IOWA STATE UNIVERSITY

Satyam Mandloi [1], Mark Furtado[1], and Alice Alipour[2]

[1]Graduate Research Assistant, [2]Assistant Professor

Network Theory Approach to Enhance the Resilience of Bridges in Seismic Prone Regions

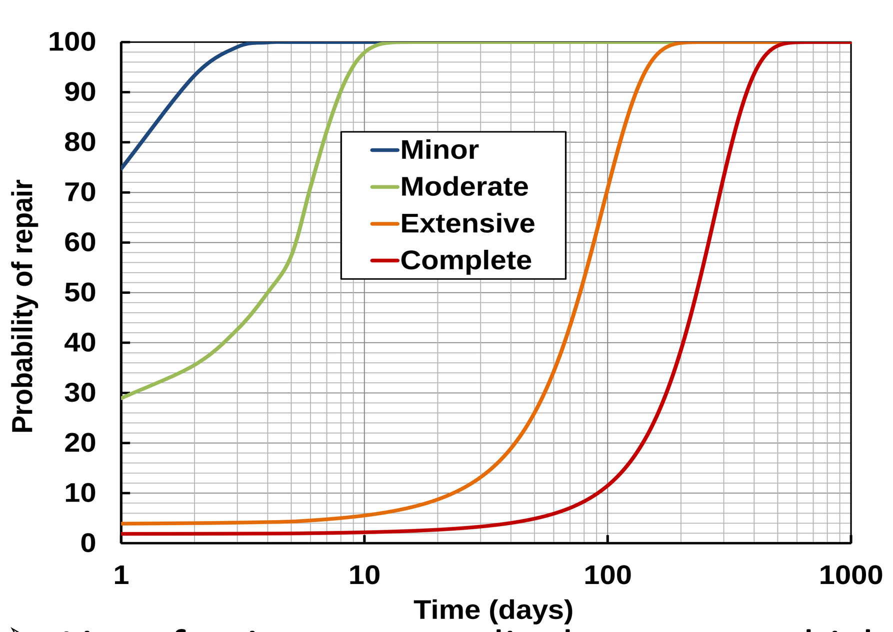
Introduction

- Seismic events can pose a serious risk to transportation networks
- Bridges are the most critical components when considering seismic events
- A model is generated that combines the seismic hazards, bridge vulnerability and network structure to quantitatively measure different dimensions of seismic resilience.
- This model is demonstrated using the San Francisco Bay area as the test bed

Network Vulnerability

- Bridge damage is discretized into four damage states: Minor, Moderate, Extensive and Complete
- Probability of failure from ground motion is calculated using fragility curves:

$$F_k(a|\zeta_k, c_k) = \Phi\left[\frac{ln\left(\frac{a}{c_k}\right)}{\zeta_k}\right]$$



- Liquefaction causes displacement which can cause failure, based on Hazus- MH model
- Direct Costs: Cost of repair of damaged bridges = Area of the bridge x Cost/Area x Damage Ratio
- Indirect Costs: Costs from decreased network performance = Delay x mean vehicle occupancy x value of time for the users
- $d = \sum_{i=1}^{N}[x_i^{'}t_i^{'}(x_i^{'})] - \sum_{i=1}^{N}[x_i t_i(x_i)]$

Resilience Framework

Collect Data

Traffic Data
- TAZs
- Network topology
- Travel demand
- Speed limits
- Roadway capacity

Earthquake Data
- Hazard locations (fault, seismic zone)
- Scenario Magnitudes

Bridge Data
- Bridge Locations
- NBI data including span data, materials
- Bridge fragility parameters
- Site conditions

Hazard Model
- Use attenuation relationship to determine earthquake intensity at sites
- Using fragility parameters, simulate the level of damage at each bridge
- Use bridge characteristics and damage state to determine repair costs
- Use damage state to determine repair time
- Determine road closures or reduction in capacity based on damage of bridges on links

Traffic Model
- Four step transportation model:
  - Trip generation estimates the productions/attractions at TAZs
  - Trip distribution ties together trip ends
  - Mode choice determines mode of transportation for these trips
  - Traffic assignment dictates route choice based on user equilibrium
- Determine the VHT of the entire network, use this to determine indirect costs

Resilience Measure

Robustness
- Perform multiple simulations of the earthquake and calculate costs immediately after the event
- Determine a robustness threshold and determine how likely the network
- Will meet this threshold

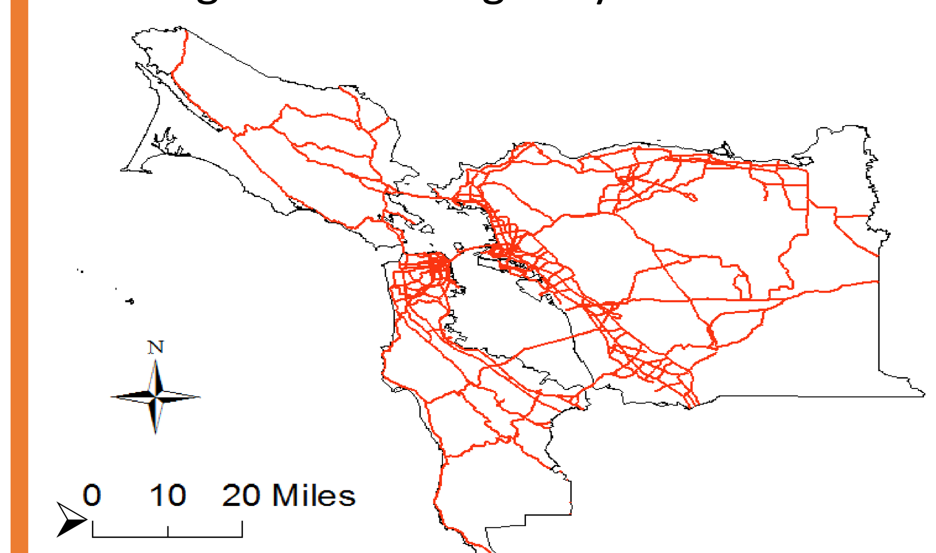
Redundancy
- Determine the α, β and γ indices
- $\alpha = \frac{\upsilon}{2n-5}$, $\beta = \frac{l}{n}$, $\gamma = \frac{l}{3(n-2)}$, where υ, n and l are the number of cycles, nodes and links respectively

Resourcefulness
- Choose the most important bridges. Betweenness Centrality was used in this study to rank bridges
- Shorten repair time of selected bridges and increase the repair costs if applicable
- Sum the costs across the repair process
- Compare the costs to a scenario where no bridges are accelerated for repair

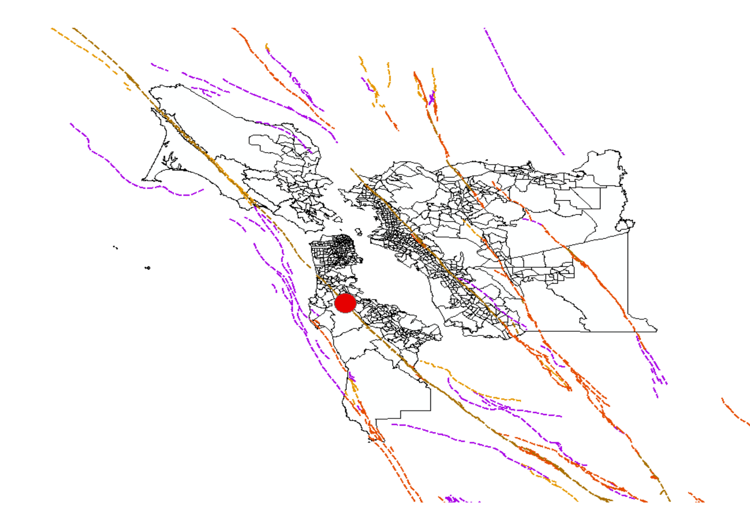
Rapidity
- Determine a threshold repair state for the network (fully repaired, 95% performance, etc.)
- Calculate the network performance throughout the repair process
- The time it takes for the network to reach the threshold performance is the rapidity for the earthquake scenario

Study Area

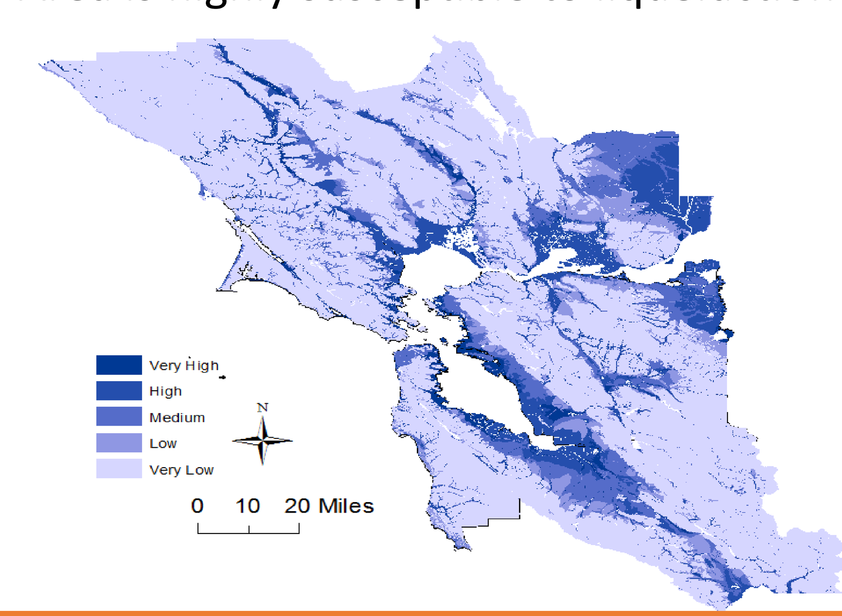
- The study was conducted on a 5 county section of the San Francisco Bay area
- 2423 total bridges are used
- Using the NHPN highway network



- Epicenter for the 7.5 scenario earthquake

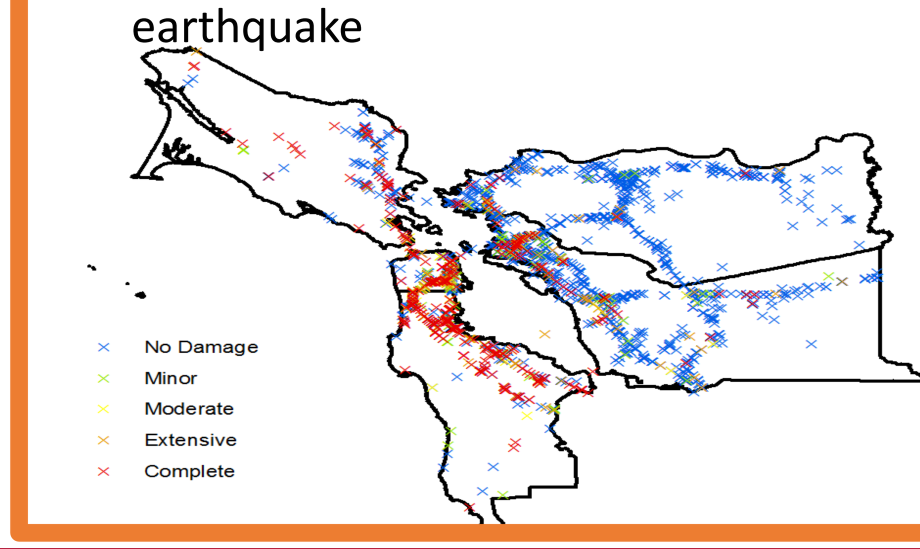


- Area is highly susceptible to liquefaction



Analysis Results

- Bridge damage states for the scenario earthquake

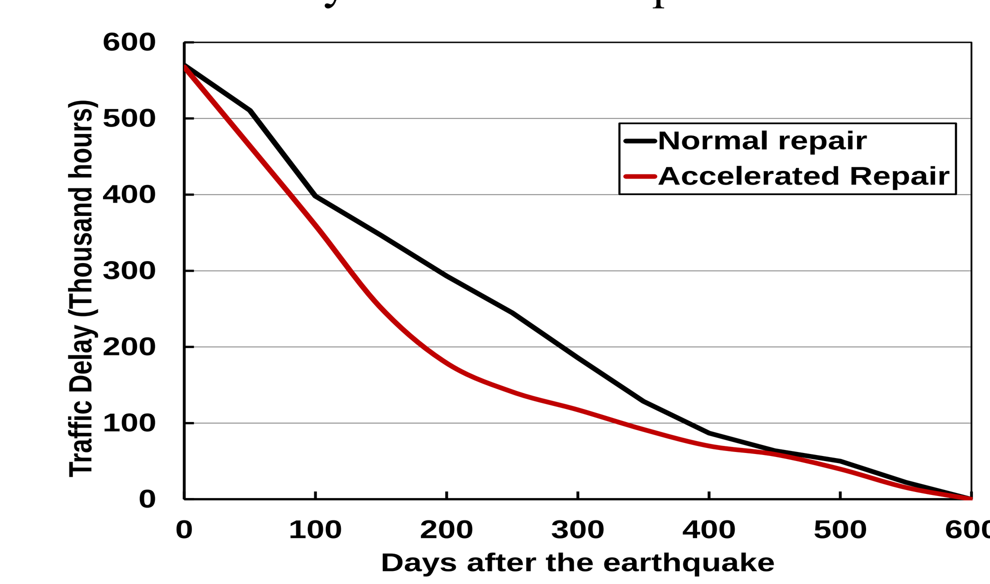


Results and Conclusion

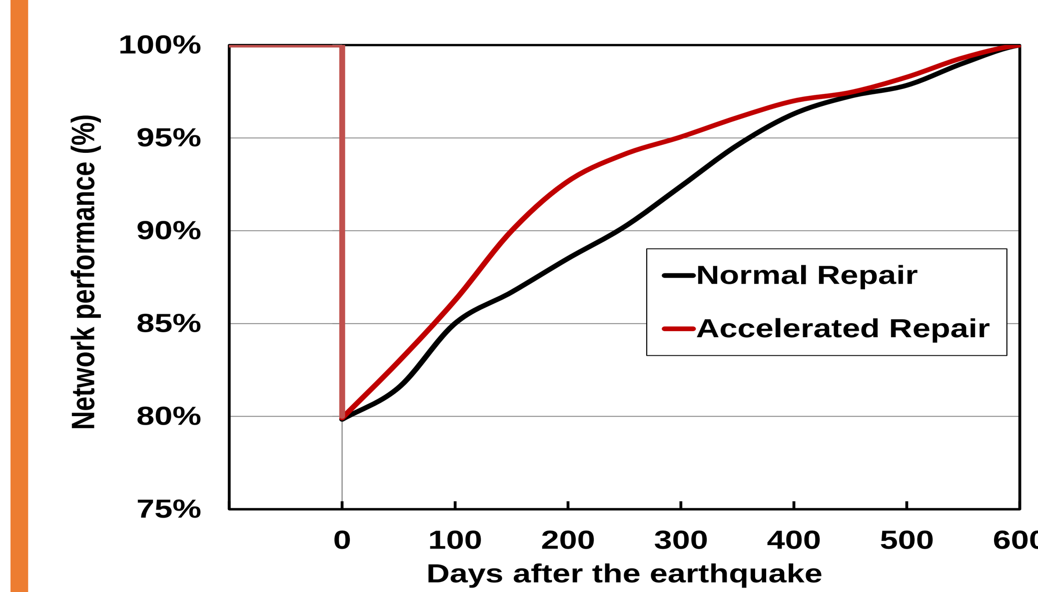
- Percentage of bridges in each damage state directly following the scenario earthquake

Damage State	No damage	Minor	Moderate	Extensive	Complete
Bridges in each damage state (%)	71.3	6.0	2.7	5.3	14.7

- Traffic delay after the earthquake



- Probability curve for the network delay



- Each of the 4 R's for resilience offers important insight into how the network recovers
- Robustness shows damage that occurs directly after the earthquake
- Redundancy gives further details into why the indirect costs from robustness analysis are what they are
- Resourcefulness is an aspect that ties into every other dimension of resilience and represents the decision making capability and capacity to provide whatever resources necessary to accelerate high priority projects
- Rapidity describes the time dimension of the repair process

Acknowledgements

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