Multi-Hazard Resilience of Transportation Infrastructure

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XP-resilience

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Research Focus and Topics of Interest

Infrastructure risk and resilience modeling

- Key emphases in the areas of
  - Structural vulnerability analysis and protection
  - Multi-hazard resilience assessment (hurricane surge, wave, earthquake, flooding, aging…)
  - Life-cycle analysis in hazard prone regions
- Application to transportation and energy infrastructure

Bridges

Port Structures

Nuclear Dry Casks

Above Ground Storage Tanks

Multiple Hazards Across U.S.

Region 10
Severe Storm
Flood
Volcano
Earthquake
Wild Fire
Tsunami
Pandemic
Economic Downturn

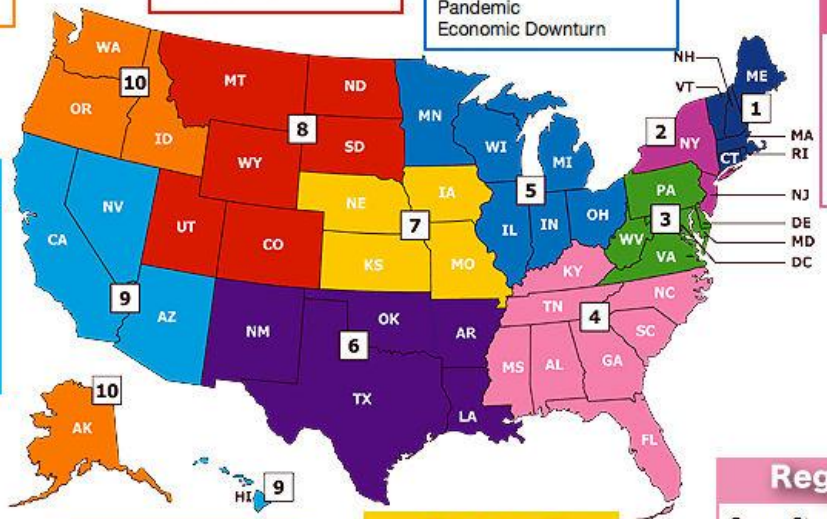
Region 8
Severe Storm
Flood
Winter Storm
Earthquake
Wild Fire
Pandemic
Economic Downturn

Region 5
Severe Storm
Flood
Winter Storm
Wild Fire
Tornado
Pandemic
Economic Downturn

Region 1
Severe Storm
Flood
Winter Storm
Hurricane
Pandemic
Economic Downturn

Region 2
Severe Storm
Flood
Wild Fire
Winter Storm
Hurricane
Pandemic
Economic Downturn

Region 9
Severe Storm
Flood
Volcano
Earthquake
Wild Fire
Tsunami
Pandemic
Economic Downturn



Region 3
Severe Storm
Flood
Wild Fire
Winter Storm
Hurricane
Pandemic
Economic Downturn

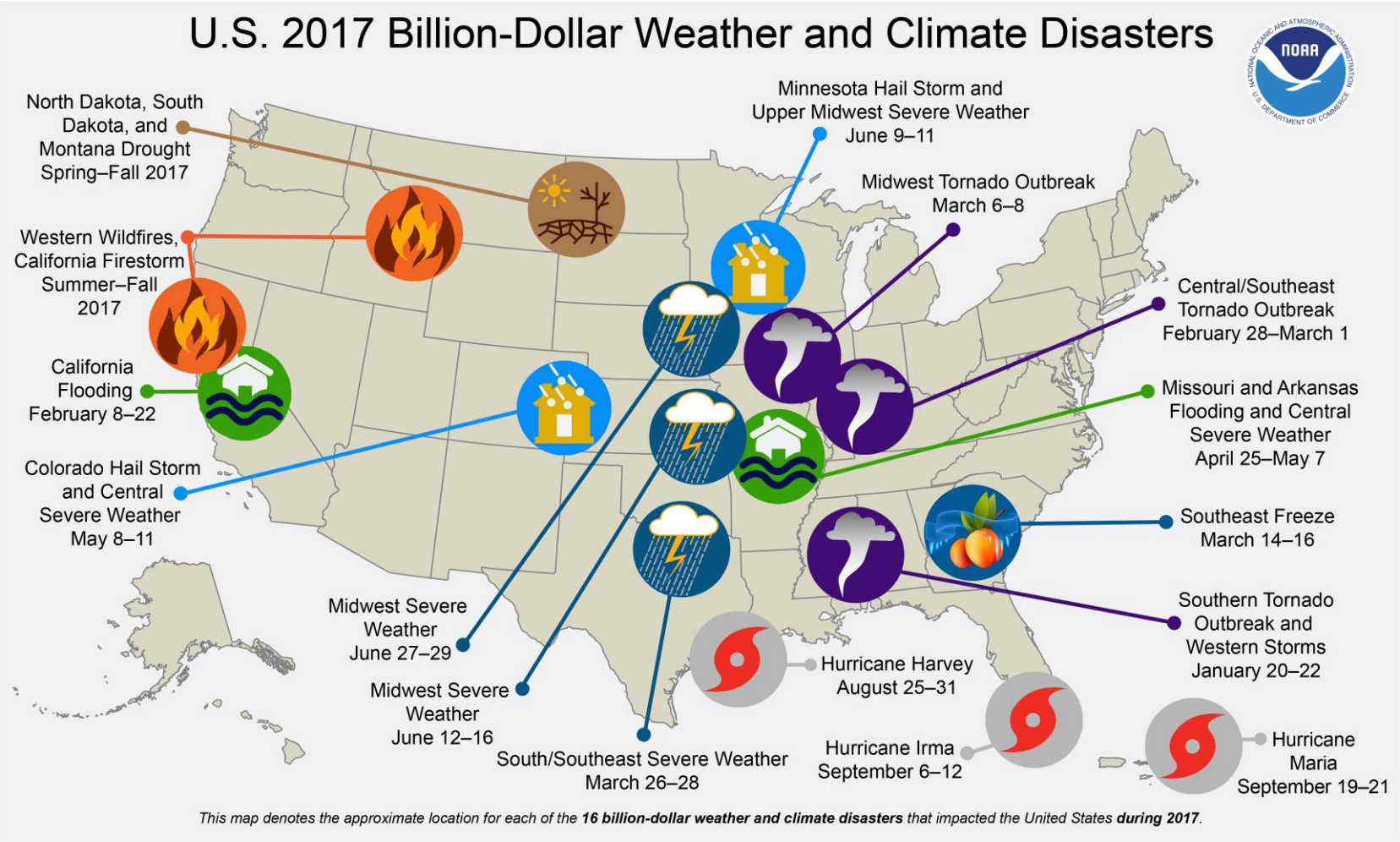
Region 4
Severe Storm
Flood
Hurricane
Earthquake
Winter Storm
Pandemic
Economic Downturn

Region 6
Severe Storm
Flood
Hurricane
Winter Storm
Wild Fire
Tornado
Pandemic
Economic Downturn

Region 7
Severe Storm
Flood
Winter Storm
Earthquake
Wild Fire
Tornado
Pandemic
Economic Downturn

www.rethinkstormshelters.com

The costly year of 2017!



https://www.ncdc.noaa.gov

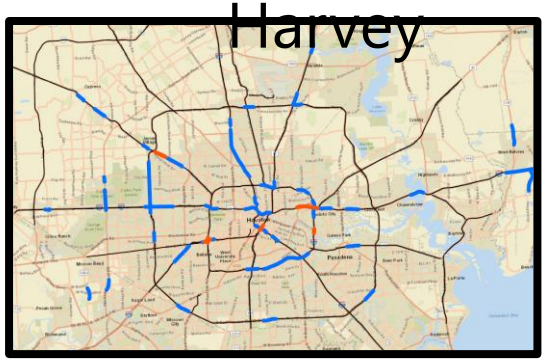
Hurricane Harvey

https://www.ncdc.noaa.gov

- Landfall on Texas coast – August 26
- Slow movement causing record rainfall and flooding in Houston – August 27-30
- As many as 290 roads closed/flooded on September 2nd – a week after (Texas Tribune)
- Major highway 6 and surrounding roads flooded due to Addicks reservoir reopen – September 20

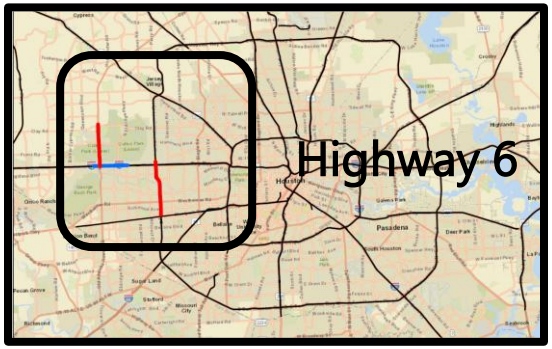
Houston Road Conditions after Harvey

Flooded
Closed



August 27, 2017

http://traffic.houstontranstar.org/

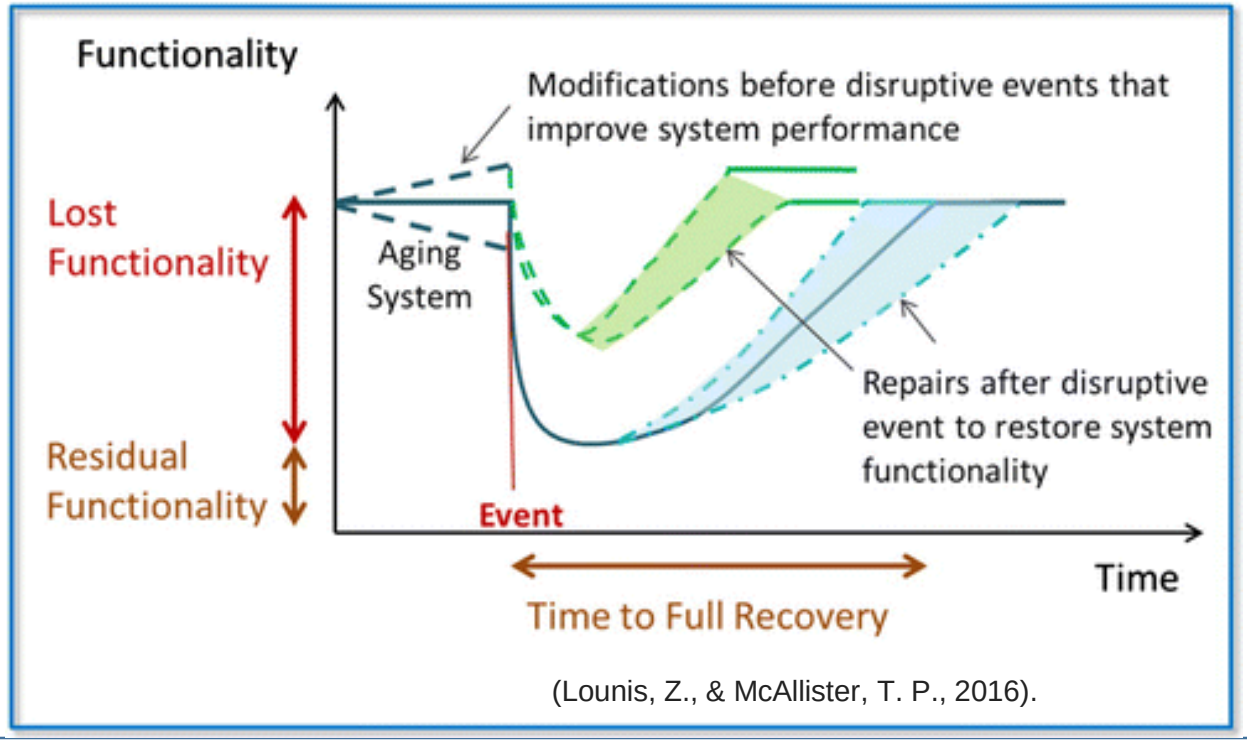


September 12, 2017

Photo taken on September 14, 2017

Hazard Resilience of Infrastructure

- Ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event (NIAC, 2009)
- Ability to prepare for and adapt to changing conditions, and withstand and recover rapidly from disruptions (NIST)



(Lounis, Z., & McAllister, T. P., 2016).

Research Overview

Develop a probabilistic framework for quantifying the resilience of transportation infrastructure subjected to multiple hazards

Outline

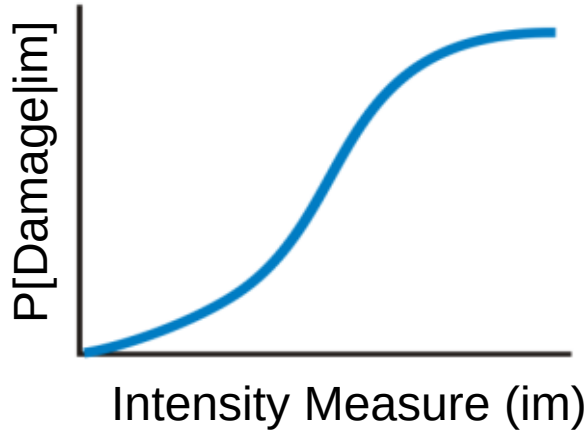
- Vulnerability modeling
- Restoration modeling
- Functionality assessment
- Applications to hurricane and earthquake

Vulnerability Modeling

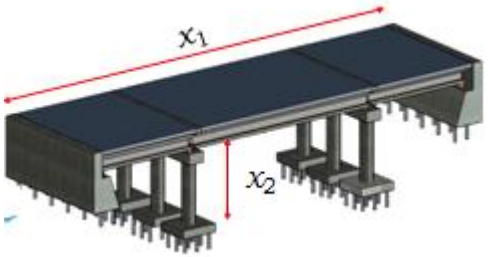
What is a Fragility Model?

Conditional reliability

$$P_f = P[Demand > Capacity \mid im]$$

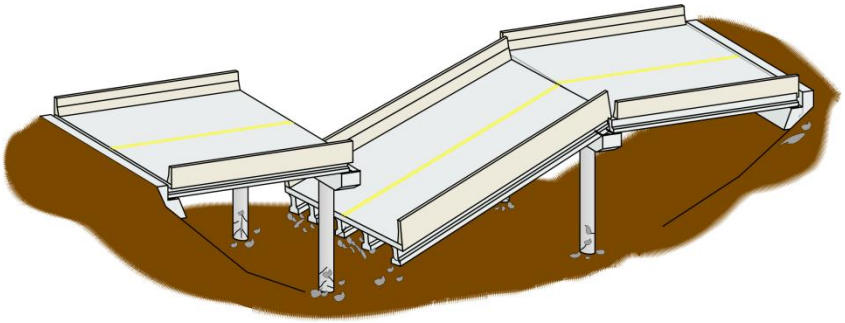


$$P_f = P[Demand > Capacity \mid im, x_1, x_2, ..., x_n]$$



Multi-Threat Fragility Modeling of Bridges

- Dual layer metamodel based parameterized fragility assessment framework
  - Individual Hazards
  - Joint Threats
  - Simultaneous Hazards



Fragility Assessment Framework

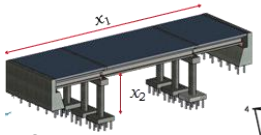
Step 1
Hazard(s) and failure type

- Select IM(s)
- Model loads

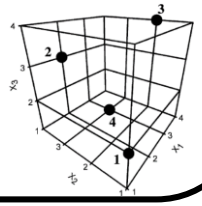
- Identify failure type

Step 2
Parameter selection

- Select bridge parameters and random variables

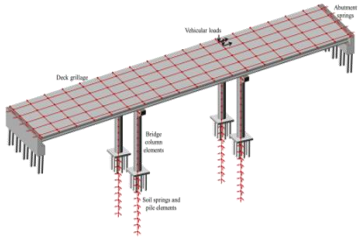


- Perform experimental design



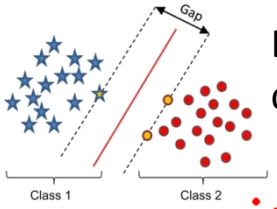
Step 3
Response assessment

- Create FE models

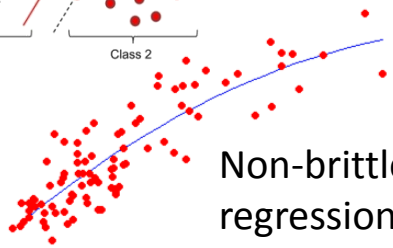


- Evaluate responses

Step 4
Metamodel fitting



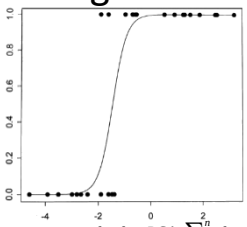
Brittle: classification



Non-brittle: regression

Step 5
Parameterized fragility

- Train logistic regression models

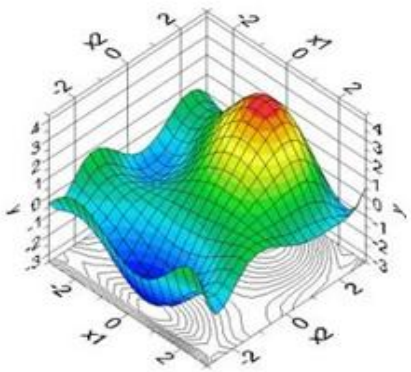


$$P[Damage \mid PGA, x_1, \ldots, x_n] = \frac{e^{\theta_0 + \theta_{PGA} PGA + \sum_{j=1}^{n} \theta_{x_j} x_j}}{1 + e^{\theta_0 + \theta_{PGA} PGA + \sum_{j=1}^{n} \theta_{x_j} x_j}}$$

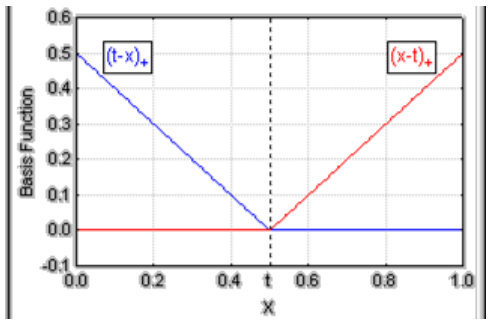
Example Metamodels: Non-brittle failures

- Machine learning techniques permit the use of finite element based non-linear time history analysis

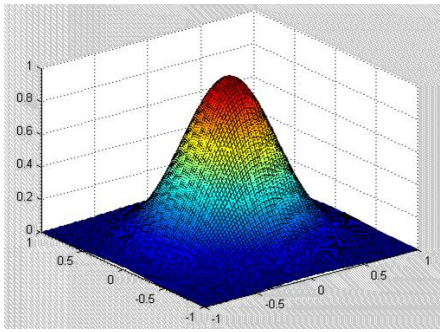
Polynomial Response Surface



Multivariate Adaptive Regression Splines (MARS)



Radial Basis Function

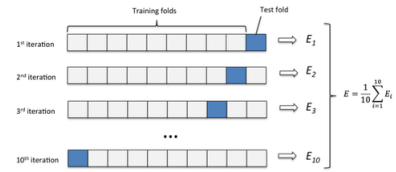


$$RMSE = \sqrt{MSE} = \sqrt{\frac{\sum_{n_p}\left(y_i - \hat{y}_i^2\right)^2}{n_p}}$$

$$R^2 = 1 - \frac{MSE}{\sigma^2}$$

$$RMAE = \frac{\max\left|y_i - \hat{y}_i\right|}{\sigma}$$

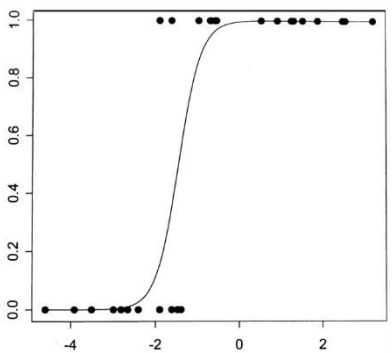
K-fold cross validation



Example Metamodels: Brittle failures

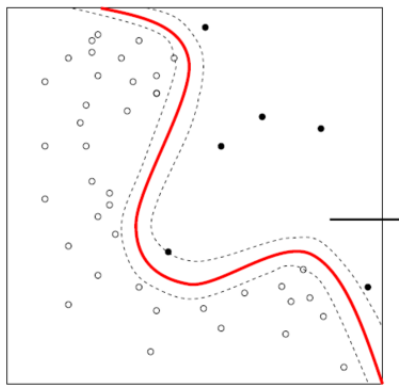
- Machine learning techniques permit the use of finite element based non-linear time history analysis

Logistic Regression

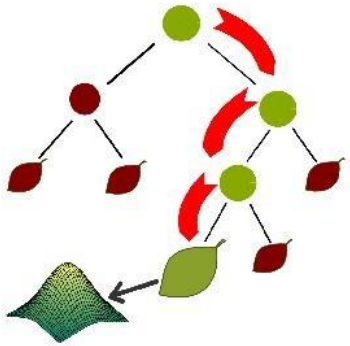


$$P_F = \frac{1}{1+e^{-(\beta_0+\beta_1 Z_c+\beta_2 H_{MAX})}}$$

Support Vector Machines



Random Forests



$$P_F = \text{majority vote}\left\{P_n\left(Z_c, H_{\max}\right)\right\}_1^{N_T}$$

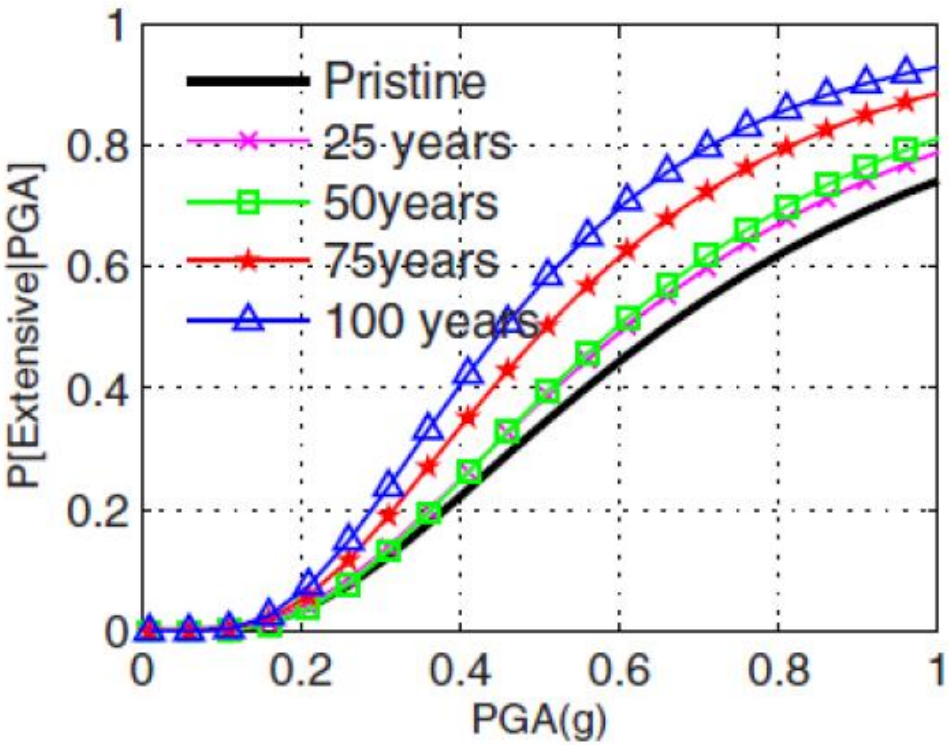
		Predicted	
		Failure	Survival
Actual	Failure	a	b
	Survival	c	d

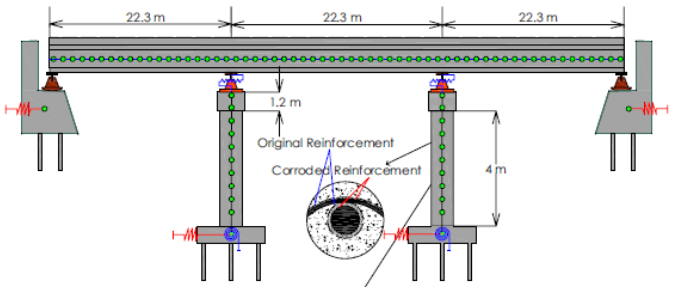
Single Hazard, Joint Threats

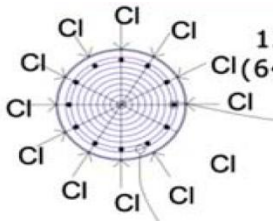
$$Fragility = P[Damage \mid PGA, x_1, \ldots, x_m]$$

- Earthquake and aging fragility

$$P_f(t) = P\left[Demand > Capacity \mid pga, t\right]$$



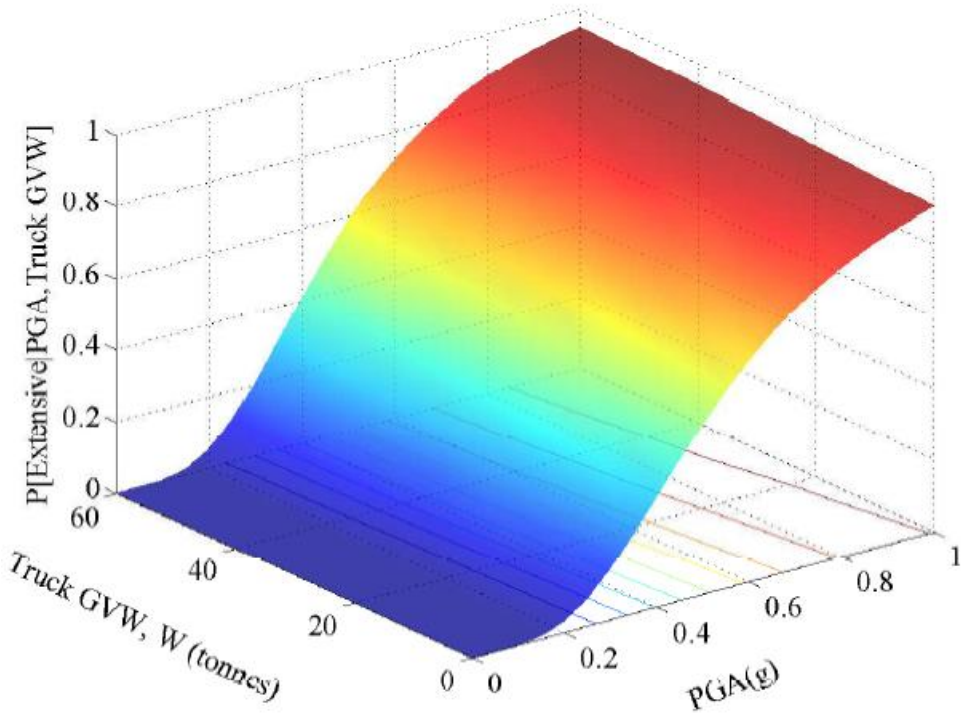


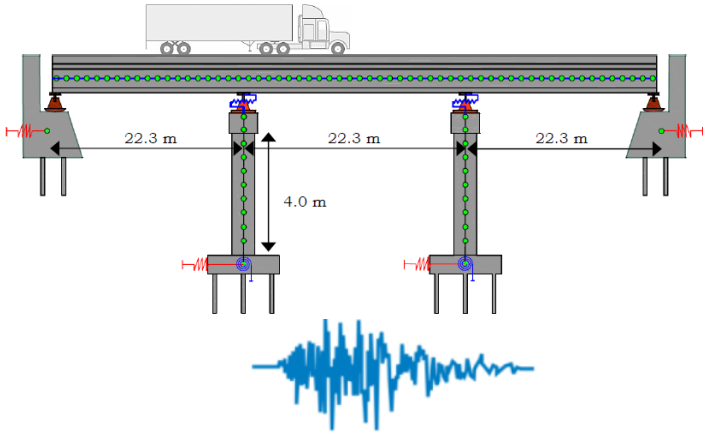


Single Hazard, Joint Threats

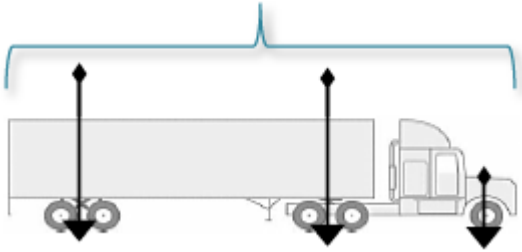
- Earthquake and truck load fragility

$$P_f = P[Demand > Capacity \mid pga, gvw]$$





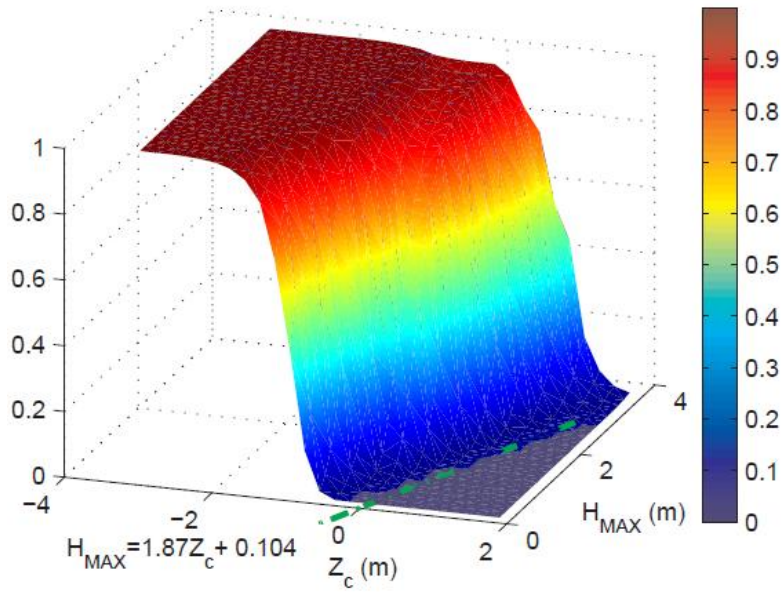
Gross Vehicle Weight (GVW)

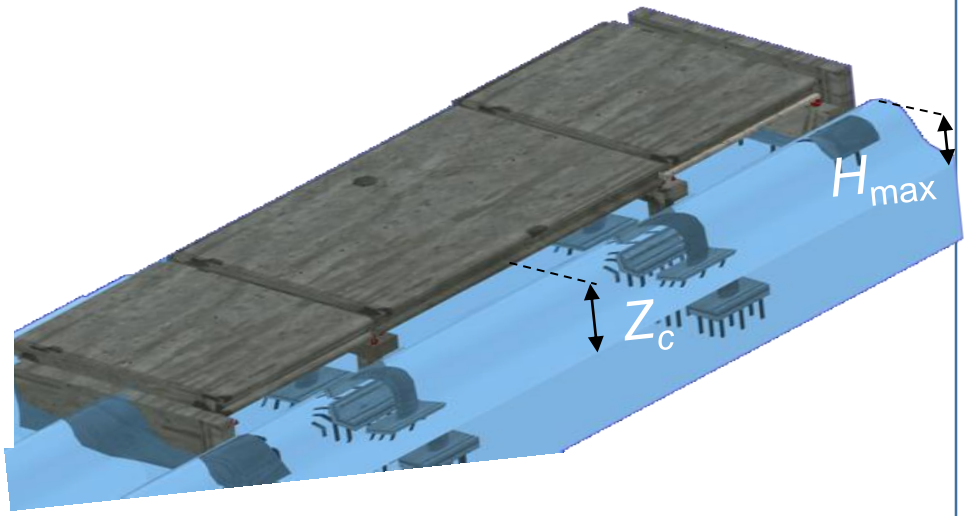


Multiple Concurrent Correlated Hazards

- Storm surge and wave from **hurricane** fragility

$$P_f = P[Demand > Capacity \mid H_{\max}, Z_c]$$





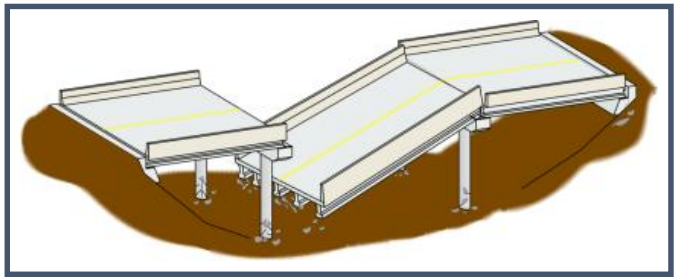
(Ataei and Padgett, 2013)

Restoration Modeling

Need for New Restoration Models

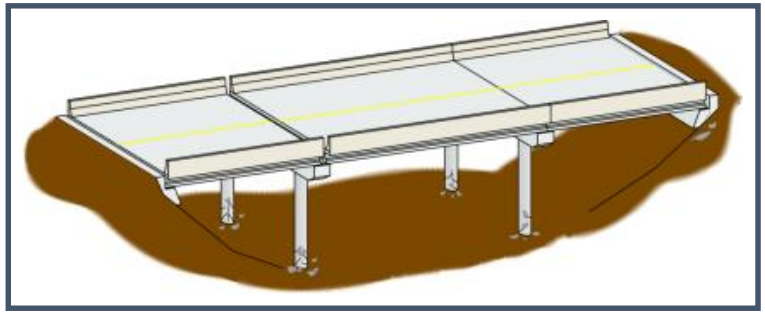
- Damage-functionality relationships for bridges

Collapse damage state



Deck collapse; column hinging; bearing unseating

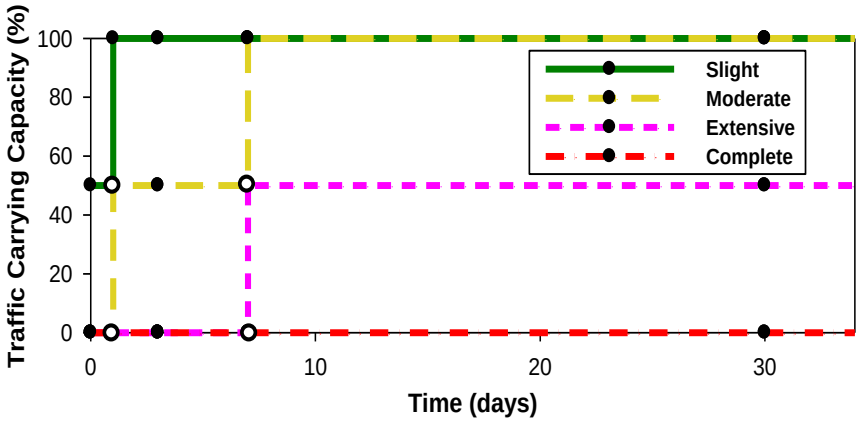
Moderate damage state



Deck misalignment; column cracking

Restoration Modeling

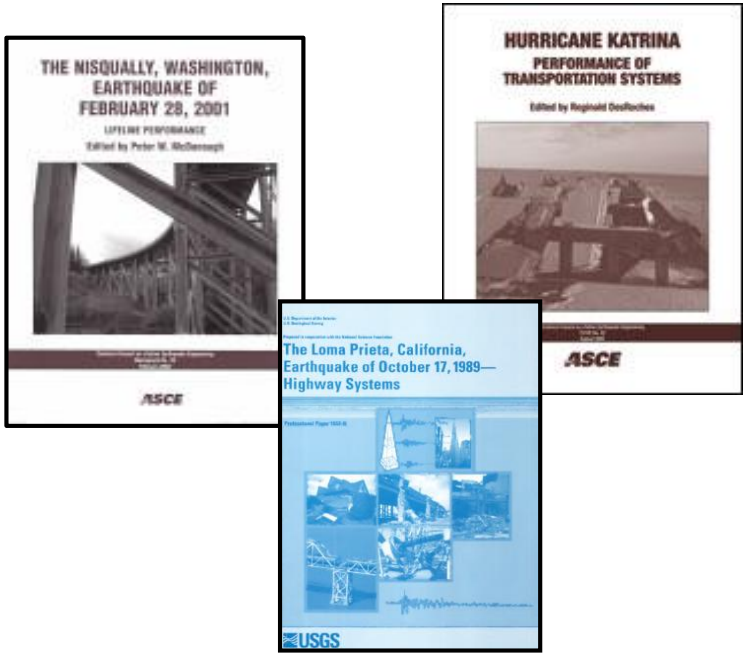
- Existing approaches
  - Expert opinion survey
  - Analytical



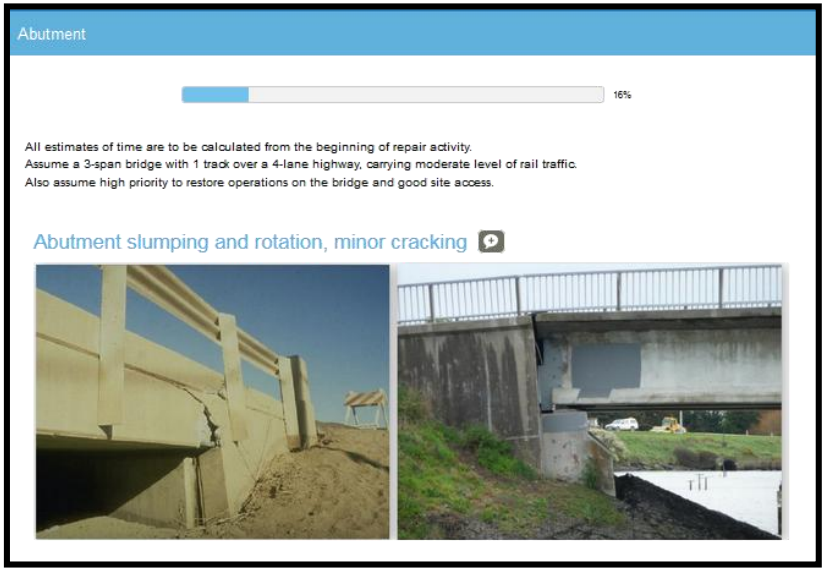
- Current limitations:
  - Generic % functionality or capacity
  - Lacking explicit connection to traffic restrictions
  - Needed for network modeling

How to build a new model?

- Damage-functionality relationships for bridges formed from data
- 2 main sources – empirical and survey based
- Use inputs to train logic tree models



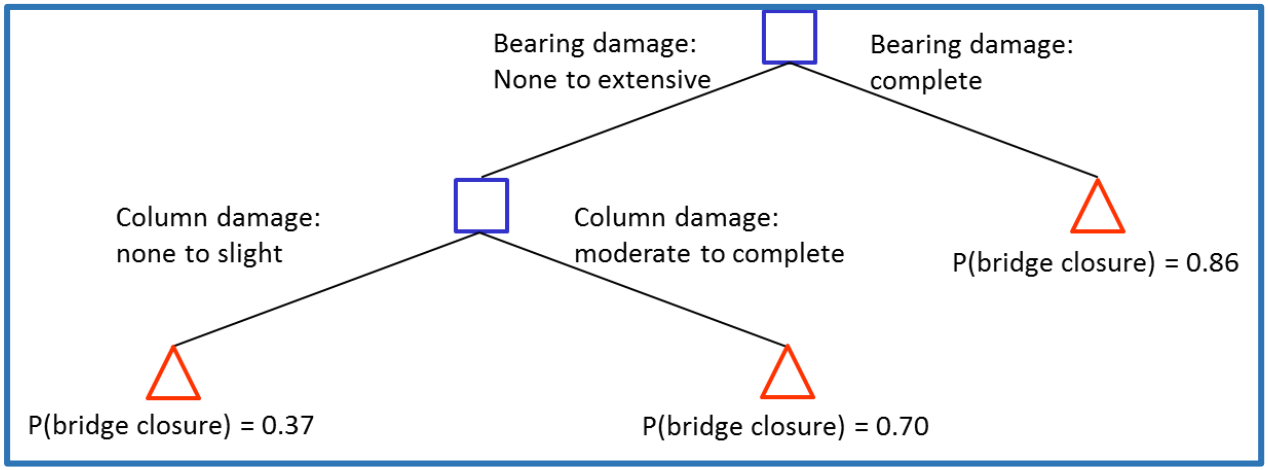
Empirical data from reconnaissance reports

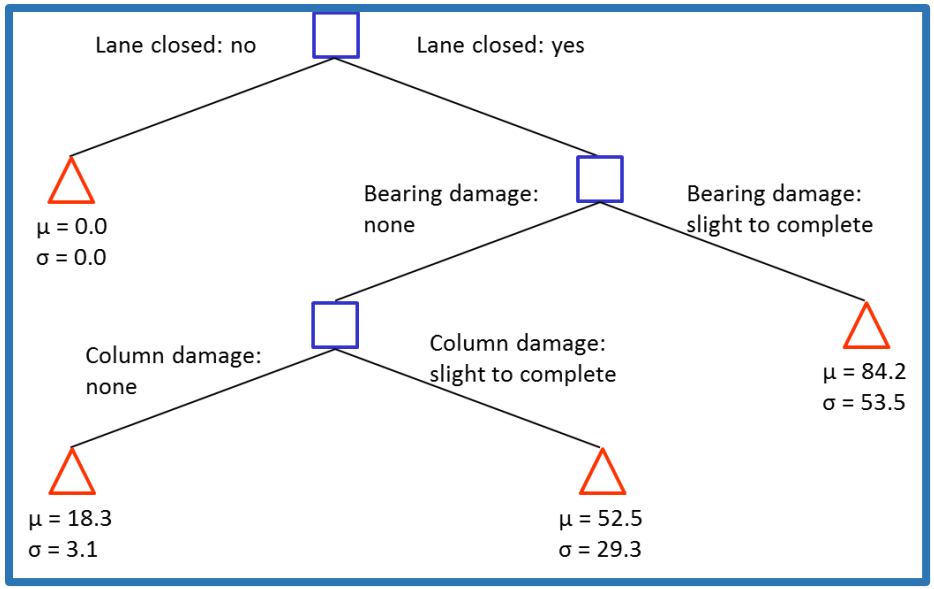


Survey on post event functionality and restoration
Questions on repair actions, repair time as well as traffic and lane restrictions included

Logic Tree Based on Bridge Functionality Data

Example of a trained logic tree: Likelihood of closure





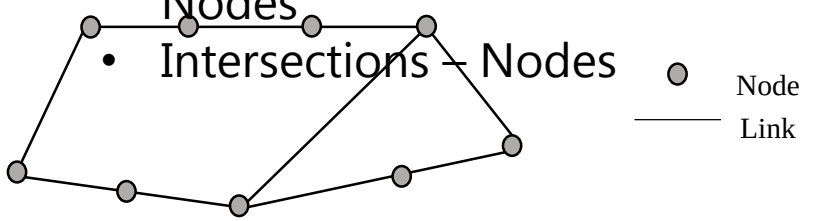
Example of a trained logic tree: Duration of closure

Network Functionality Assessment

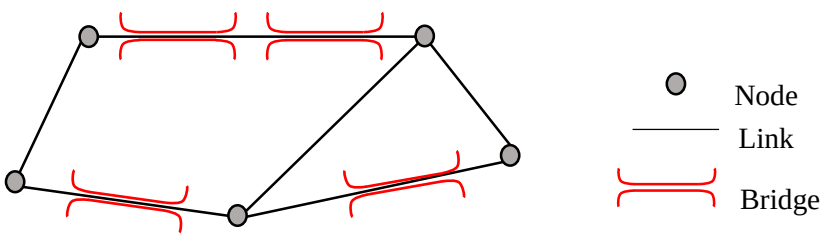
Network Modeling

Regional Network Modeling

- Roads – Links
- Bridges – Links or Nodes
- Intersections – Nodes

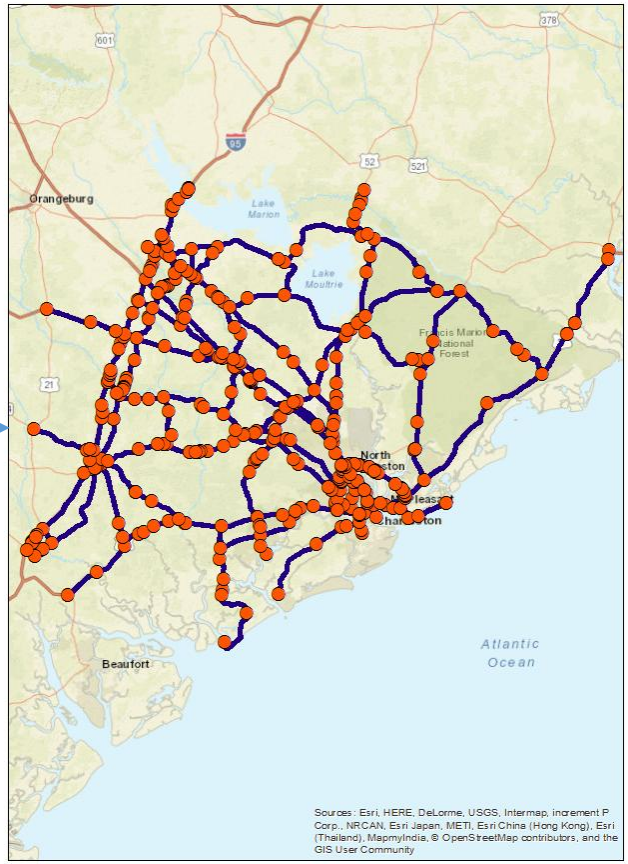


(a) Bridges as nodes



(b) Bridges as part of links

Charleston Road network



Common Network Functionality Metrics

Connectivity between different points of network

Increased travel time across network

Increased travel distance across network

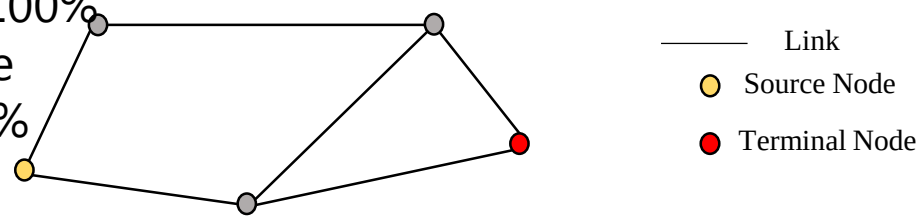
Economic and social loss

Freight demand carried

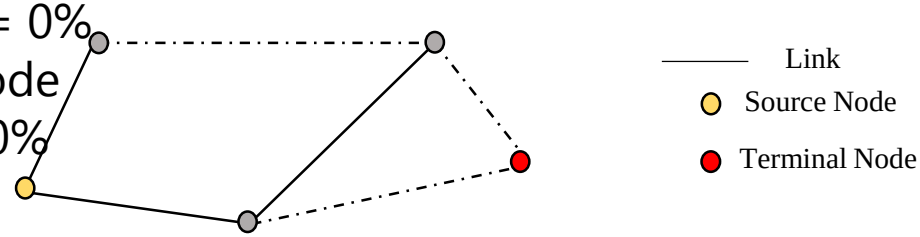
Connectivity Analysis

- Algebraic connectivity – availability of a path from "Source" to "Terminal" or called s-t connectivity
- Optimal for accessibility and evacuation based studies
- Can also be used for all nodes to all nodes connectivity study

s-t connectivity = 100%
All node to all node connectivity = 100%

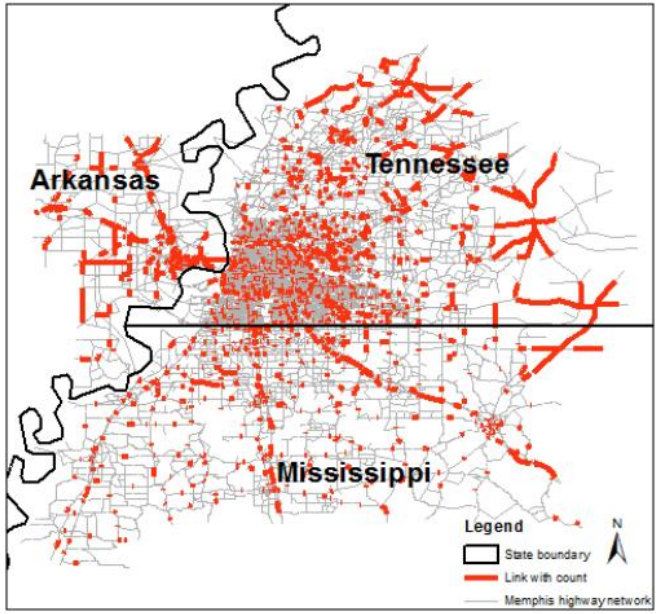


s-t connectivity = 0%
All node to all node connectivity = 60%



Network Flow Analysis

- Travel demand based on Origin-Destination trips
- Traffic flow capacity modeling similar to FHWA and DOT models
- Disruptions and congestions leading to increased travel time and travel distance across network
- Assumptions on equilibrium model for travel time
- Opportunities for improvement

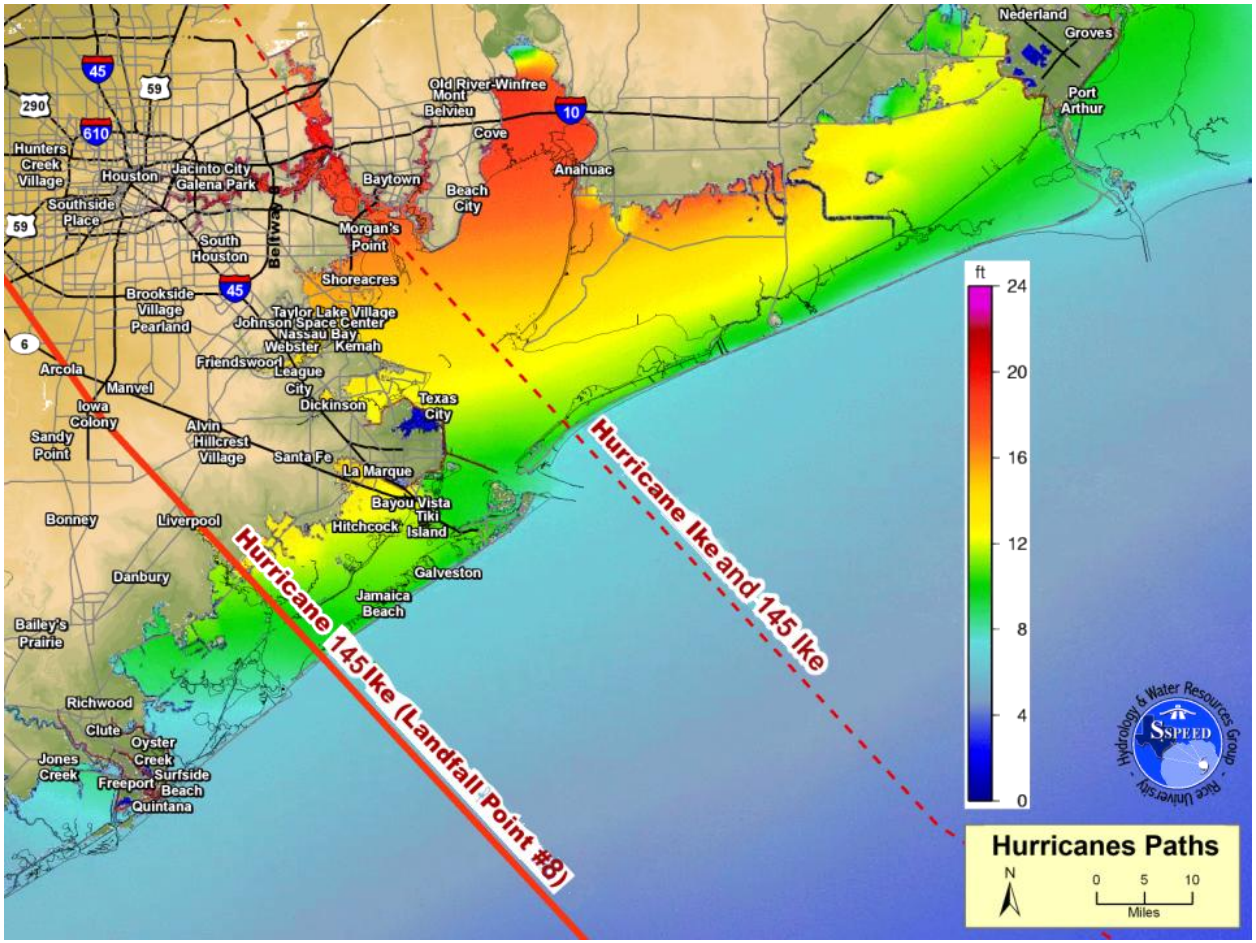


Memphis MPO Travel Demand Model

Regional Applications of Resilience Modeling Tools

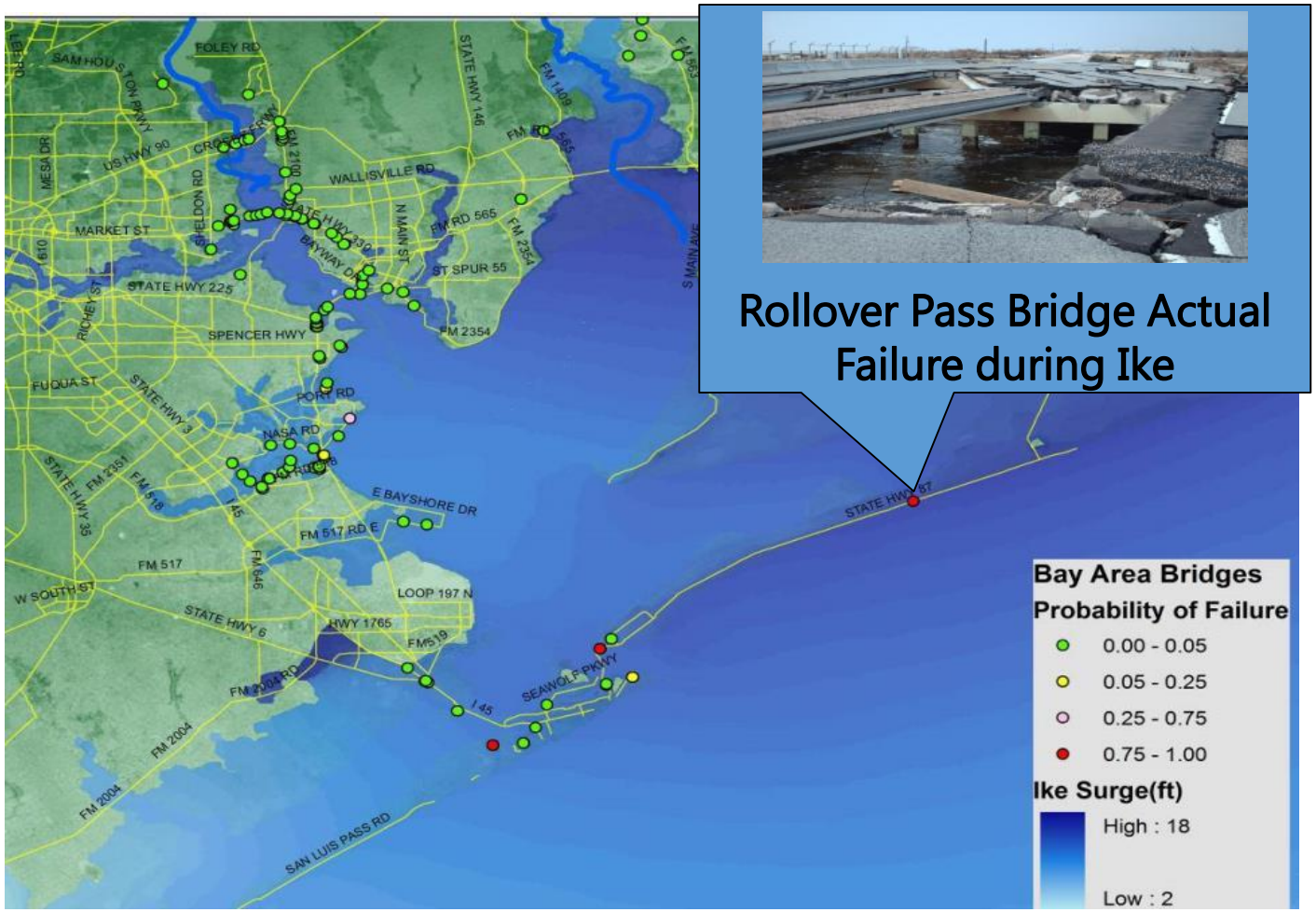
Regional Hurricane Vulnerability Assessment

Houston and Galveston: Hurricane Ike Scenario



Bridge Vulnerability

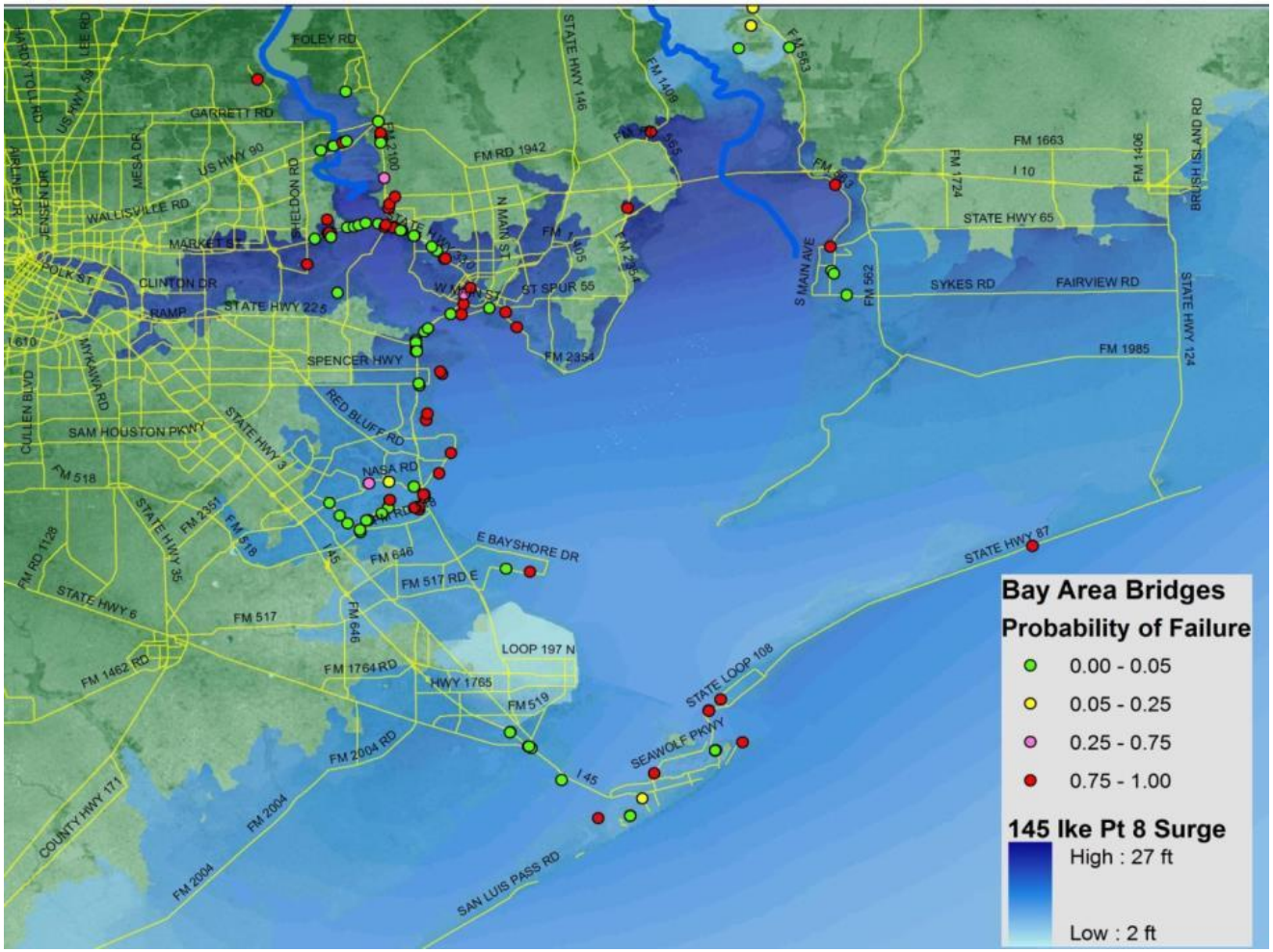
Houston and Galveston: Hurricane Ike Scenario



Bridge Vulnerability

Houston and Galveston: 145 Ike Pt 8 Scenario

Failure Probability (%)	No. of Bridges
0-5	69
5-25	7
25-75	8
75-100	52

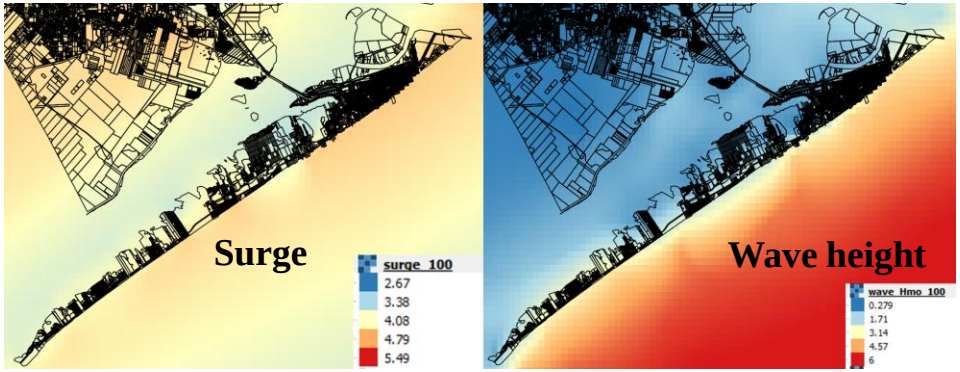


Transportation Network Assessment

Galveston, TX: Hurricane Storm Scenario

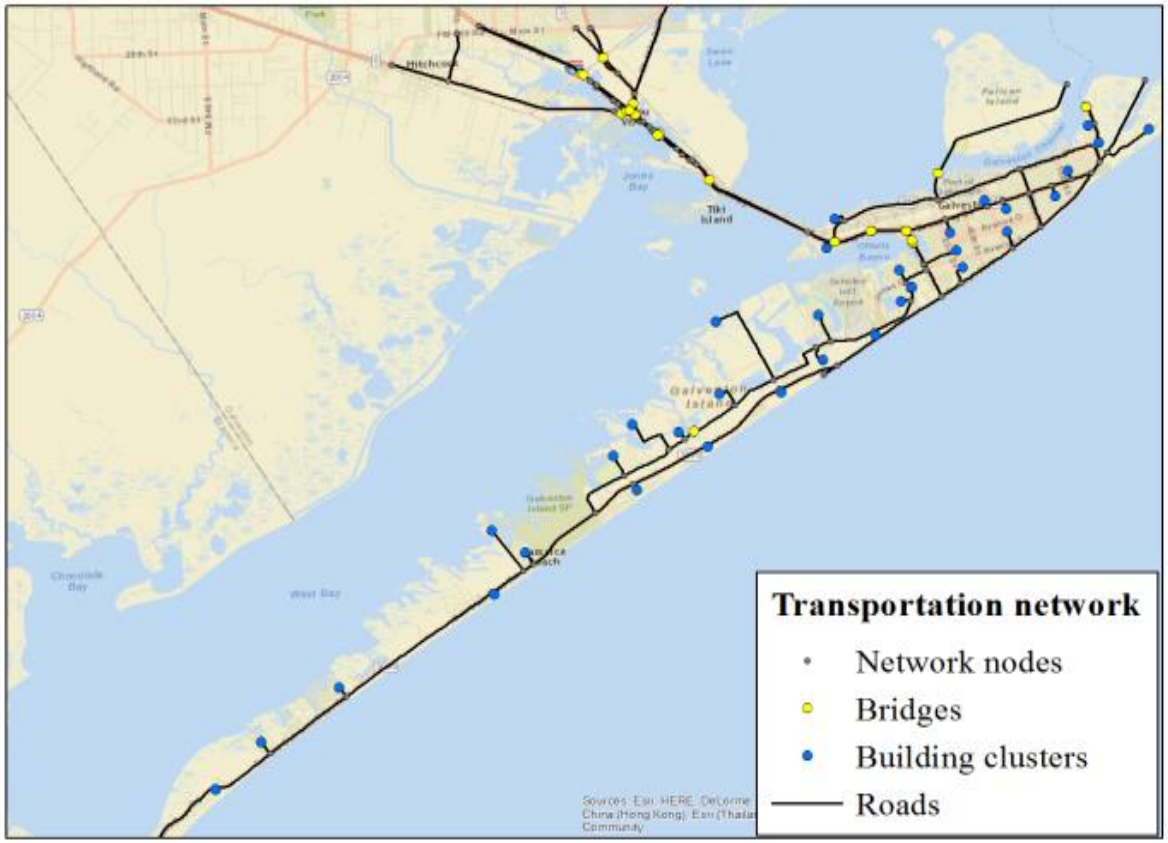
Hurricane scenarios investigated:

- Storm realizations that "resemble" different intensities
  - Scenario 1 → Low intensity level ~ 100 yr
  - Scenario 2 → High intensity level ~ 500 yr
- Surrogate model-based hurricane hazard characterization
- Trained based on dataset from US Army Corps Engineers (USACE)



Transportation Network Model

Galveston Highway Network



Network details:

- 163 roadway links
- 144 nodes
  - 25 bridge nodes
  - 32 building cluster nodes → Nodes that accessibility is assessed
- Currently **only** bridge nodes can fail
- In the future incorporation of potential roadway link failure

Bridge Vulnerability

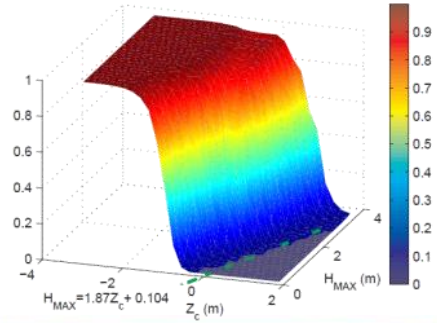
Fragility Model (Ataei and Padgett 2013):

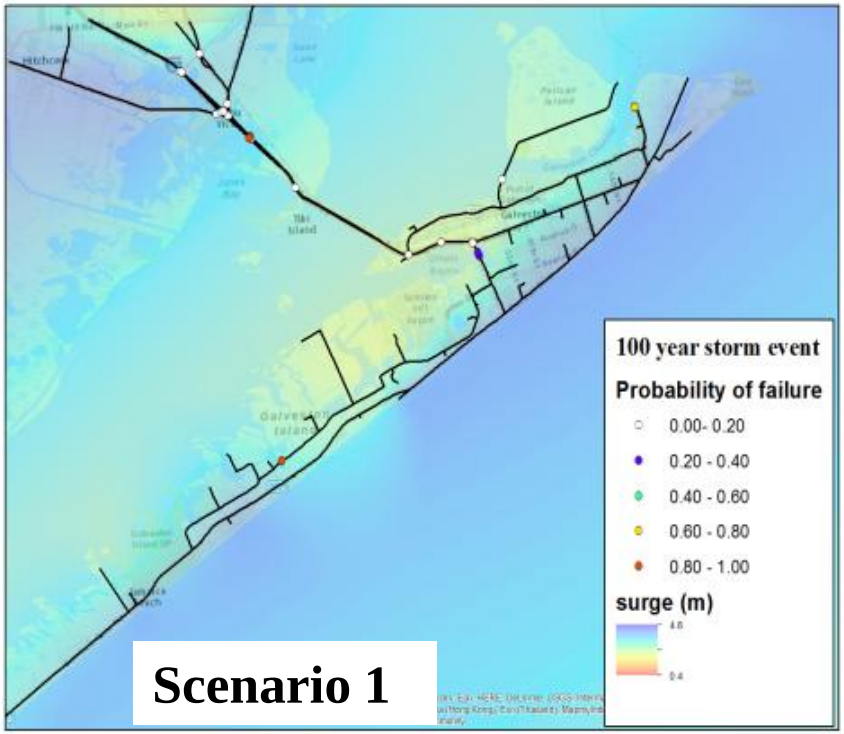
P[fail] = P[bridge deck unseating] = $f(H_{max}, Z_c, SW)$

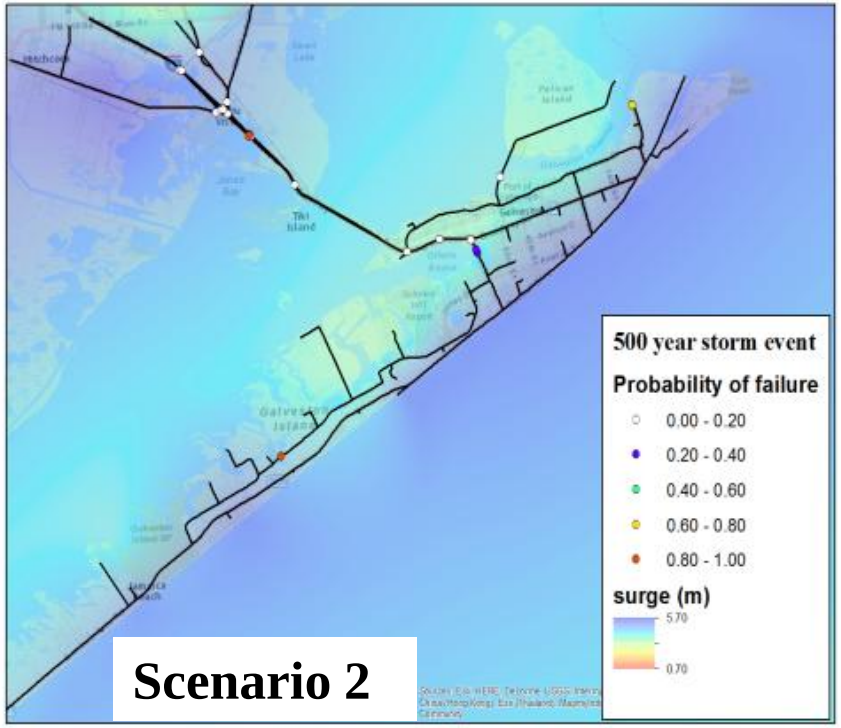
H_{max} : maximum wave height

Z_c : relative surge elevation

SW: span mass

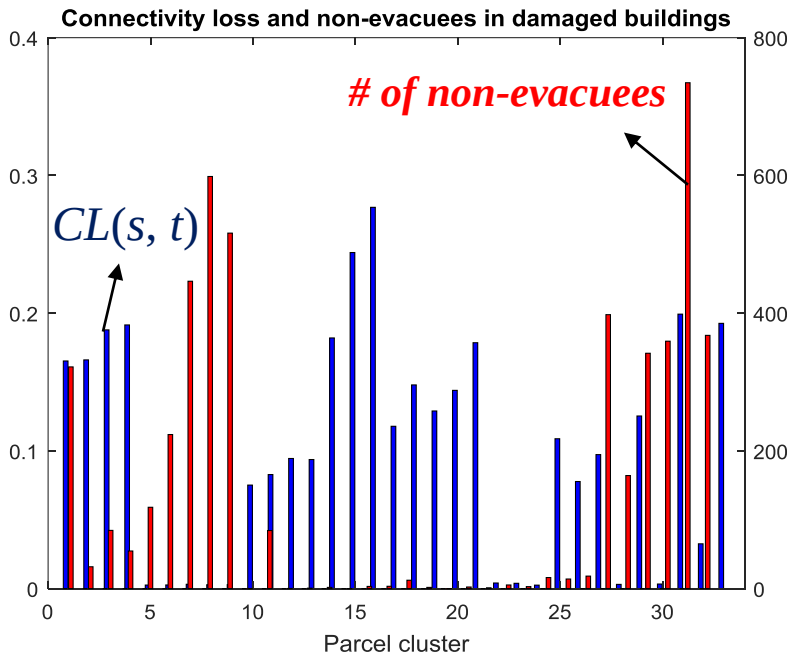




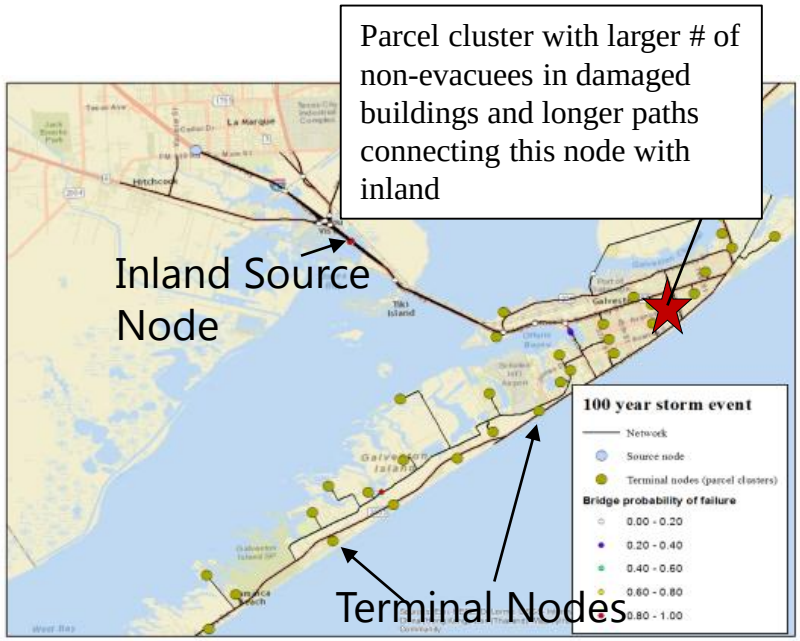


Network Functionality

Network Functionality Metric: Node accessibility or connectivity loss (CL) from inland to non-evacuees in damaged buildings on coast



(collaboration w/Rosenheim, Peacock, Johnson, Cox)

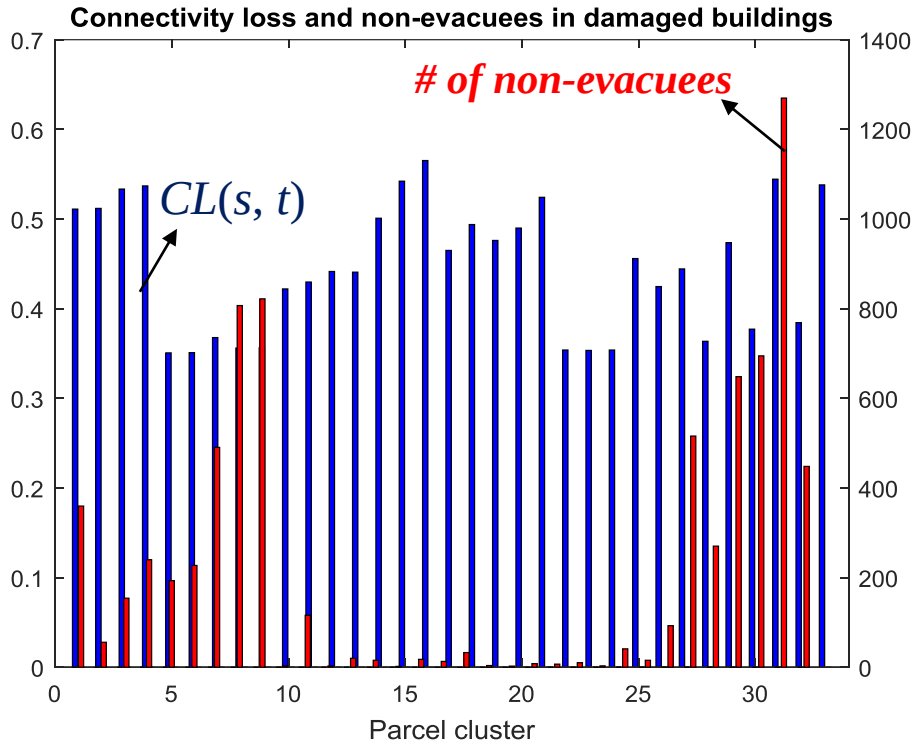


Low Intensity (Scenario 1)

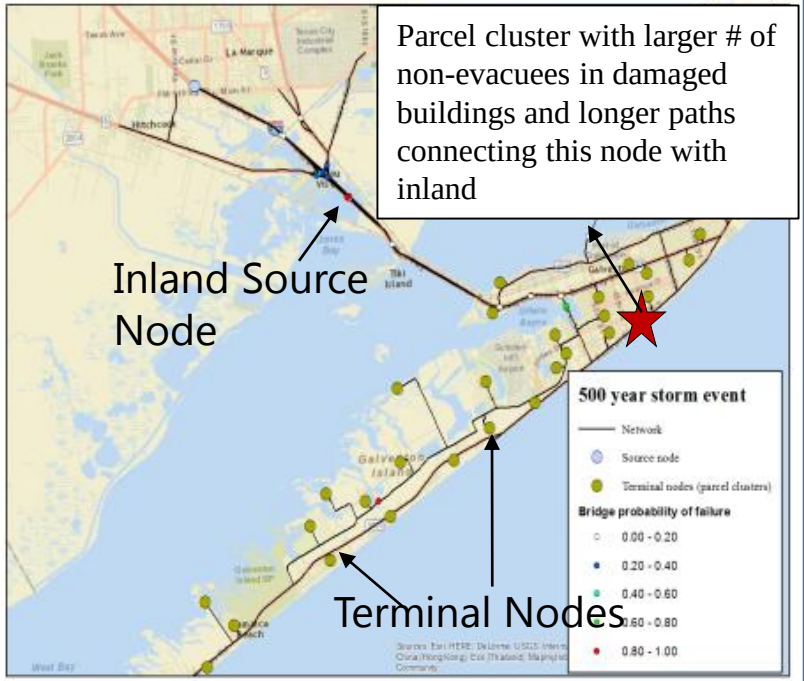
Probability of non-connectivity: $P_F(s, t)$ = **0.1%** for all terminal nodes

Network Functionality

Network Functionality Metric: Node accessibility or connectivity loss (CL) from inland to non-evacuees in damaged buildings on coast



(collaboration w/Rosenheim, Peacock, Johnson, Cox)



High Intensity (Scenario 2)

Probability of non-connectivity: $P_F(s, t)$ = **35%** for all terminal nodes

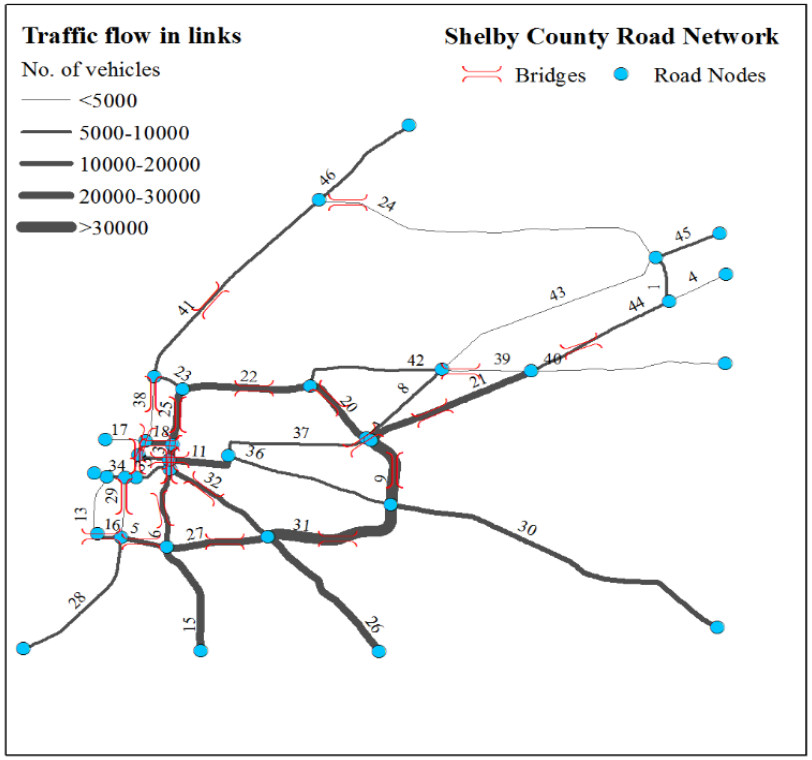
Transportation Network Resilience Assessment

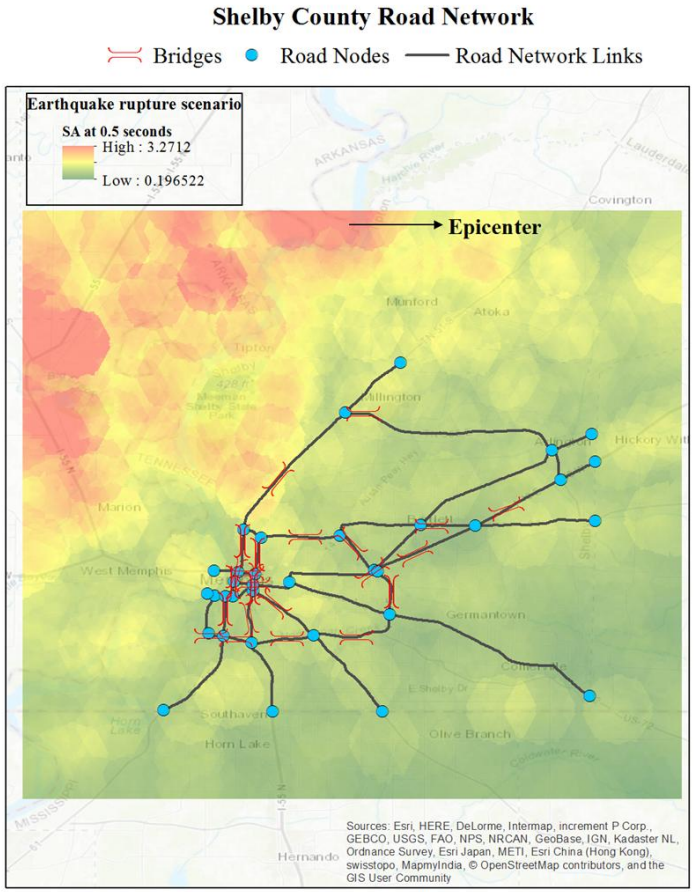
Shelby County, TN: Earthquake Scenario

Earthquake scenario investigated:

- 7.5 moment magnitude scenario with the rupture site along the New Madrid Fault

Before earthquake

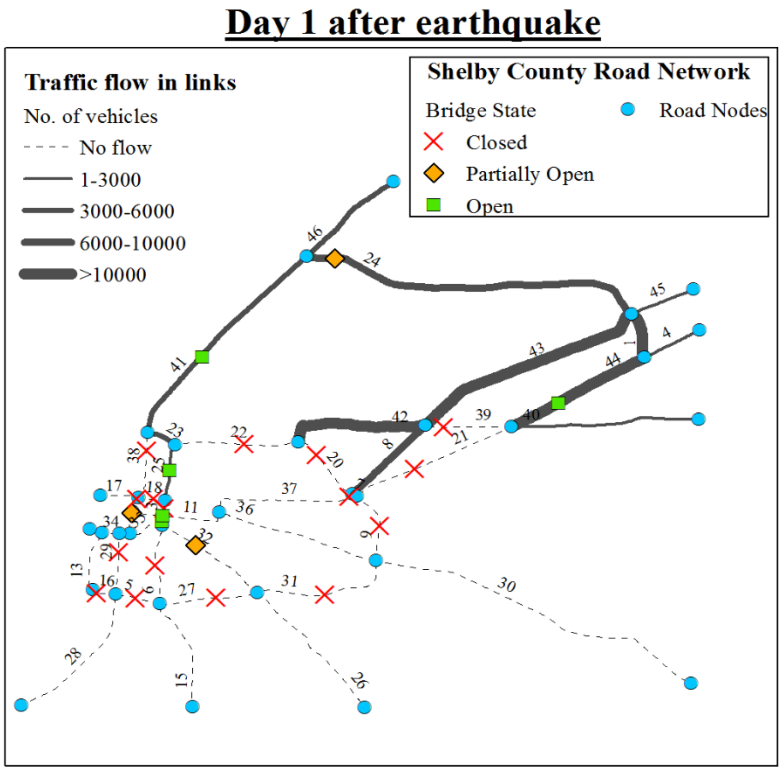


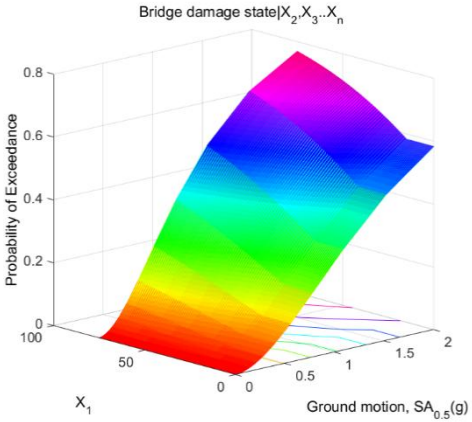


Bridge Vulnerability and Network Disruption

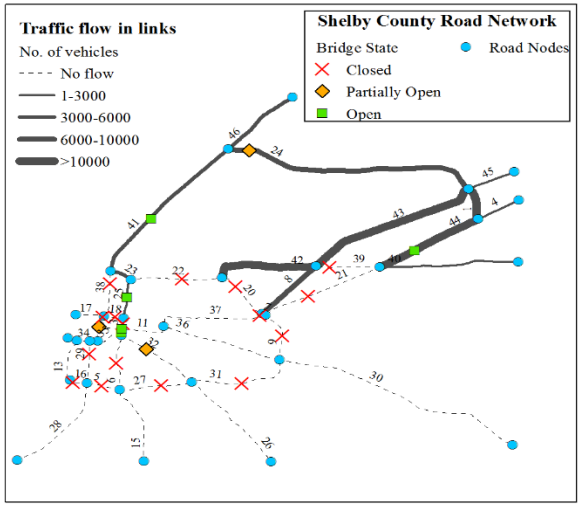
$$P_f = P(Demand > Capacity | SA_{0.5}, x_1, x_2 .. x_n)$$

x_1, x_2, ..x_n – Bridge parameters such as column height, deck width

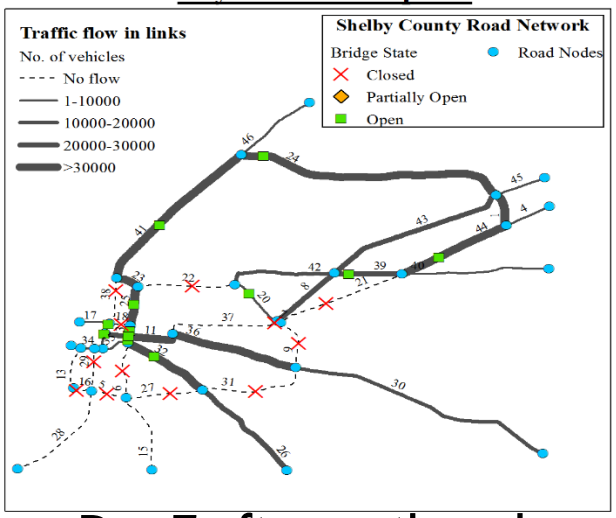




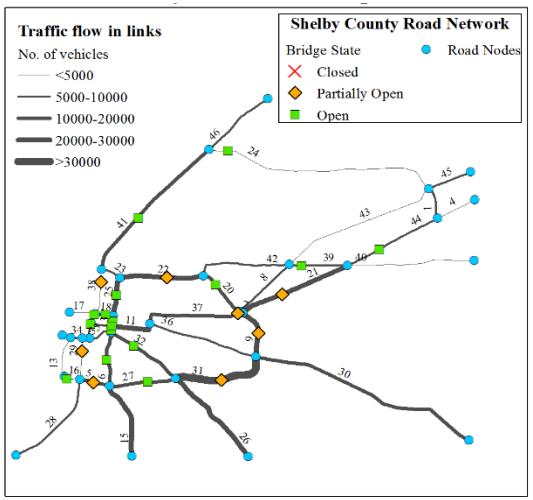
Network Functionality Evolution: Traffic flow



Day 1 after earthquake



Day 7 after earthquake

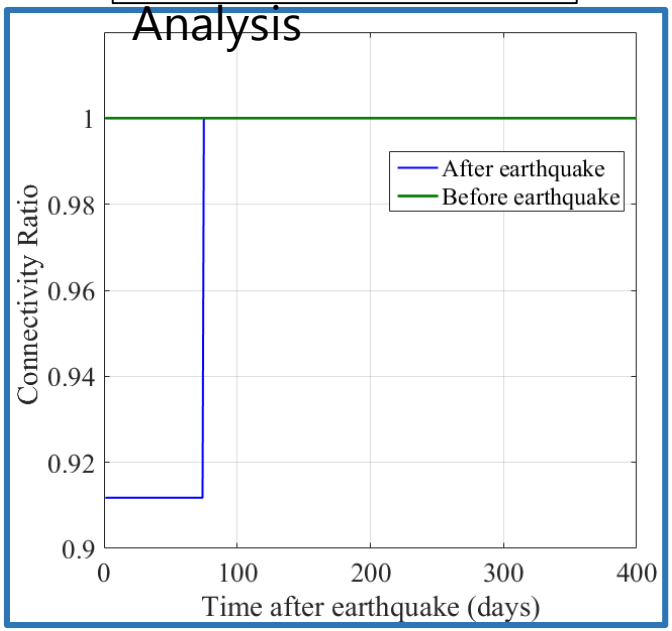


Day 240 after earthquake

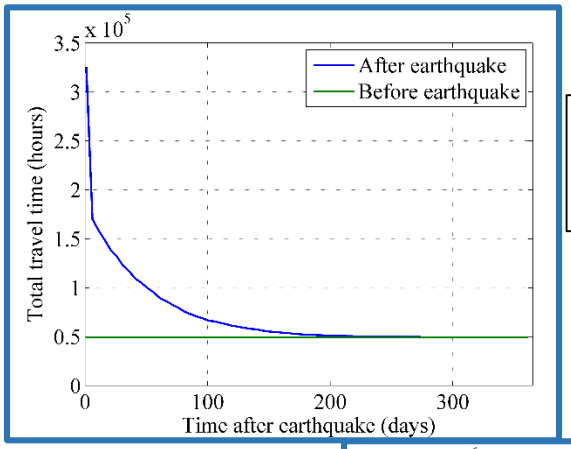
Network Functionality Evolution

Network Functionality Metric: Node connectivity ratio, Travel time in network and Travel distance in network

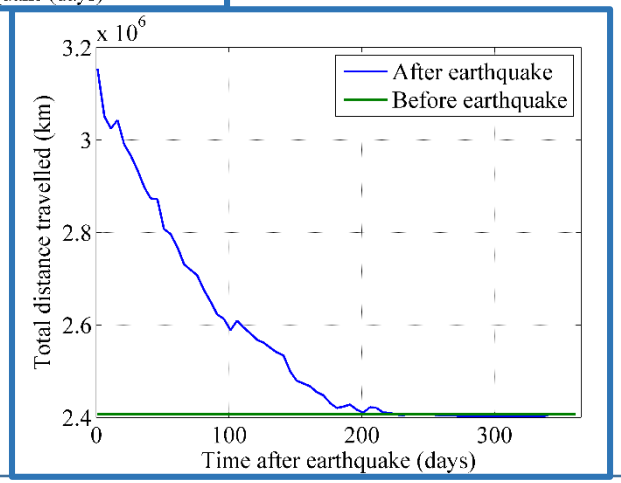
Connectivity Analysis



$$Connectivity\ Ratio = \frac{No.\ of\ Connected\ Nodes}{Total\ Nodes}$$



Network Flow Analysis



Conclusions

- Three important inputs for resilience assessment:
  - Vulnerability assessment
  - Restoration modeling
  - Network functionality modeling
- Resilience assessment can support risk mitigation and pre-event planning or post-event response and recovery
- Future work to address limitations, e.g. resource constraints, damage to other components, etc.
- Opportunity for extension to other civil infrastructure, threats and exposure conditions

THANK YOU

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GRA and Post-Doctoral opportunities available