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ATLSS Advanced Technology for Large Structural Systems Engineering Research Center

Disaster Resilience Analysis Through Multiple Temporal and Spatial Scales

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NHERI Researchers Workshop:
Advanced Simulation for Natural Hazards Mitigation

Lehigh University – December 5-6, 2016

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ATLSS Advanced Technology for Large Structural Systems Engineering Research Center

National Science Foundation
Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP)
"Probabilistic Resilience Assessment of Interdependent Systems"

Pennsylvania Infrastructure Technology Alliance
"Processing high-resolution industrial recovery time-series for infrastructure resilience analysis"

Lehigh University
P.C. Rossin College of Engineering and Applied Science
Department of Civil and Environmental Engineering
ATLSS Engineering Research Center

Resilience

«The term "resilience" means 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.»

[Presidential Policy Directive 21 – Critical Infrastructure Security and Resilience (2013)]

Resilience

Risk

Structural Safety and Reliability

Hazard → Damage probability → Consequences → Recovery

Disaster Management & Long Term Losses

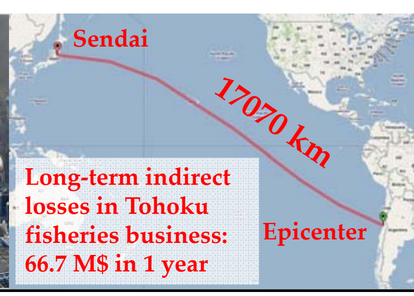
Extreme event occurs
e.g. earthquake, hurricane, tsunami

Time

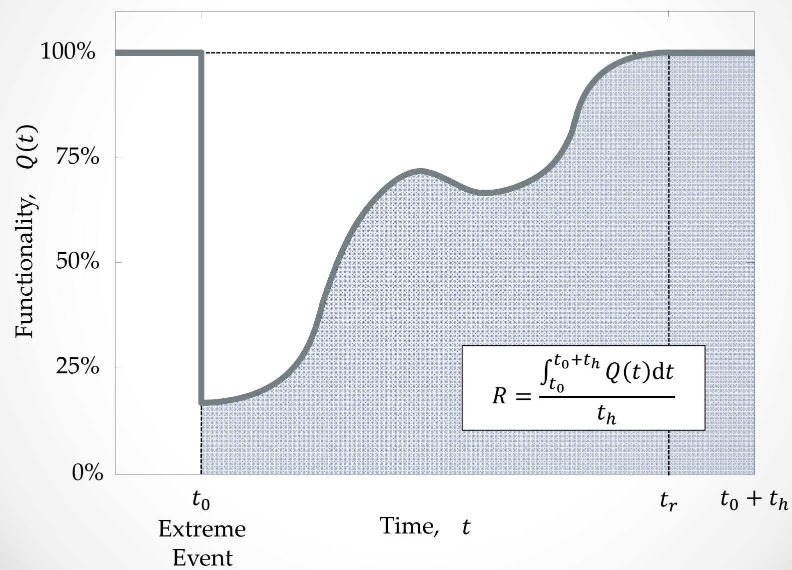
Immediate Losses

Losses due to inefficient disaster response

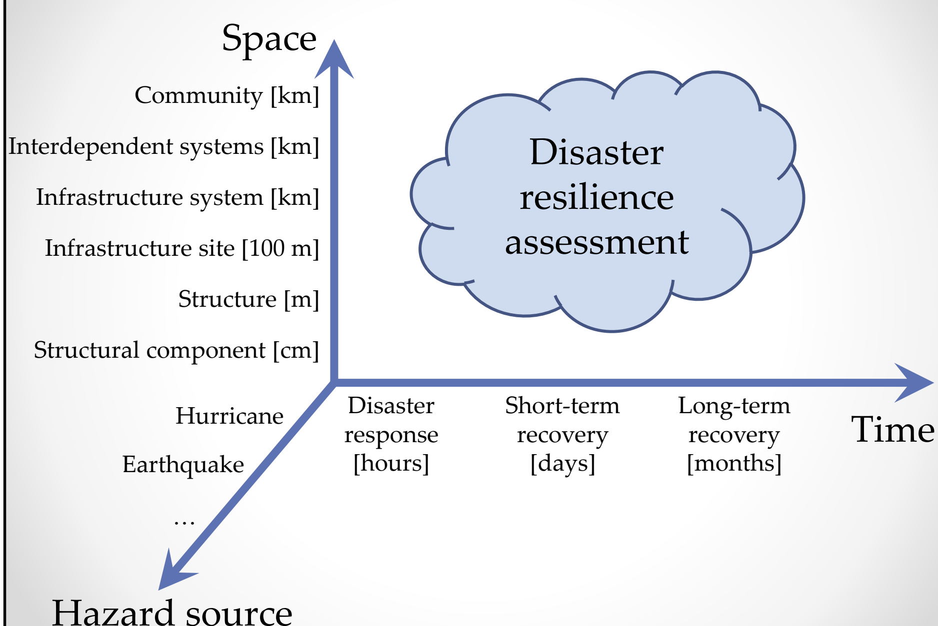
Losses due to long term reduction of functionality



Resilience is about functionality

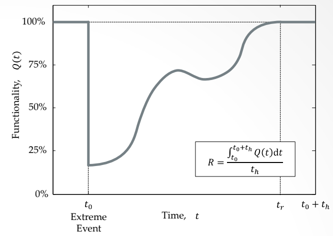


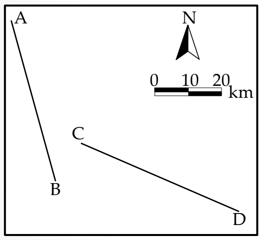
Resilience is multifaceted



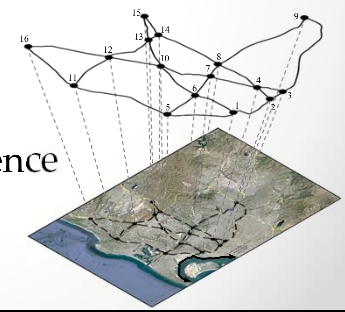
Outline

Introduction





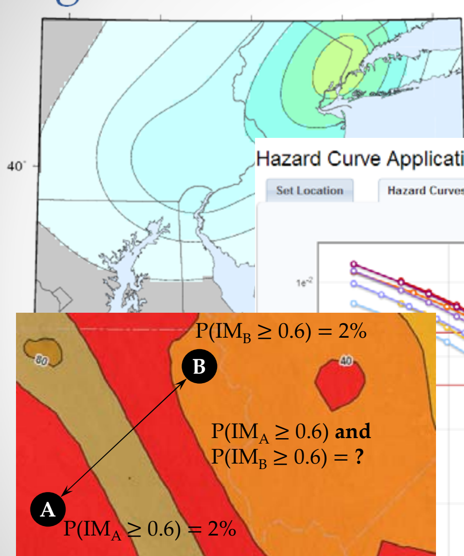
Regional hazard modeling

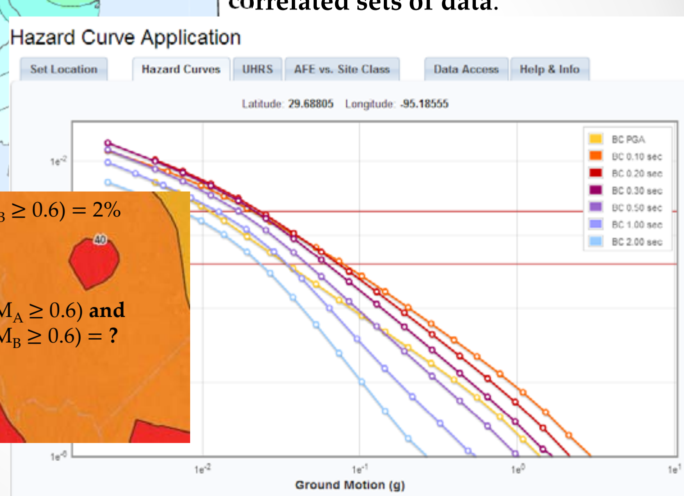


Transportation network resilience

Regional hazard modeling

Hazard maps (e.g., seismic from USGS) provide information on one site.
For **regional analyses**, we need to have **correlated sets of data**.





Source: USGS

Correlated hazard

Assess the correlation

Very appealing, because it gives high control.

Usually requires strong assumptions or simplifications.

- Covariance matrix estimation
- Autocorrelation fitting
- Approximate analytical models

Smart scenarios selection

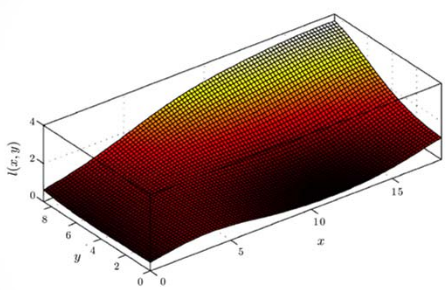
Select a suite of scenario events that, in an ensemble sense, matches the probability of exceedance at a grid of locations.

- Matching of the marginal distribution is imposed
- Correlation is provided (*hopefully*) by the fact that scenarios are real or realistic.

- Hazard-consistent sampling
- K-means clustering
- Optimization-based approaches

Intensity maps as random fields

Observation:
The IM is a 2D random field, non-Gaussian and non-homogeneous.



- ➢ Can we simulate few truly representative samples?
- ➢ How can we match the correlation?
- ➢ Can we even assess the correlation… ?
- ➢ Is there a framework that can do all this in an automated way?

Functional Quantization

IM Maps

Optimal representation of:			
	Gaussian	non-Gaussian	random functions
	stationary	non-stationary	
	uni-dimensional	multi-dimensional	

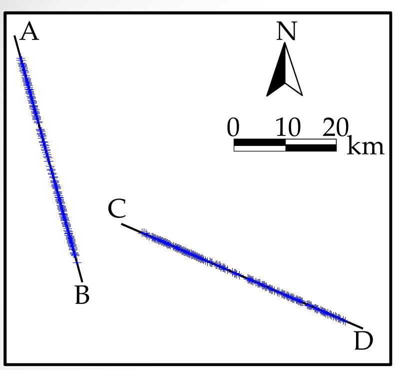
with a **small-to-moderate** number of samples

$$N = \frac{t_{available}}{t_{single\ run}}$$

Hazard Quantization (HQ)

[Christou, Bocchini & Miranda (2016). Optimal representation of multi-dimensional random fields with a moderate number of samples: application to stochastic mechanics. *Probabilistic Engineering Mechanics*.]

Numerical application

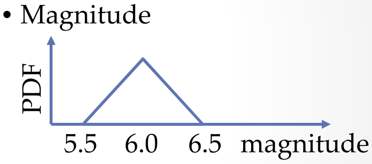


Known faults
× Center of rupture

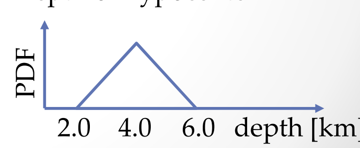
Attenuation relation & rupture
Abrahamson and Silva (1997)

Probabilistic characteristics

- Location of epicenter:
  Fault AB: 50% Fault CD: 50%
  Position along fault uniformly distributed
- Magnitude

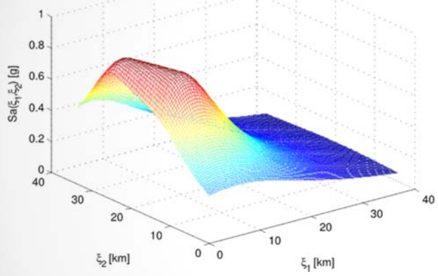


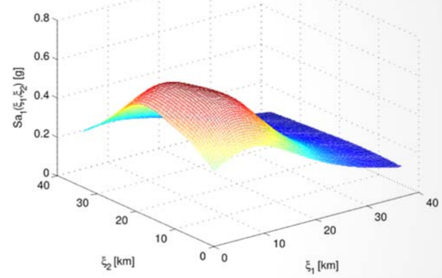
- Depth of hypocenter



Numerical application

Median $S_a(\xi_1, \xi_2, T = 0.1s)$
[g]



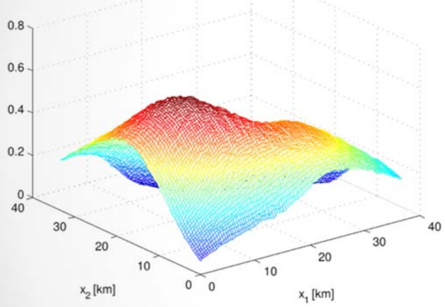


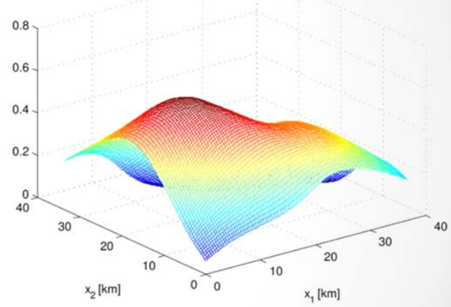
One random sample

Associated quantum
$N = 50$

Numerical application: hazard consistency

Probability of exceedance $P[S_a(T = 0.1s) > 0.4g]$



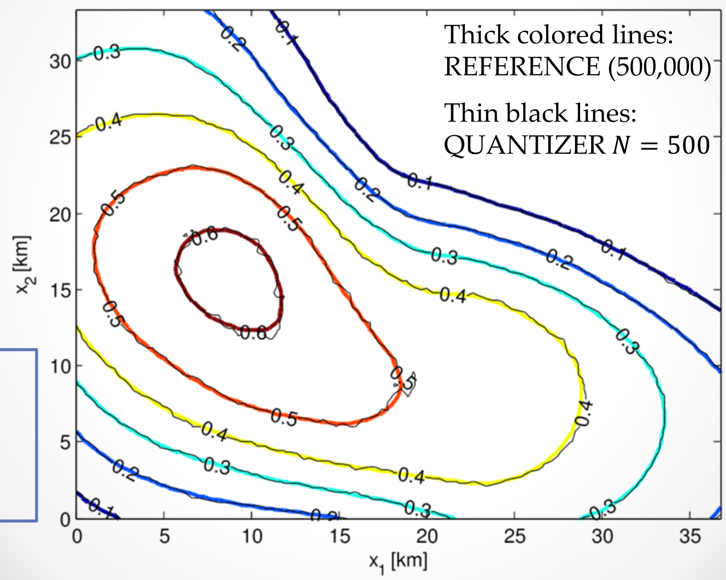


Approximamation
(quantizer with
$N = 500$)

Reference solution
(500,000 samples)

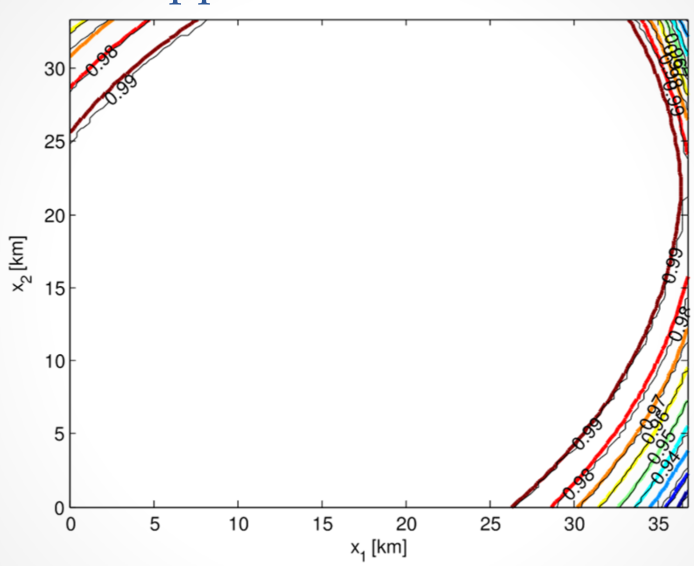
Numerical application: hazard consistency

Probability of exceedance $P[S_a(T = 0.1s) > 0.4g]$



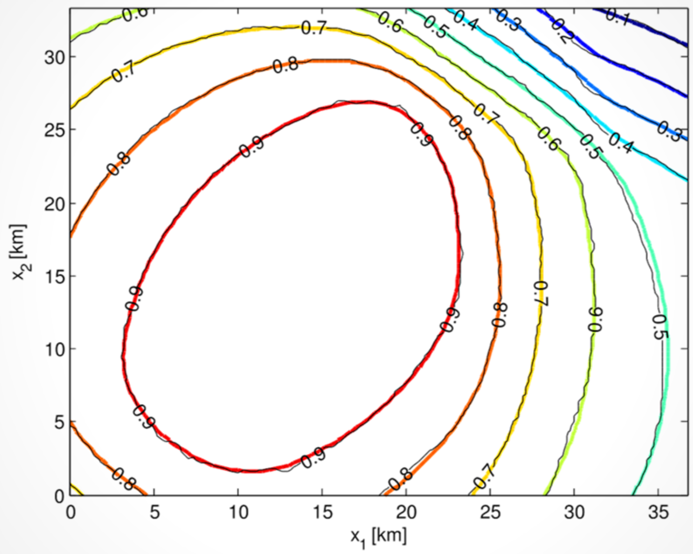
Similar results also for other periods

Numerical application: hazard consistency



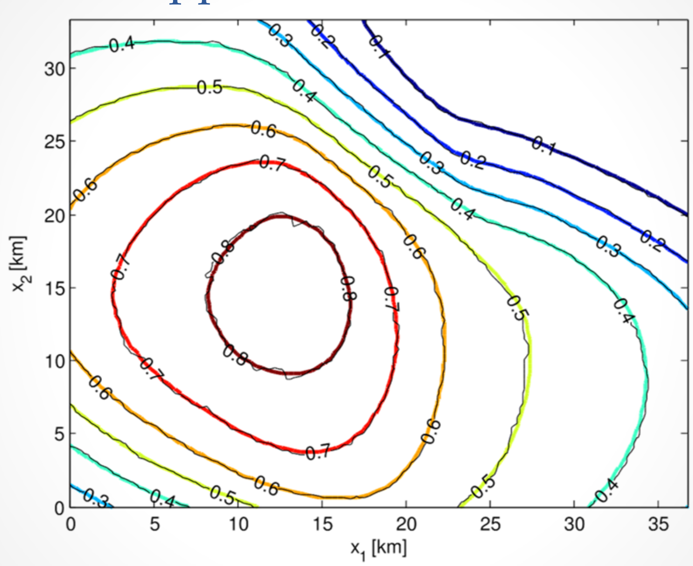
Probability of exceedance $P[S_a(T = 0.1s) > 0.1g]$

Numerical application: hazard consistency



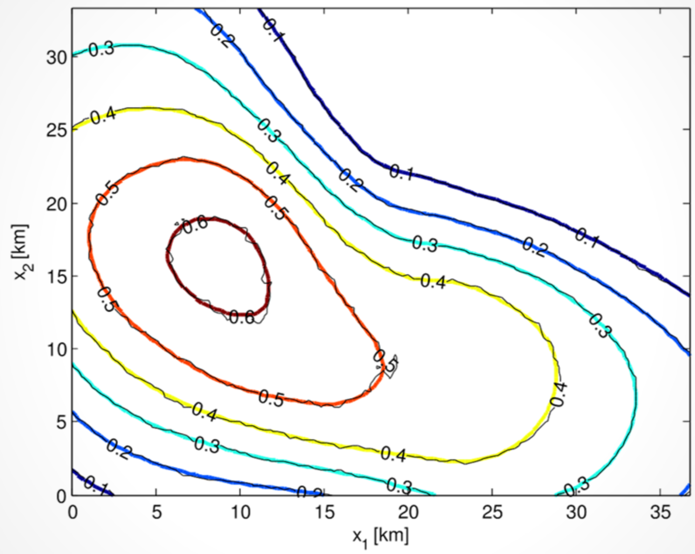
Probability of exceedance $P[S_a(T = 0.1s) > 0.2g]$

Numerical application: hazard consistency



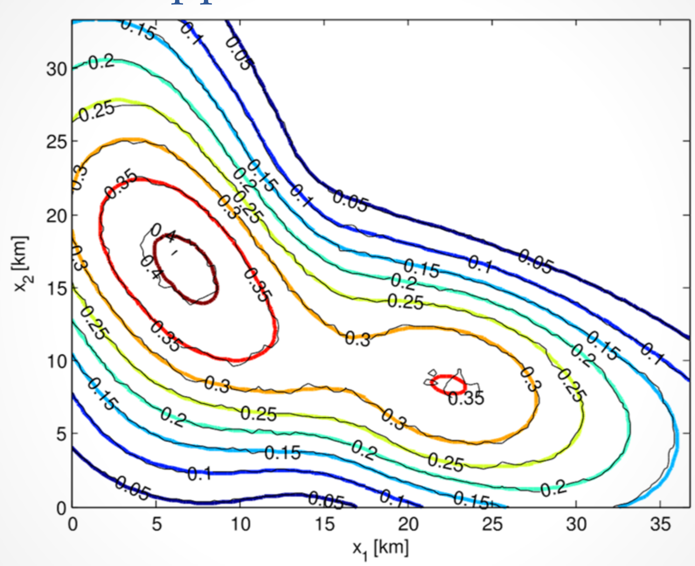
Probability of exceedance $P[S_a(T = 0.1s) > 0.3g]$

Numerical application: hazard consistency



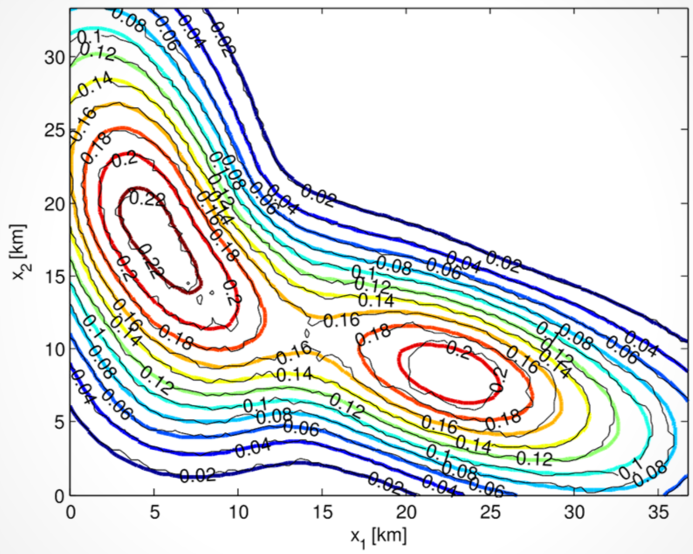
Probability of exceedance $P[S_a(T = 0.1s) > 0.4g]$

Numerical application: hazard consistency



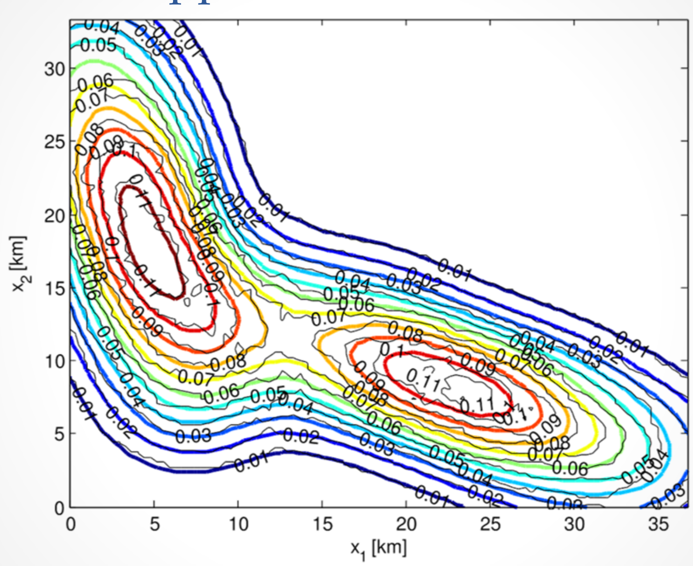
Probability of exceedance $P[S_a(T = 0.1s) > 0.5g]$

Numerical application: hazard consistency



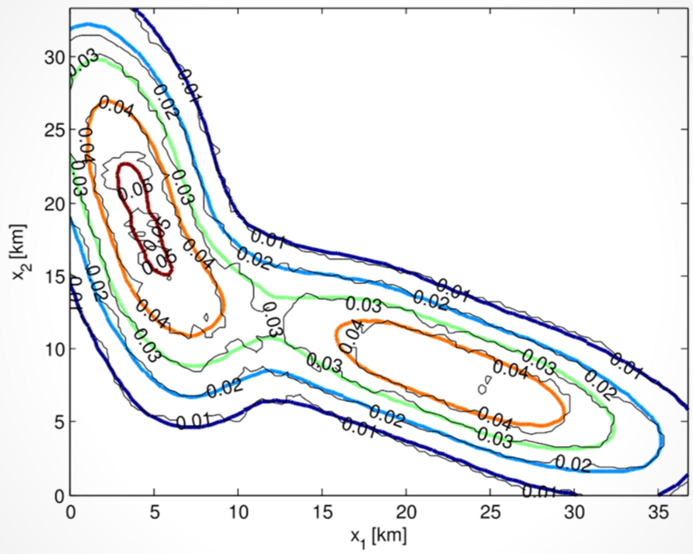
Probability of exceedance $P[S_a(T = 0.1s) > 0.6g]$

Numerical application: hazard consistency



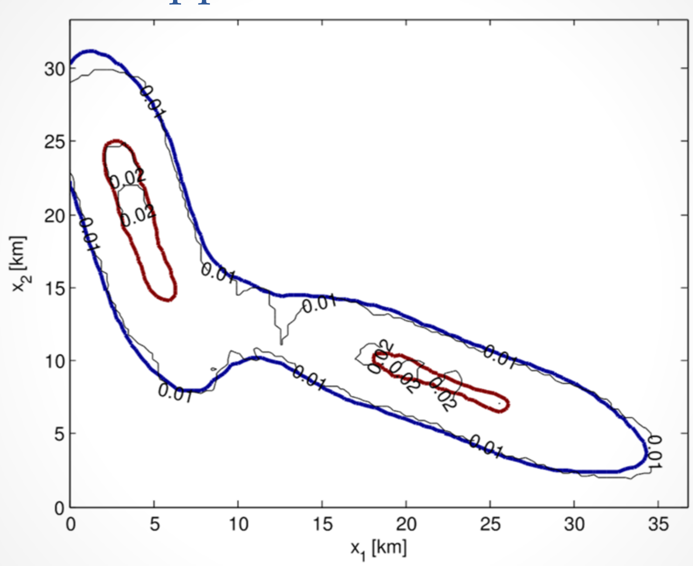
Probability of exceedance $P[S_a(T = 0.1s) > 0.7g]$

Numerical application: hazard consistency



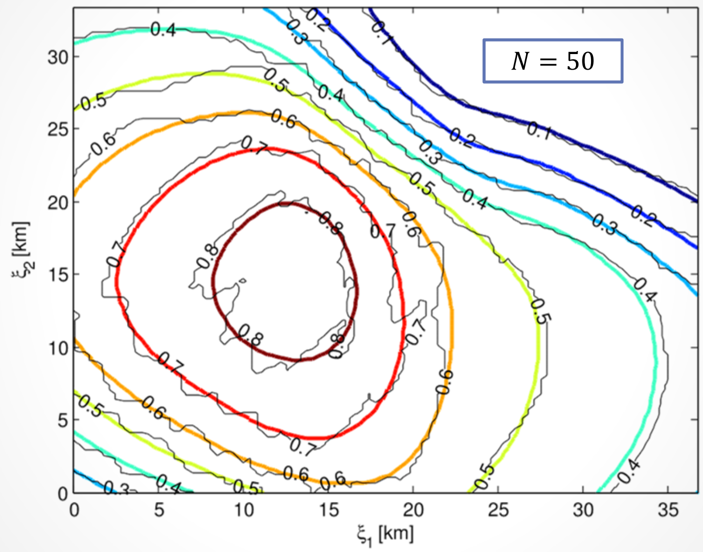
Probability of exceedance $P[S_a(T = 0.1s) > 0.8g]$

Numerical application: hazard consistency



Probability of exceedance $P[S_a(T = 0.1s) > 0.9g]$

Numerical application: hazard consistency



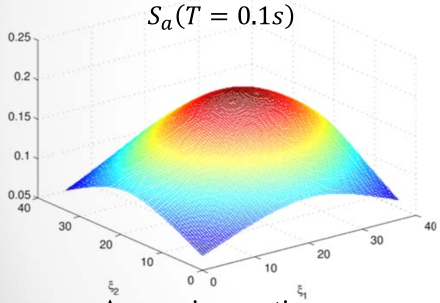
Probability of exceedance $P[S_a(T = 0.1s) > 0.3g]$

Numerical application: correlation

The field is non stationary, so the autocorrelation is a 4D function.

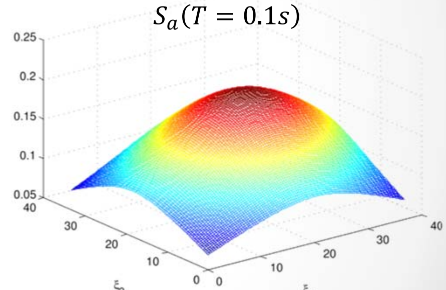
To plot it, we actually computed it only on "strips" of the field.

Autocorrrelation function of $S_a(T = 0.1s)$



Approximamation (quantizer with $N = 500$)

Autocorrrelation function of $S_a(T = 0.1s)$



Reference (500,000)

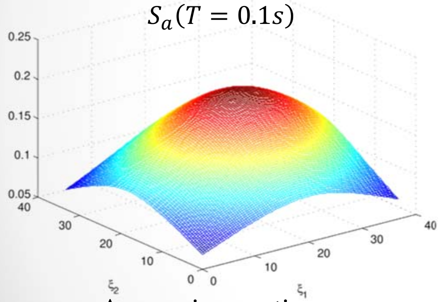
Similar results for other periods and for other strips

Numerical application: correlation

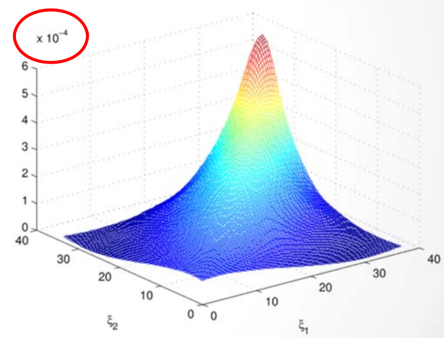
The field is non-stationary, so the autocorrelation is a 4D function.

To plot it, we actually computed it only on "strips" of the field.

Autocorrrelation function of $S_a(T = 0.1s)$



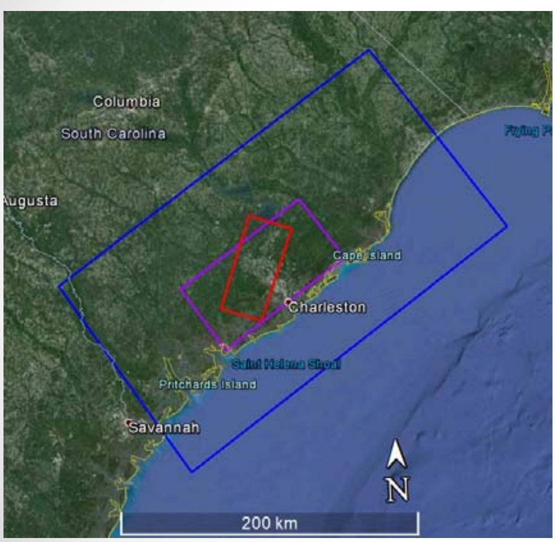
Approximamation (quantizer with $N = 500$)



Difference: Approximation - Reference

Similar results for other periods and for other strips

Numerical application: South Carolina

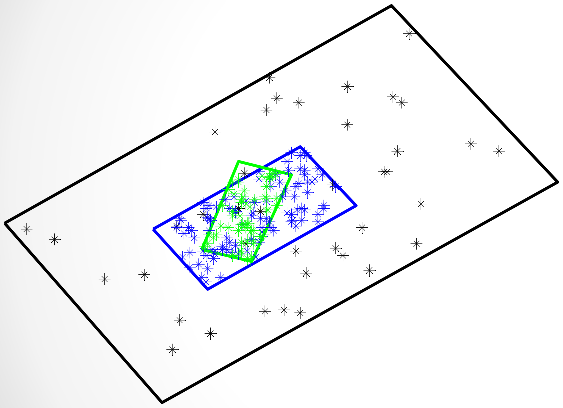


USGS Central and Eastern United States Seismic Source Characterization project (CEUS-SSCn)

No clearly defined fault

- **Local (purple region)**
- **Narrow (red region)**
- **Regional (blue region)**

Numerical application: South Carolina

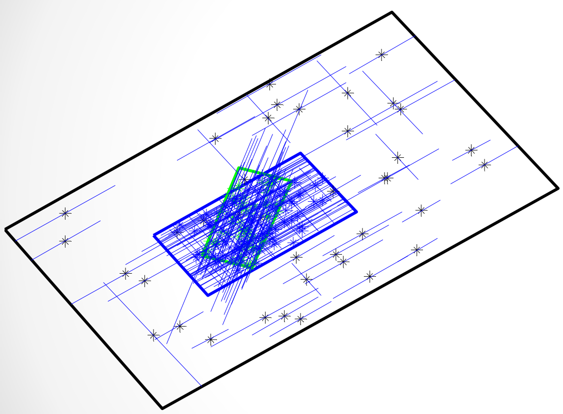


All events are modeled to occur on vertical strike-slip faults
Magnitudes: model as a uniform distribution of ±0.25 M bins centered on the corresponding magnitude values

E(M)	weight
6.7	0.10
6.9	0.25
7.1	0.30
7.3	0.25
7.5	0.10

200 sample events

Numerical application: South Carolina



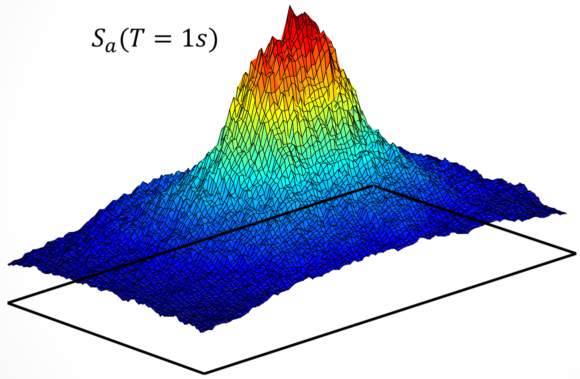
Local (purple region)
weight: 0.50
Orientation: parallel to the long axis (strict boundaries)

Narrow (red region)
weight: 0.30
Orientation: parallel to the long axis (w/o strict boundaries)

Regional (blue region)
weight: 0.20
Orientation:
parallel to the long axis; weight 0.80 (strict boundaries)
Vertical to the long axis; weight 0.20 (strict boundaries)

200 sample events

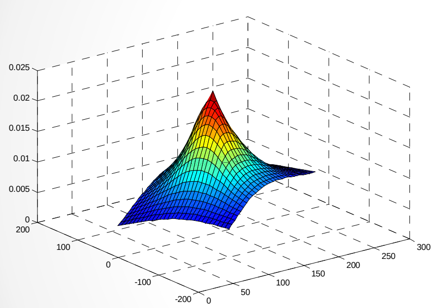
Numerical application: South Carolina



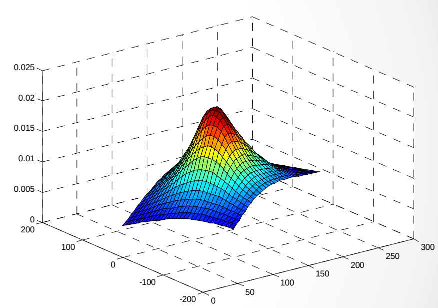
One quantum
Quantizer size $N = 50$

Numerical application: South Carolina

Autocorrelation, with
respect to the central point

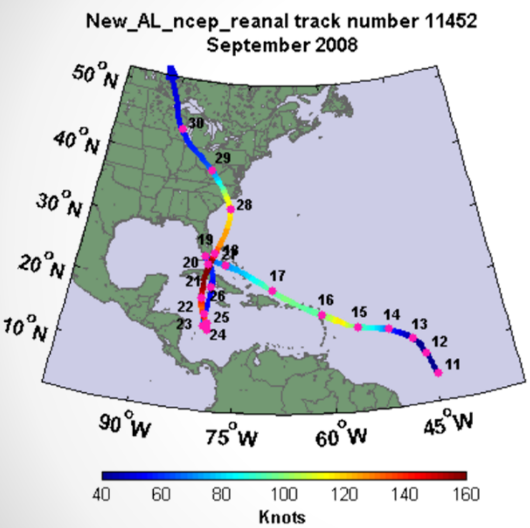


Exact
Sample size $N = 500{,}000$



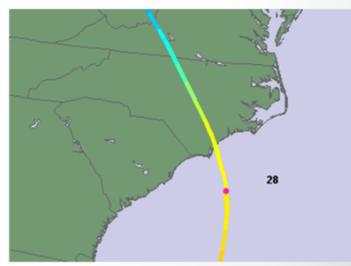
Quantizer
Quantizer size $N = 150$

Numerical application: South Carolina

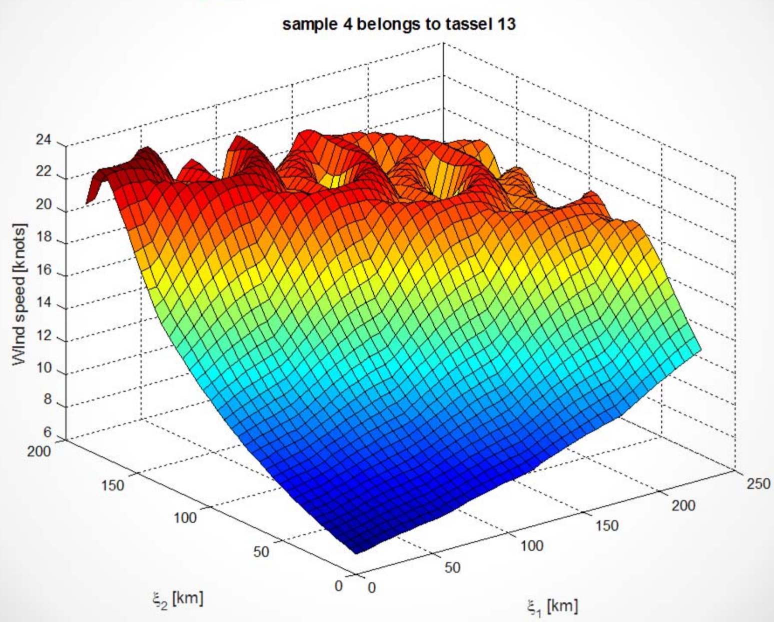


Hurricanes

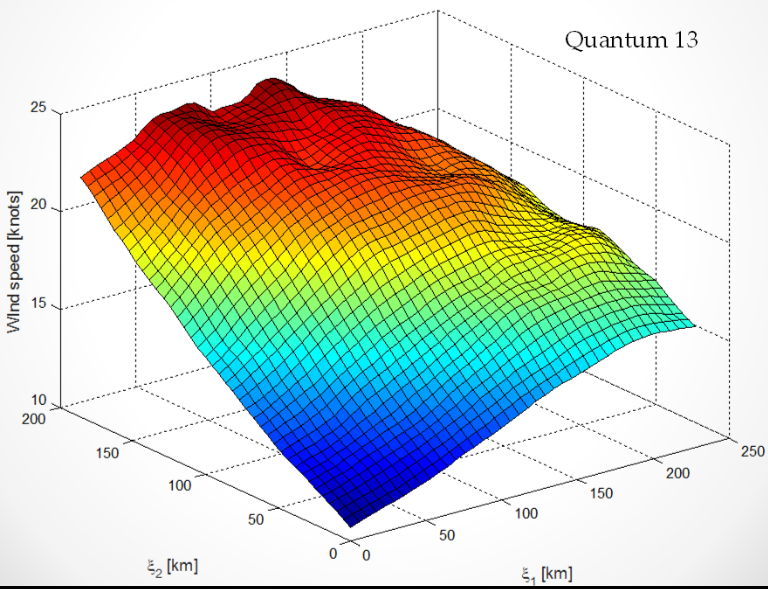
Synthetics or taken from the HURDAT database



Numerical application: South Carolina

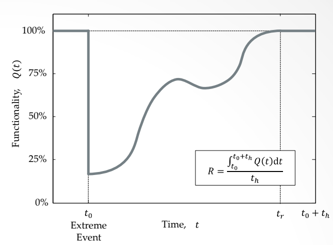


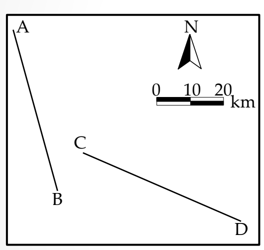
Numerical application: South Carolina



Outline

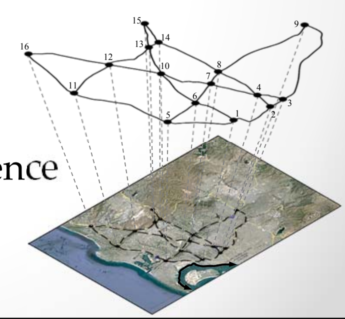
Introduction



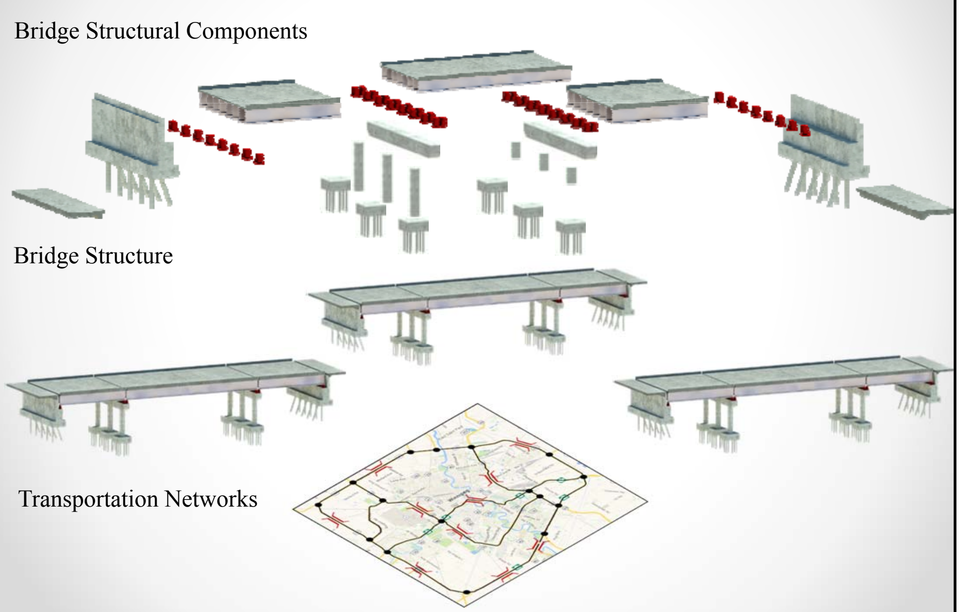


Regional hazard modeling

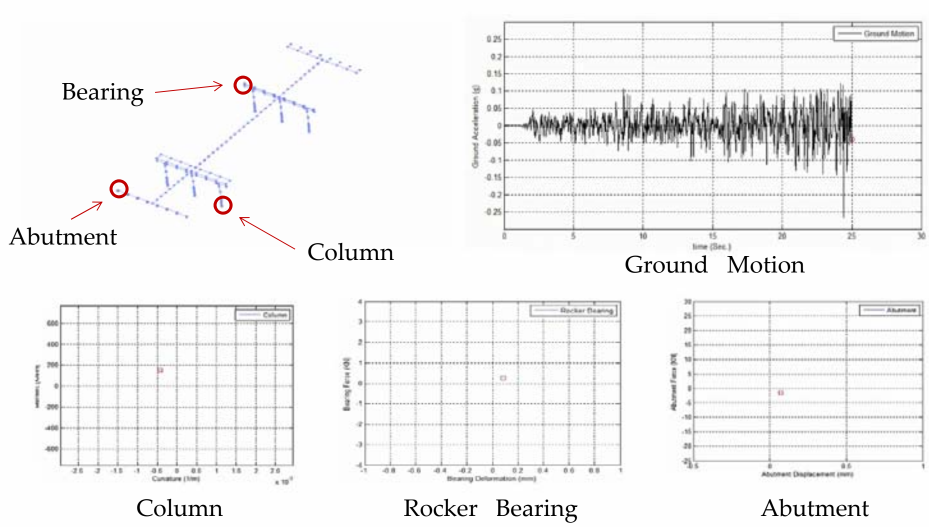
Transportation network resilience



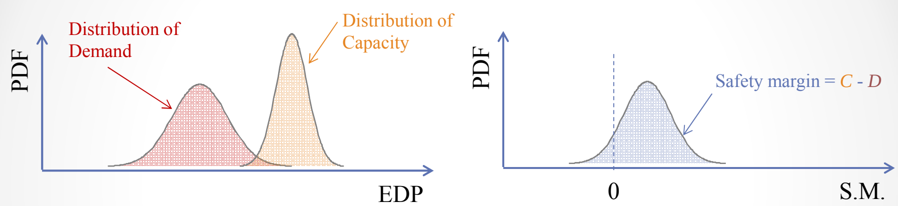
Multi-scale resilience assessment

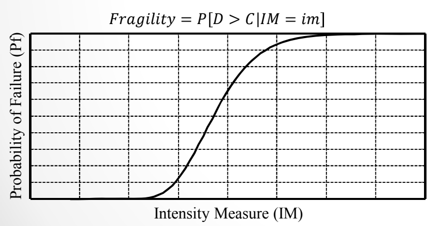


Component fragility



Component fragility





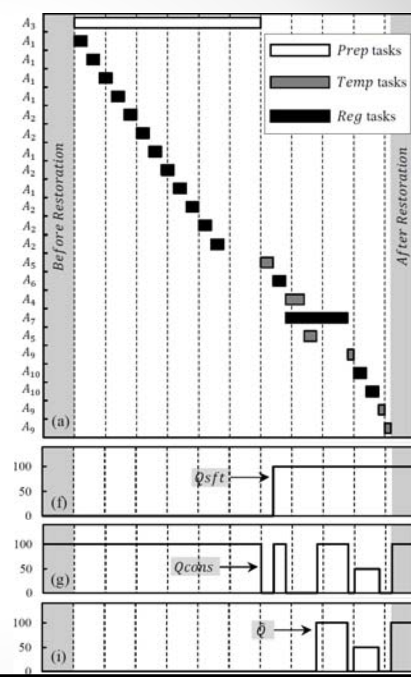
Repair-based limit states and associated probabilities [also considering meta-components]

Recovery simulation

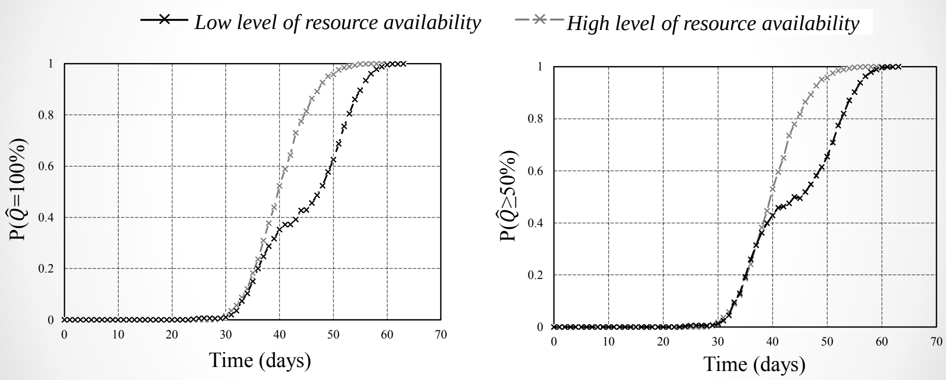
Restoration construction schedule:

Functionality based construction-induced traffic disruptions:

Filtering unrealistic openings:



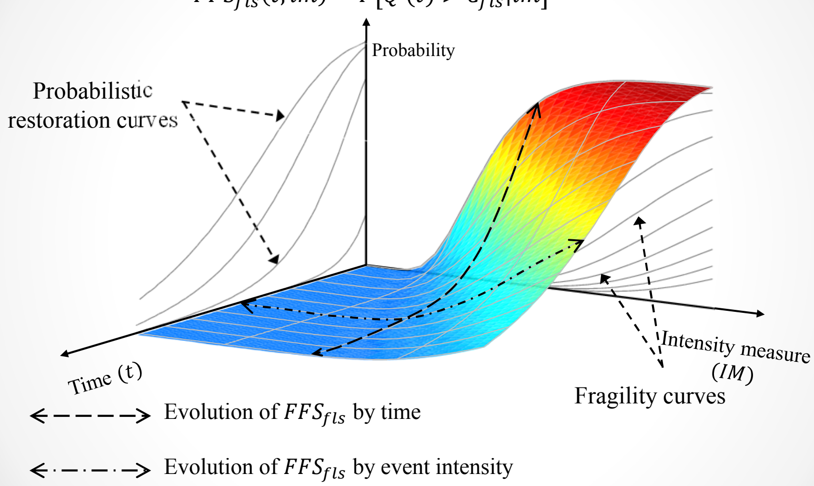
Probabilistic restoration functions



[Karamlou & Bocchini (2016). From component damage to system-level probabilistic restoration functions for a damaged bridge. *Journal of Infrastructure Systems*, ASCE]

Functionality-Fragility Surface

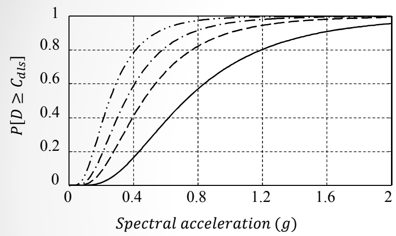
$$FFS_{fls}(t, im) = P[\bar{Q}\,(t) > C_{fls}|im]$$

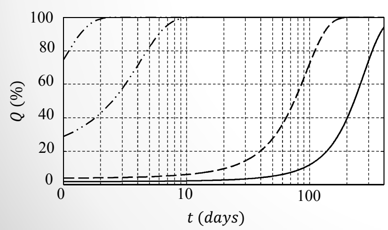


[Karamlou & Bocchini (2016). Functionality-fragility surfaces: a tool for probabilistic resilience analysis of bridges. In Book of Abstracts of EMI 2016 / PMC 2016, ASCE]
[Karamlou & Bocchini (2016). Introducing Functionality-Fragility Surfaces. *Under review*]

Functionality-Fragility Surface

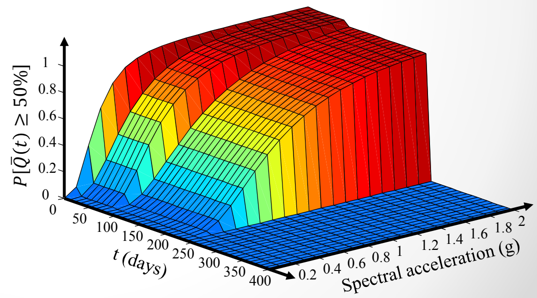
FFS Using the Available Data (HAZUS):



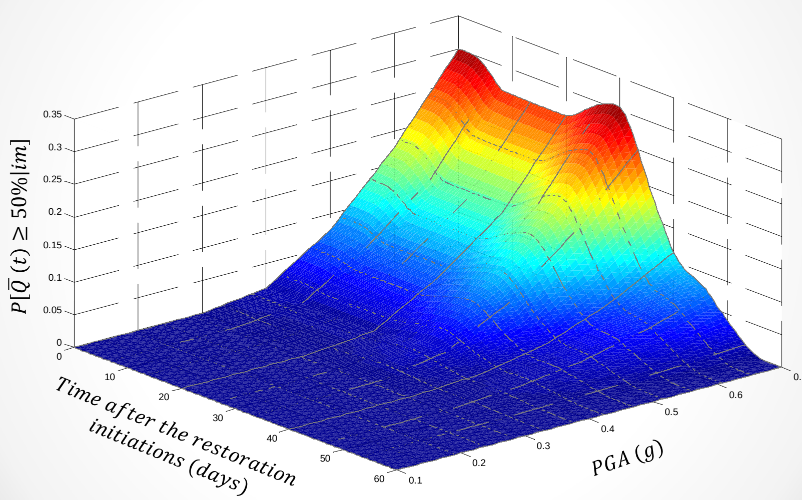


$$FFS_{fls}(t, im) = \int_{dm} G\left[fm_{fls}(t)\middle|dm\right] \cdot dG[dm|im]$$

$$= \sum_{\forall dls_i} P\left[\bar{Q}(t) \geq C_{fls}\middle|dls_i\right] \cdot P\left[D = C_{dls_i}\middle|im\right]$$



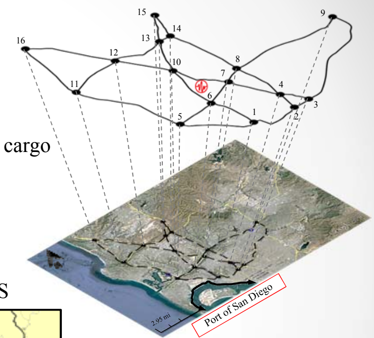
Functionality-Fragility Surface



Functionality-Fragility Surface

Port of San Diego Highway Network:

- One of the largest ports in California
- 6th port in the US in terms of value of the shipped cargo
- 10th port in the US in terms of the volume of the shipped cargo
- An strategic port used for transit of military equipment
- Total number of 238 bridges



Google Earth

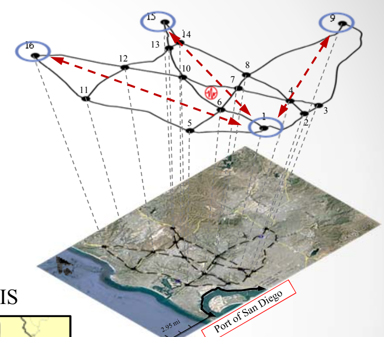
HAZUS-Arc GIS

[Karamlou, Bocchini (2016). Sequencing algorithm with multiple-input genetic operators: application to disaster resilience. *Engineering Structures*]

Functionality-Fragility Surface

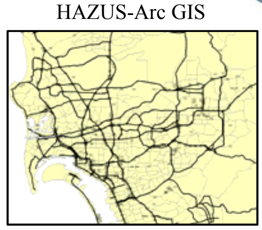
Network modeling and input optimization parameters:

- Subjected to a seismic scenario (used HAZUS-MH)
- 80 damaged bridges
- $NSA_{max} = 5$, $t_h = 3$ years
- Maximize the long-term and medium-term resilience
- Complete traffic analysis for network performance



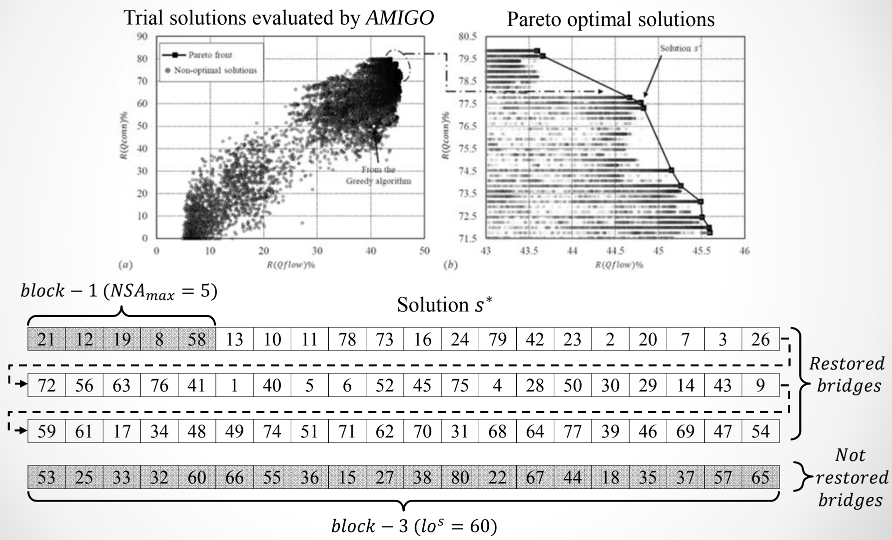
Google Earth

HAZUS-Arc GIS

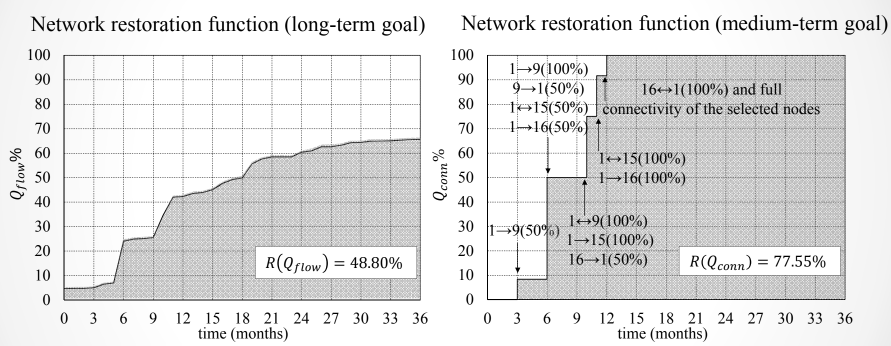


[Karamlou, Bocchini (2016). Sequencing algorithm with multiple-input genetic operators: application to disaster resilience. *Engineering Structures*]

Optimal post-disaster restoration



Optimal post-disaster restoration



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Thank you

Dr. Paolo Bocchini's Research Group