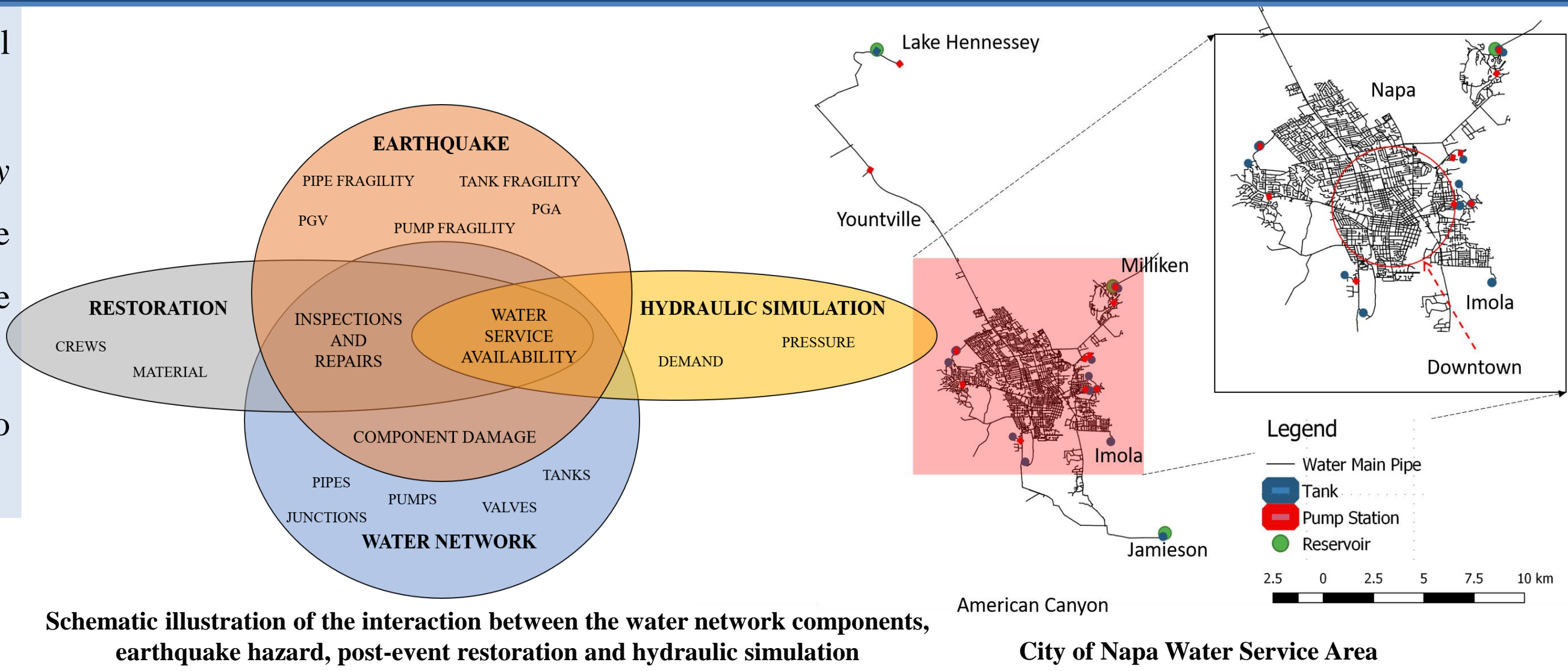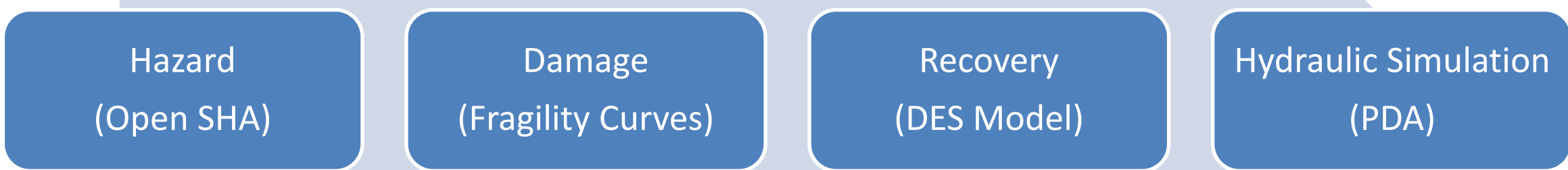# End-to-End Simulation Model for Seismic Risk and Resilience Assessment
of Water Distribution Systems

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1) Ph.D. Candidate, University of California, Los Angeles
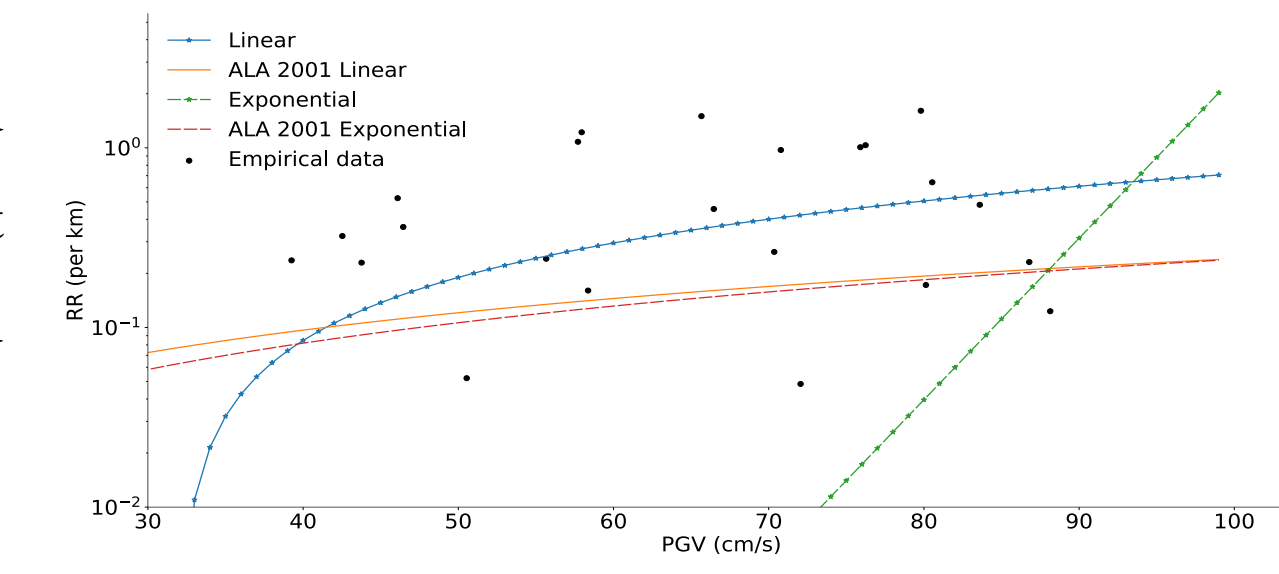2) Assistant Professor, University of California, Los Angeles

1. Introduction

- Water systems are vital to the well-being of communities since they contribute to the functionality of all building clusters as well as other lifeline systems (e.g., energy and transportation systems).
- Prior studies on economic losses caused by water service disruption suggest that *duration of functionality loss is just as critical as the geographical extent and severity of damage*. Therefore, models that capture the spatial distribution of component-level physical damage and loss and restoration of functionality, are needed to develop effective risk mitigation and emergency management plans for water systems.
- The current study uses pipe damage, inspection and repair data from 2014 South Napa earthquake to validate a Discrete Event Simulation (DES) model of city's water system.

Schematic illustration of the interaction between the water network components, earthquake hazard, post-event restoration and hydraulic simulation

City of Napa Water Service Area

| Hazard (Open SHA) | Damage (Fragility Curves) | Recovery (DES Model) | Hydraulic Simulation (PDA) |

2. Development of Pipe Damage Fragilities

- Using the 2014 pipe damage data, linear and exponential models are constructed using least squares regression. These models are compared with the ALA (American Lifelines Alliance) 2001 linear and exponential models.
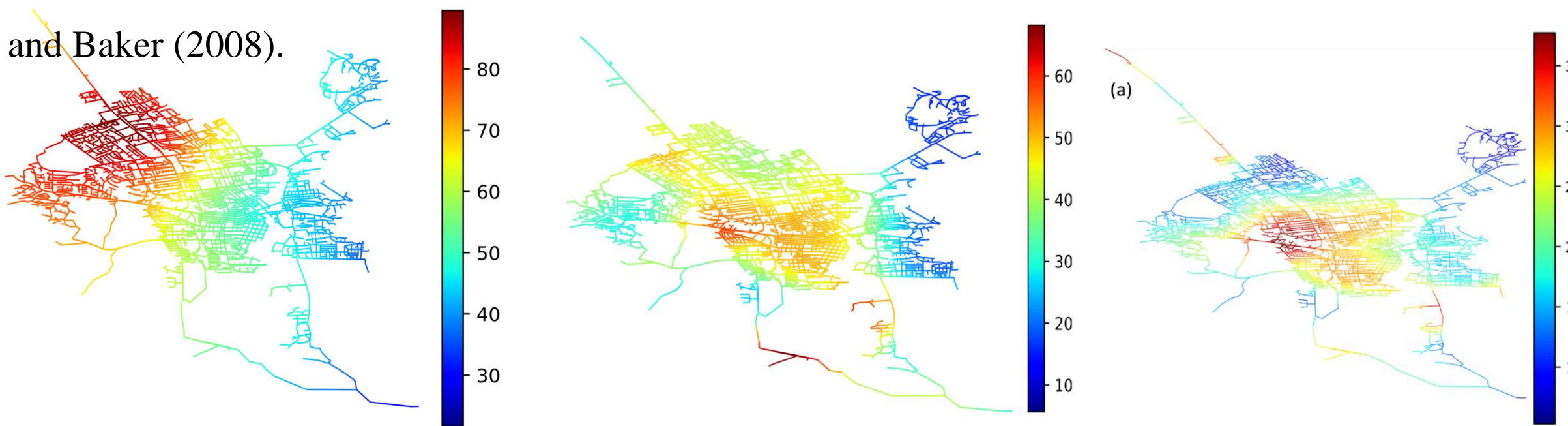- Linear formulation adopted in this study.

Empirical repair rate (RR) model developed using data from 2014 event

$$RR \text{ (per km)} = 0.01053 \times PGV \text{ (cm/s)} - 0.33649$$

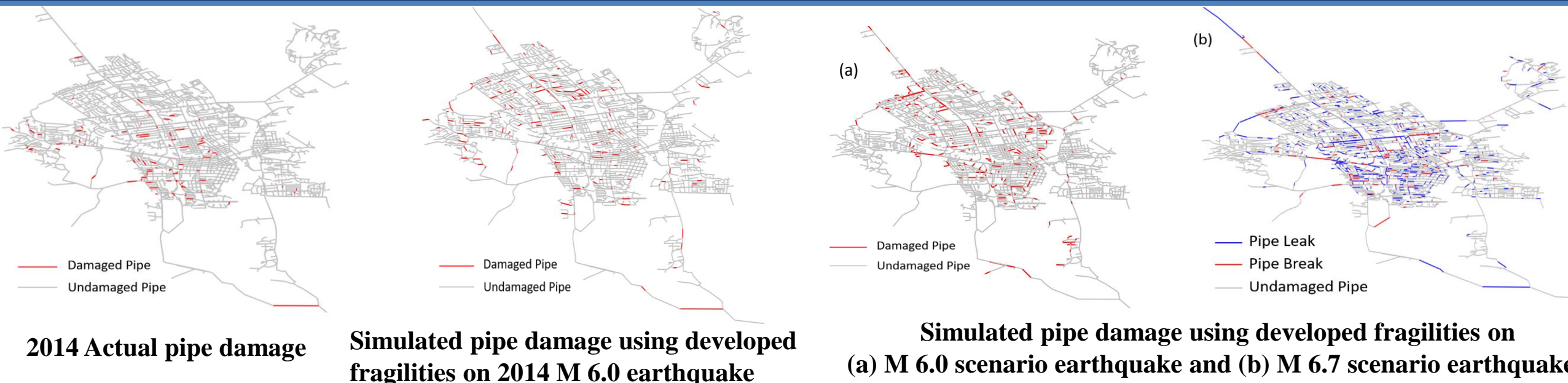|	Damage State (DS)	Damage Description
DS0	No Damage	No break or leak
DS1	Leakage	At least one leak along the pipe length
DS2	Failure	At least one break along the pipe length

Pipe Fragility Curve

3. *Hazard*

- OpenSHA is used to generate ground motion maps for scenario earthquakes.
- A M 6.7 (chosen based on magnitude-area relationship) earthquake occurring on the West Napa fault with epicentral location of N 38.22 W 122.13 (same as 2014 event) is used as the scenario event.
- Campbell and Bozorgnia 2014 ground motion attenuation relationship is used to obtain the median shaking intensities and spatially correlated shaking intensities are generated using the model by Jayaram and Baker (2008).
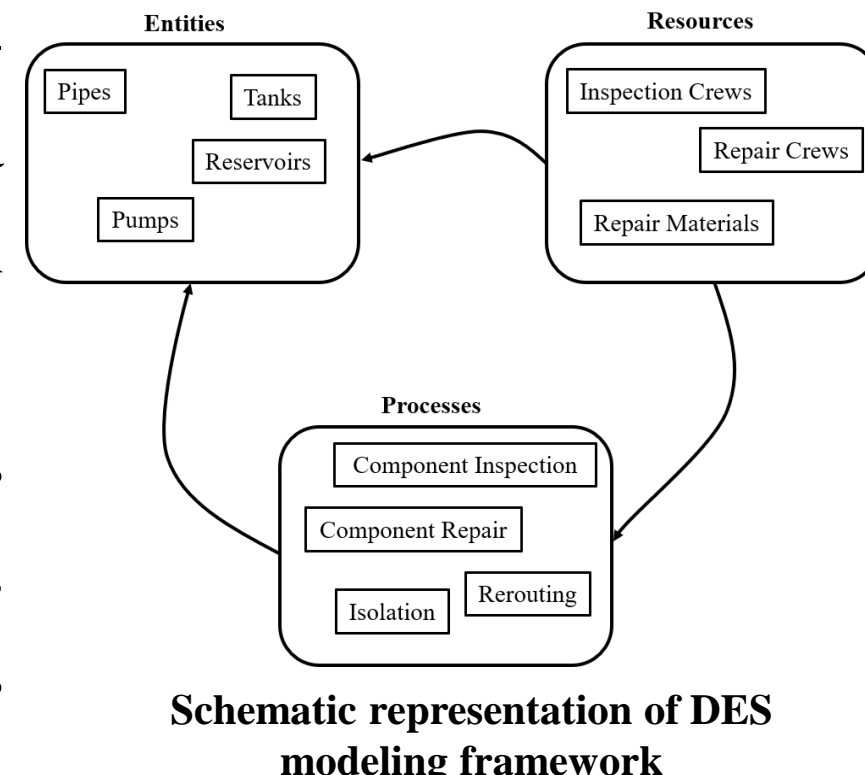

Spatial distribution of PGV (cm/s) for (a) 2014 M 6.0 event, (b) Scenario M 6.0 event, (c) Scenario M 6.7 event

4. *Damage*

2014 Actual pipe damage

Simulated pipe damage using developed fragilities on 2014 M 6.0 earthquake

Simulated pipe damage using developed fragilities on (a) M 6.0 scenario earthquake and (b) M 6.7 scenario earthquake
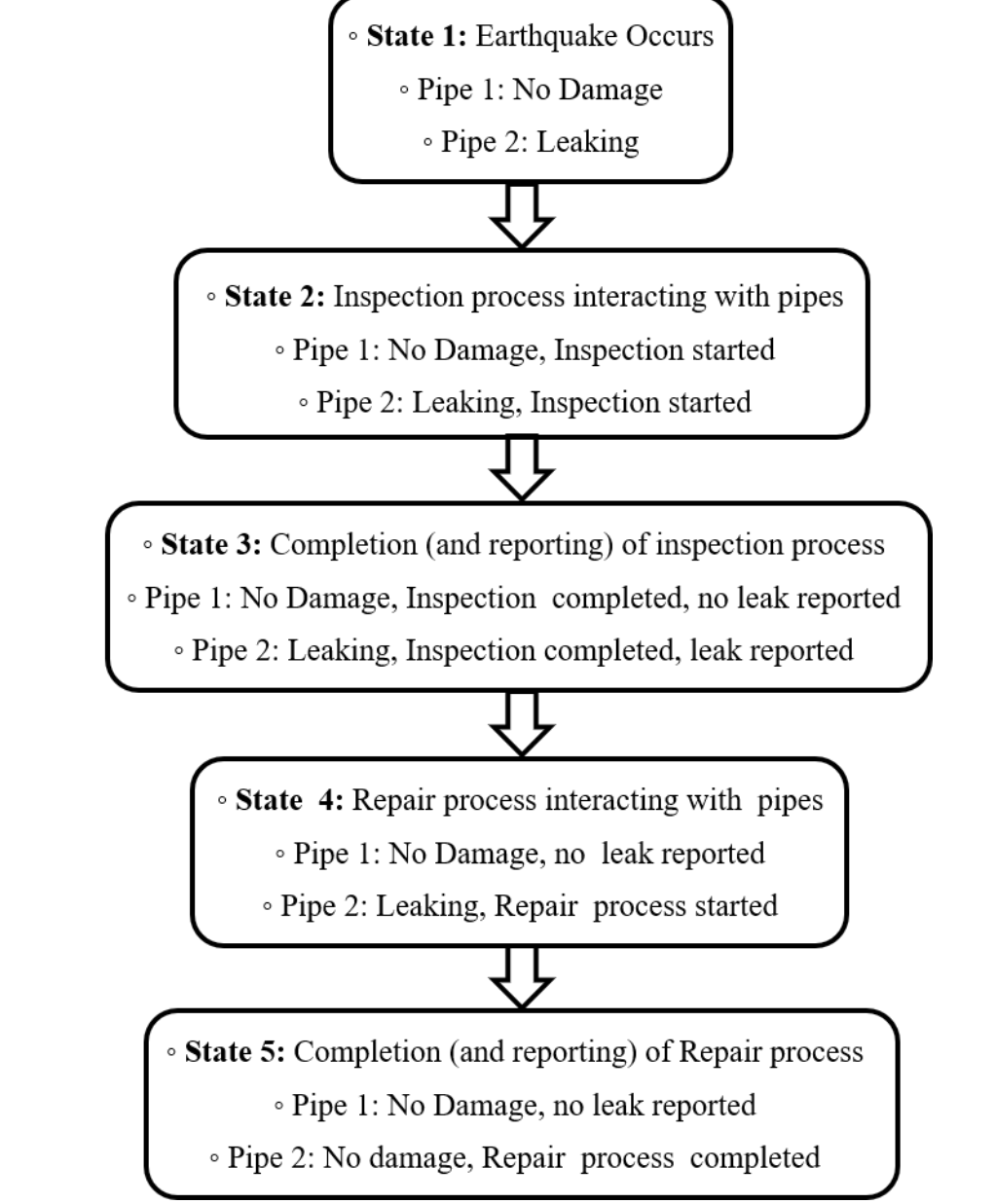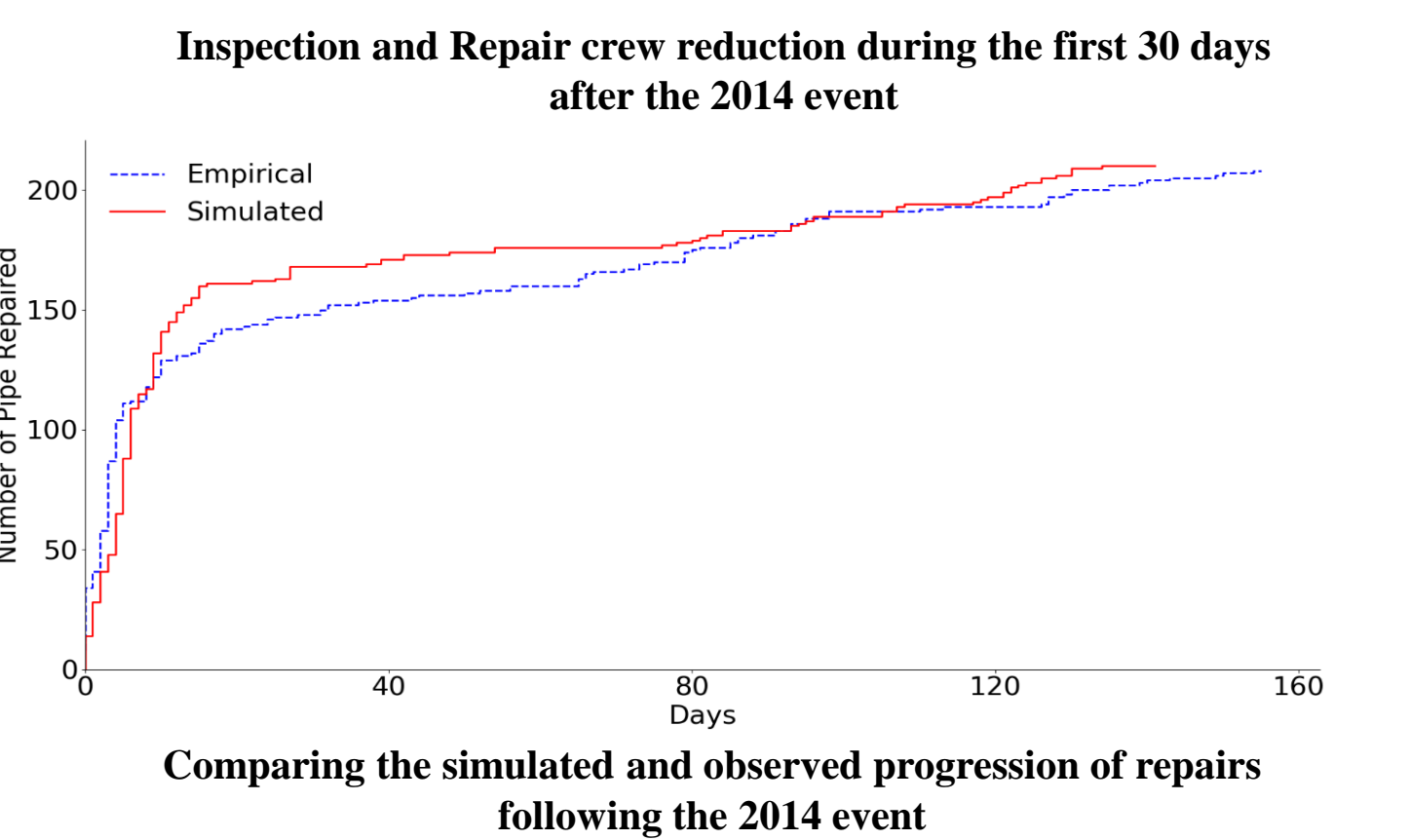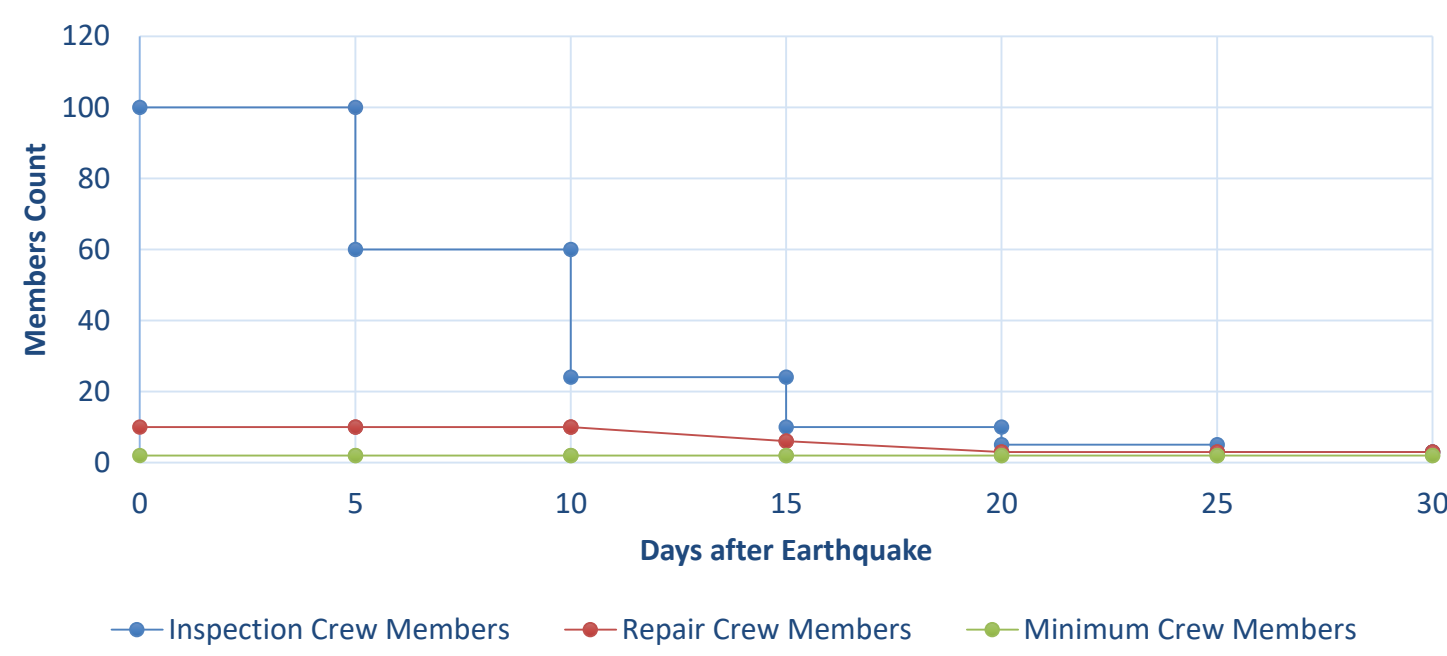
5. Discrete Event Simulation

- Discrete event simulation (DES) is used to model the earthquake-induced disruption and restoration of functionality for the Napa water system. DES model represents the behavior of a complex system as a sequence of events that occur at discrete points in time.
- The core elements of DES model includes: Entities: specific objects within system, Attributes: set of features specific to each entity, Events: occurrences that affect state of an entity, Resources: objects that provide service to entities, Time: discrete points in time domain.

Schematic representation of DES modeling framework

5. *Recovery*

- Model validation achieved by tuning temporal and resource-related parameters.

Inspection and Repair crew reduction during the first 30 days after the 2014 event

Comparing the simulated and observed progression of repairs following the 2014 event

- The calibrated DES framework is used to model the inspection, repair and water service restoration following the M 6.7 earthquake. The uncertainty in the inspection and repair processes are captured by assigning probability distributions and associated parameters to the number of crews (inspection: 10-120, repair: 20-40) and their durations.

Schematic illustration of the timing and occurrence of a set of discrete events (and their associated processes) for a hypothetical two-pipe water distribution system

	Event	Min	Mode	Max
Inspections	Trunk or Distribution Damage Tank Pump	0.5 hour	1 hour	2 hours
Repairs	Distribution Leak	3 hours	4 hours	6 hours
	Distribution Break	4 hours	6 hours	12 hours
	Trunk Leak	4 days	4 days	6 days
	Trunk Break	6 days	8 days	10 days

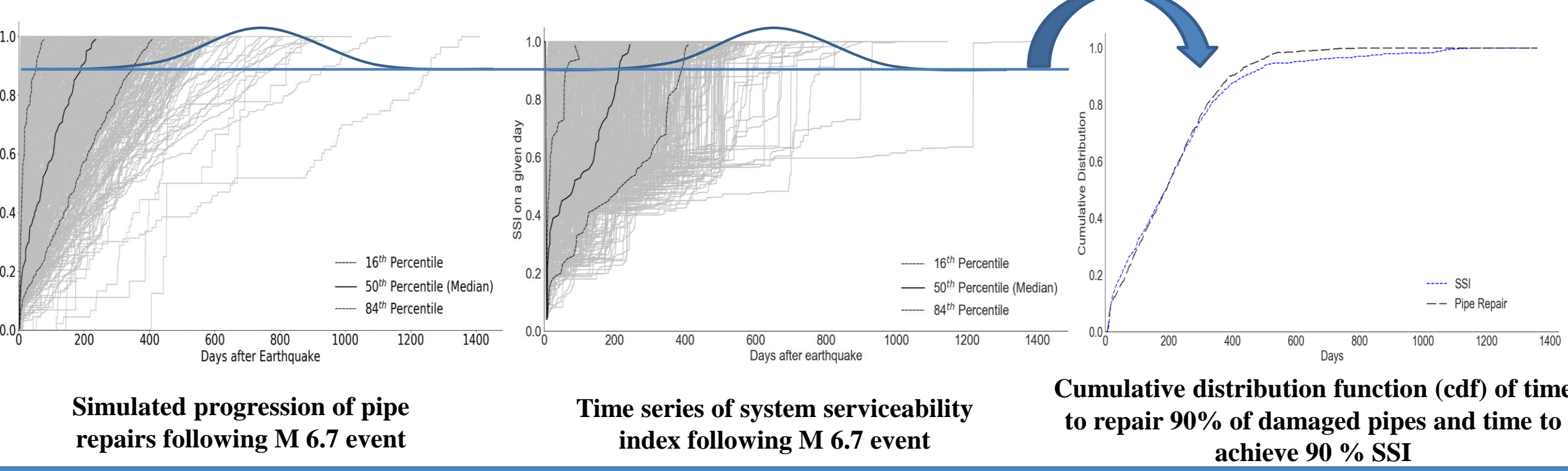|	Event	Mean (days)	σ (days)
Repairs	Pumping Plants	slight/minor	0.9	0.3
		moderate	3.1	2.7
		extensive	13.5	10.0
		complete	35.0	18.0
	Water Storage Tanks	slight/minor	1.2	0.4
		moderate	3.1	2.7
		extensive	93.0	85.0
		complete	155.0	120.0

Event duration distributions

6. *Hydraulic Simulation*

- Pressure driven analysis is performed on each repair curve focusing on quantifying the effect of pipe damage and the inspection/repair processes on the satisfaction of nodal demand.

$$SSI_j = \frac{\sum_{i=1}^{n} q_{i,j}}{\sum_{i=1}^{n} d_i}$$

SSI_j is the system serviceability index for a damage realization j, n is the number of demand nodes in the system, $q_{i,j}$ is the actual water flow supplied to the user at node i under the jth damage realization, and d_i is the water demand at node i

Simulated progression of pipe repairs following M 6.7 event

Time series of system serviceability index following M 6.7 event

Cumulative distribution function (cdf) of time to repair 90% of damaged pipes and time to achieve 90 % SSI

7. Summary and Conclusion

- A discrete event simulation (DES) model of post-earthquake water system functionality disruption and restoration is validated using data from a real event and extended to a hypothetical scenario.
- New fragility functions were developed and compared with industry standards.
- Multiple sources of uncertainty were propagated within the scenario-based assessment including the level of pipe damage conditioned on the shaking intensity, resource rescheduling and the network component inspection and repair times.
- Associated cumulative density functions are then developed to enable a probabilistic evaluation of restoration-based performance targets.