Disaster Resilience Analysis
Through Multiple Temporal and Spatial Scales

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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.”


Disaster Management & Long Term Losses

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

Immediate Losses  Losses due to inefficient disaster response  Losses due to long term reduction of functionality

Total losses for the economy: 15-30 Billion $

March 2011 9.0 Richter

Sendai

Fukushima Power Plant

17070 km

Epicenter

Long-term indirect losses in Tohoku fisheries business: 66.7 M$ in 1 year

February 2010 8.8 Richter
Resilience is about functionality

\[ R = \int_{t_0}^{t_0 + t_r} Q(t) \, dt \]

\[ t_0 \quad \text{Extreme Event} \quad t \quad t_r \quad t_0 + t_r \]

Resilience is multifaceted

Disaster resilience assessment

Space
- Community [km]
- Interdependent systems [km]
- Infrastructure system [km]
- Infrastructure site [100 m]
- Structure [m]
- Structural component [cm]

Hazard source
- Hurricane
- Earthquake
...
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.

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.

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

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

with a small-to-moderate number of samples

\[ N = \frac{t_{\text{available}}}{t_{\text{single run}}} \]

Hazard Quantization (HQ)


Numerical application

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

Attenuation relation & rupture
Abrahamson and Silva (1997)
Numerical application

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

One random sample

Associated quantum $N = 50$

Numerical application: hazard consistency

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

Approximation (quantizer with $N = 500$)

Reference solution (500,000 samples)
Numerical application: hazard consistency

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

Thick colored lines: REFERENCE (500,000)
Thin black lines: QUANTIZER $N = 500$

Similar results also for other periods

Numerical application: hazard consistency

Probability of exceedance $P[S_a(T = 0.1\ s) > 0.1\ g]$
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 $P[S_a(T = 0.1\text{s}) > 0.6\,g]$
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.

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

Approximation (quantizer with $N = 500$ )

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.

Approximation (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.

<table>
<thead>
<tr>
<th>M</th>
<th>weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.7</td>
<td>0.10</td>
</tr>
<tr>
<td>6.9</td>
<td>0.25</td>
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<tr>
<td>7.1</td>
<td>0.30</td>
</tr>
<tr>
<td>7.3</td>
<td>0.25</td>
</tr>
<tr>
<td>7.5</td>
<td>0.10</td>
</tr>
</tbody>
</table>

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)
Numerical application: South Carolina

$S_u(T = 1s)$

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

Sample 4 belongs to tassel 13
Numerical application: South Carolina

Outline

Introduction

Regional hazard modeling

Transportation network resilience
Multi-scale resilience assessment

Bridge Structural Components

Bridge Structure

Transportation Networks

Component fragility

Bearing

Abutment

Column

Ground Motion

Column

Rocker Bearing

Abutment
Component fragility

Fragility = \( P[D > C | IM = im] \)

Safety margin = \( C - D \)

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

\[ FFS_{T15}(t, im) = P[\bar{Q}(t) > \gamma_{T15} | im] \]


Functionality-Fragility Surface

Using the Available Data (HAZUS):

\[ FFS_{f(t, \text{im})} = \int_{d_m} G[f_m(t)] dm \cdot dG[dm|\text{im}] \]

\[ = \sum_{d_{\text{dis}}} P[Q(t) \geq C_{\text{dis}}] \cdot P[D = C_{\text{dis}}|\text{im}] \]

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

Network modeling and input optimization parameters:
- Subjected to a seismic scenario (used HAZUS-MH)
- 80 damaged bridges
- $N_S A_{\text{max}} = 5, \tau_h = 3$ years
- Maximize the long-term and medium-term resilience
- Complete traffic analysis for network performance

Optimal post-disaster restoration

Trial solutions evaluated by AMIGO

Pareto optimal solutions

Solution $s^*$

$block = 1 (NSA_{max} = 5)$

$block = 3 (lo^e = 60)$

$Restored bridges$

$Not restored bridges$

Optimal post-disaster restoration

Network restoration function (long-term goal)

$R(Q_{time}) = 48.80\%$

Network restoration function (medium-term goal)

$R(Q_{max}) = 77.55\%$
Thank you

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