Integrating PBEE and Network Analysis to Measure Resilience Performance Objectives

Presenter: Luis Ceferino. **Research Team:** M. Markhvida, G. Cremen, P. Heresi, A. Hulsey, M. Balbi, A. Kiremidjian, J. Baker, G. Deierlein

STANFORD URBAN RESILIENCE INITIATIVE

John A. Blume Earthquake Engineering Center

Civil and Environmental Engineering Department, Stanford University

Earthquake Resilience

- Resilience agencies (e.g., [1]) have published "current" and "target" regional resilience performance of key city infrastructure after an earthquake scenario (see Fig. 1).
- Two dimensions of the recovery process: <u>functionality</u> and <u>time after the earthquake</u>.
- Analysis of the dependencies of the urban networks (e.g., power, water) has been identified as essential for community recovery modeling [3].
- Previous regional risk estimation techniques (e.g., HAZUS) built initial robust methodologies for assessing <u>expected values</u> of earthquake consequences.
- Currently, there is <u>no systematic methodology</u> for probabilistic quantification of regional resilience performance objectives that integrates advances in both earthquake engineering and network analysis, which enables the modeling of <u>urban systems' dependencies</u>.

TARGET STATES OF RECOVERY FOR SAN FRANCISCO'S BUILDINGS AND INFRASTRUCTURE

INFRASTRUCTURE CLUSTER FACILITIES	Event occurs	Phase 1 Hours			Phase 2 Days		Phase 3 Months		
		4	24	72	30	60	4	36	36+
CRITICAL RESPONSE FACILITIES AND SUPPORT SYSTEMS									
Hospitals	■							X	
Police and fire stations	■		X						
Emergency Operations Center	■								
Related utilities		■				X			
Roads and ports for emergency		■		X					
CalTrain for emergency traffic				■	X				
Airport for emergency traffic				■ X					
EMERGENCY HOUSING AND SUPPORT SYSTEMS									
95% residence shelter-in-place			■					X	

Figure 1. "Current" (in blue) and "target " (in X) performances in San Francisco after Mw 7.2 on the San Andreas Fault. The "current" performance was assessed by expert opinion (Source: [1]).

Objectives and Scope

- Provide a framework to support ongoing resilience planning initiatives, incorporating the analysis of <u>built environment vulnerabilities</u> and <u>key urban interdependencies</u>.
- Measure "current" resilience performance and assesses the likelihood of reaching community scale Resilience Performance Objectives **(RPO)** (e.g., performance targets in SPUR (Fig. 1)) by utilizing Performance Based Earthquake Engineering (PBEE) and explicitly incorporating network analysis of interdependent urban systems.
- This framework does not attempt to refine or advance specific risk or network analysis techniques, but to provide a way to unify current resilience, network and risk research and channel it towards helping decision makers measure resilience goals.

Framework: Steps for evaluating resilience performance objectives (RPO)

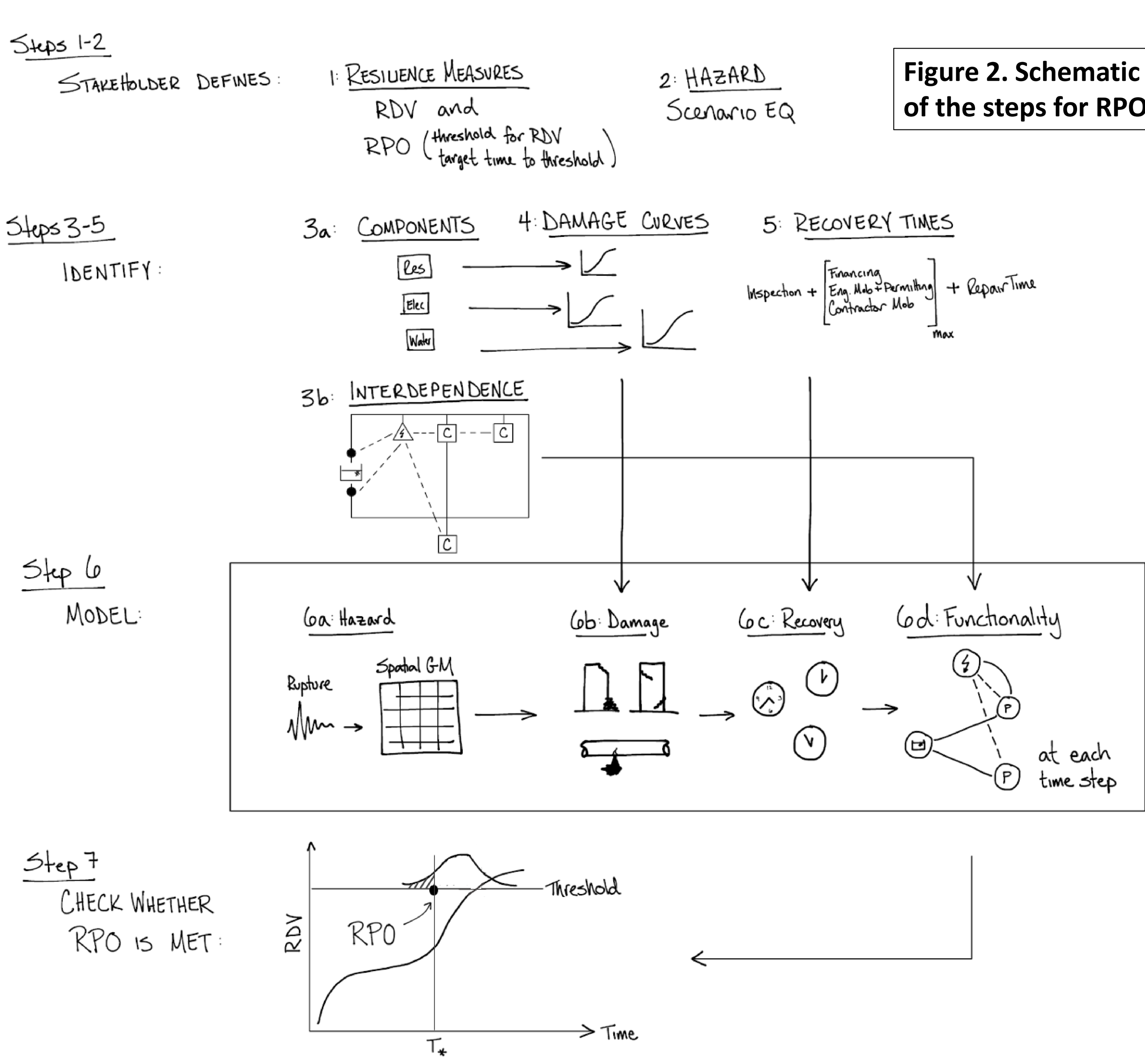

Figure 2. Schematic representation of the steps for RPO quantification.

Proof of Concept: Measuring shelter-in-place availability

Objective: model availability of shelter-in-place in 3 communities after a Mw 7.0 earthquake.

Shelter-in-place – building repaired + water and wastewater systems functioning.

Step 1: Resilience Decision Variables (RDV) and Resilience Performance Objective (RPO)

- Stakeholder: the municipality and the tenants.
- RDV: percentage of housing units that can function as shelter in-place.
- RPO: 95% of housing units, 24 h after the earthquake.

Step 2: Hazard

Mw 7.0 EQ. Ground motion is simulated for a 70x25 km area with a resolution of 1x1km.

Step 3: Urban components and interdependencies

- **Building stock (green triangles):** 3 communities with 30 buildings each comprised of 3 types of reinforced concrete building (see Fig. 3).
- **Water network (in blue):** water reservoir delivers water through two main pipes and pumps to the communities, the thermoelectric plant and the substation.
- **Power network (in red):** thermoelectric plant delivers power to the substation, and then the power is distributed to the pumps, the wastewater treatment plant and the communities.
- **Wastewater network (in magenta):** wastewater from the thermoelectric plant and the communities is pumped to the water treatment plant.

<u>The urban networks are interdependent</u>:

- Thermoelectric plant needs water for cooling and wastewater network to function.
- Pumps (water and wastewater) need power to function.

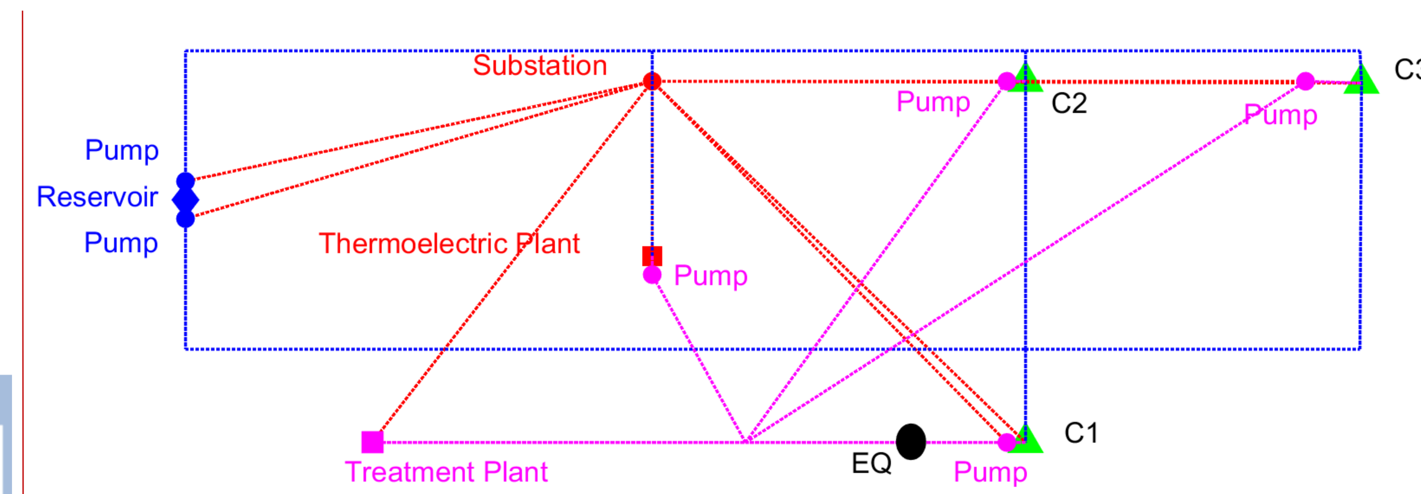

Figure 3. Earthquake scenario (in black) and built environment: 3 communities (in green), water (in blue), power (in red), and wastewater (in magenta) networks.

Step 4: Damage susceptibility of urban components

All the buildings and network components shown in Fig. 3 and described in Step 3 (except for the electric power lines) are considered susceptible to damage and have associated fragility functions selected from [2], [6], [7].

Step 5: Recovery paths of urban components

- Recovery paths defined according to HAZUS and the REDi procedure.
- Buildings: physical repair times and impeding factors (inspection, engineering mobilization, contractor mobilization, financing, and permitting) were included.
- Network components: recovery modeled as per [2] methodology, with no impeding factors.
- For a given community, correlation in the recovery times of buildings was considered by sampling impeding factors of buildings in different damage states from a multivariate lognormal distribution with a correlation coefficient of 0.5.

Step 6: Modeling of the urban system under earthquake stress

1. Sample different realizations of correlated ground motions (see Fig. 4).
2. Sample damage states and recovery times for each urban system component
3. Apply network analysis to each realization of the dynamic interdependent network to verify delivery of water to the 3 communities at each time step after the earthquake.

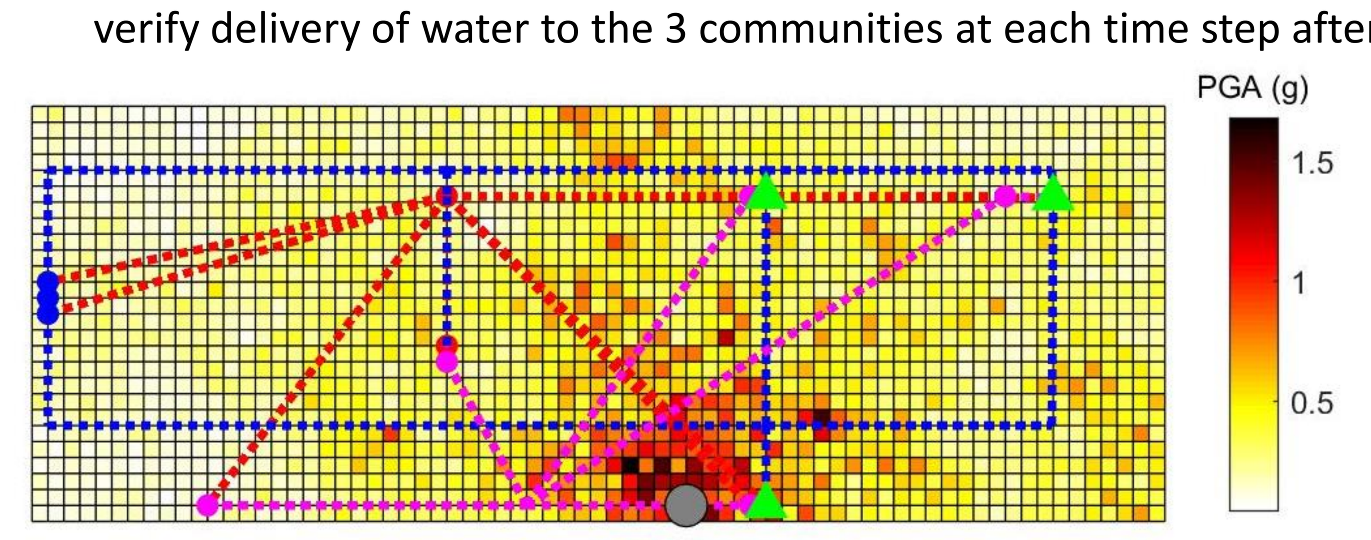

Figure 4. A realization of peak ground acceleration (PGA) affecting the urban system.

Step 7: Probability of meeting RPO and time required to meet the RDV threshold

The distribution of the RDV and is shown in Figure 5. To the left, where impeding factors in the recovery are considered, the "current" performance is far below the resilience "target" (RPO). No realization met with the RPO, and the 80% central confidence interval revealed that 95% shelter-in-place is reached between 1.2 and 3.2 years. This striking mismatch between the "current" and "target" is similar to the expected shelter in-place performance in San Francisco (Fig. 1). To the right, where impeding factors are not considered, no realization met the RPO, and 80% central confidence interval was 0.20 to 1.1 years.

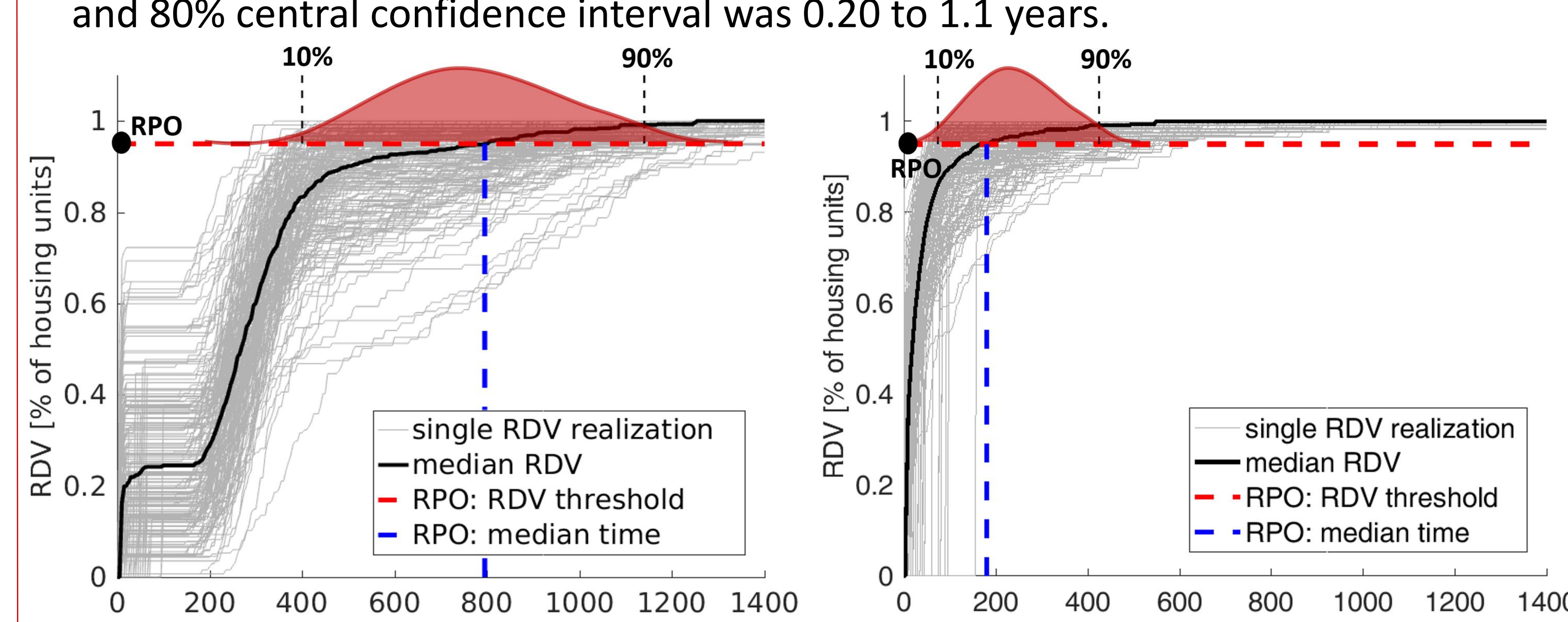

Figure 5. RDV (% of shelter in-place units) distribution after the earthquake with (left) and without (right) impeding factors.

Summary and Continuing Work

- A probabilistic framework for assessing "current" and "target" regional resilience performance of key urban functions was presented.
- The framework is based on earthquake risk analysis and network analysis to measure the likelihood of achieving earthquake resilience performance objectives (RPO) in communities.
- A proof of concept example is presented to demonstrate the applicability of the framework.
- The example showed the relevance of the impeding factors on the recovery.

<u>Continuing work will include:</u>

- Extension of the case study to real communities and networks.
- Analysis of the most contributing factors, or 'bottlenecks' in recovery process.
- Inclusion of impeding factors in network systems' recovery.
- Introduction of repair sequencing in distributed networks.

References

[1] San Francisco Planning + Urban Research Association (SPUR). (2009). The resilient city: defining what San Francisco needs from its seismic mitigation policies. San Francisco, CA.

[2] FEMA.(2003). "HAZUS-MH MR4 technical manual, multi-hazard loss estimation methodology earthquake model." FEMA 366, Washington, DC.

[3] National Institute of Standards and Technology (NIST). (2015). NIST Special Publication 1190: Community Resilience Planning Guide for Buildings and Infrastructure Systems Volume I (Vol. I).

[4] Villar-Vega, M., Silva, V., Crowley, H., Yepes, C., Tarque, N., Acevedo, B., Hube, A., Gustavo, C., Santa María, H. (2017) Development of a Fragility Model for the Residential Building Stock in South America. Earthquake Spectra: Vol. 33, No. 2, pp. 581-604.

[5] González, A., Dueñas-Osorio, L., Sánchez-Silva, M., & Medaglia, A. L. (2016). The Interdependent Network Design Problem for Optimal Infrastructure System Restoration. Computer-Aided Civil and Infrastructure Engineering, 31(5), 334–350.

[6] Burton, H., Deierlein, G., Lallemant, D., Lin, T. (2016). Framework for Incorporating Probabilistic Building Performance in the Assessment of Community Seismic Resilience. Journal of Structural Engineering, 142(8).

[7] S.-S. Jeon and T. D. O'Rourke, "Northridge Earthquake Effects on Pipelines and Residential Buildings," Bulletin of the Seismological Society of America, vol. 95, no. 1, pp. 294–318, Feb. 2005.