resilience

- Identify the earthquake hazards (PGD most critical)
- Analyze component fragilities: reduce fragility with
  - Good design detailing
  - Good maintenance
  - Robustness, Redundancies, and isolation
- Assess potential damages to subsystems performance
- Compare to performance objectives
- Identify consequences of reduced services
- Recognize material costs are small amount of project costs – use life-cycle costs when assessing robust pipes
- Develop guidelines, policies and plans for consistent incremental improvements (**cannot accomplish everything in short-term**)

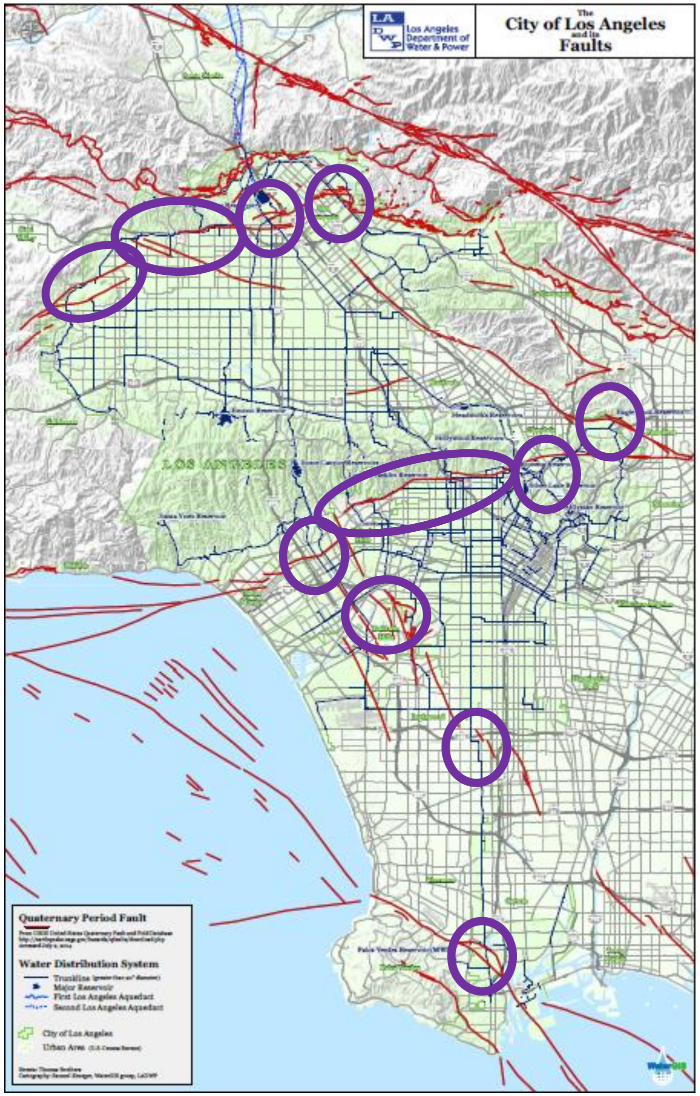
Seismic Hazards

- Ground Shaking
- Surface Fault Rupture
- Liquefaction
- Landslides
- Other ground failures



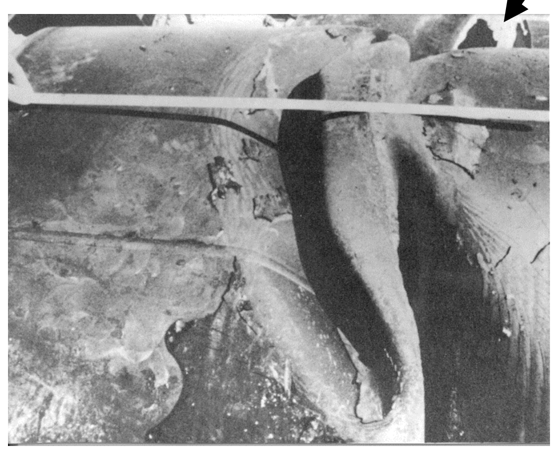
Earthquake Faults

- 20+ active surface faults in LA
- Numerous additional blind faults
- Several areas of significant threat to transmission pipe
- All threaten distribution pipe

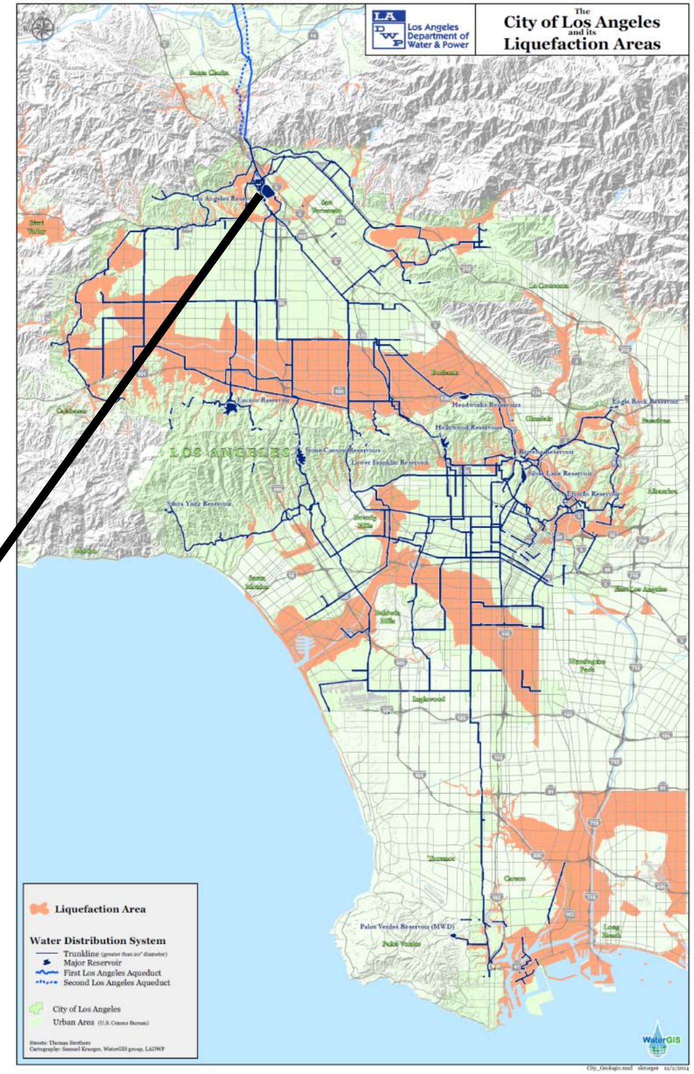


Liquefaction Potential

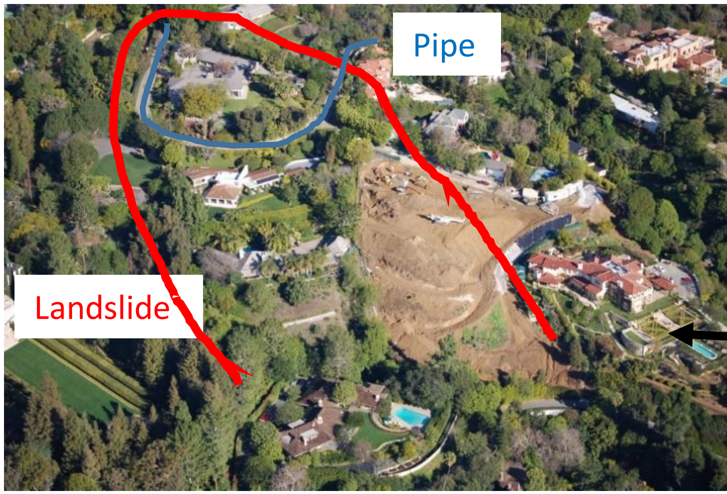
- Large areas of LA have potential for soil liquefaction during shaking
- Liquefaction can cause large ground movements and severe pipe damage
- Combination of ground shaking, surface fault rupture, and liquefaction can result in significant LA Water System disruptions.



Granada Trunk Line,
Van Norman Complex -
1971

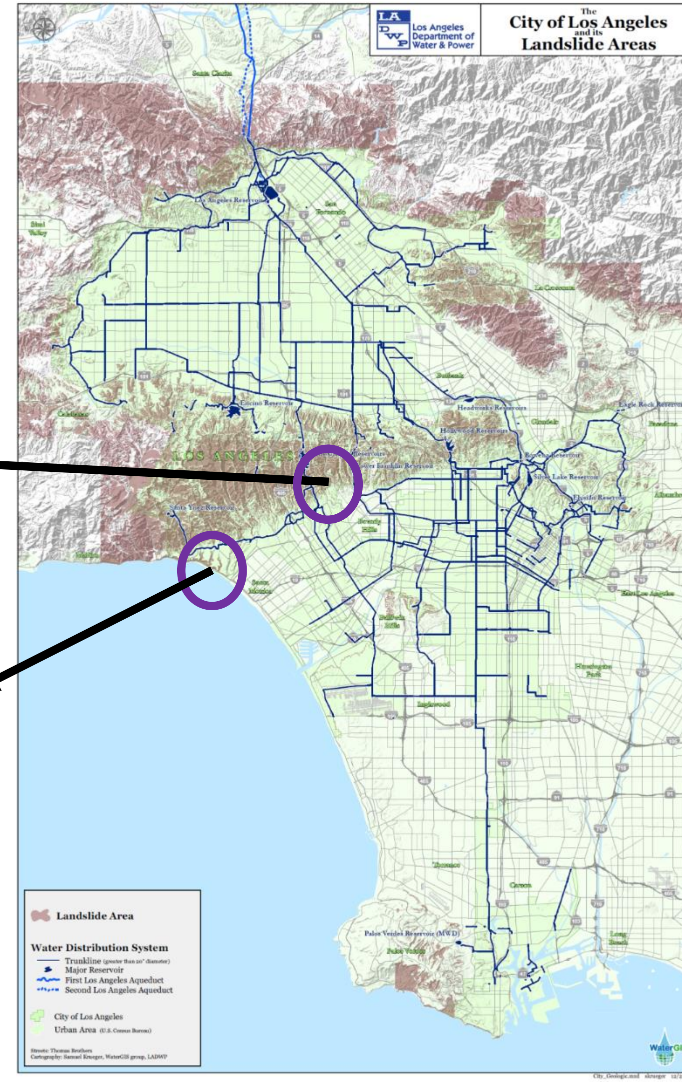


Landslides



Nimes Road Landslide – Bel Air

Asilomar Landslide - Pacific Palisades



Seismic Resilient Pipe Network

- Long term goal is to replace all pipes in the City with seismic resistant pipes
- Begin with most strategic locations
- Develop funding/implementation plan

Examples of Kubota Earthquake Resistant Ductile Iron Pipe. Provide resilience for multiple hazards

Proposed Outline for Creating Seismic Resilient Pipe Network (SRPN)

- Identify pipe materials and joint types that provide adequate seismic resistance
  - Based on expected ground motions and ground failure
  - Applies to pipe replacement and rehabilitation
- Identify critical/important pipes
  - Risk based
  - Community resilience
  - Classify pipes based on their seismic importance (e.g., see ALA, 2005).
- Replace critical pipes based on seismic risk and in collaboration with the Asset Management and Pipe Replacement Programs
- When funding and resources available – add specific seismic pipe projects to accelerate SRPN development

Proposed Outline for Creating Seismic Resilient Pipe Network (SRPN)

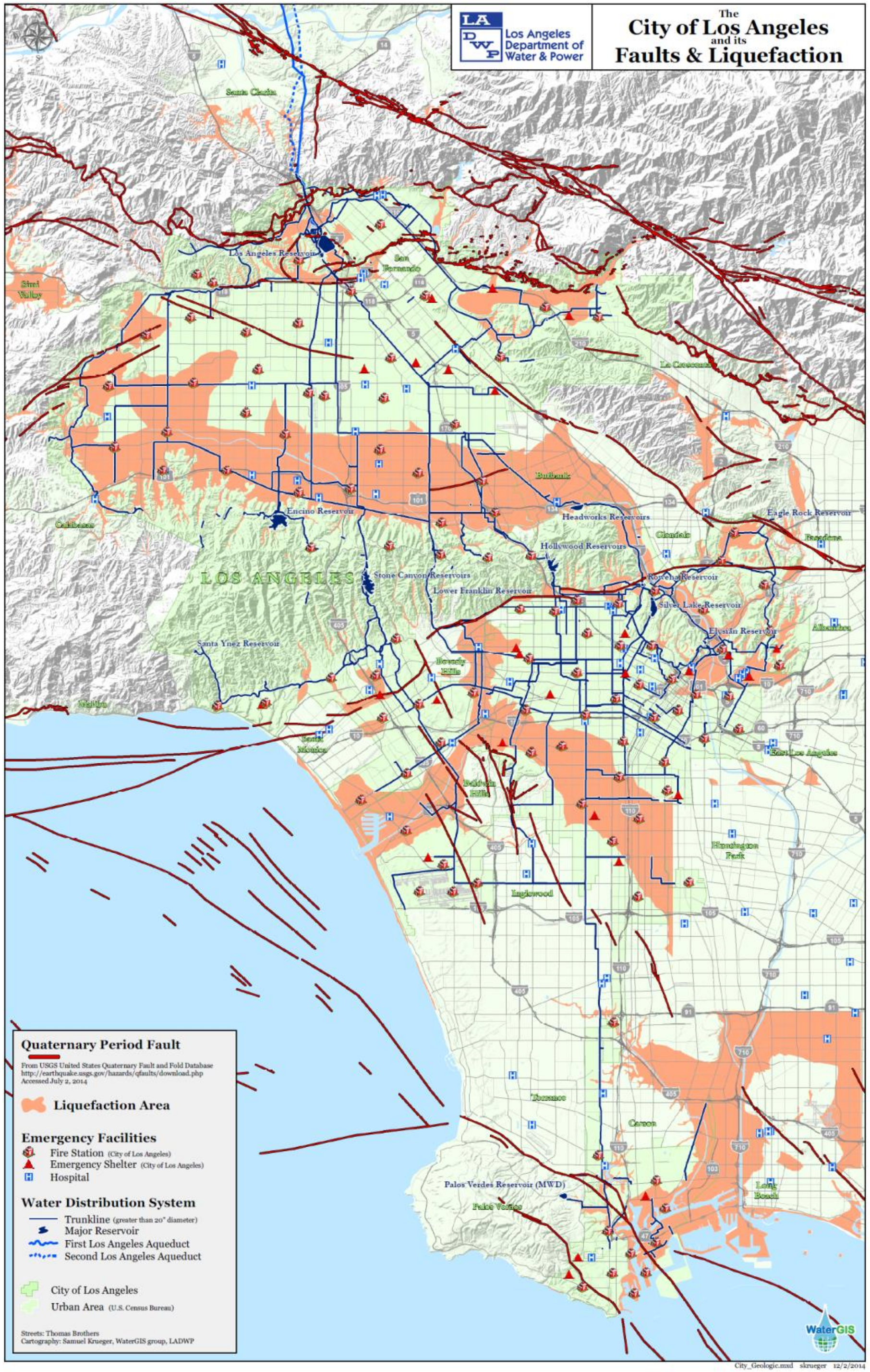
- Since entire network cannot be cost-effectively replaced with seismic resistant pipe in the short-term:
  - Recognize that earthquake damages and water service outages will occur
  - Develop plan for restoring all post-earthquake water services within an acceptable timeframe (determine with community input)
  - Ensure water service restorations achieve community resilience needs (i.e., fire fighting, critical facilities)
- Develop long-term network improvement program (e.g. 25 to 50 years – or more)
  - Entire transmission and distribution network cannot be improved in the short-term (i.e. 5 to 10 years)

Proposed Outline for Creating Seismic Resilient Pipe Network (SRPN)

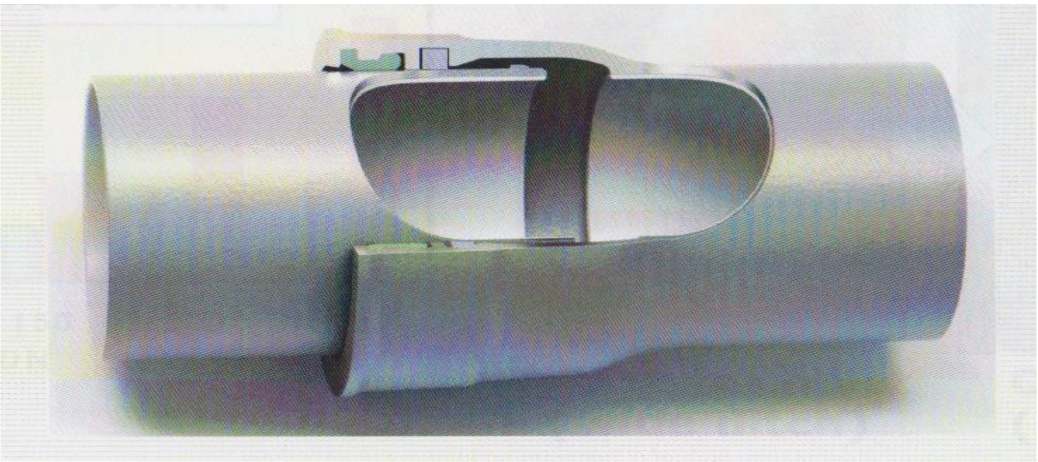
- Prepare guidelines to aid in developing consistent seismic improvements by many different people over long timeframes
  - Use earthquake experts to prepare maps, material lists, related tools, etc. to aid asset managers and distribution engineers in incorporating long-term seismic improvements
- Using current network, develop layout for long-term seismic improvement build-out that includes:
  - Seismic hazards
  - Pipe classification
  - Layout dimensions consistent with Fire Department equipment capabilities to relay water

Critical Facilities

- Goal: Prevent earthquake hazards from cutting off water to facilities critical for community recovery
- Need resilient back-bone network capable of withstanding damage so water can be provided soon after earthquake
  - Hospitals
  - Emergency Shelters
  - Firefighting
  - Etc.

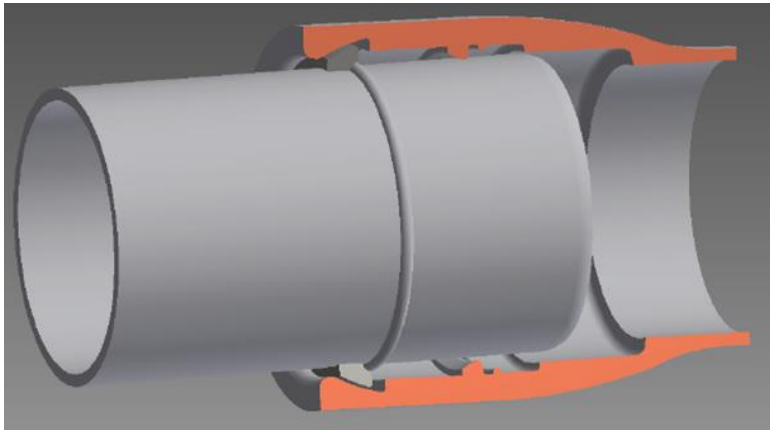


Pipe Materials - Future Opportunities



Kubota Earthquake Resistant Ductile Iron Pipe

HDPE AWWA C906



US Pipe TR-Extreme Ductile Iron Pipe

Molecularly Oriented PVC
AWWA C909

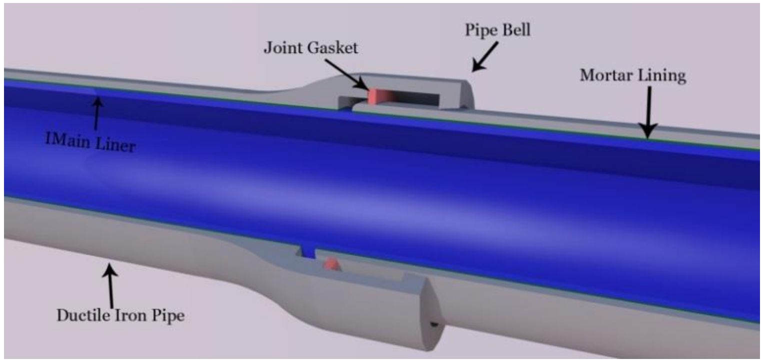
Pipe Rehabilitation Opportunities

- Several pipe materials and joint-types provide opportunities for helping to develop a seismic resilient pipe network
- Each to be evaluated and selected based on site conditions and applicability to different water system infrastructure [no specific endorsement given to any product]
- Some possible rehabilitation methods and materials are described here

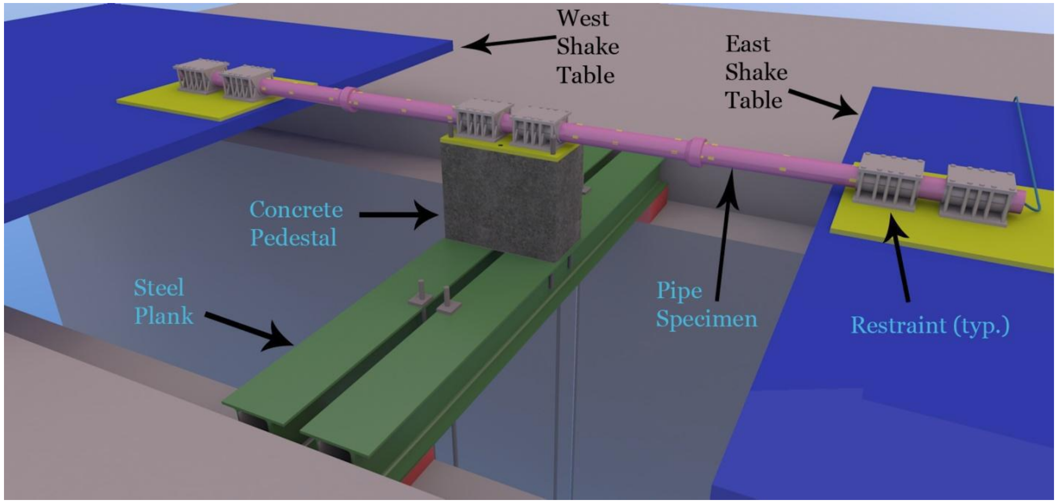
Fiber wrap

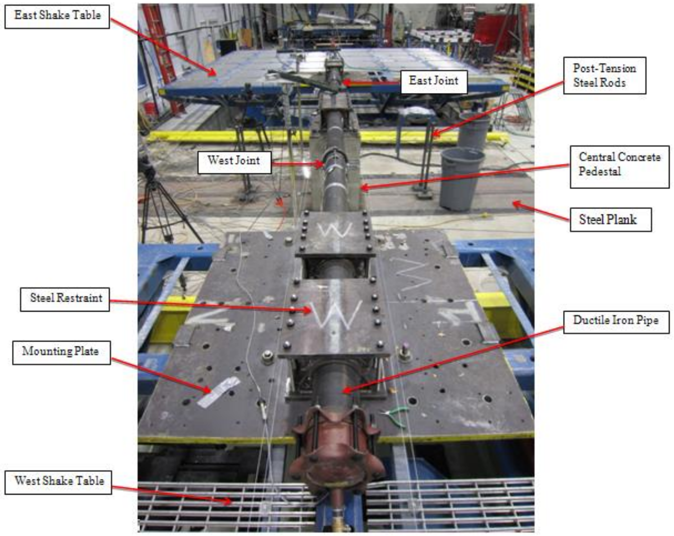
- Application to welded steel bell and spigot joints
- Tested at Cornell University
  - Wrapped by Fyfe
- Prevents buckling of bell under large compression loads

In-Situ Linings



- In-Situ composite linings
  - Help bridge failures of base materials and hold pressure
- Tested at University at Buffalo – under pressure
  - InsituForm Technologies (Chesterfield Mo.)
  - Others have potential application (need testing)





Figures courtesy A. Filiatrault, University at Buffalo

Polyethylene Pipes (PE pipe)

- PE pipe has shown capability of withstanding large ground movements
  - HDPE Testing at Cornell University

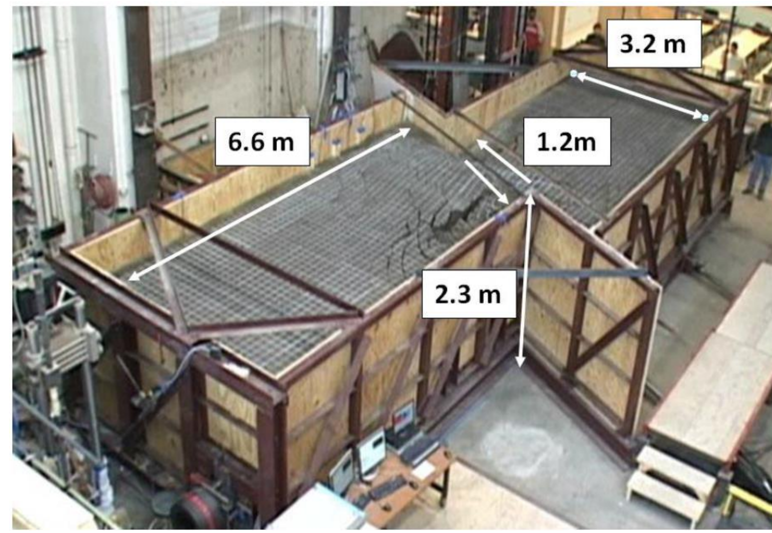
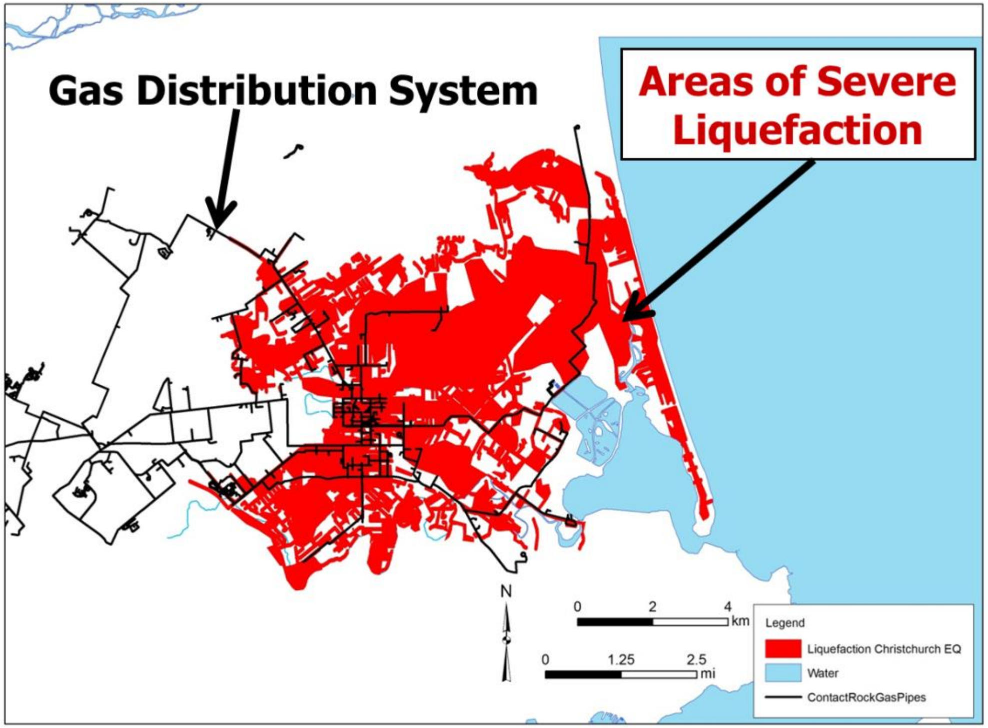
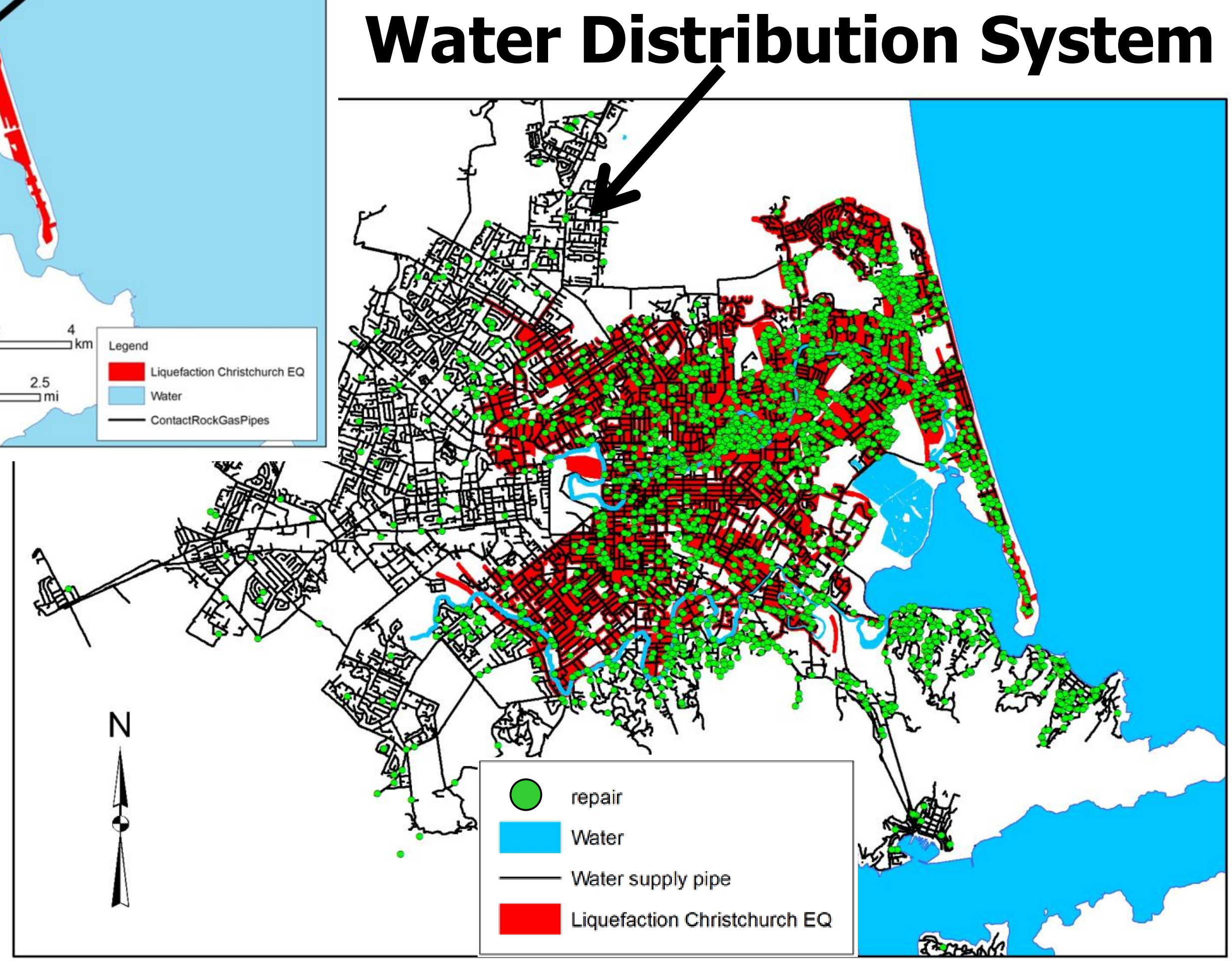


Figure courtesy T. O'Rourke, Cornell University

  - MDPE and HDPE have successful seismic application in Christchurch, New Zealand
  - **Application requires proper design and construction, with firm understanding of PE pipe!**





Figures courtesy T. O'Rourke, Cornell University

Christchurch, New Zealand

PE PIPELINES AFTER 4 Sept 2010 EQ, Christchurch, NZ installed where severe liquefaction induced damages occurred

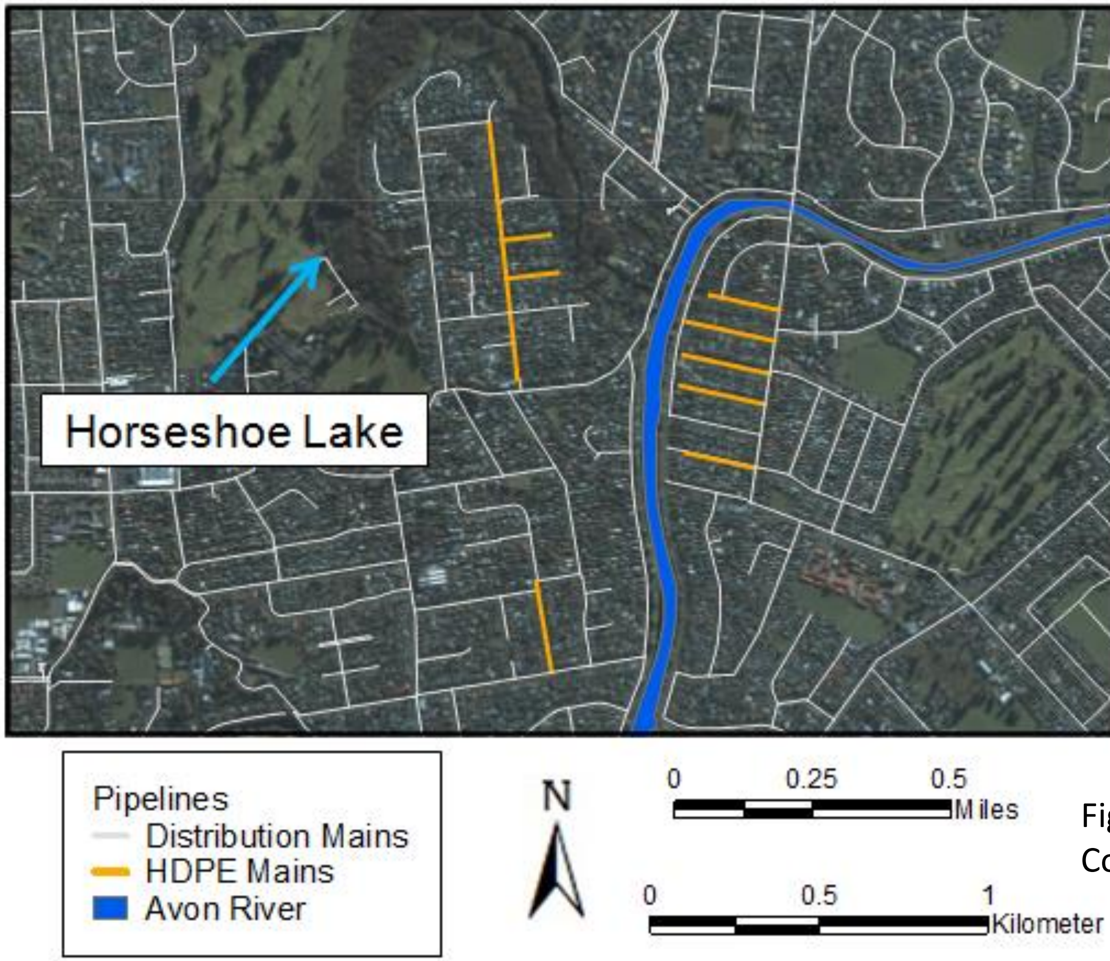


Figure courtesy T. O'Rourke, Cornell University

NO REPORTED PE DAMAGE after 3 more earthquakes causing large liquefaction-induced lateral spreading

Ductile Iron

- Several companies starting to supply seismic resilient DI pipe in the USA
    - Kubota Corp
        - Small and large diameter
        - Pipe-in-Pipe capability useful for rehabilitation
        - 40-years experience, numerous earthquakes
    - US Pipe
        - Small diameter only at present
        - ~1 year experience, no earthquakes
    - American Pipe
        - Small diameter only at present
        - No experience

Kubota Earthquake Resistant Ductile Iron Pipe

- **No Damage or Leaks** after 40-years of use
- Experienced many large Japanese earthquakes
- Subjected to several meters of permanent ground deformation

Figure courtesy Kubota Corp.

Current Lineup of ERDIP

Joint	75～400 [3 ~16"]	500～1000 [20 ~ 40"]	1100～2600 [44 ~104"]	Type
GENEX	Push on			
NS		Mechanical		
S			Mechanical	
US (For tunnel)		28"- Mechanical	Mechanical	

* Same Earthquake-Resistant Performance among these joints

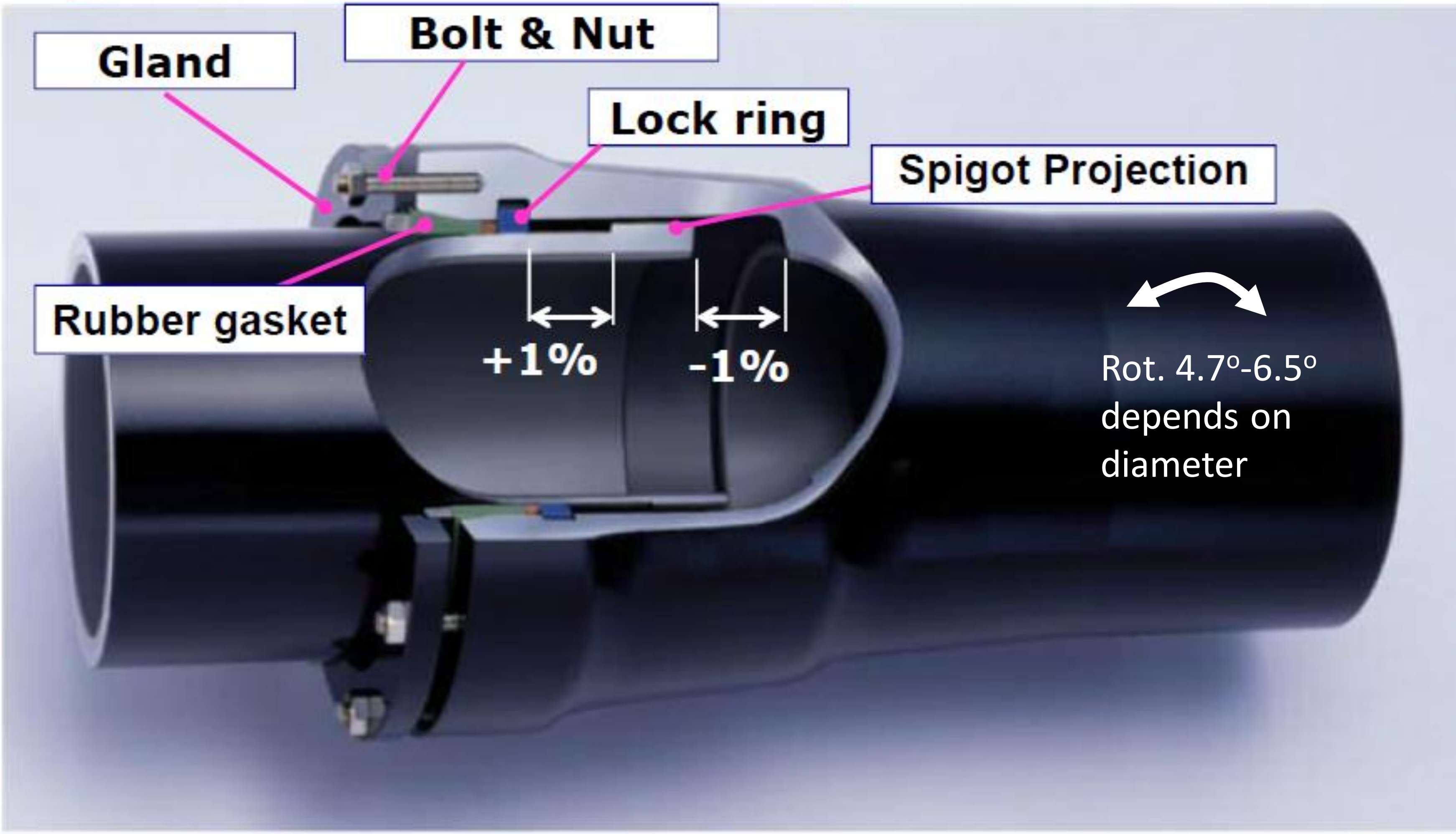
9

Rehab applicable

Large diameter

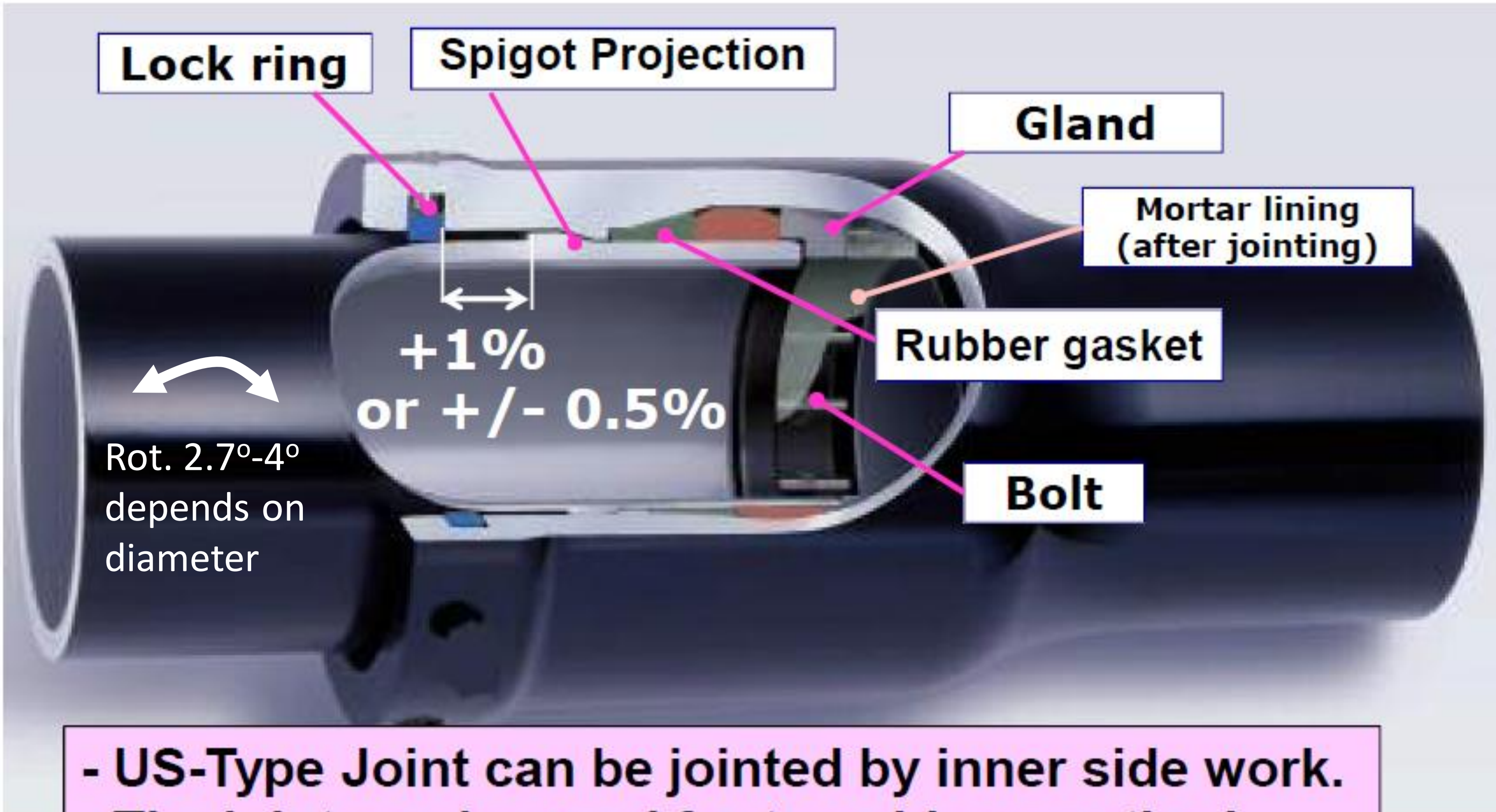
44"-104" S-type joint

Figure courtesy Kubota Corp.



44"~104" US type joint

Figure courtesy Kubota Corp.



- US-Type Joint can be jointed by inner side work.
- The joint can be used for trenchless method such as shilled tunnel method.

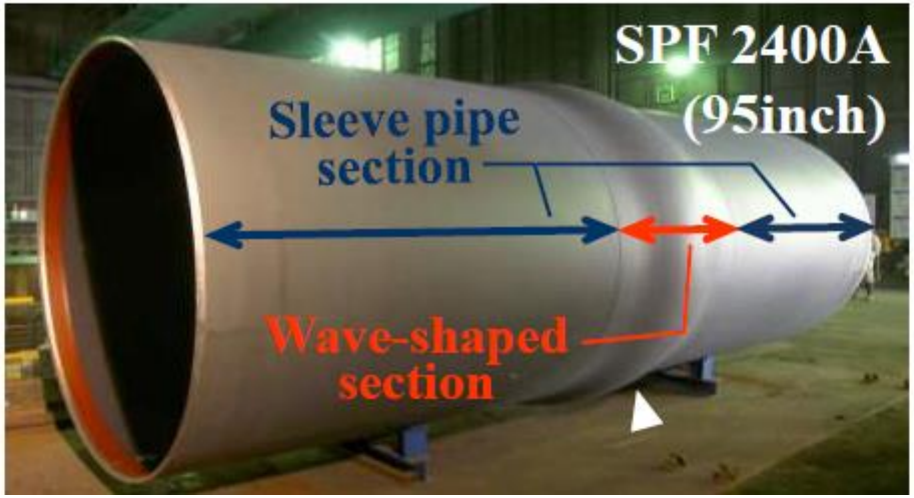
Steel

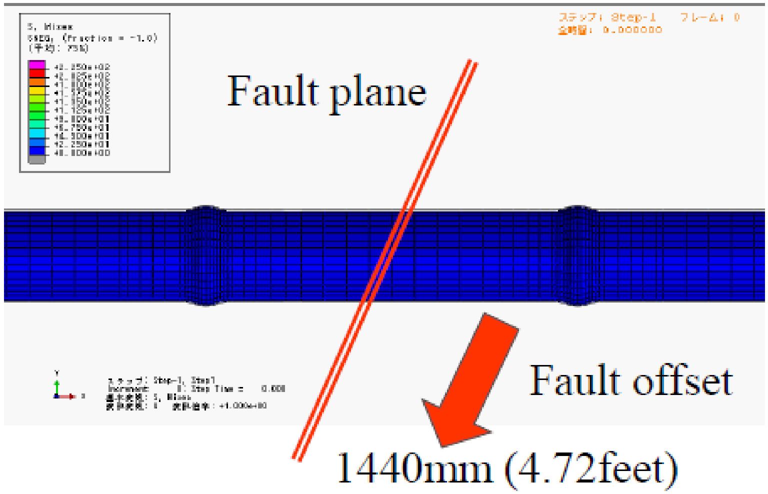
- Steel designed for earthquake hazards can provide seismic resilience
- Generally good seismic performance overall (lower fragility than most pipe materials)
- Steel lining technologies
  - Slip-line: loose fit or grout annular space
  - Collapsed Can

Figure courtesy MWDSC

Steel

- Steel Pipe for Crossing Faults (SPF)
- JFE Engineering Corporation
- Developed in Japan
- Tested at Kyoto University and planned tests at Cornell University
- Kobe Waterworks Bureau, Kobe, Japan, installed at fault crossing (1995 rupture zone)
- Existing steel pipe can be rehabilitated using SPF by inserting special designed sections at proper locations.
- Potentially useful at landslide margins.
- Need relatively well defined ground rupture





Figures courtesy JFE Engineering Corporation

Polyvinylchloride (PVC) Pipe

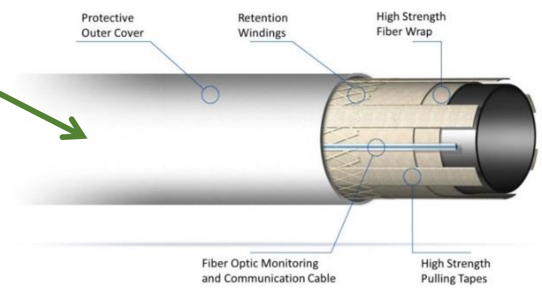
- Molecular Oriented PVC = PVCO
- Relatively new product, potential resilience application
- Highly ductile
- Joints can be restrained
- Tested at Cornell University

Figure courtesy T. O'Rourke, Cornell University

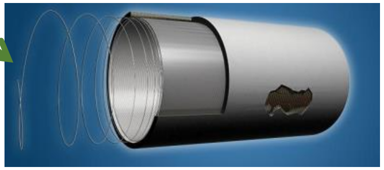
Hybrid Pipelines

- New hybrid pipes coming into water market
  - Many are outcomes of oil industry
- Potential for resilience application for specific conditions
- FlexSteel®

- Smart Pipe®



- StrongPIPE ®

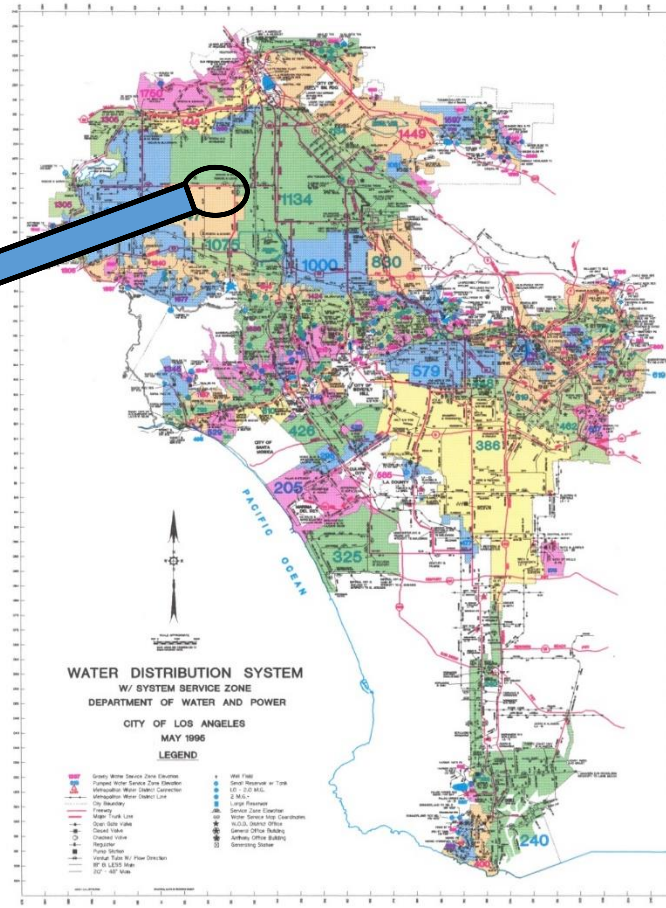


- Some not applicable for multiple connections forming grid-type network, or tapping

Example Resilience Application

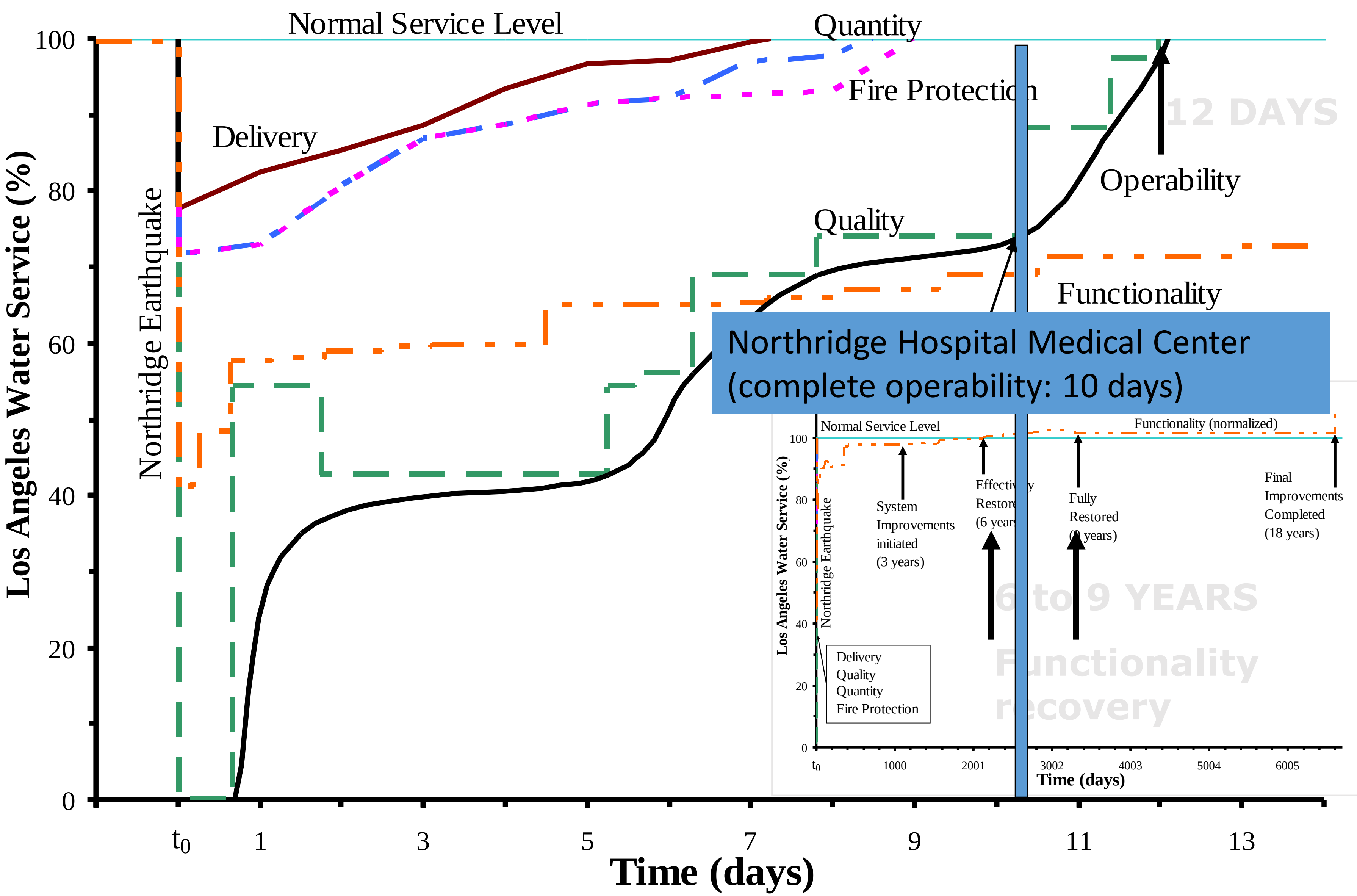
Seismic Resilience and Retrofit Strategy Example

Northridge Hospital Medical Center



- 9.3 km^2 (3.6 mi^2) area in San Fernando Valley
- Pipes damaged in 1994 Earthquake
- Ground failure area
- 72,000 m (236,054 ft) of distribution pipe
  - Diameters range from 51 to 510 mm (2” to 20”)
- Hospital
- Residential
- Commercial

OPERABILITY VS FUNCTIONALITY



QUANTIFYING SERVICES

- Services can be quantified by the ratio:

$$\frac{\text{number of customers with service after the earthquake}}{\text{number of customers having the service before the earthquake}}$$

- Calculation Methodology
  - Take area(s) where services are not being met
  - Count number of services (or people, businesses, etc) in area
  - Calculation is relatively independent of system layout and operations (except for Functionality)
- Functionality service estimates require full understanding of systemic capabilities
- Restoration curves are plots of this quantification over time

Quantifying Functional Services

$$S_f = \frac{m}{N} = \frac{1}{N}\sum_{i}^{\eta} m_i \frac{F_P F_R}{1+R}\bigg|_{equiv} = \frac{1}{N}\sum_{i}^{\eta} m_i E_i$$

F_p = Performance Factor ≥ 0 (related to operability)

F_R = Reliability Factor ≥ 0 (related to structural capacity)

R = Redundancy Factor

$\frac{m}{N}$ ⇨ $\frac{\text{number of customers with service after the earthquake}}{\text{number of customers having the service before the earthquake}}$

$$R_j = \frac{\sum Q_j}{Q_j} - 1 \qquad Q_j \leq \overline{Q}_i \qquad \sum R_j \geq 0$$

Q = Flow Rate through components and routes

Routes in parallel

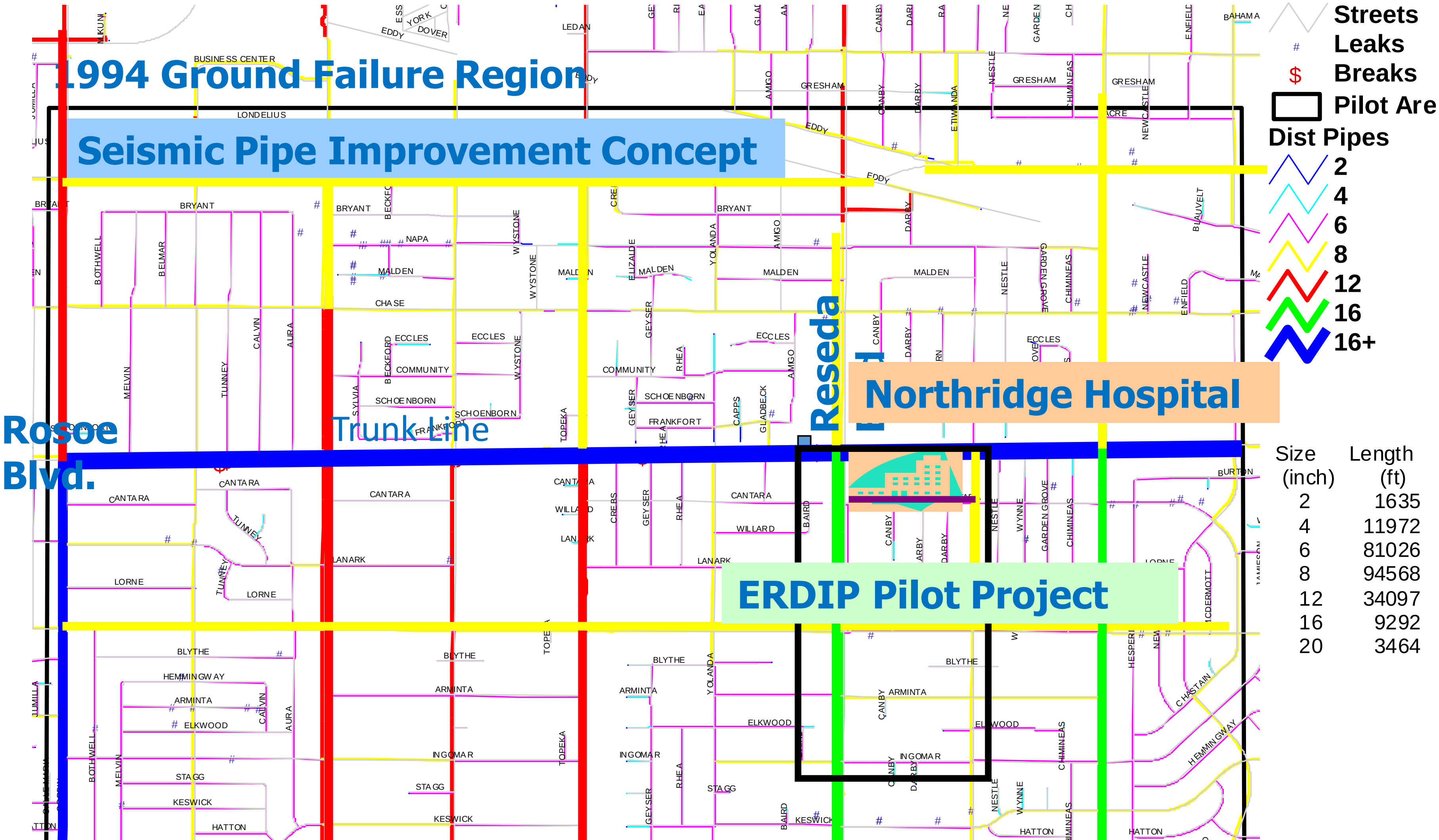
$$E_k = \prod \frac{F_{P_j} F_{R_j}}{1+R_k}$$

Routes in series

$$E_k = \sum \frac{\prod_j F_{P_{jl}} F_{R_{jl}}}{1+R_l}$$

Equations shown only to express methodology

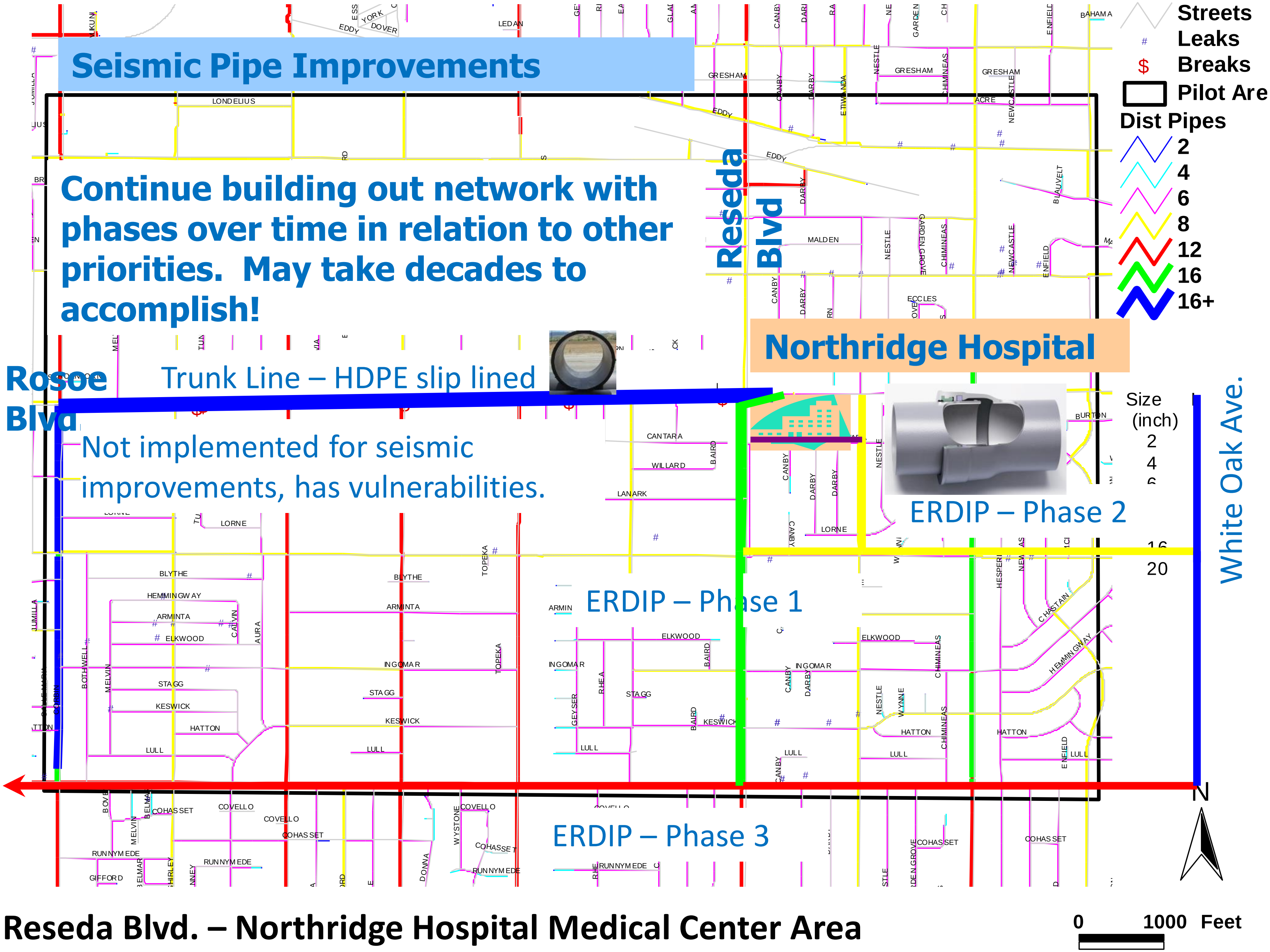
CASE STUDY:
Los Angeles Water System
1994 Northridge Earthquake



Size (inch)	Length (ft)
2	1635
4	11972
6	81026
8	94568
12	34097
16	9292
20	3464

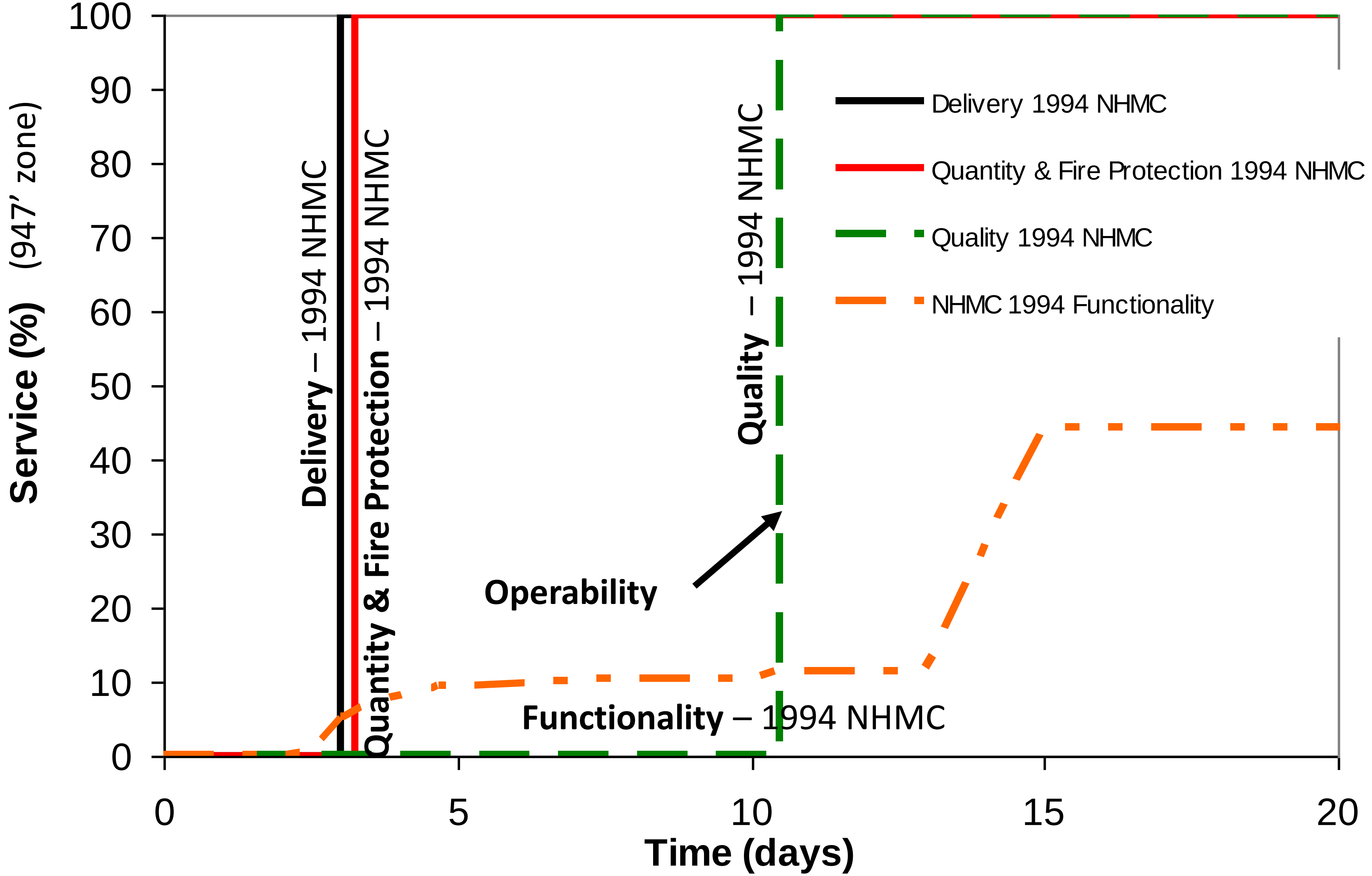
Not all 1994 leaks would have been prevented, but regional reliability increased and damaged can be isolated (with installed valves) to limit service outages

Roscoe Blvd. Area



Reseda Blvd. – Northridge Hospital Medical Center Area

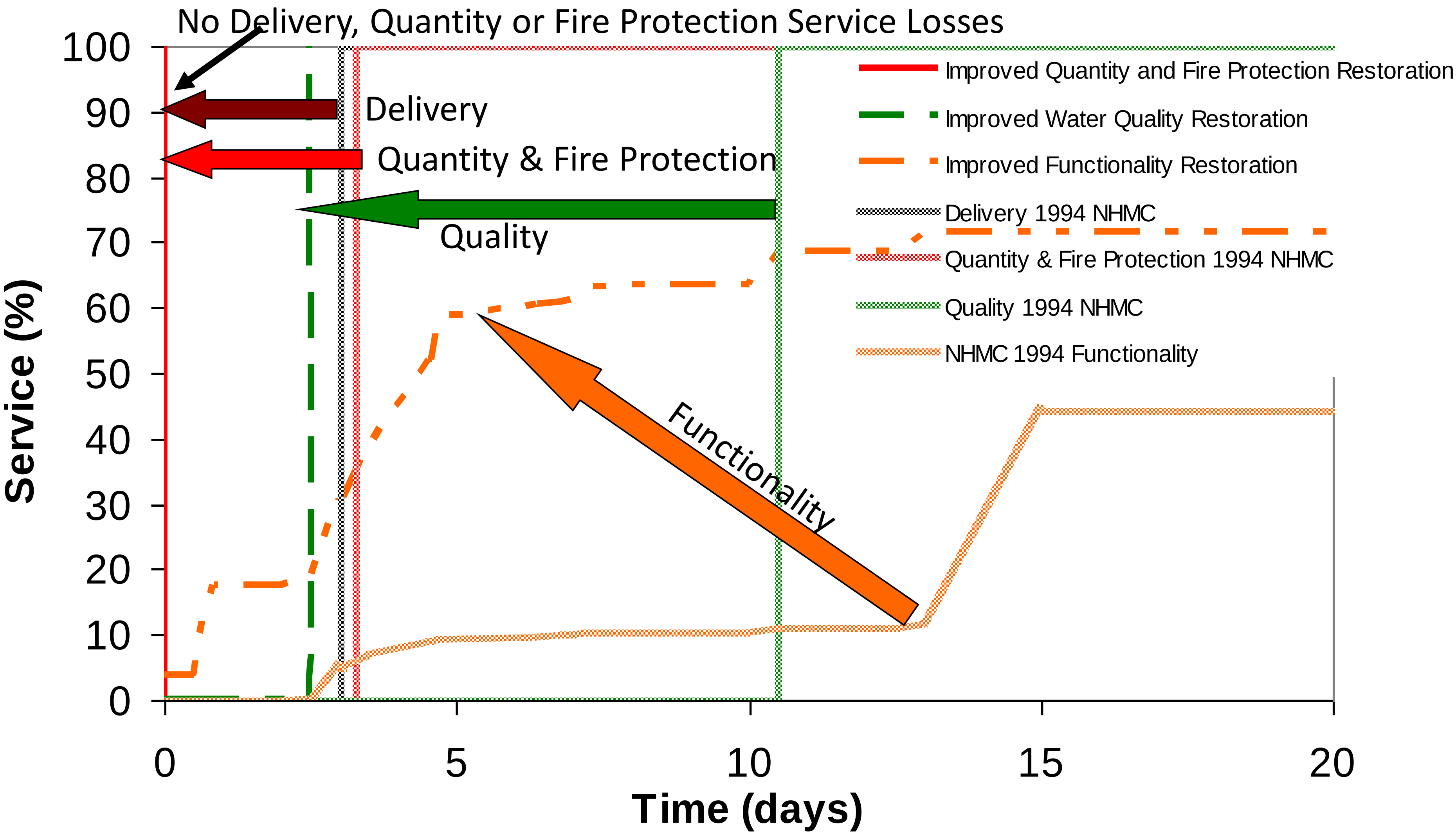
1994-NHMC Water Service Restorations



Improved Water Services

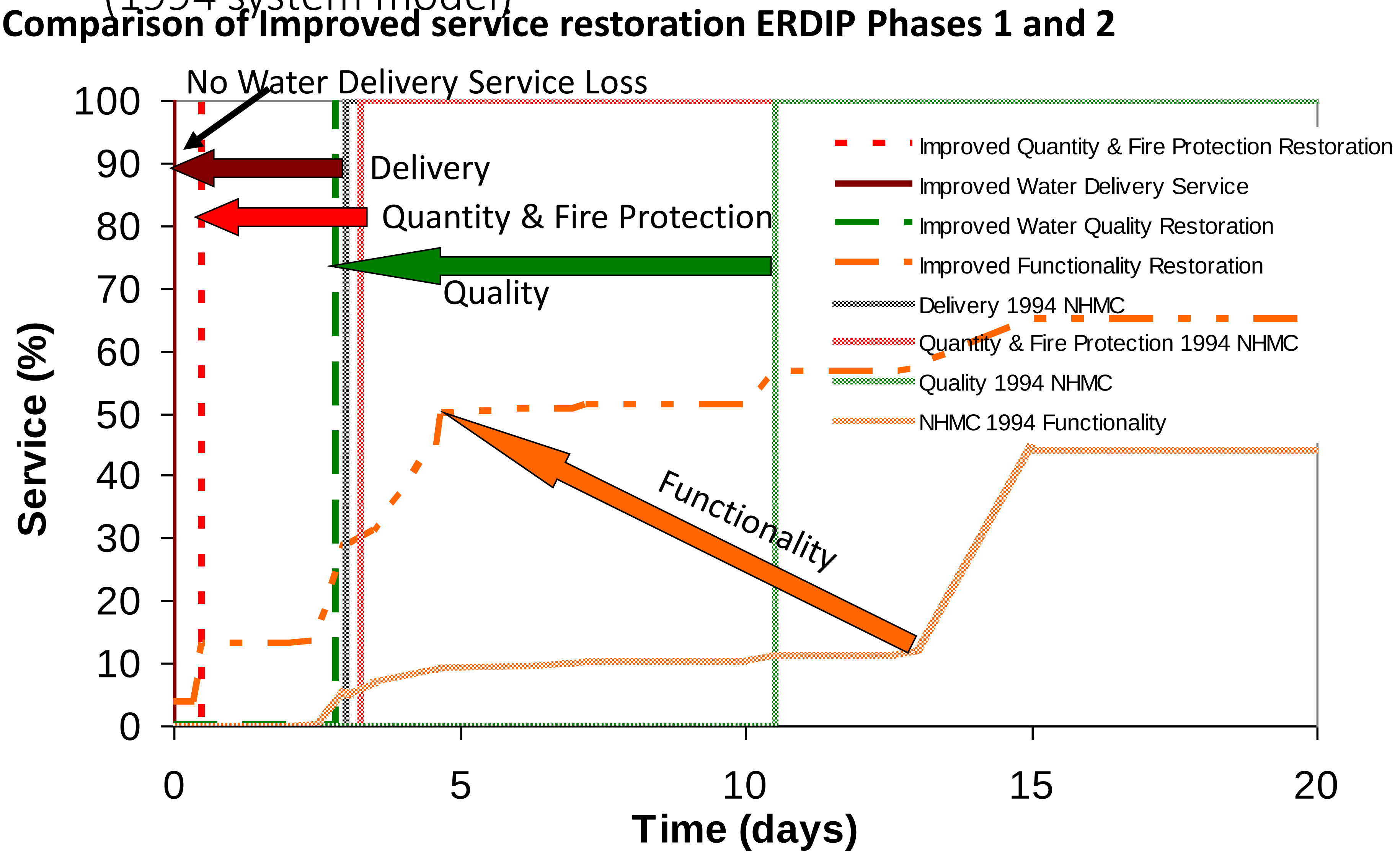
(1994 system model)

Comparison of Improved service restoration ERDIP Ph 1 + RoTL slip line

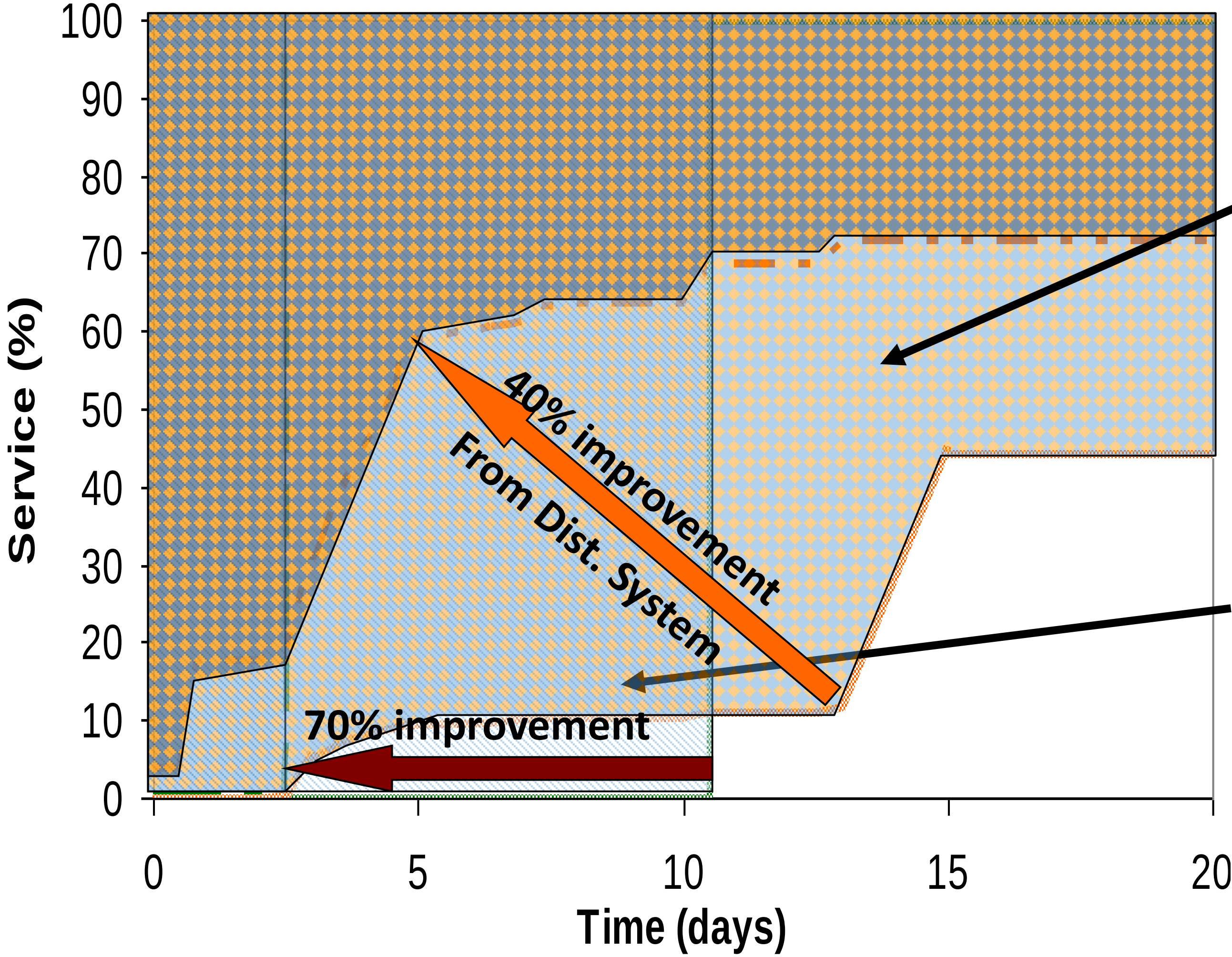


Improved Water Services

(1994 system model)



Resilience

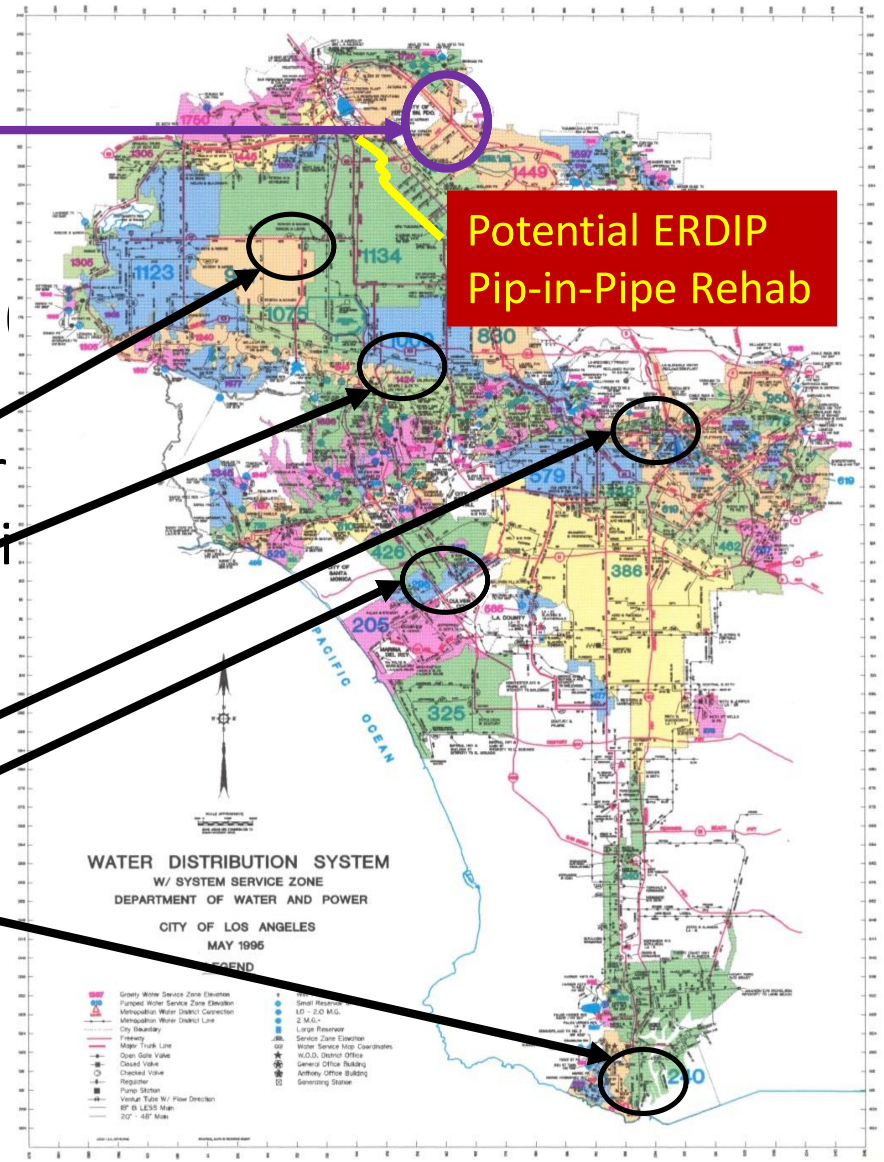


Water system Resilience estimated by area of Functionality curve.

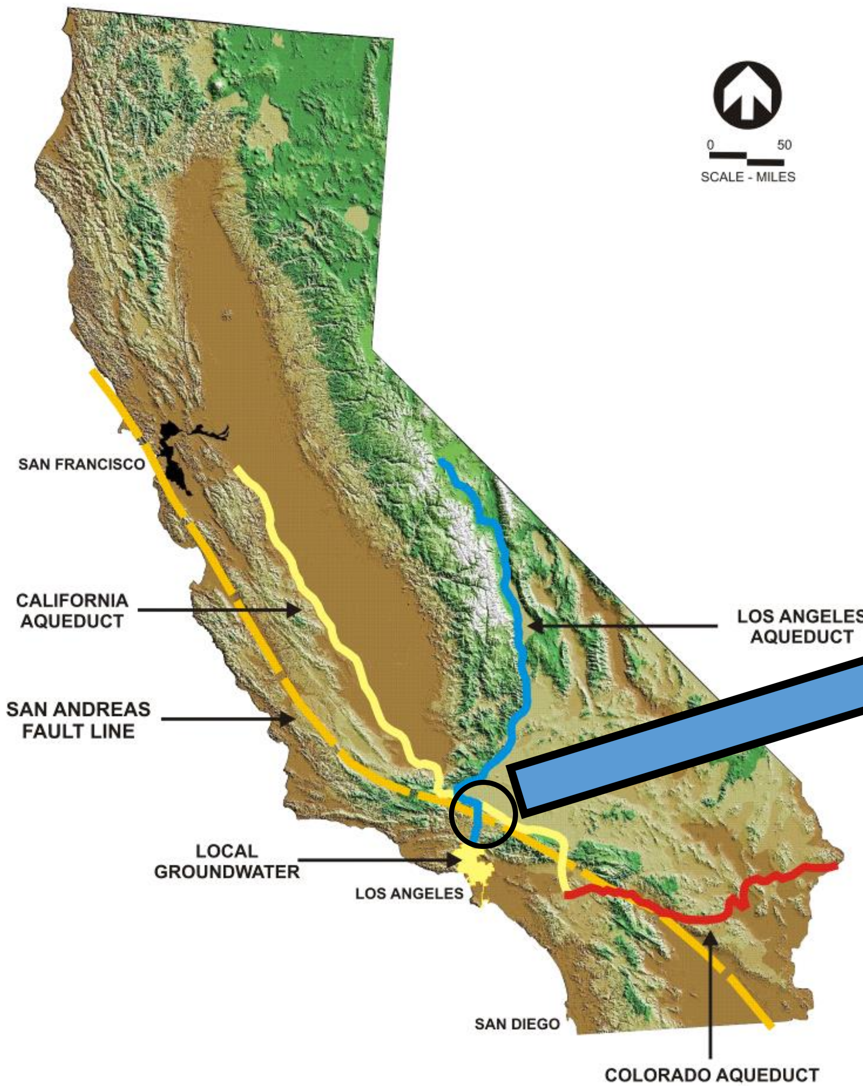
Water system contribution to Community Resilience estimated by area of Operability curve.

ERDIP Installation Sites

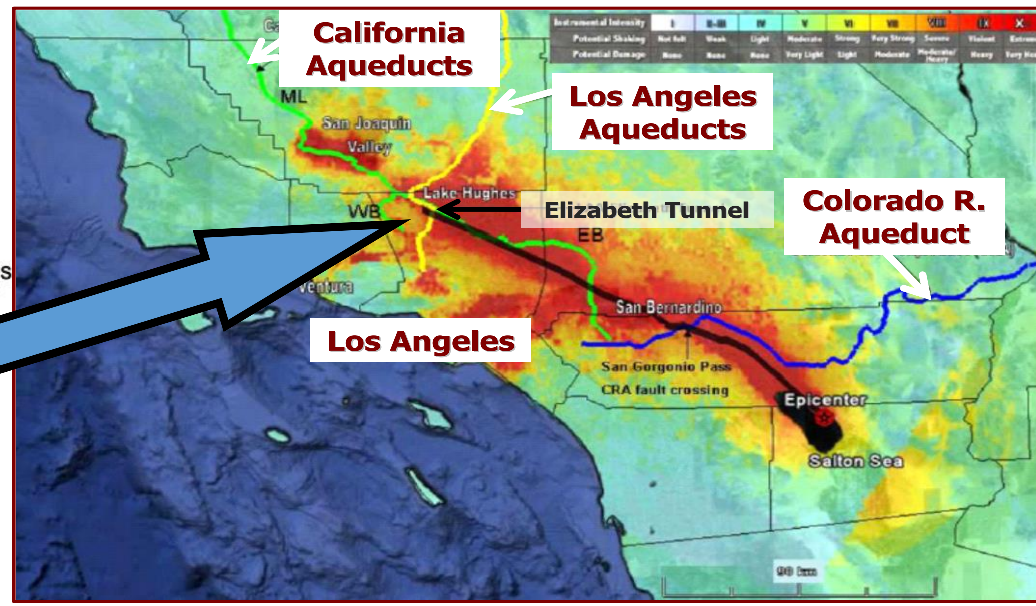
- Foothill Trunk Line (54” dia)
  - Crossing 1971 fault rupture
- 5 Pilot Project Sites [150mm (
  to 300mm (12”) dia]
  - Contour Drive, East Valley Distr
  - Reseda Blvd., West Valley Distri
  - Temple Street, Central District
  - Western District
  - 94th Street, Harbor District
- Others in design and procurement phases



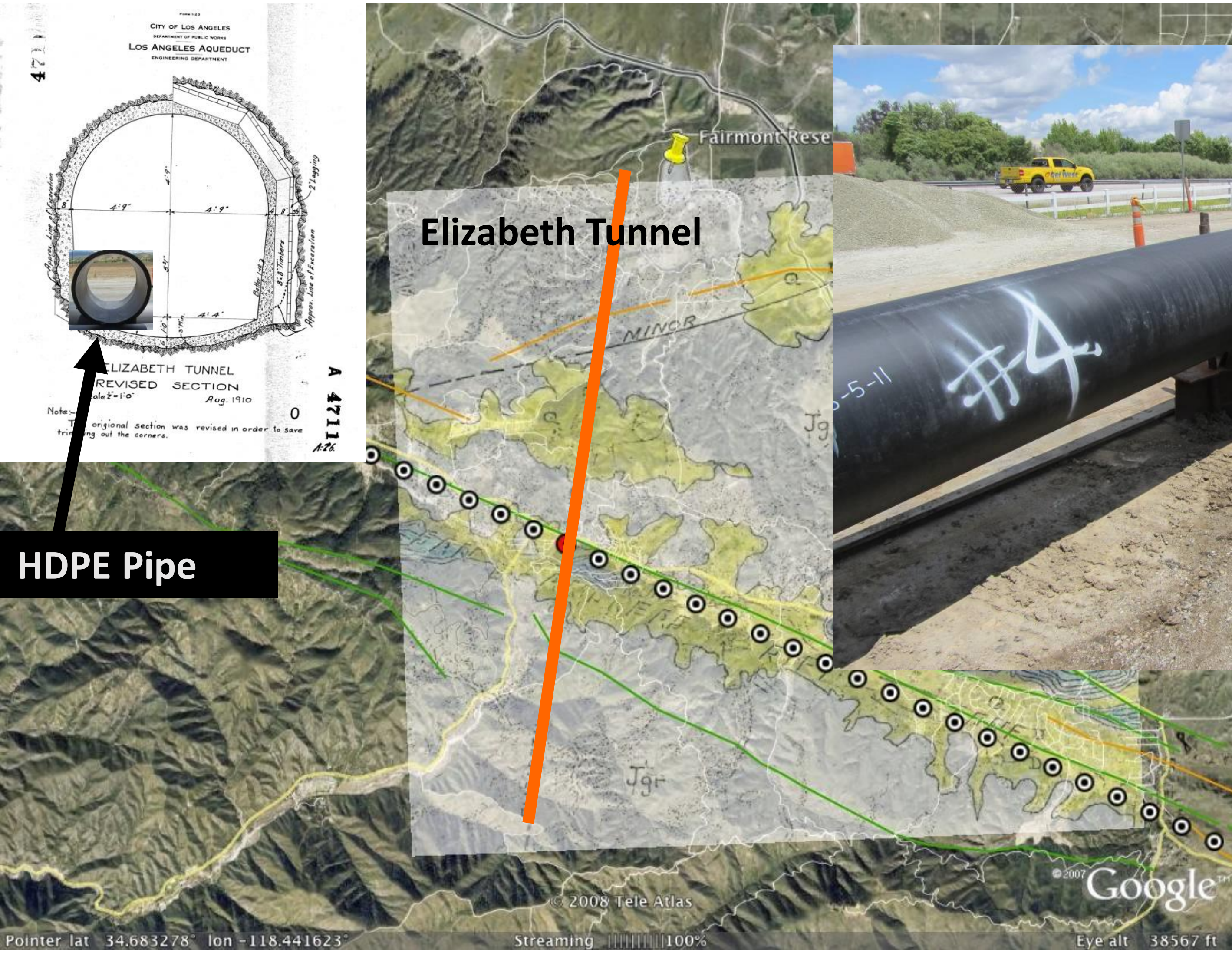
Los Angeles Aqueduct Supply
San Andreas Fault Crossing



Elizabeth Tunnel



Los Angeles Aqueduct Elizabeth Lake Tunnel HDPE Pipe Installation



allow water
flow after
fault rupture