Uncertainty Modeling in Seismic Risk Assessment at Urban/Regional scale

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2018, January 16th – BRGM, Orléans, France
Uncertainty Modeling in Seismic Risk Assessment at Urban/Regional scale

1. Systemic framework (interactions)
2. HAZARD
   - Seismologists
3. FUNCTIONAL CONSEQUENCES
   - Other domain experts
     - Power networks
     - Water supply networks
     - etc
4. DAMAGE
   - Structural engineers

Probability of Loss
- Direct
- Indirect
Systemic framework: interactions

• Seismic hazard model
• System of systems model (damage & functional models)

Failures may propagate within the power network:
Short-circuits!

INTERNAL SUB-STATION MODEL

Nodes may be tied to nodes in other network for their functioning (e.g. do I get power at appropriate voltage? FLOW ANALYSIS)

Cluster of components

Every building cell is tied to the closest node in each network (reference node)

Interpolation

Grid size related to spatial correlation length

Attenuation to grid points (spatial correlation)

Systemic framework: uncertainty

Uncertainty

Network of random variables

Physical level

Surface

Bedrock
System functional model

- Functional models

\[
\begin{align*}
A_{n_v \times n_v} &= \begin{bmatrix}
1 & 0 & 1 & 1 \\
0 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 \\
\end{bmatrix} \\
I_{n_e \times n_v} &= \begin{bmatrix}
1 & 0 & 1 & 1 \\
0 & 1 & 0 & 1 \\
1 & 0 & 0 & 1 \\
1 & 0 & 1 & 0 \\
0 & 0 & 1 & 1 \\
\end{bmatrix} \\
I^*_{n_e \times n_v} &= \begin{bmatrix}
0 & -1 & 1 & 0 \\
0 & -1 & 0 & 1 \\
-1 & 0 & 0 & 1 \\
-1 & 0 & 1 & 0 \\
0 & 0 & -1 & 1 \\
\end{bmatrix} \\
q_{n_e \times 1} & \quad \text{edge flows} \\
Q_{n_d \times 1} & \quad \text{node demands} \\
Q_i = 0 & \quad \text{if junction}
\end{align*}
\]

Balance (flow continuity at nodes)
\[
I^T_D q - Q = 0
\]

Resistance (line loss)
\[
\Delta h - r(q) = \left( I^T_S h_S + I^T_D h_D \right) - r(q) = 0 \quad \text{with } r(q) = Rq \cdot |q|
\]

Head driven
\[
\begin{align*}
I^T_D \tilde{q} - \tilde{Q} = 0 \\
I^T_S \tilde{h}_S + I^T_D \tilde{h}_D - \tilde{r}(\tilde{q}) = 0
\end{align*}
\]

Additional demands
\[
Q_{\text{seismic}} (\tilde{h}_D) = 0
\]

\[
\left( I^T_S h_S + I^T_D h_D \right) - \tilde{r}(\tilde{q}) = 0
\]
System performance metrics

Power network in Sicily: scenario event ($T_R=500y$)

Travel time in “peace time”

Road network in Calabria

Scenario event ($T_R=500y$)
Systemic framework: uncertainty

- Forward simulation: the distribution of system-level performance metrics is obtained by post-processing simulation results.
- This can be represented by simple Naïve formulation: we simply state that the system depends on the components…

Number of links prohibitive for real-sized systems for an explicit conditional probability table (CPT)
Systemic framework: towards a BN-based DSS

- Forward simulation → Bayesian inference on the network of random variable
- Likely state of unobserved components given evidence on other system portions → real-time decision support system

Not easy to set-up + cannot deal with flow-metrics

A set of plausible realizations is not a plausible set of all possible realizations…

Systemic framework: towards a BN-based DSS

- Works for real systems
- Road network in the Pyrenees
- 982 nodes: 18 TAZs
- 2200 edges: 73 vulnerable (146 considering two edges per pair of nodes - directed graph)

Component damage model

- Damage given intensity: conditional probability model $p(C_i | S_i)$
  - $p(C_i | S_i)$ is obtained from one or more fragility functions $p(LS_{i,j} | S_i)$
  - $S$ represents only one parameter of ground motion
  - Conditional on $S$, other parameters change from site to site
  - Fragility is thus structure & site-dependent

- Fragility can be obtained based on:
  - field damage data ← difficult to generalize
  - numerical simulation ← need for better/ more reliable models
Numerical evaluation of fragility curves $p(LS_{i,j} | S_i)$

- Post-processing of structural response obtained by inelastic response history analysis for multiple realizations of ground motion

- Alternative techniques:
  - Cloud analysis
  - Incremental dynamic analysis
  - Multiple-stripe analysis

- Multiple-stripe analysis emerged as the most appropriate
Numerical fragility functions

- d4 project: 500 existing RC girder bridges (detailed info available)
  - PSHA + multiple stripe analysis to establish seismic risk
    - Inelastic response-history analysis (9x10=90 per bridge)
    - Consistent choices on modeling and damage definition

Numerical fragility functions

- RINTC project (ongoing): code-conforming buildings
  - PSHA + multiple stripe analysis to establish seismic risk
  - Corrected conditional-spectrum compatible motions
  - Inelastic response-history analysis (10x20=200 per building)
  - Consistent cross-typology modeling and damage definition

Inclusion of soil-structure interaction (dyn. impedance + modified input motion)

Regular and irregular, 2 and 3 storey, URM and RM buildings

Steel and precast concrete industrial halls

Regular 3, 6 and 9 storey, frame, wall-frame and isolated infilled RC buildings

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Numerical fragility functions

- These large-scale efforts have confirmed that response results (and hence fragility functions) are sensitive to:

**Structural modeling**

Columns, beams, walls

**Definition of collapse**

State evolution approach

Response history to collapse for motion A
Monotonic response
Response history to collapse for motion B
Monotonic response
Deformation @ collapse for motion A
Deformation @ collapse for motion B

Simplified constant capacity

\[ V_b \]
Monotonic response

\[ 0.5V_{b,\text{max}} \]
Deformation @ collapse for all motions
Numerical fragility functions

- These large-scale efforts have confirmed that response results (and hence fragility functions) are sensitive to:

**Uncertainty modeling**
Changes both median and dispersion of response

**Correlation structure!**
- Inter-member/Inter-floor
- Intra-member
- Inter-member/Intra-floor

**Zero correlation**
- Assumed correlation
- Perfect correlation
Consistent portfolio-wise fragility assessment

- D4 Project: development of a tool for consistent automatic modeling & fragility analysis of girder bridges

bridge database (a)  bridge information model (b)

bridge finite element model (c)  multiple stripe analysis (d)

Reliability of typological fragility curves

- Data base of >500 bridges consistently modelled and assessed
- Query criteria: multiple simply-supported spans, single-stem hollow-core piers, height between 5m and 30m, rubber bearings
  - According to all classifications (HAZUS, Turkish, Greek, etc) bridges would fall into a single typology → a single fragility
- Retrieved 9 bridges

**Loss distribution**

Component loss \( l = 1 \) with probability \( p_i \) (Bernoulli), system loss \( L = \sum l_i \). Distribution of \( L \)?

If we express \( p_i = p + \Delta p_i \rightarrow \mu'_L = \mu_L + \Sigma \Delta p_i \) and \( \sigma'^2_L = \sigma^2_L + \Sigma \Delta p_i - \Sigma(2p\Delta p_i + \Delta p_i^2) \)

Mean fragility \( F(x) \)

- Uniform hazard
  - \( \mu_L = np \)
  - \( \sigma^2_L = npq \)
  - \( p = F(x) \)

- Individual fragility \( F_i(x) \)
  - \( \Sigma \Delta p_i = 0 \)
  - \( \mu'_L = \mu_L \)
  - \( \sigma'^2_L < \sigma^2_L \)
  - \( p = F(x) \)

- Individual fragility \( F_i(x) \)
  - \( \Sigma \Delta p_i = 0 \)
  - \( \mu'_L = \mu_L \)
  - \( \Delta p_i \ll 1 \)
  - \( \sigma'^2_L \to \sigma^2_L \)

Realistic cases

- Non-uniform hazard \( x_i \)
  - \( \Sigma \Delta p_i \neq 0 \)
  - \( \mu'_L \neq \mu_L \)
  - \( \sigma'^2_L \neq \sigma^2_L \)
  - \( p = F(\bar{x}) \)

- System loss \( L \)
  - \( \Sigma l_i \)
  - \( \mu'_L \to \mu_L \)
  - \( \sigma'^2_L \to \sigma^2_L \)

- Component loss \( l \)
  - \( \Sigma l_i \)

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BN-based fragility model

- Prediction of component state or fragility based on surrogate model with few easily observable parameters trained on the 500 bridge dataset
- Single BN for bridges with different number of piers?
  - In most cases pier conditioning failure is either the shortest or the tallest

BN-based fragility model

BN-based fragility model

- Fragility obtained from BN-based model point-wise, assigning evidence for the bridge (i.e. input data) to “white” variables, and reading probability of $Y_{LD}>1$ vs PGA.
BN-based fragility model

- Further advantages:
  - BNs unlike conventional regression, provide a fragility even when sub-set evidence is provided. More information will simply constrain more the curve
  - The model CPT can be established based on BOTH the numerical simulations and the field damage data, integrating the two main approaches to fragility evaluation

Performance at the component-level (bridge)

- Six sample bridges

Wrap-up

- Uncertainty in urban/regional risk assessment enters into:
  - Spatially-distributed hazard model
  - Component damage model (fragility)
  - System model

- Still much to do on all three fronts:
  - System:
    - Even the deterministic model is still quite behind:
      - Demand-driven/capacity-constrained flow equations for all systems missing
      - Post-event demands: modelling attempts just starting
    - If real-time use is aimed at, efficient BN set-up and inference are needed
  - Component:
    - Computing reliably \( p(C|S) \) is no easy or fast business
    - Typological fragility curves, observational or expert-judgement-based, are not the solution (can be used for direct loss only)
    - Surrogate fragility models needed for reliable/affordable indirect loss evaluation
      - Huge effort to provide fragility data for calibration of these models
      - Field data needed to constrain parameters' correlation and variability
Acknowledgements

• Funding:

  • European Commission:
    • FP7 project **SYNER-G** – Systemic analysis framework
  • Italian Department of Civil Protection:
    • *Reluis* project **RINTC** – Seismic risk of Italian code-conforming buildings
    • EUCENTRE project **d4** – Seismic vulnerability of Italian highway bridges

• Contributors:

  • Francesco Cavalieri, Pierre Gehl, Alessio Lupoi, Fabrizio Mollaioli, Fabrizio Noto, Solomon Tesfamariam, Graeme Weatherill