Hazard Identification & Asset (network) Vulnerability (Resilience) Assessment

UCL CEGE, UK

Dina D'AYALA, Pierre GEHL, Khaled TALIB, Mira WANG

CSIC, Spain

María-José JIMÉNEZ and Mariano GARCÍA-FERNÁNDEZ

Final Dissemination Conference

29 September 2016, Madrid, Spain

Objectives / Challenges

- Spatial extent of critical infrastructure ➔ components may be exposed to a wide range of hazard types
- How to reconcile damage events from different hazard types?
- How to harmonize multi-risk assessment over the whole infrastructure?

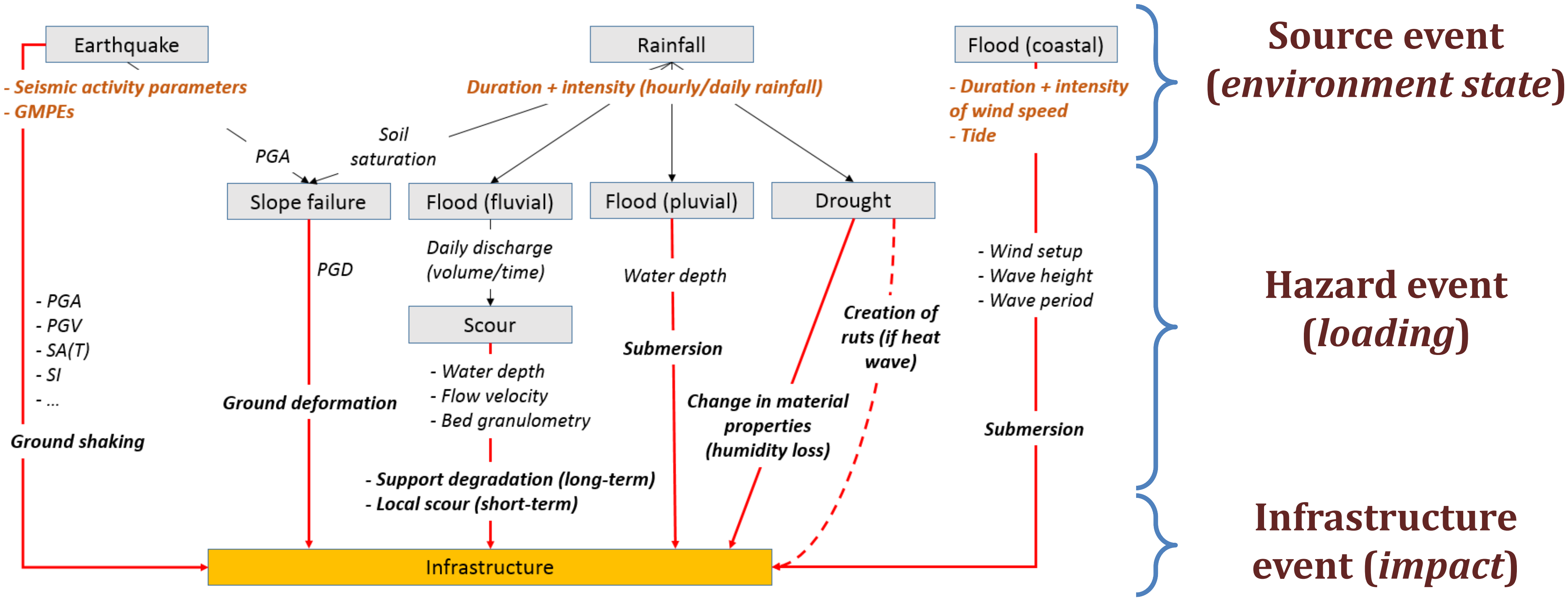
➔ Use of a Bayesian framework to assemble hazard-specific fragility curves

- Interdependency between infrastructure elements ➔ high dimensionality of the space of solutions
- Functionality loss of elements is more important than direct repair costs
- Spatial consistency of hazard input (i.e. scenario-based approaches)

➔ Application of Bayesian Networks in complement to simulation-based methods (e.g. FP7 SYNER-G project, OOFIMS tool)?

Single and Multi-Risk Assessment

- **Interactions at the HAZARD level**



➔ Generation of cascading hazard events and joint independent hazard events

➔ Spatial (geographical extent of infrastructure) and temporal (return periods of source events) modelling

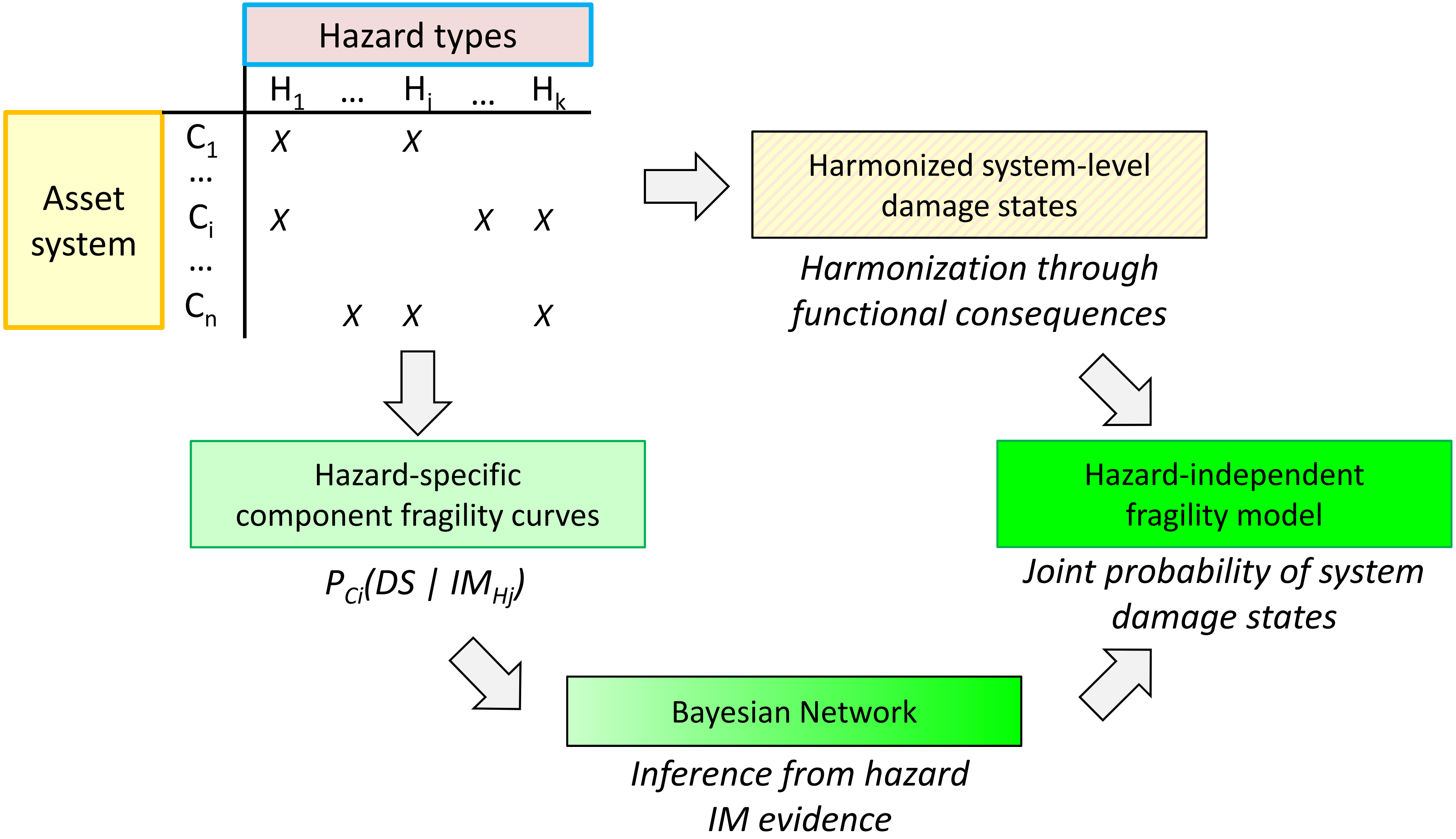
Single and Multi-Risk Assessment

- **Interactions at the EXPOSURE/VULNERABILITY level?**

- Spatial extent of critical infrastructure ➔ components may be exposed to a wide range of hazard types
- How to reconcile damage events from different hazard types?
- How to harmonize multi-risk assessment over the whole infrastructure?

- Development of a method to derive fragility models that are consistent between hazard types
- Use of a Bayesian framework to assemble hazard-specific fragility curves
- Application to roadway bridges, exposed to earthquakes (**EQ**), fluvial floods (**FL**) and ground failures (**GF**)

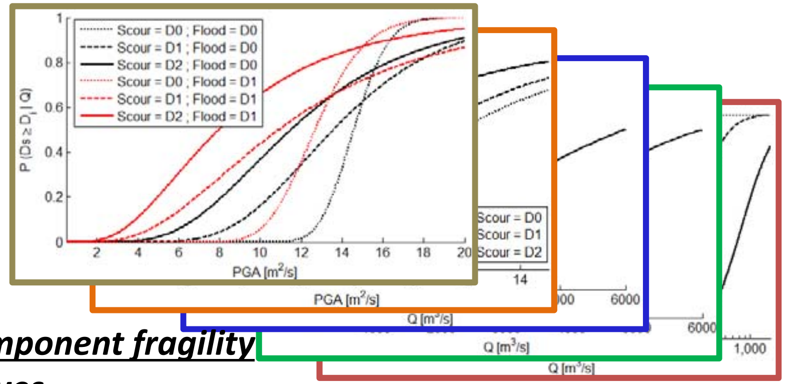
Overview of the proposed approach



Harmonized fragility functions

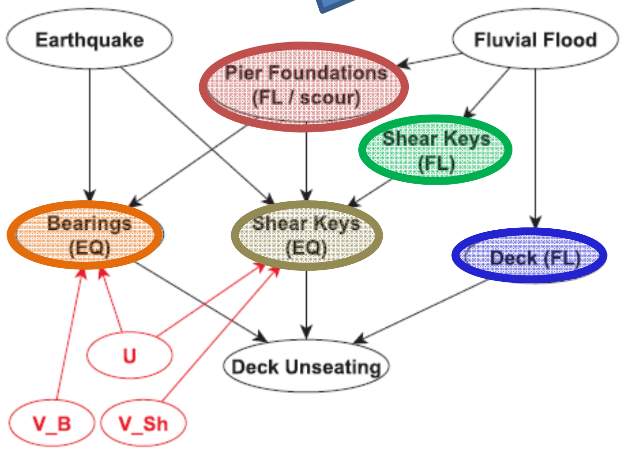
Failures modes

		HAZARD		
		Earthquake	Ground failures	Floods
		- Ground shaking	*- Slope failure* *- Rock fall* *- Settlement*	*- Submersion* *- Scour* *- ...*
CRITICAL INFRASTRUCTURE	Tunnels	*- Component 1* *- ...* *- Component i* *- ...*		
	Bridges	*- Component 1* *- ...* *- Component i* *- ...*		*- Damage mechanism* *- Component fragility curve*
	Road segments	*- Component 1* *- ...* *- Component i* *- ...*		

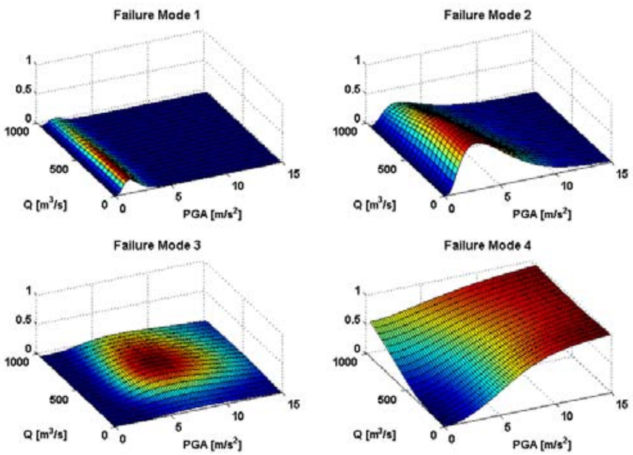


Component fragility curves

Bayesian Network



Multi-risk fragility



Multi-hazard scenarios

- Multi-risk event taxonomy proposed by Lee & Steinberg (2008):
  - *Single* event;
  - *Combined* events: single event triggering multiple loading mechanisms;
  - *Subsequent* events: unrelated single events triggered by different sources and possibly separated in time;

- Proposed multi-risk scenarios:
  - *Single* event: flood (**FL**)
  - *Combined* events: earthquake-induced ground failure (**EQ ➔ GF**)
  - *Subsequent* events: flood follow by an earthquake (**FL + EQ ➔ GF**)

➔ Multi-risk fragility framework should be consistent with all these cases

Seismic Hazard Modelling

CSIC, Spain

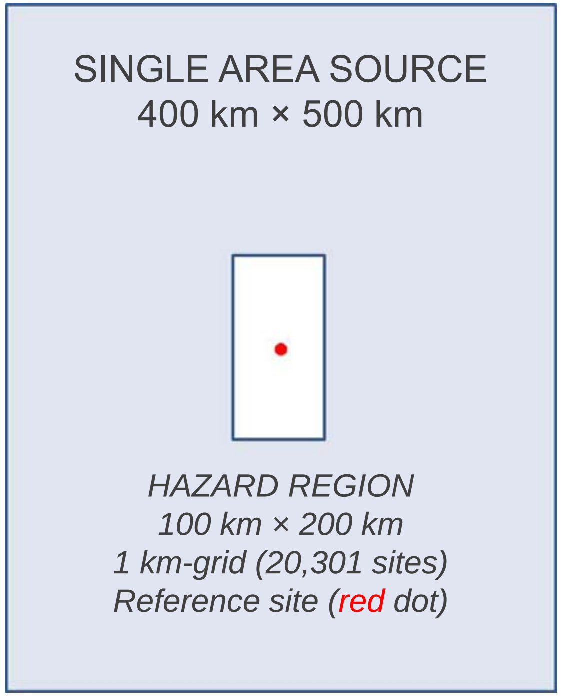
(*María-José JIMÉNEZ and Mariano GARCÍA-FERNÁNDEZ*)

Final Dissemination Conference

29 September 2016, Madrid, Spain

Seismic Hazard Approach

- Development of a seismic hazard approach best suited to consider **low probability ground motions** affecting critical transport infrastructures networks.
- Probabilistic-based approach applying **Monte Carlo simulation** techniques (the most adapted when dealing with low-probability ground motions)
  - *Allows for building **long-duration synthetic earthquake catalogues** (3×10^6 years) to derive low-probability ground motions*
  - *More **powerful and flexible handling of uncertainties**, and making straightforward the link with probabilistic risk analysis*
  - *Provides a distribution of maximum ground-motion amplitudes that follow a general **extreme-value distribution***
  - *Facilitates the analysis of the occurrence of extremes, i.e., very low probability of exceedance, from unlikely combinations; which could be **applied in the development of stress tests***
- Development of **extreme motion hazard deterministic scenarios**



Seismic Hazard Model

Extreme ground-motion scenarios for selected combinations of modelling inputs which include:

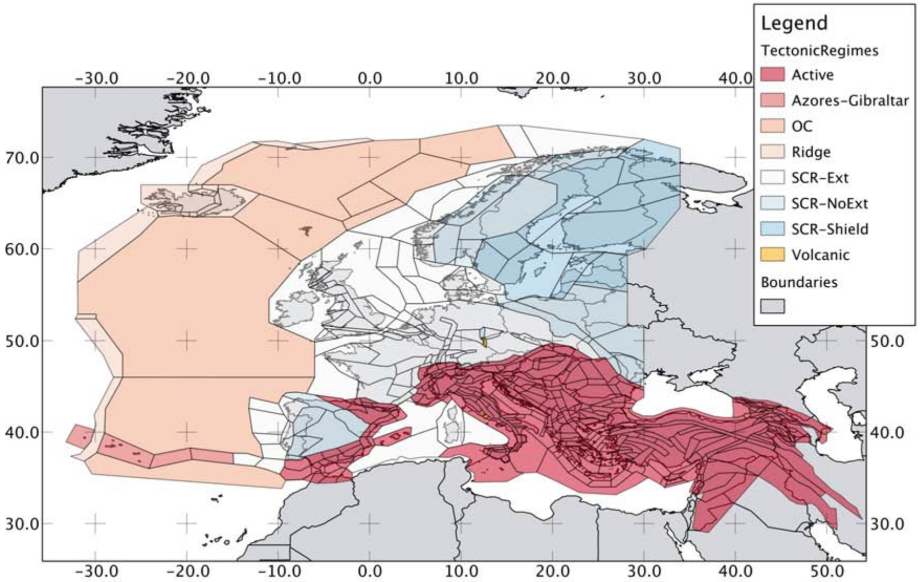
(a) Seismic activity model (4)
(b) Ground motion model (2)
(c) Hazard level (3)
(d) Fractile of extreme ground motions (3)

- Value at the **reference site** is the extreme ground motion corresponding to the selected hazard level (*i.e., annual probability of being exceeded*) and fractile/percentile (p) of extreme values (*i.e., only 100-p% of extremes are larger*)
- Assuming that the same parameters generating the extreme value at the centre apply to all grid points, **extreme motion hazard deterministic scenarios** (72 scenarios) are obtained for the whole hazard region

Seismic Activity Models

Derived from area source model of European SHARE project

- **High activity** (*from SHARE_Active 203 sources, 31% area*)
- **Moderate activity** (*from SHARE_SCR-Ext 80 sources, 40% area*)
- **Moderate-to-low activity** (*from SHARE_SCR-NoExt 17 sources, 15% area*)
- **Low activity** (*from SHARE_SCR-Shield 8 sources, 13% area*)



SHARE

Area Source Model v6.1 (2013)

SHARE – SEISMIC HAZARD HARMONIZATION IN EUROPE

Seismic Activity Models

Seismic Activity Model	N_0/yr	β	weight	z(km)	weight	M_{max}	weight
High activity (SHARE_Active)	28571	1.950	0.10	2.5	0.10	7.00	0.50
	28571	2.303	0.60	10.0	0.40	7.20	0.20
	107143	2.000	0.10	18.0	0.50	7.40	0.20
	107143	2.303	0.10			8.00	0.10
	214286	2.303	0.10				
Moderate activity (SHARE_SCR-Ext)	143	2.150	0.15			6.50	0.50
	2857	2.303	0.85	uniform		6.70	0.20
				2 - 22		6.90	0.20
						7.10	0.10
Moderate-to-low activity (SHARE_SCR-NoExt)	214	2.303	0.50			6.50	0.50
	2143	2.303	0.50	uniform		6.75	0.20
				2 - 26		6.95	0.20
						7.20	0.10
Low activity (SHARE_SCR-Shield)	264	2.303	0.75			6.50	0.50
	514	2.303	0.25	uniform		6.70	0.20
				30-35		6.90	0.20
						7.10	0.10

Ground Motion Models

Two models based on those developed by Atkinson and Adams (2013) in the 2015 edition of the National Building Code of Canada, for V_{S30}=760 m/s soils

- **Generic Low Attenuation** (*derived from ENA*)
- **Generic High Attenuation** (*derived from Wcrust*)

Hazard level

Three levels of **annual probability**, P1, of exceeding ground-motion values at the reference site: **4×10^{-4}**, **2×10^{-4}**, and **10^{-4}** per year. They correspond to mean return periods of 2,500, 5,000, and 10,000 years (*1/P1 = mean return period*)

Fractile of extreme ground-motions

Three options of **fractiles** of extreme ground-motion values at the reference site: **0.50**, **0.75** and **0.90**. They refer to percentile, p, of 50th, 75th, and 90th *(i.e., only 100-p% of extremes are larger*)

Spatial Variability

Hypothesis: Spatial correlation (covariance) not direction dependent

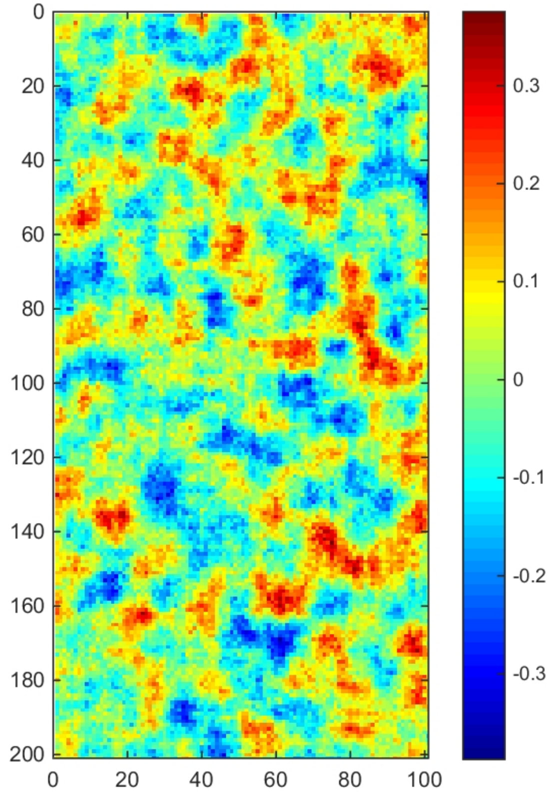
Approach: Running averaging window on a 2D normal random field

10,000 random fields

Selected **18 realizations**:

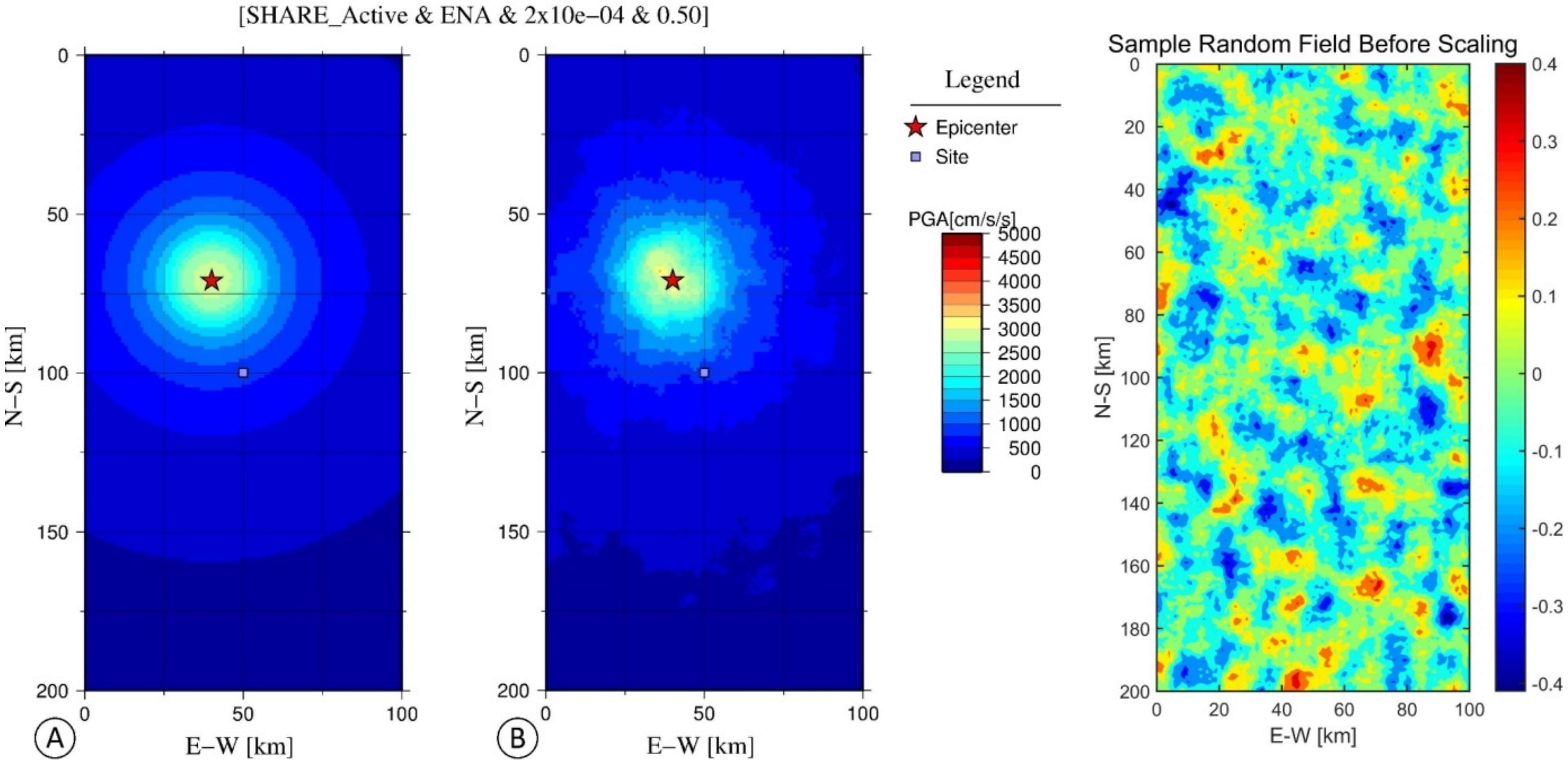
< 2% distortion in reference site

=> 1296 scenarios



Scenario example

High activity & Generic Low Attenuation & 2×10^{-4} & 0.50

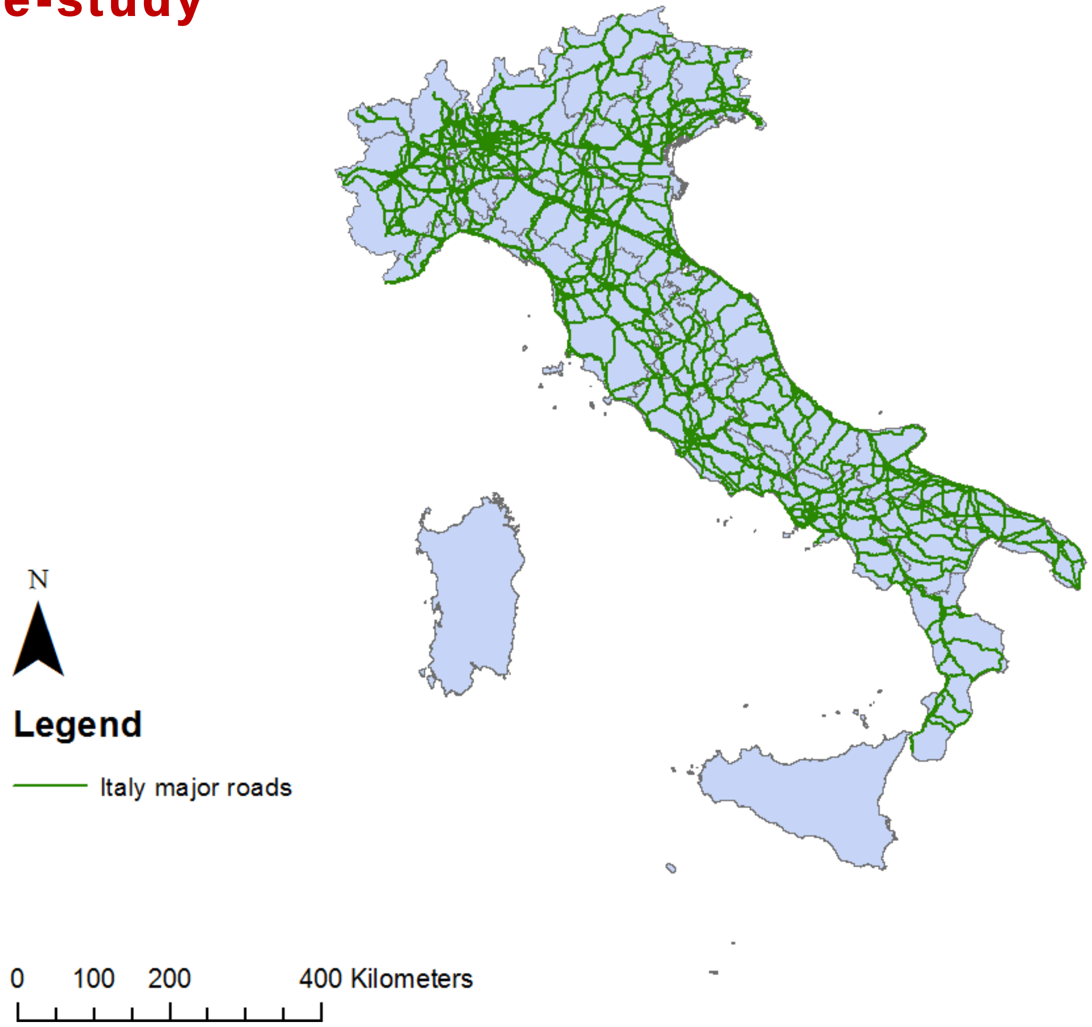


From Asset damage to network damage

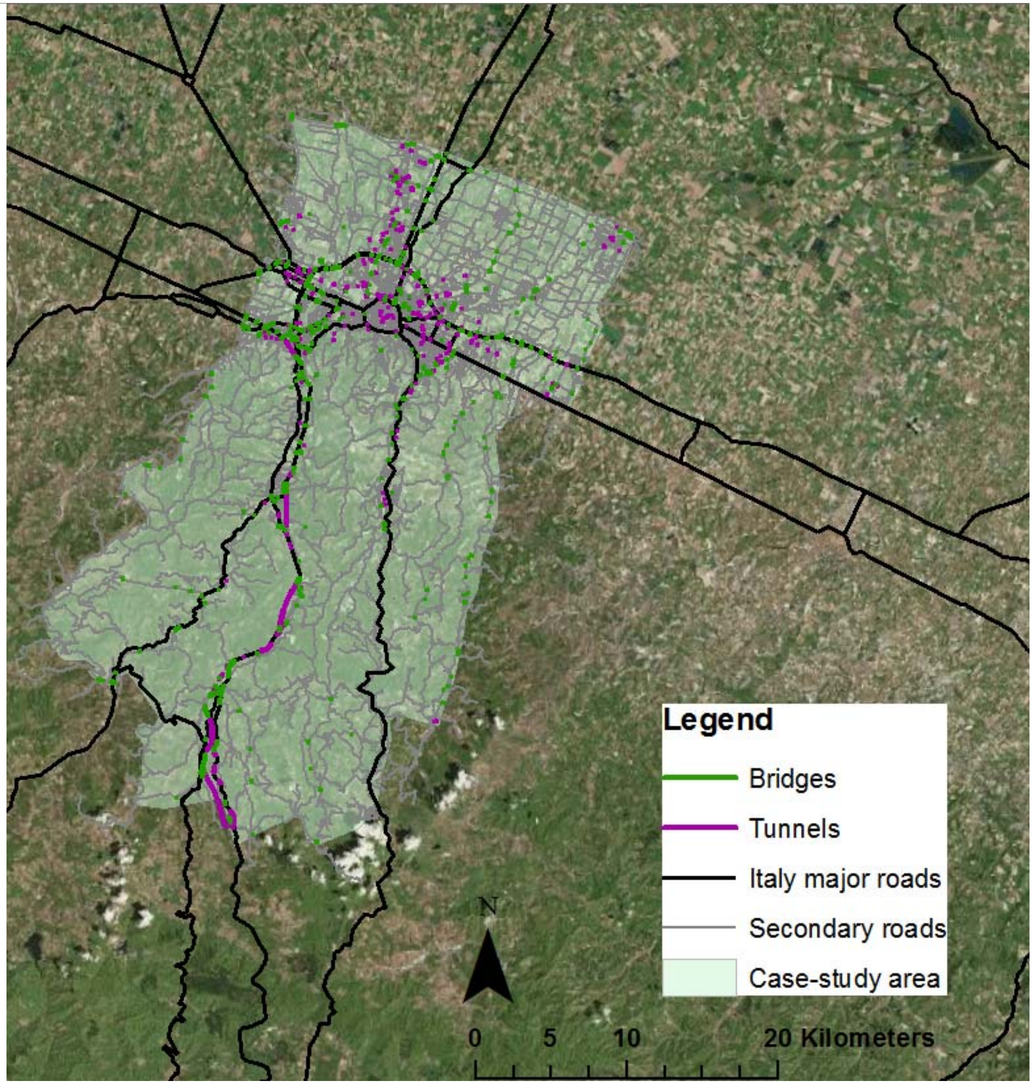
Final Dissemination Conference

29 September 2016, Madrid, Spain

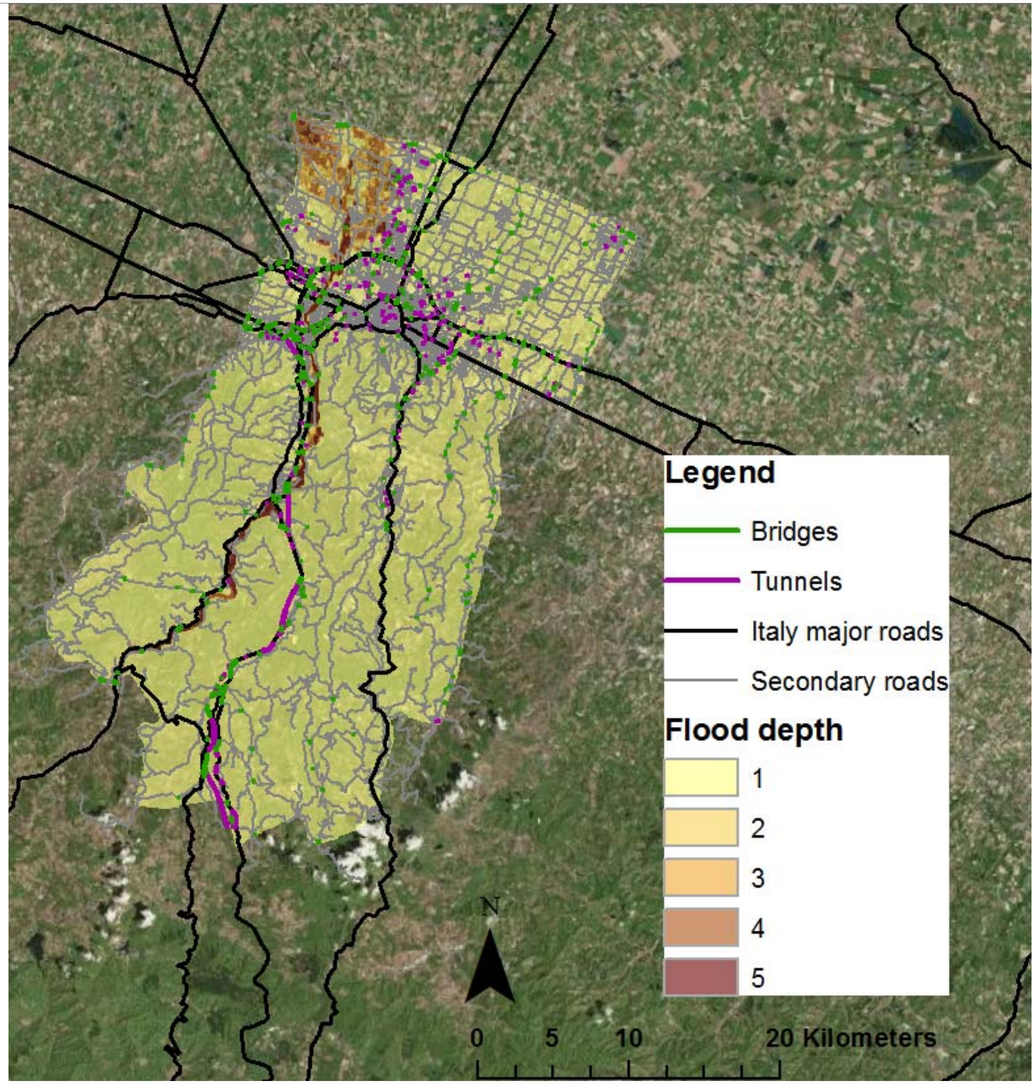
The INFRARISK case-study



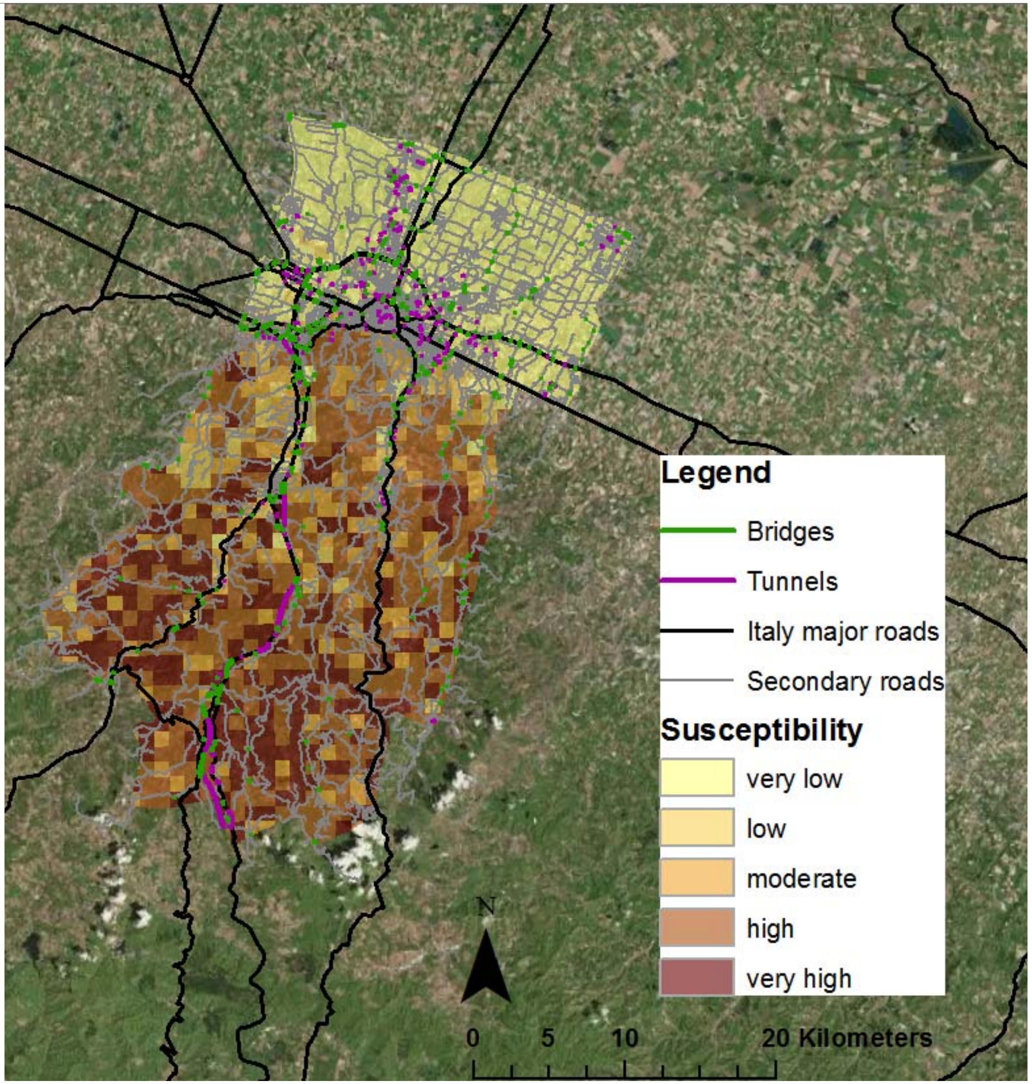
The INFRARISK case-study
Bologna area



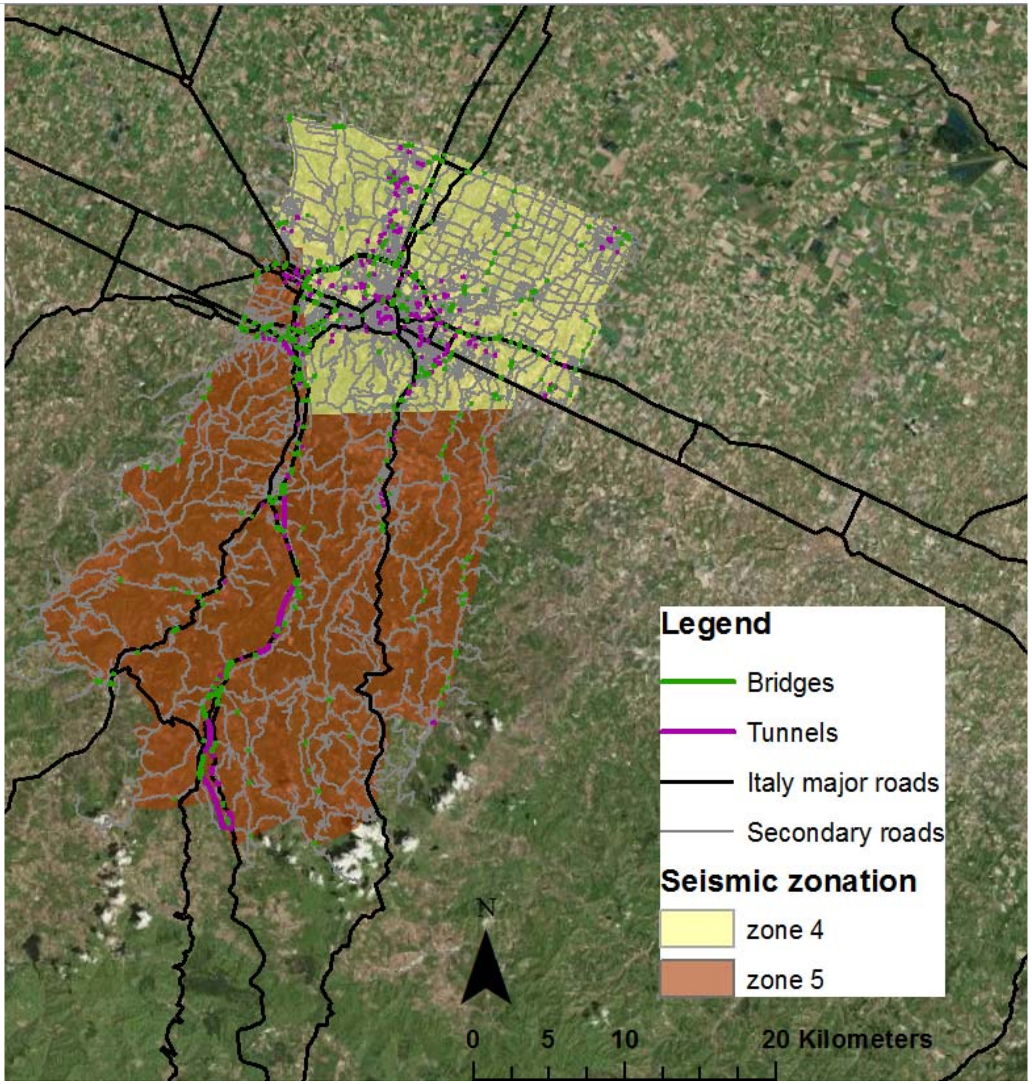
Hazard identification
- Historic flood events



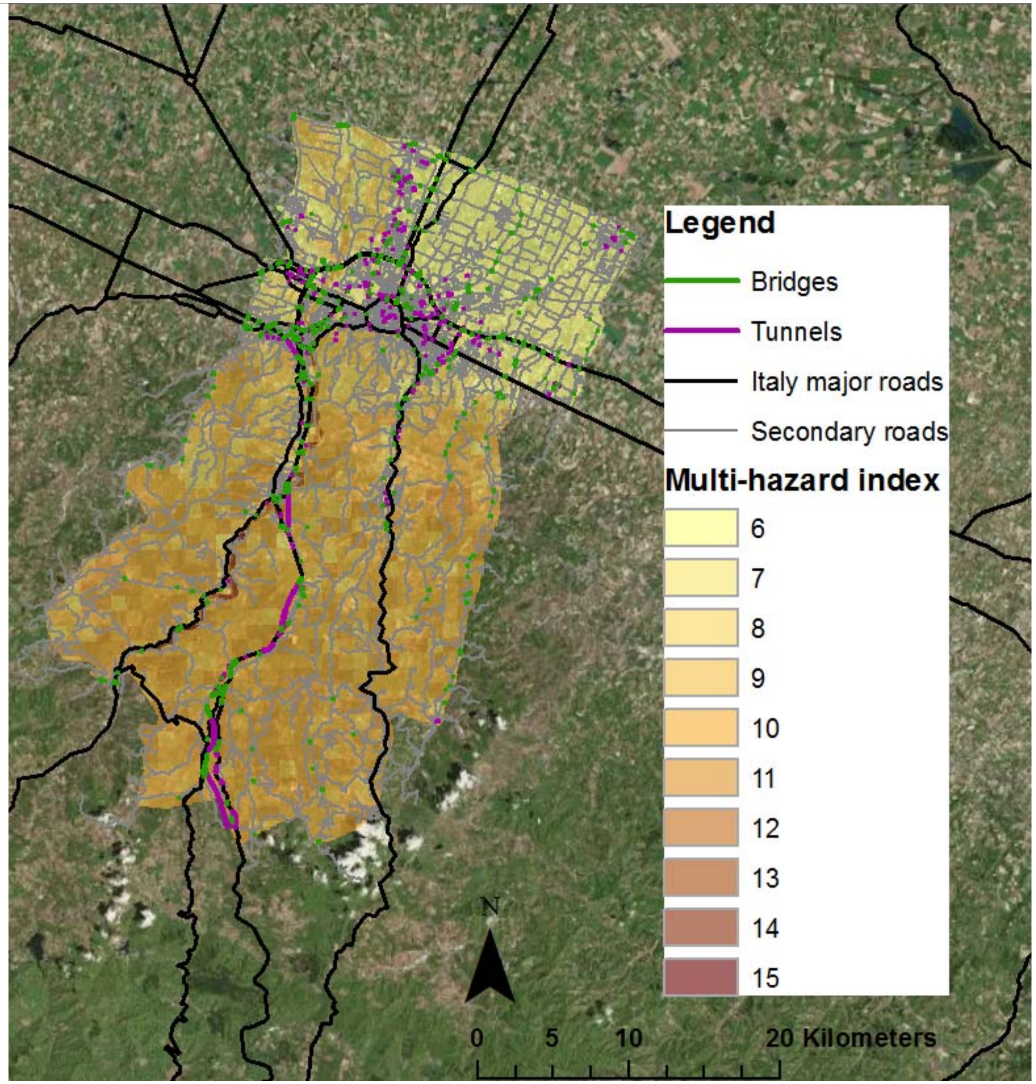
Hazard identification
- Landslide susceptibility



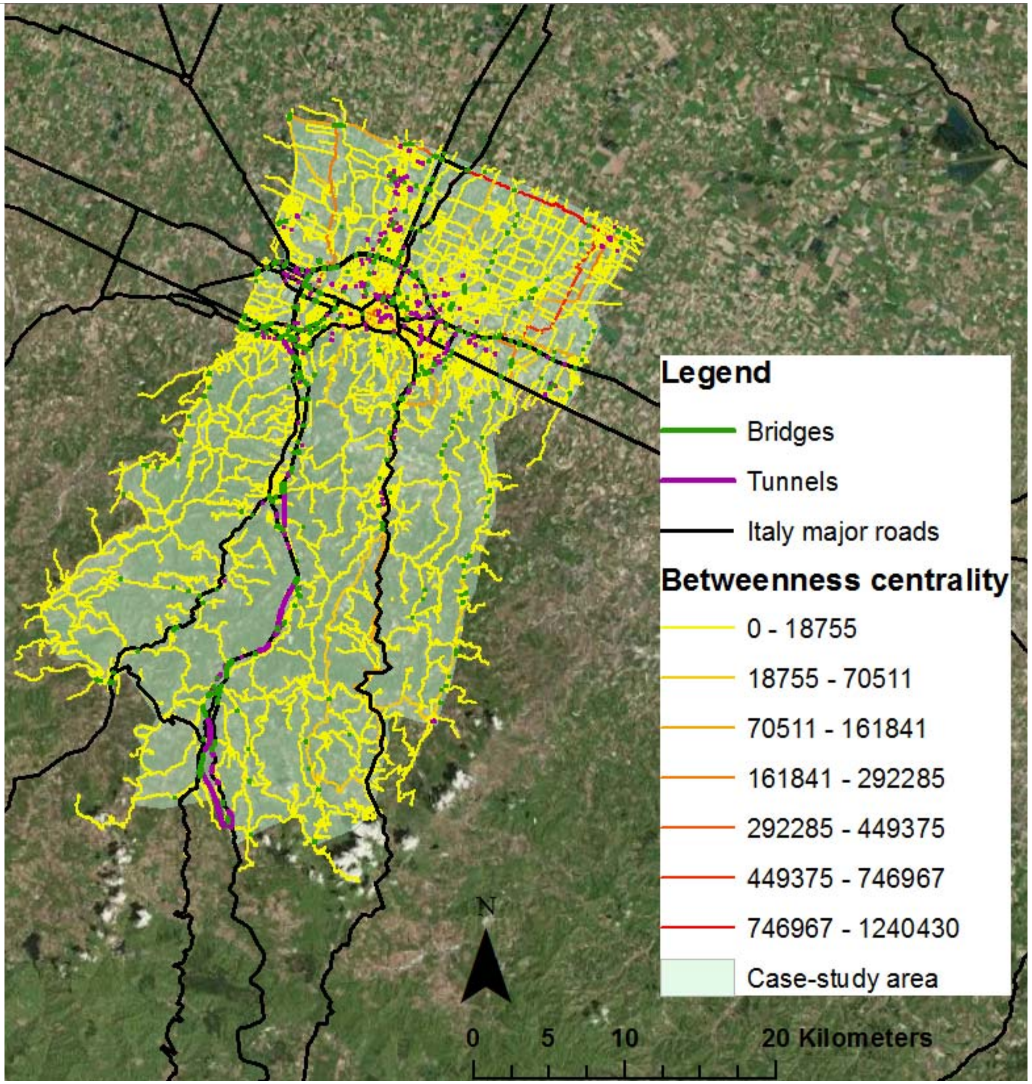
Hazard identification
- Seismic zonation



Hazard identification
- Aggregated hazard

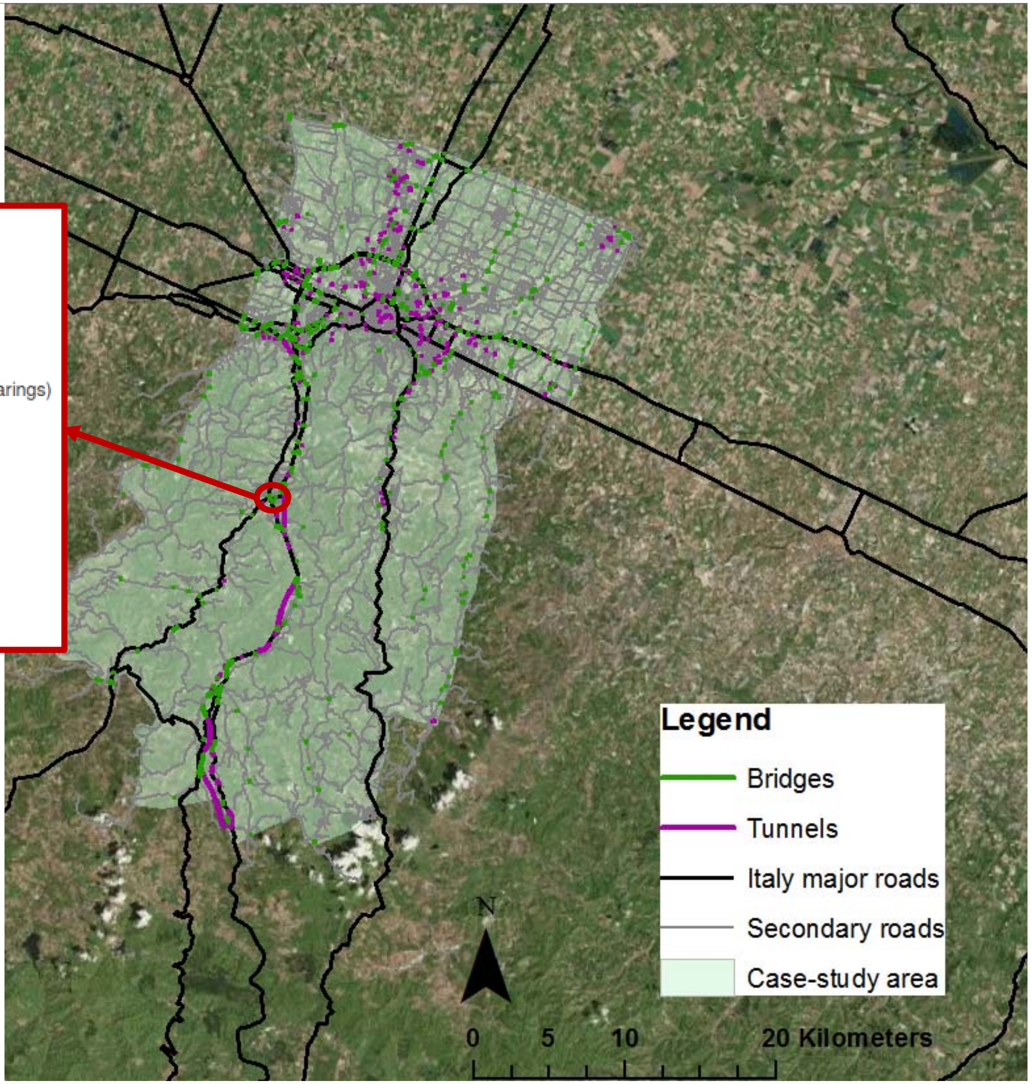


Criticity of infrastructure
- Betweenness centrality



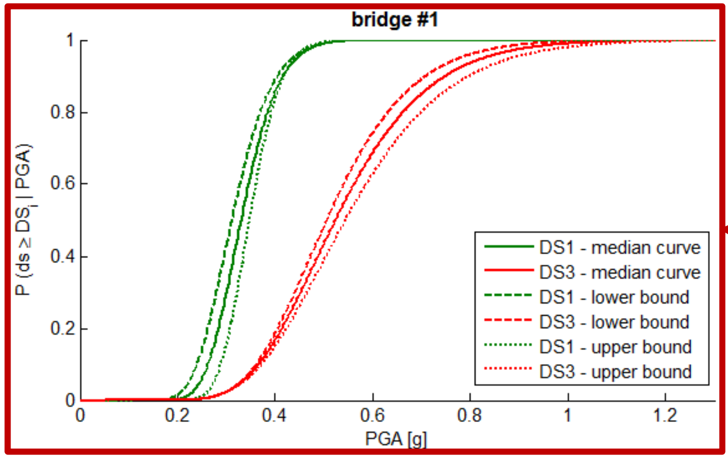
Exposure model
- Taxonomy of bridges

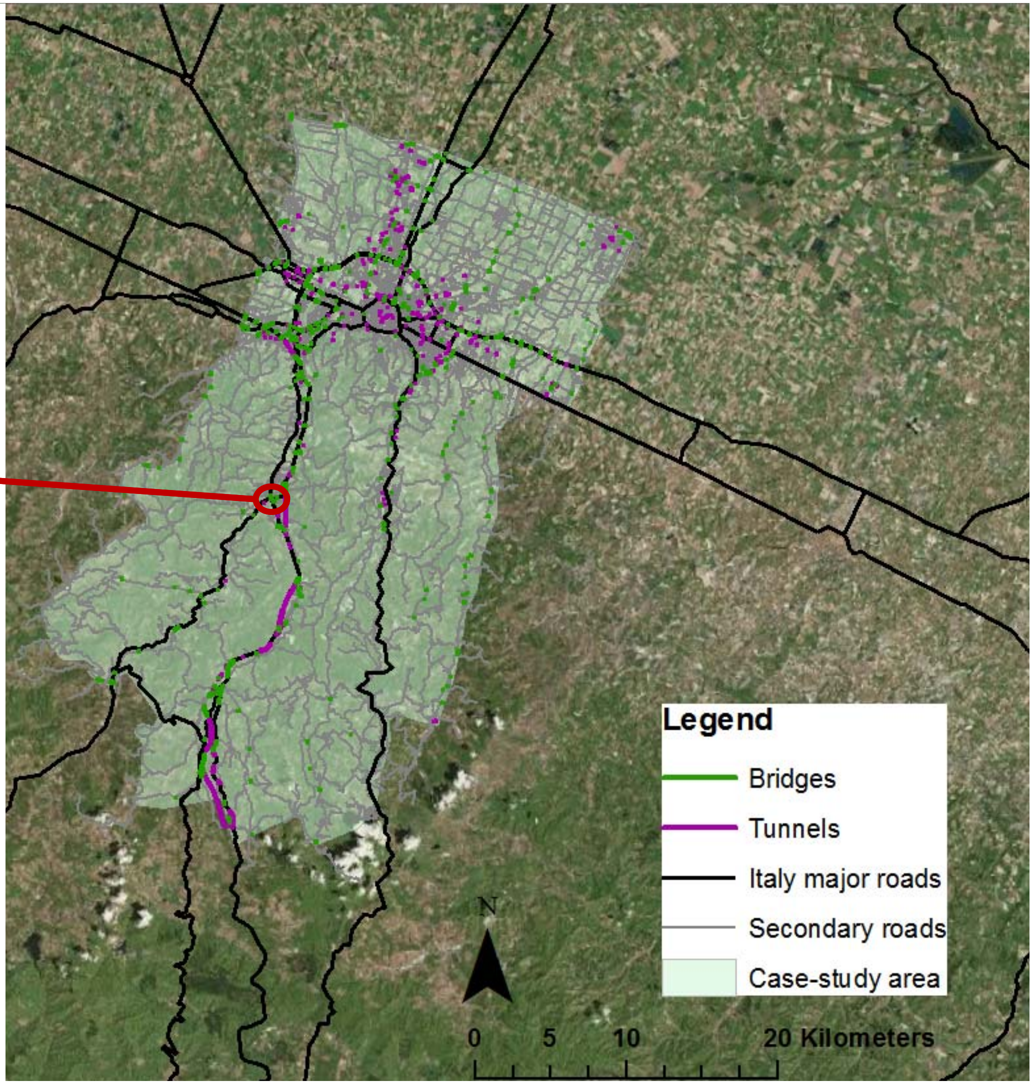
Name:	**Type of Column section 1:** Rectangular
Note:	**Type of Column section 2:** Solid
Where: 11.295521, 44.494518	**Spans:** Multi-span
Material MM1: Concrete	**Span length:** 25-45m
Material MM2: Prestressed concrete	**Connection to abutment:** Isolated (through bearings)
Bridge width: <20m	**Bridge configuration:** Regular
Bridge length: <50m	**Type of deck 1:** Undefined
Deck structural system: Simply supported	**Type of deck 2:** Undefined
Pier to deck connection: Isolated (through bearings)	**Number of columns for pier:** Undefined
Type of pier: Multi-column pier	**Pier height:** Undefined
Level of seismic design: Seismic design	**Number of spans:** Undefined



Fragility model

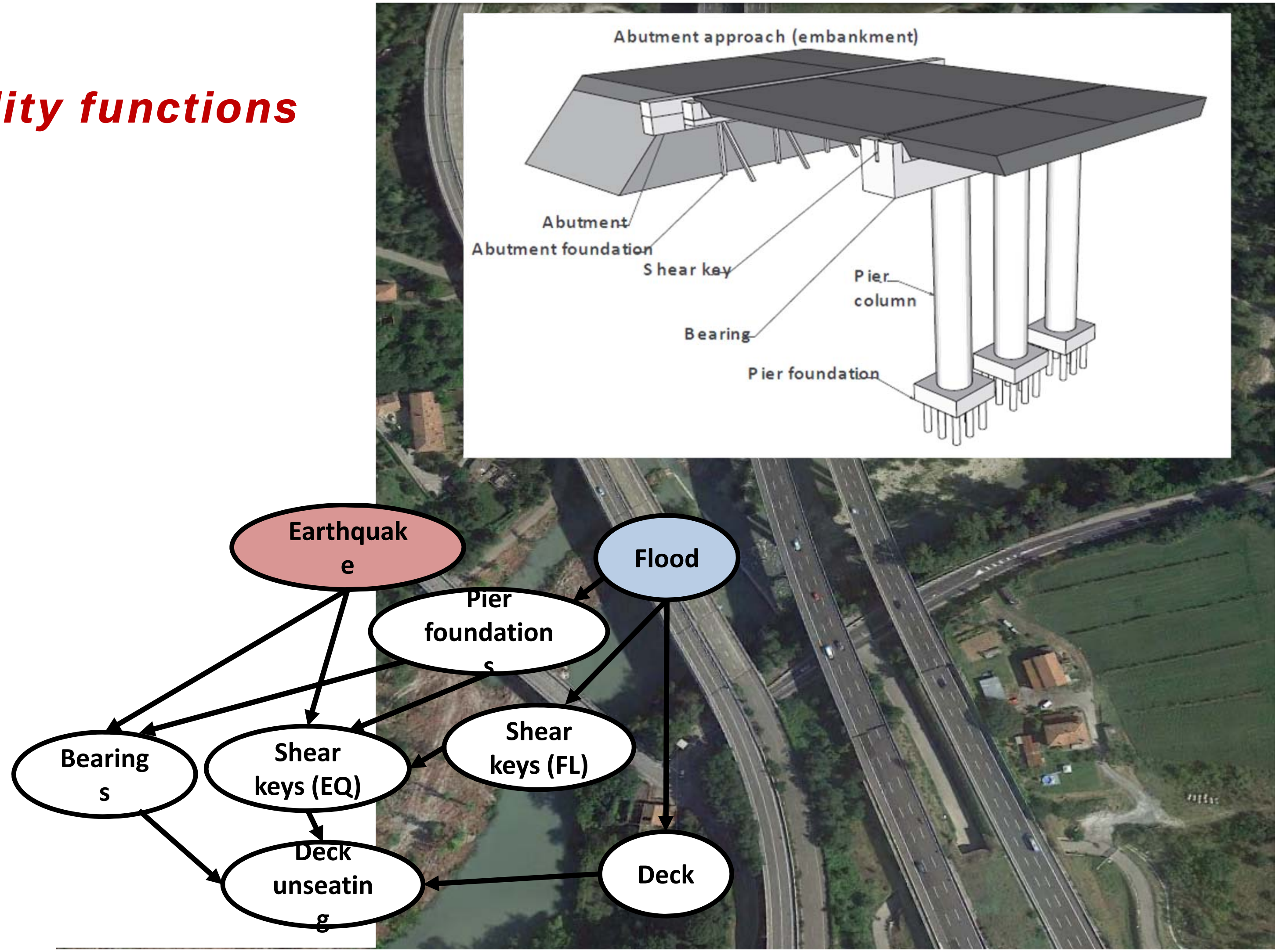
- Seismic fragility curves



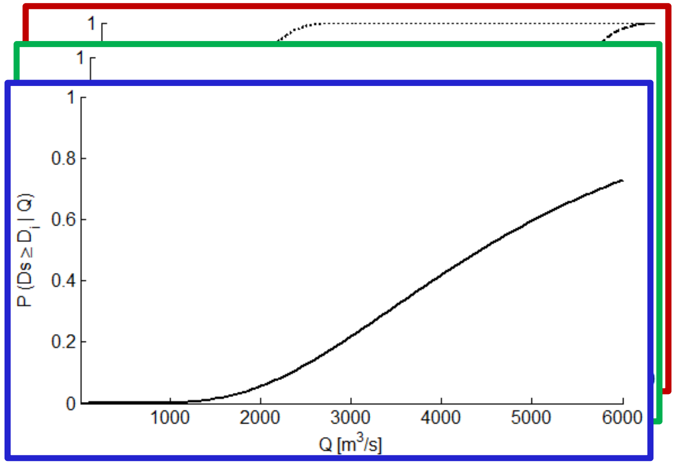


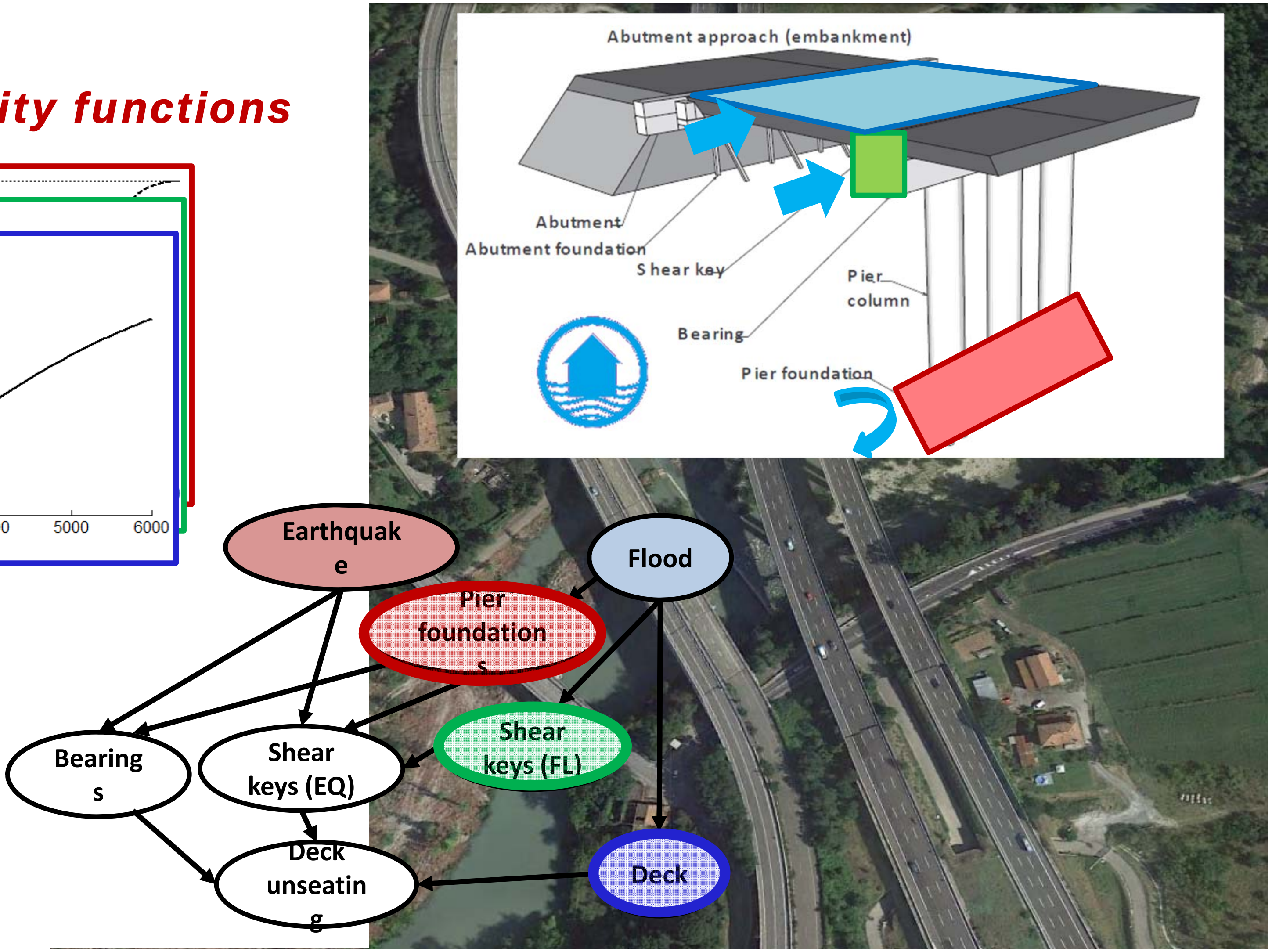
Fragility model
- Multi-risk fragility functions

Fragility model
- Multi-risk fragility functions



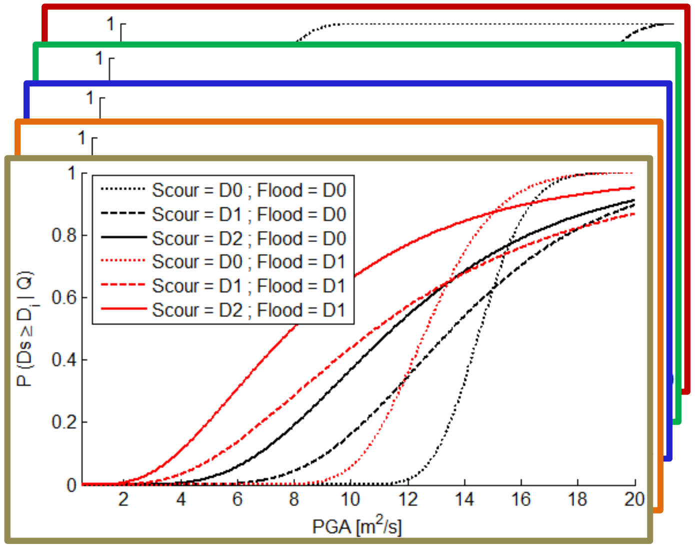
Fragility model
- Multi-risk fragility functions

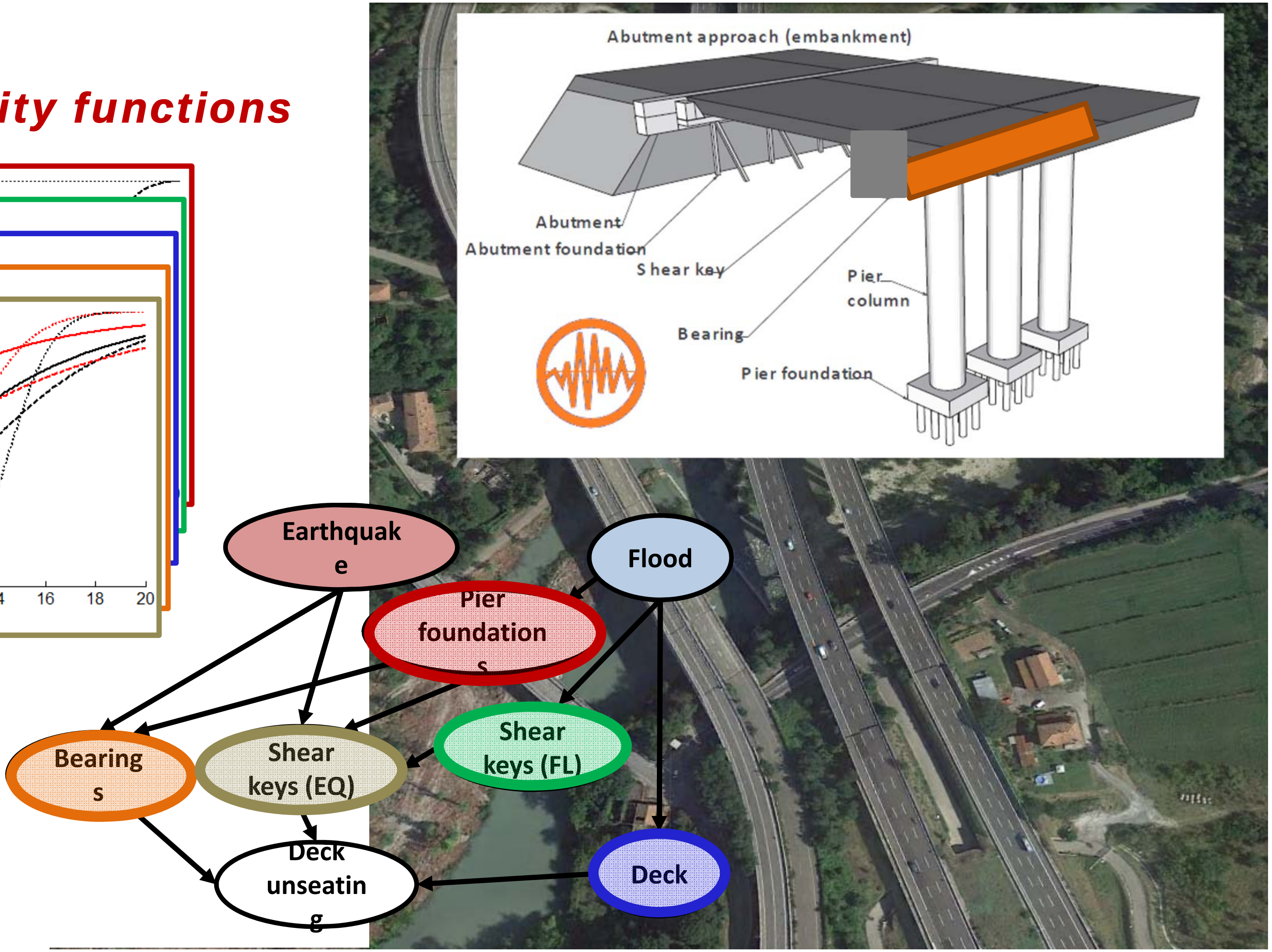




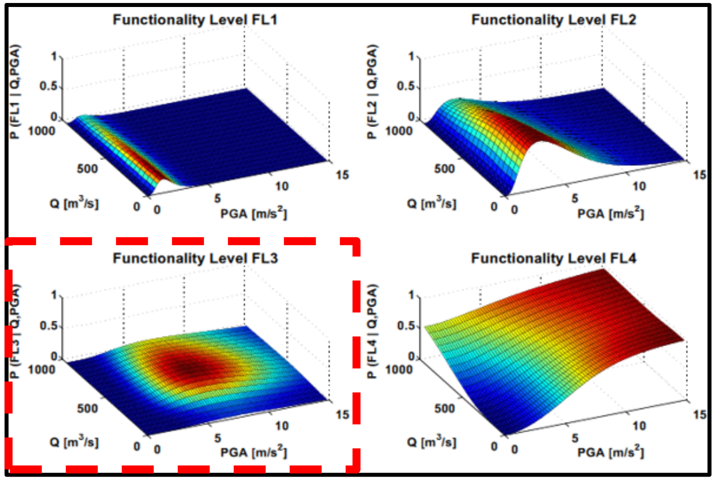
Fragility model

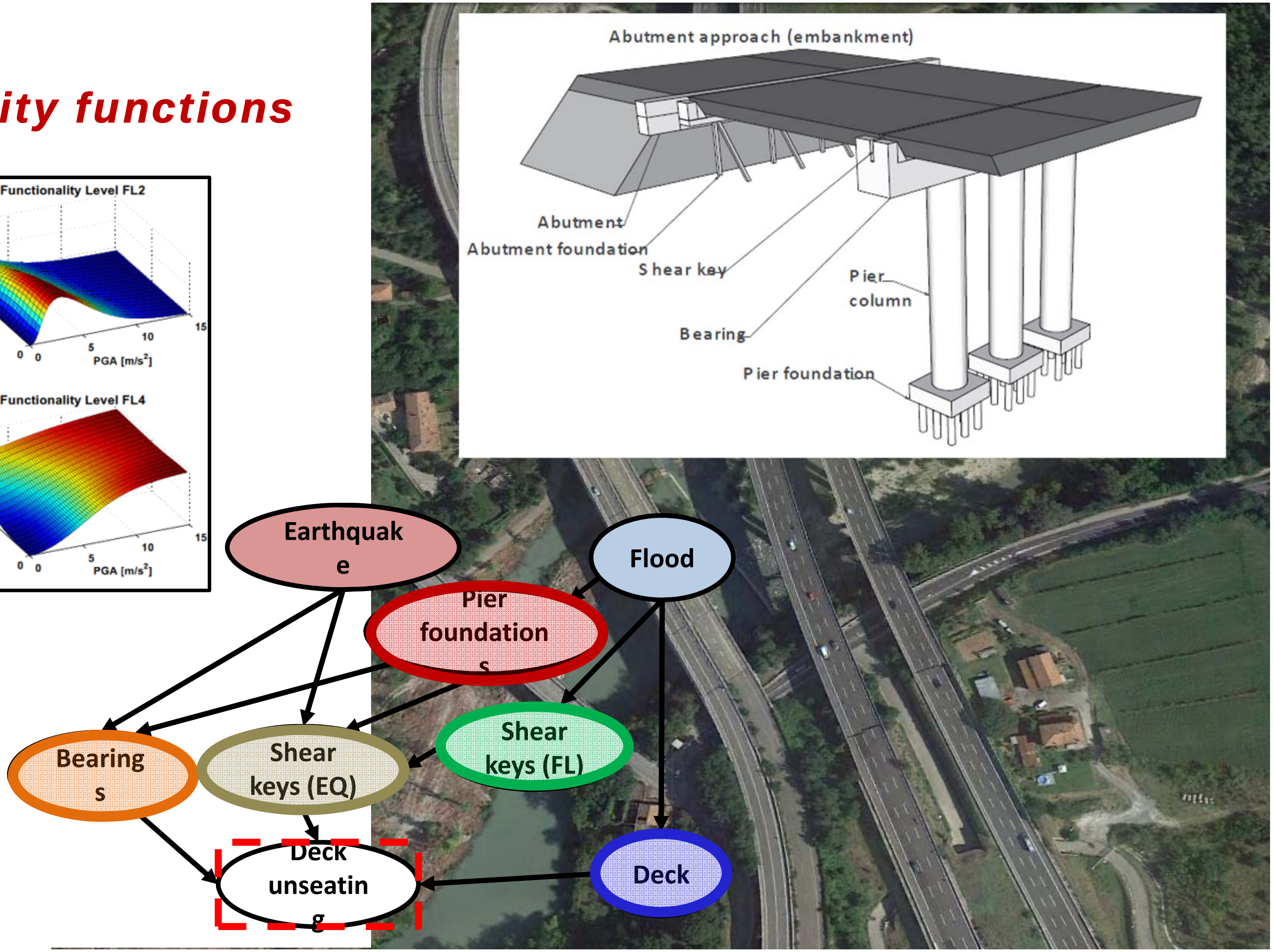
- Multi-risk fragility functions





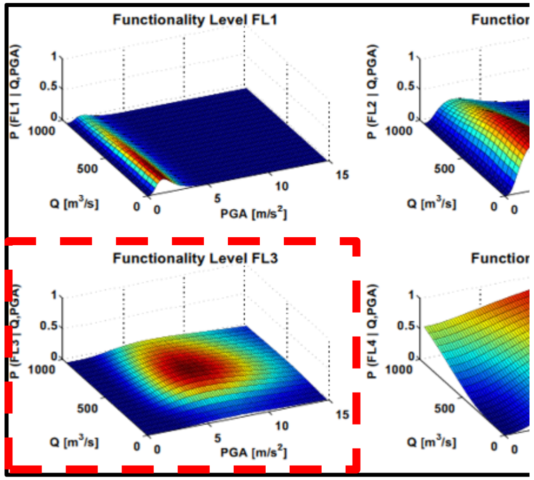
Fragility model
- Multi-risk fragility functions

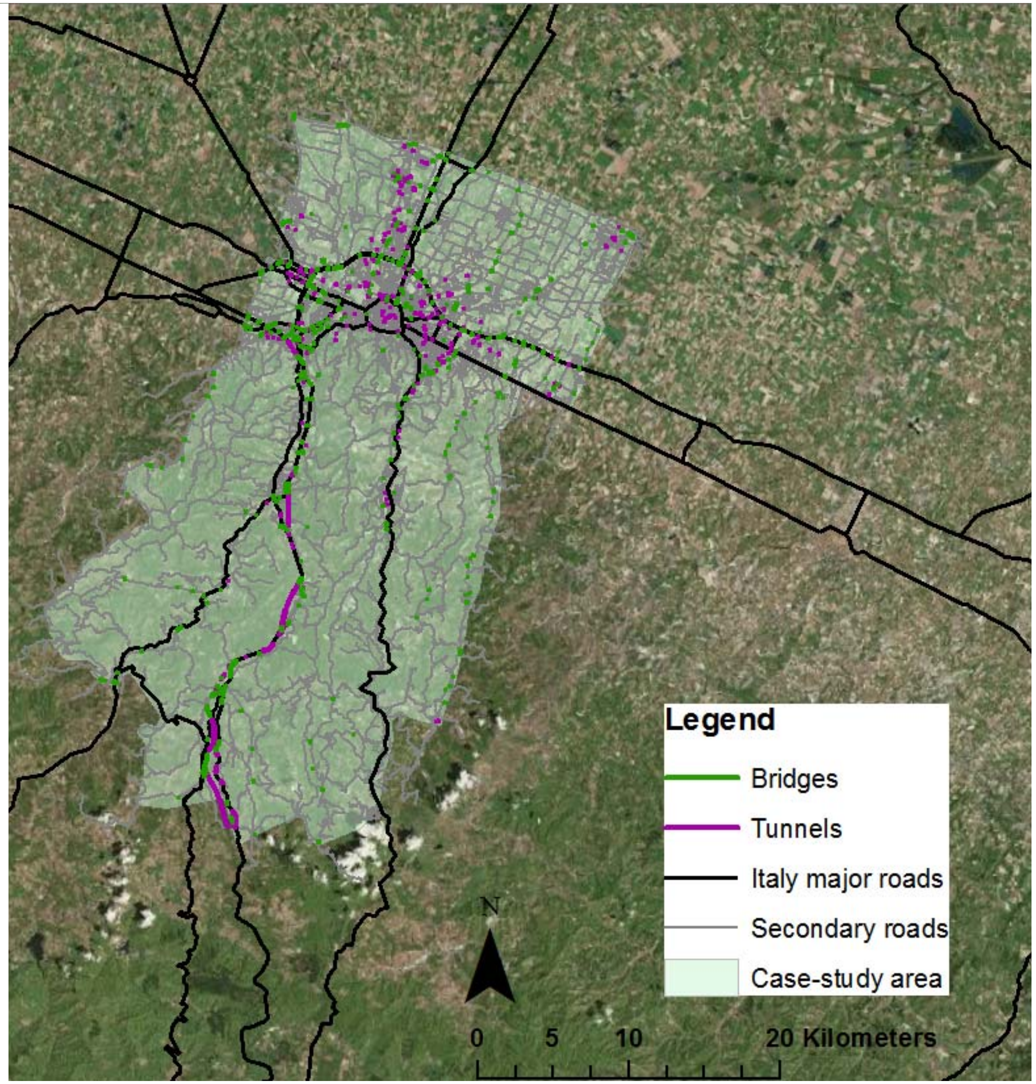




Fragility model

- Multi-risk fragility functions





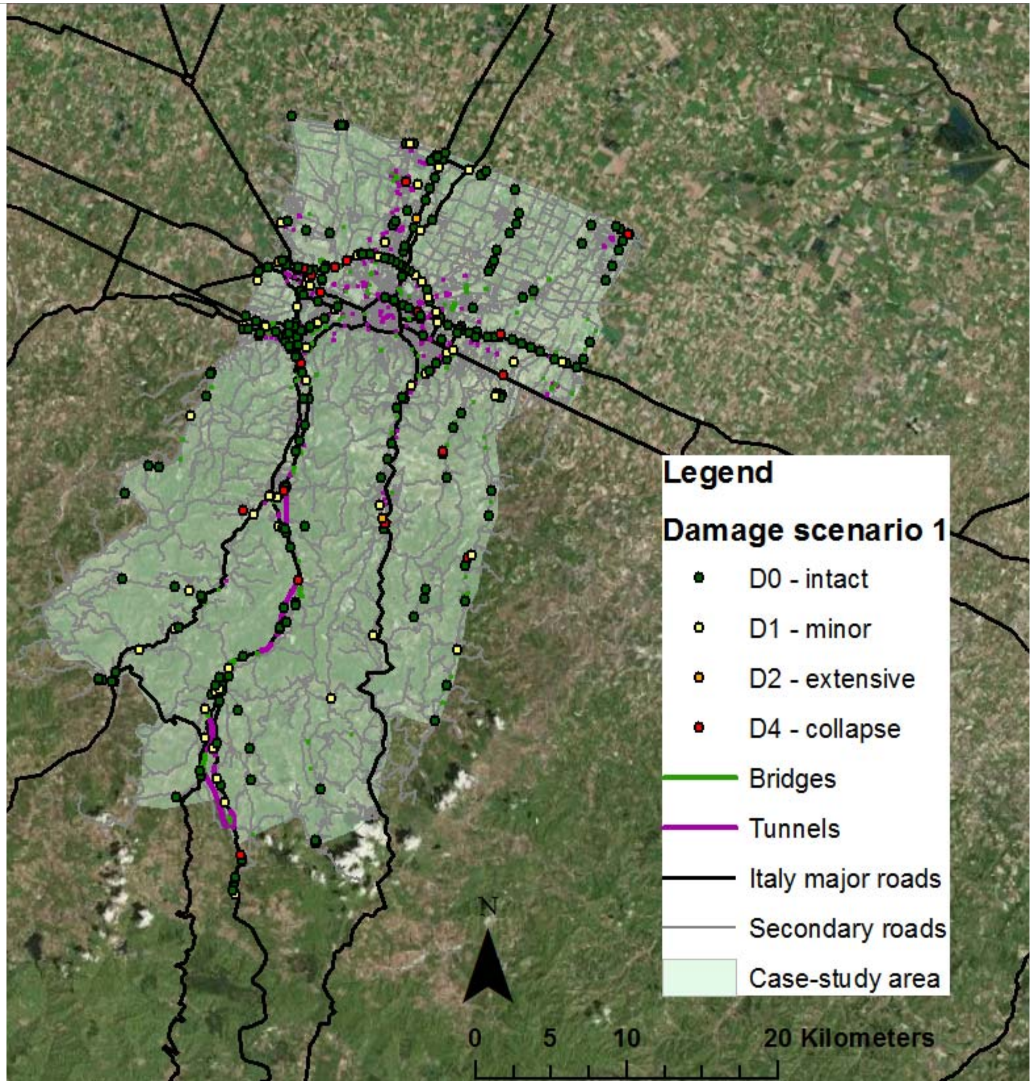
INFRARISK

UCL

Physical damage map
- Seismic damage to bridges

Damage states are randomly sampled given the damage probabilities

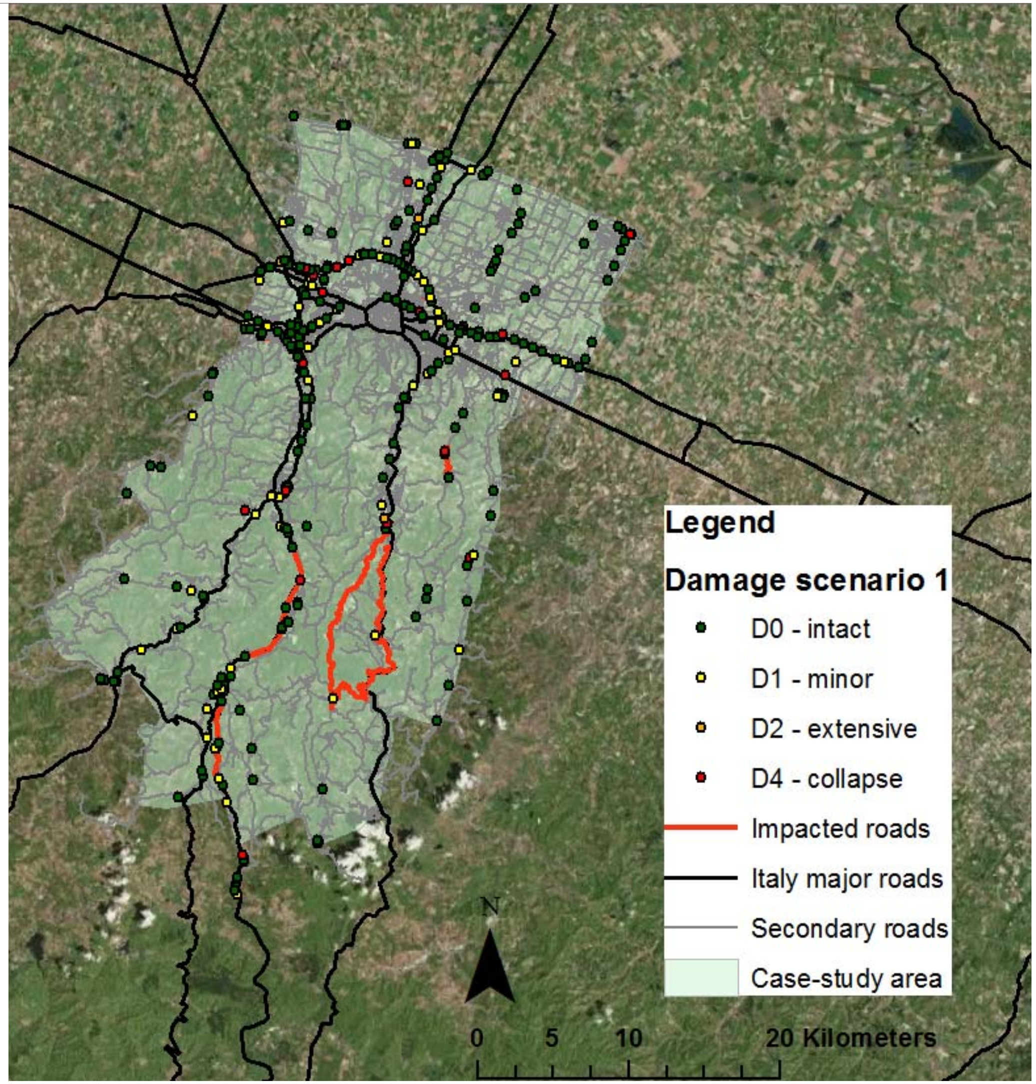
Damage scenario 1



Functional consequences
- Impacted road segments

Damage states are randomly sampled given the damage probabilities

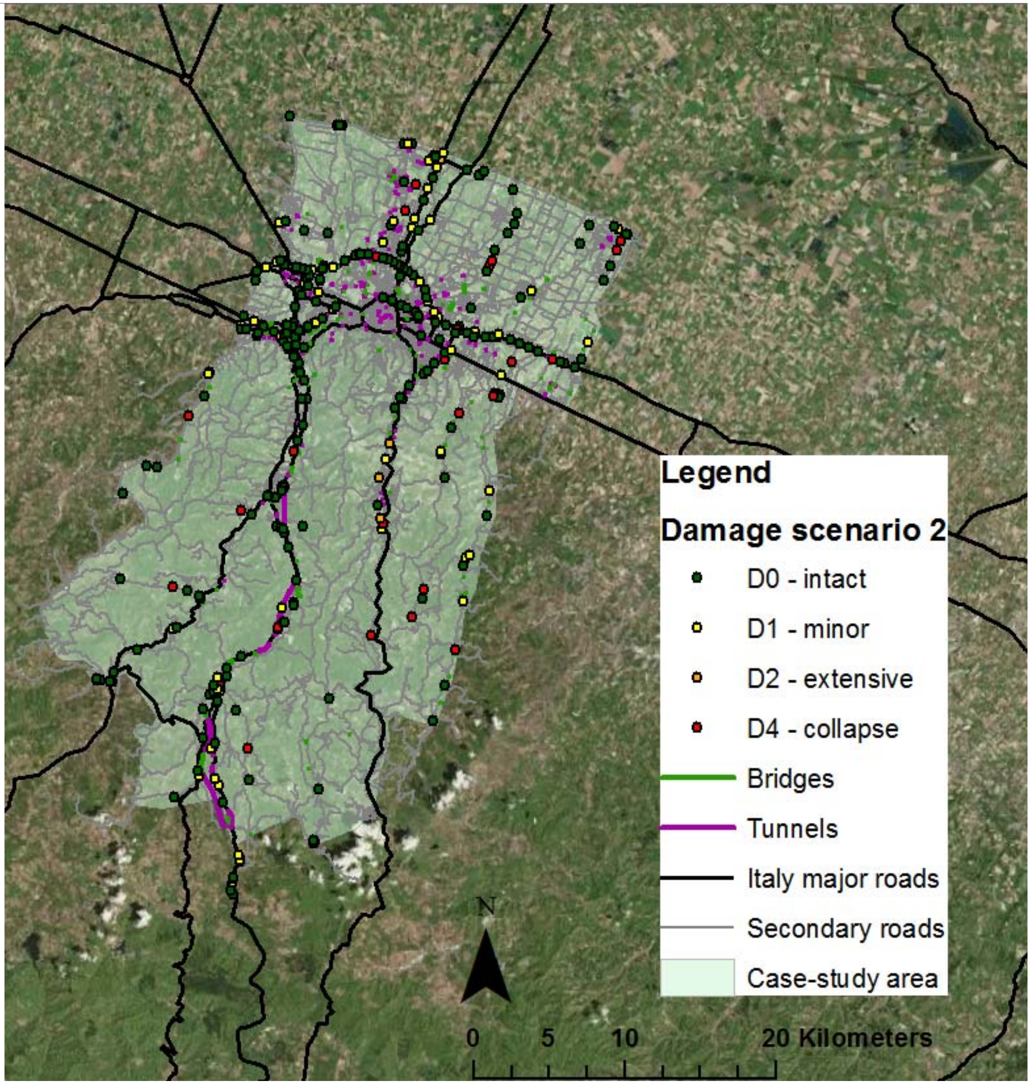
Damage scenario 1



Physical damage map
- *Seismic damage to bridges*

Damage states are randomly sampled given the damage probabilities

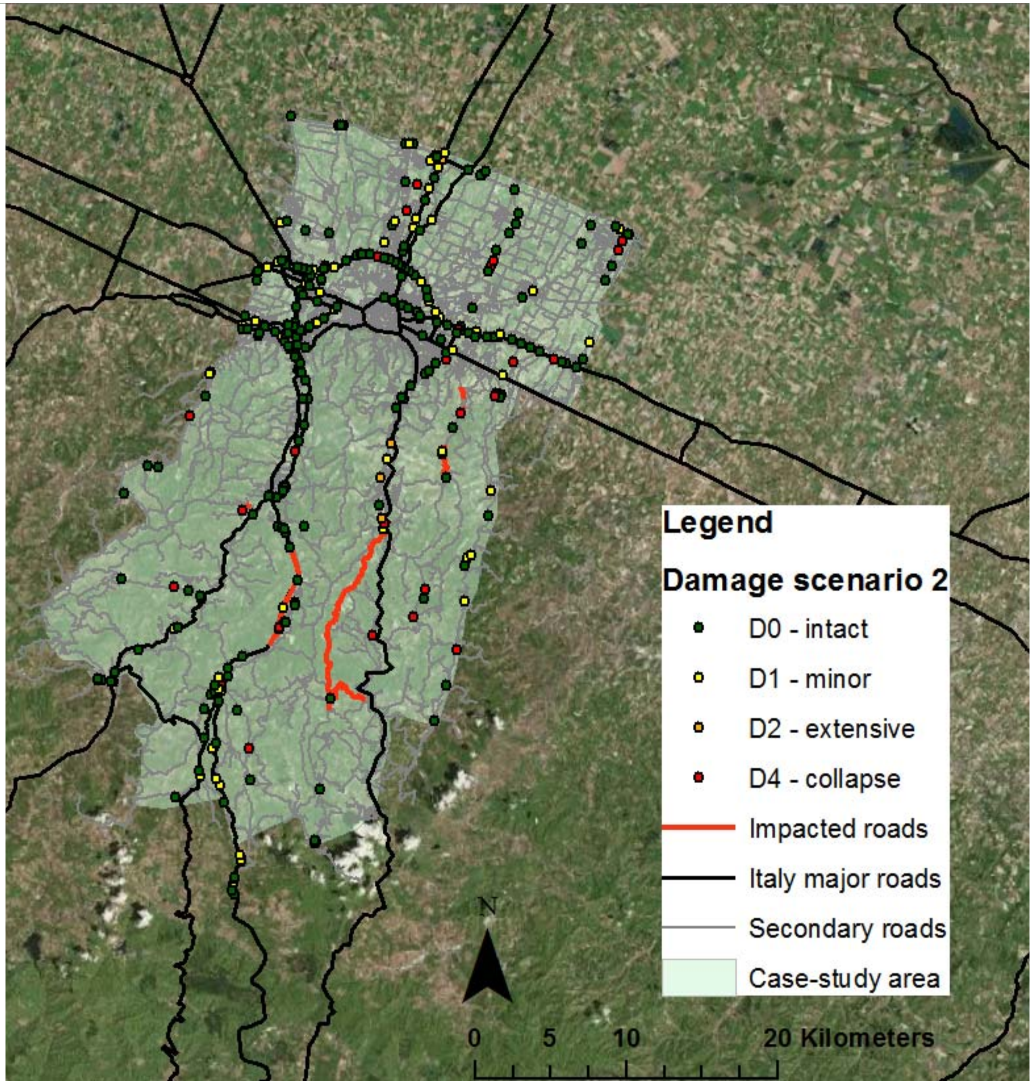
Damage scenario 2



Functional consequences
- Impacted road segments

Damage states are randomly sampled given the damage probabilities

Damage scenario 2



From Physical damage to functionality loss and resilience

Final Dissemination Conference

29 September 2016, Madrid, Spain

Bridge failure modes

> Identification of around 50 damage mechanisms ➔ what are their effects on the bridge functionality?

ID	Component	Sub-type	Failure mode	Damage 'Severity'	Description
Earthquake hazard					
1	Pier	-	Bending	D1	- Minor cracking/spalling - Yielding
				D2	- Cracking/spalling (still structurally sound)
				D3	- Column degrading without collapse (structurally unsafe)
				D4	- Column collapsing - Reinforcement buckling
2	Pier	-	Shear	D3	- Brittle shear failure
3	Pier	-	Tilting	D4	- Tilting of substructure due to foundation failure
4	Abutment	-	Piles	D1	- Minor cracking/spalling
				D2	- First yielding point
				D3	- Ultimate deformation - Vertical offset
5	Abutment	-	Backfill	D1	- Gap closure
				D2	- Passive resistance of backfill soil is reached
				D4	- Ultimate displacement

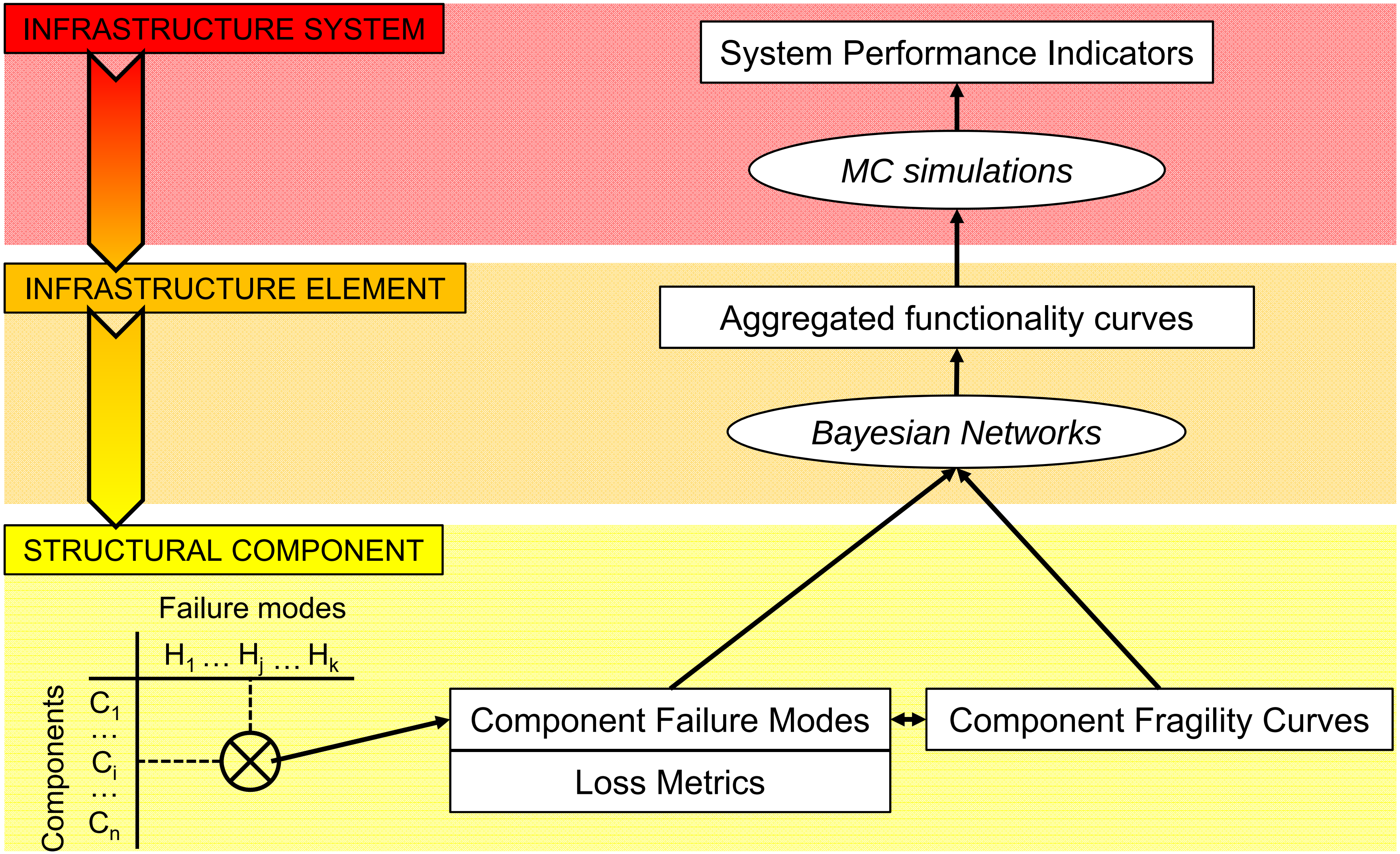
ID	Component	Sub-type	Failure mode	Damage 'Severity'	Description
					of the backfill system
		-	Transverse loading	D1	- Gap closure - Minor cracks
				D2	- Extensive cracking/spalling
				D3	- Failure
				D4	- Deck unseating
		Fixed	-	D2	- Shear strength reached
				D4	- Deck unseating
		Steel pendulum	-	D1	- Bearing capacity under non-seismic conditions
				D2	- Vertical instability
				D4	- Deck unseating
		Sliding/ roller	-	D1	- Bearing capacity under non-seismic conditions
				D4	- Deck unseating
		Bolted neoprene	-	D1	- 150% of rubber shear strain amplitude
				D2	- 200% of rubber shear strain amplitude
				D3	- 300% of rubber shear strain amplitude
				D4	- Deck unseating
		Unbolted neoprene	Friction/ slipping	D1	- Friction resistance is reached
				D3	- Pad dimensions are reached
				D4	- Deck unseating
12	Bearing	Unbolted neoprene	Rollover	D1	- 1/3 of pad dimensions are reached
				D2	- 1/2 of pad dimensions are reached

ID	Component	Sub-type	Failure mode	Damage 'Severity'	Description
				D3	- Pad dimensions are reached
				D4	- Deck unseating
		Elastomeric w/ dowels	-	D1	- Noticeable deformation
				D2	- Possible deck realignment and dowel fracture
				D3	- Girder retention and deck realignment
				D4	- deck unseating
		-	-	D1	- Minor cracking - Curvature limits reached
				D4	- Deck collapse
		-	Slope failure	-	- Differential displacements leading to deck collapse
		-	Subsidence/ settlement	-	- Settlement of soil under approach embankment
		-	Local scour	-	- Scour depth (below/ within/above footing)
		-	Streambed downcutting	-	- Piers are affected - Culverts are undercut
		-	Local scour	-	- Scour depth (below/ within/above footing)
		-	Streambed downcutting	-	- Abutments are affected - Culverts are undercut
		-	Overtopping	-	- Shifting of deck due to hydraulic pressure

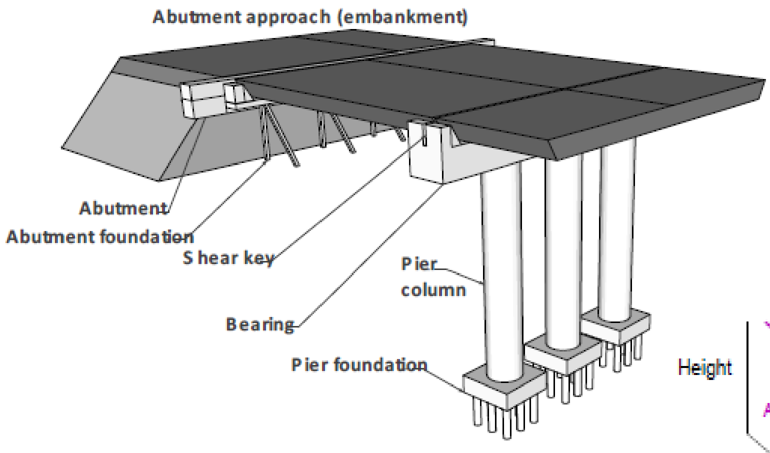
...pe	Failure mode	Damage 'Severity'	Description
	Debris accumulation	-	- Reduction of flow capacity - Backup of water flow
	Channel modification	-	- Shifting/migration of waterway channel alignment

Review and taxonomy of qualitative damage scales

Proposed strategy

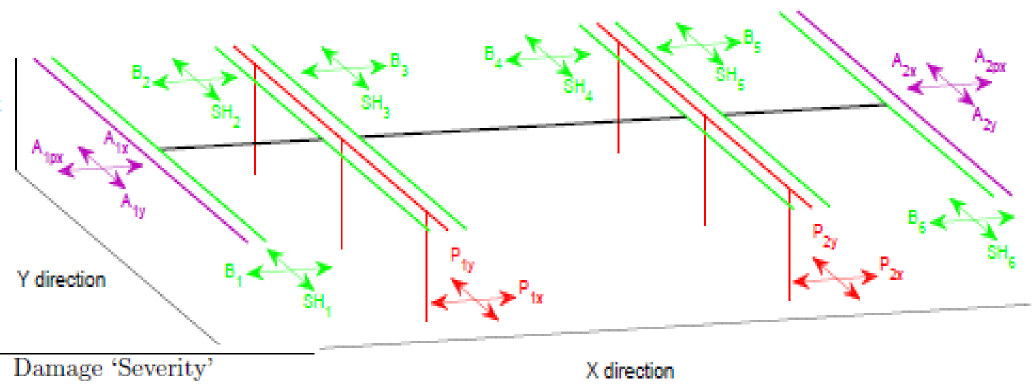


Application to a bridge example



Multi-Span Simply-Supported Concrete (MSSSC) bridge proposed by Nielson (2005)

22 vulnerable components when considering both loading directions:

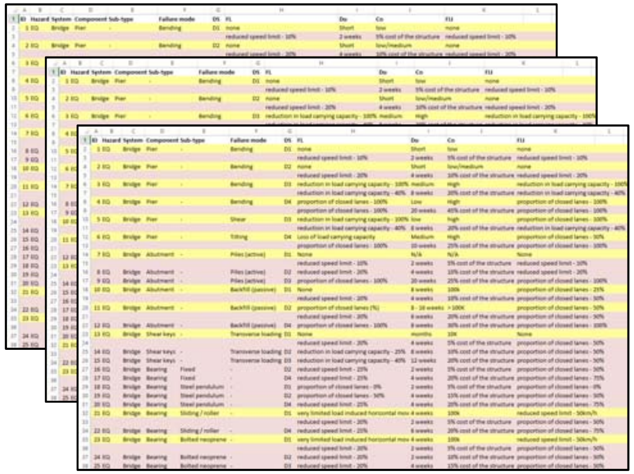


ID	Component	Failure mode	EDP	DS1	DS2	DS3	DS4
				Damage 'Severity'			
1	Pier	Bending	Section curvature	0.005	0.008	0.014	0.020 (X)
				0.015	0.024	0.041	0.061 (Y)
4	Abutment	Piles	Deformation in tension [mm]	7.6	25.4	200.0	– (X)
				7.6	25.4	200.0	– (Y)
5	Abutment	Backfill	Deformation in compression [mm]	19.2	25.4	–	192.0 (X)
				–	–	–	– (Y)
6	Shear key	-	Deformation [mm]	–	–	–	– (X)
				25.0	25.5	25.5	406.0 (Y)
13	Fixed bearing	-	Deformation [mm]	10.5	10.5	12.5	152.0 (X)
				–	–	–	– (Y)
	Expansion bearing	-	Deformation [mm]	10.5	25.0	34.5	152.0 (X)
				–	–	–	– (Y)

Identification of 18 failure modes at the component level

Functionality models at component level

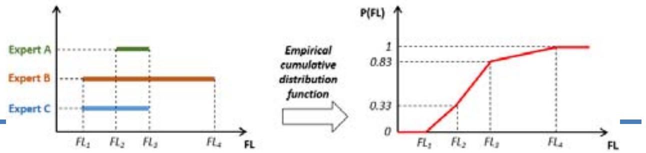
Expert-based survey



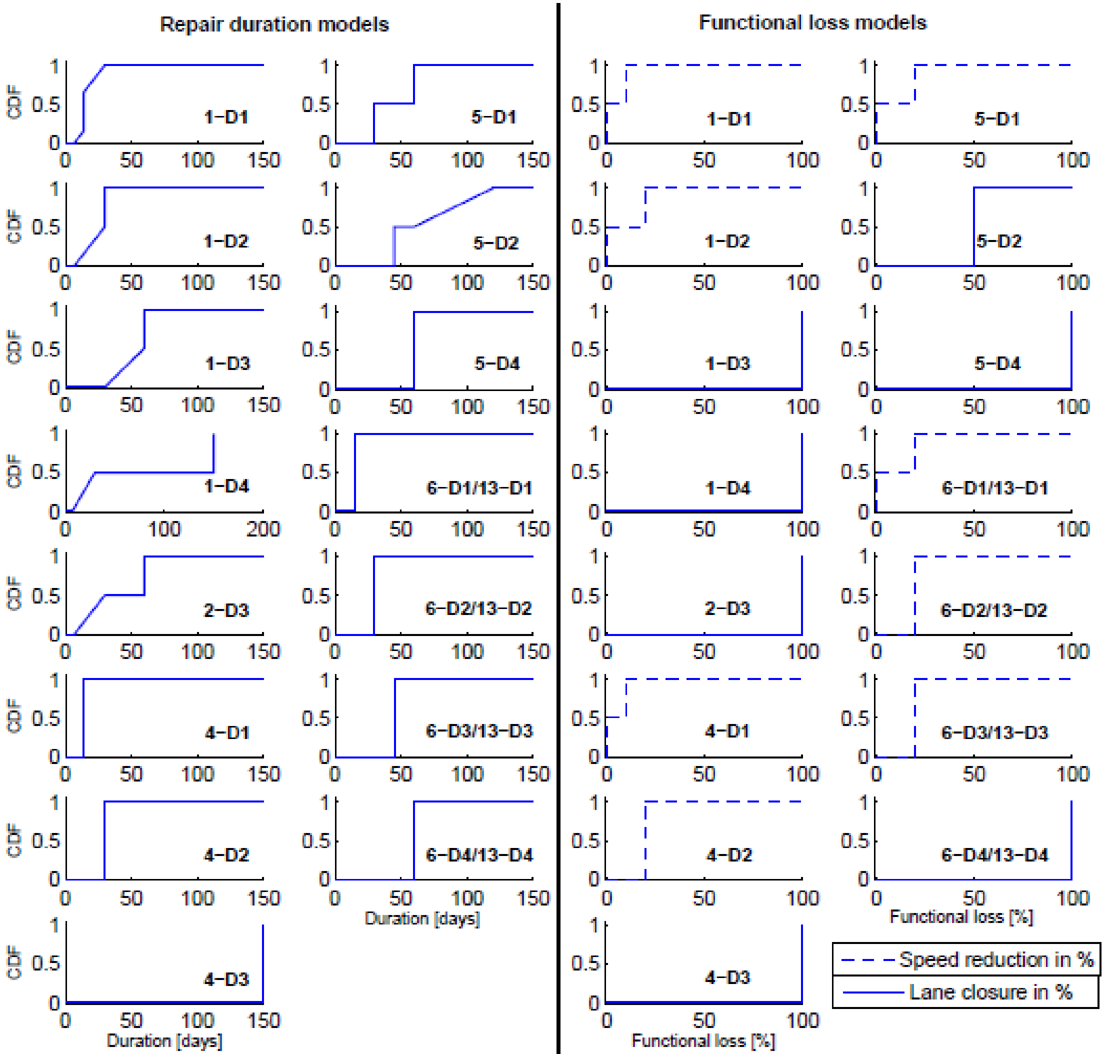
Current limits:

- Limited amount of data points
- No 'seed' questions

Statistical treatment ('pooling')



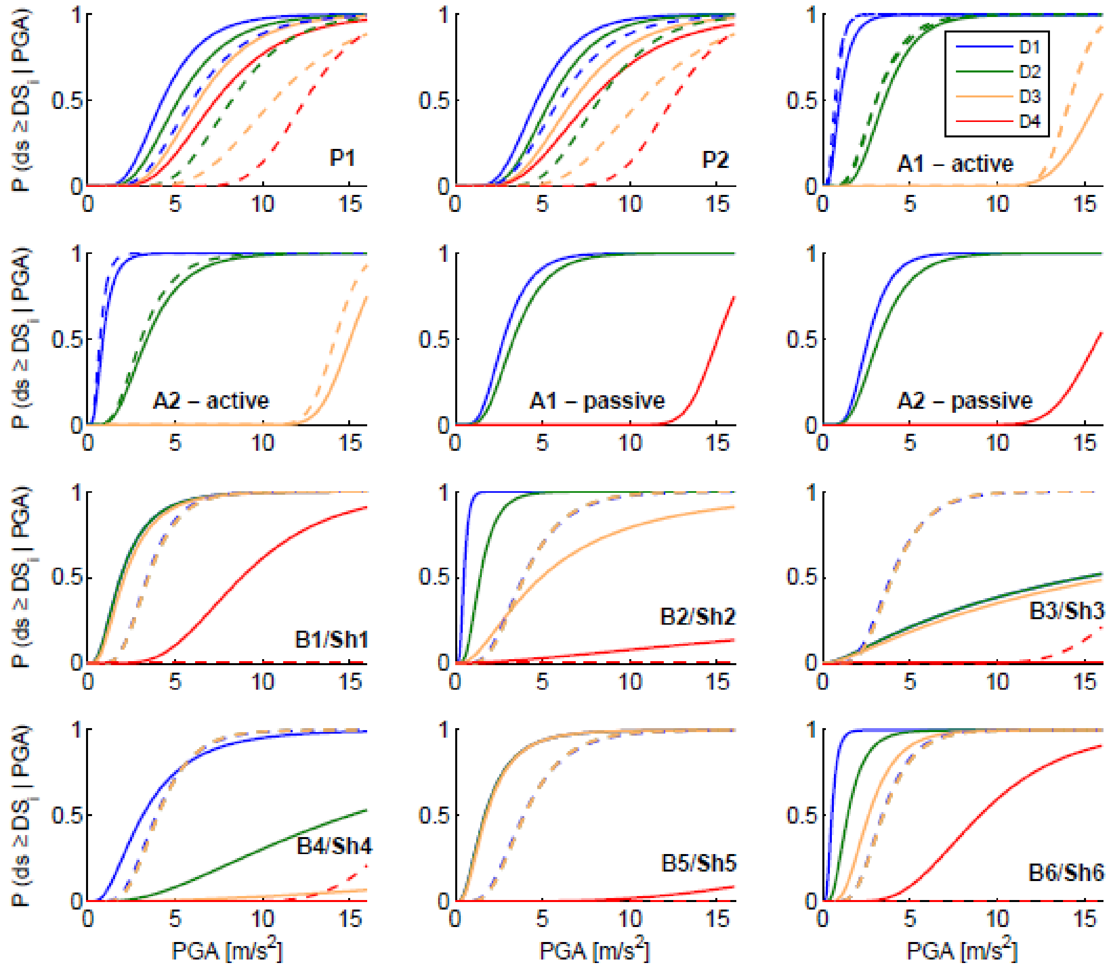
Functionality models for downtime duration and functional losses



Component fragility curves

> Non-linear dynamic time-history analyses of a finite element model of the bridge:

- *The response of each component is taken separately to derive component fragility curves*
- *The responses of all components are used to build a correlation matrix (accounting for statistical dependence)*



Correlation between damage events

> Statistical dependence ➔ Introduction of a Dunnett-Sobel class of variables:

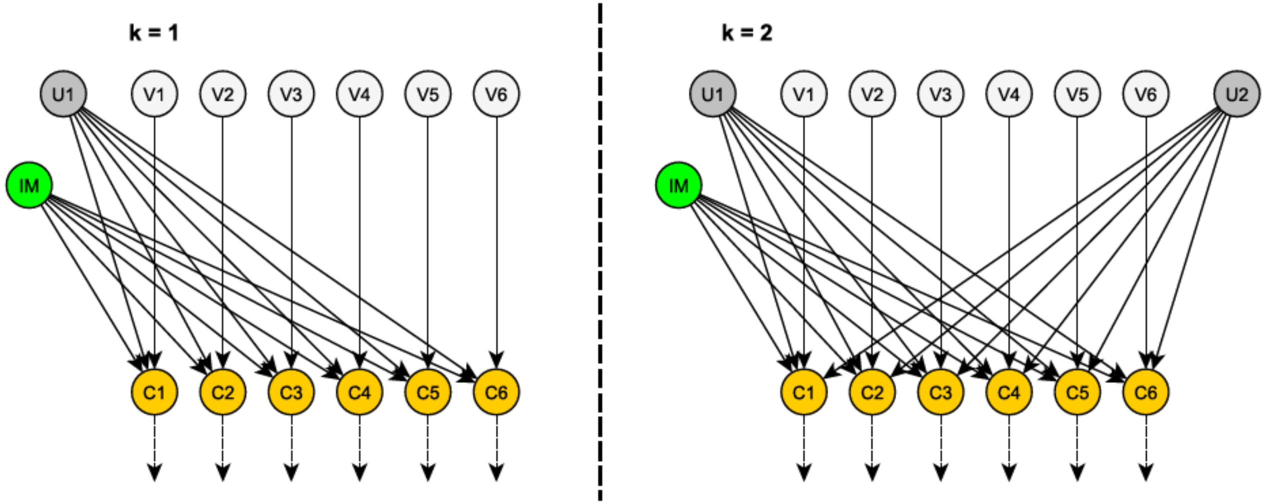
$$Z_i = \sqrt{1 - \sum_{j=1}^{k} r_{ij}^2} \cdot V_i + \sum_{j=1}^{k} r_{ij} \cdot U_j$$

> Approximation of the correlation matrix between of Z_i safety factors:

$$\rho_{il} \approx \sum_{j=1}^{k} r_{ij} \cdot r_{lj}$$

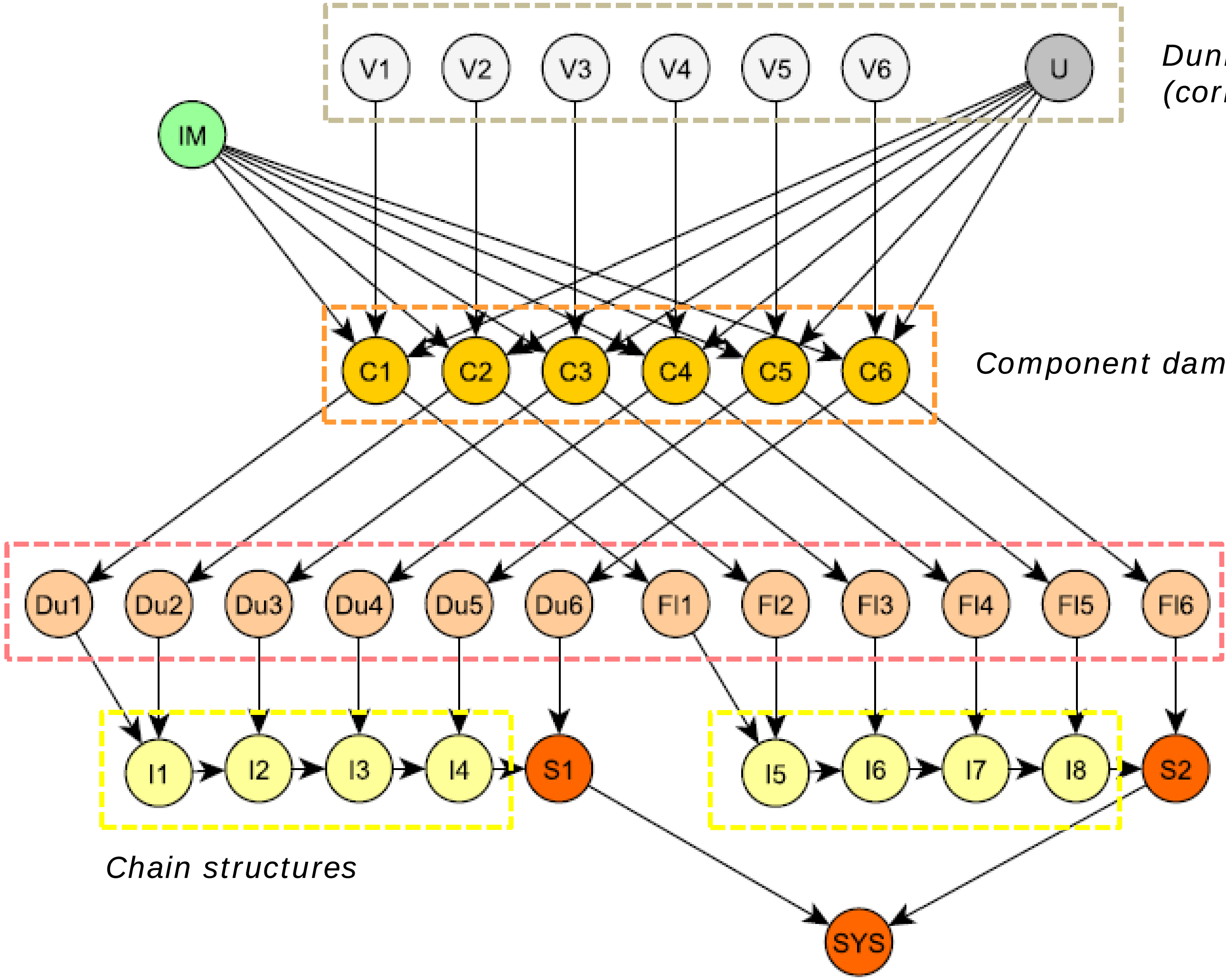
> V_i ➔ Standard normal variable specific to each component

> U_j ➔ Standard normal variable common to all components



Representation of the variables in a Bayesian Network

Assembling failure modes



Dunnett-Sobel variables (correlation structure)

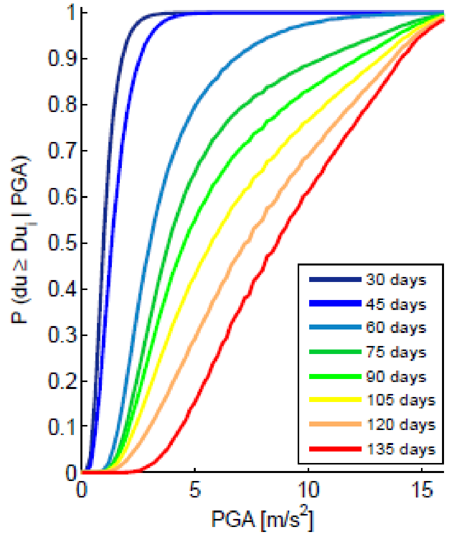
Component damage states

Functionality models (repair duration and functional losses)

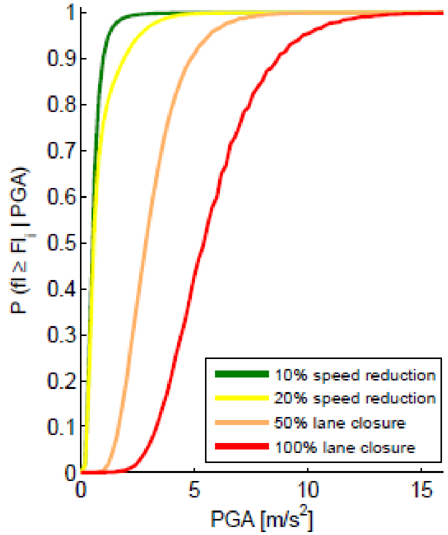
Chain structures

Derivation of functionality loss curves

- Solving of the Bayesian Network for increasing values of IM
- Observing the updating of the probabilities at nodes S1 and S2

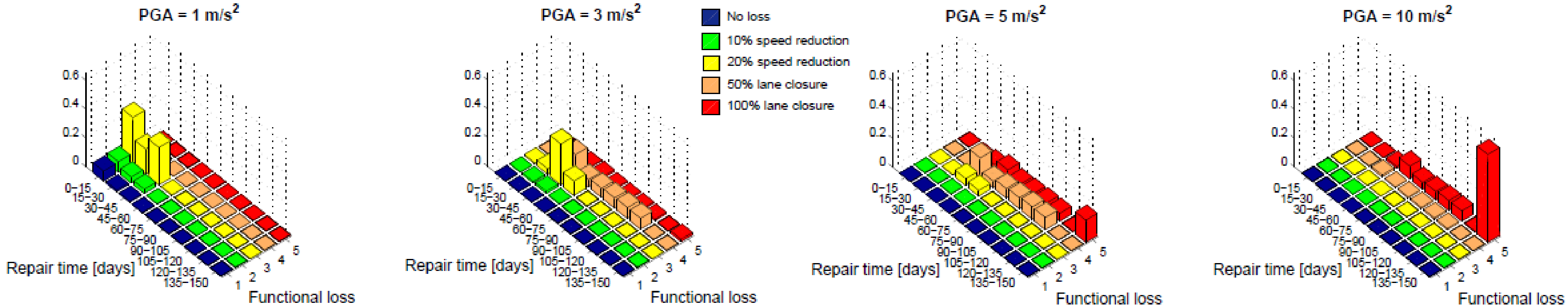


Repair duration

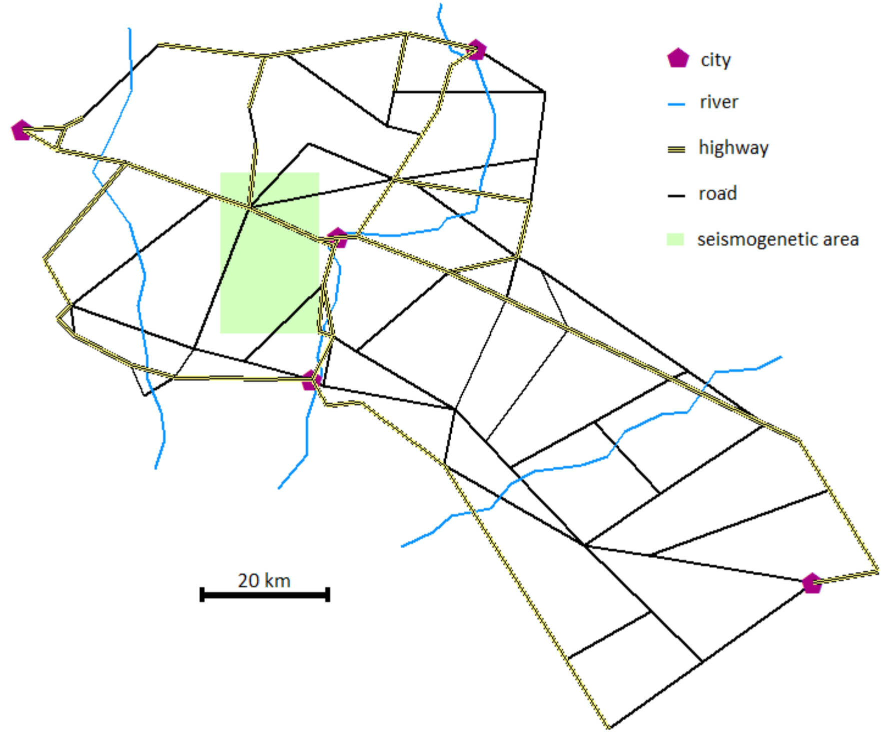


Functional loss

- Observing the updated probability at node SYS provides access to joint probabilities of occurrence:



Application to a road network analysis



- *Virtual proof-of-concept for illustration purposes*
- *Each edge is assumed to contain a bridge (111 bridges)*
- *Seismic events are probabilistically sampled (Monte-Carlo simulation)*
- *Network is assumed to link 5 cities of interest*

Performance Indicator 1 = *averaged ratio of increased travel times between selected cities*:

$$R_{TT} = \frac{1}{n}\sum_{i=1}^{n}\frac{TT_{i,d}}{TT_{i,0}}$$

For *n* inter-city travels (*n* = 10)

Performance Indicator 2 = *single connectivity loss between each city:*

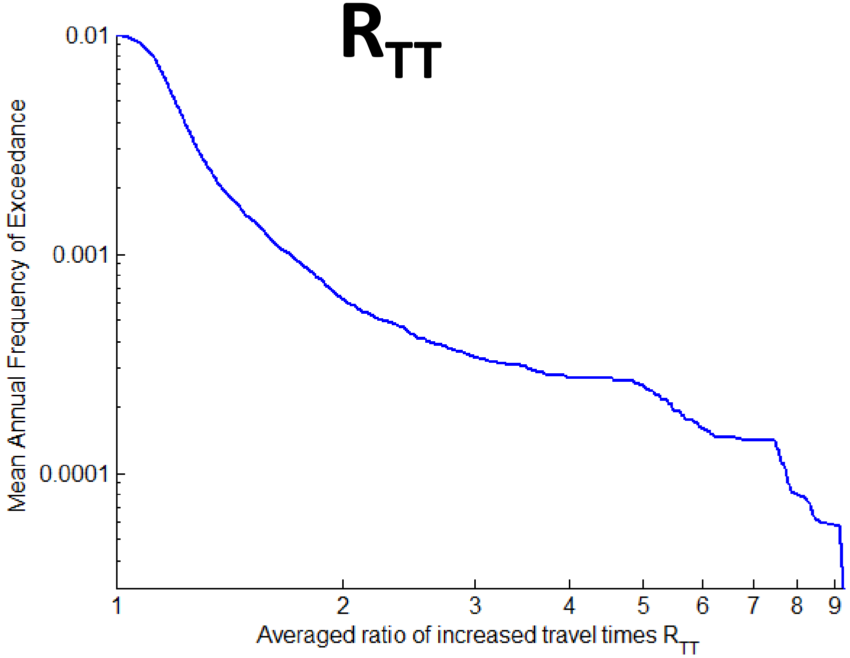
$$SCL = 1 - \left\langle \frac{N_{s,j,d}}{N_{s,j,0}} \right\rangle_j$$

For *j* = 1..5 (# of cities)

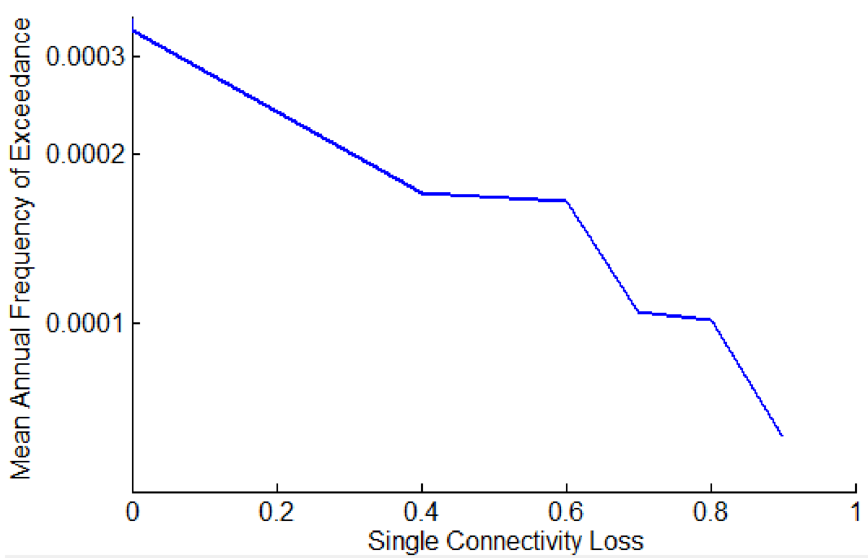
Annual probability of exceedance

- The empirical CDF of the performance indicator is derived from 5,000 runs
- Assumed seismic activity parameter: 0.01 annual rate of EQ occurrence

R_{TT}



SCL



More refined capacity-based performance indicators would require high computational costs (e.g. traffic models, etc.)

Computation of the resilience index

- Performance indicator (system loss):

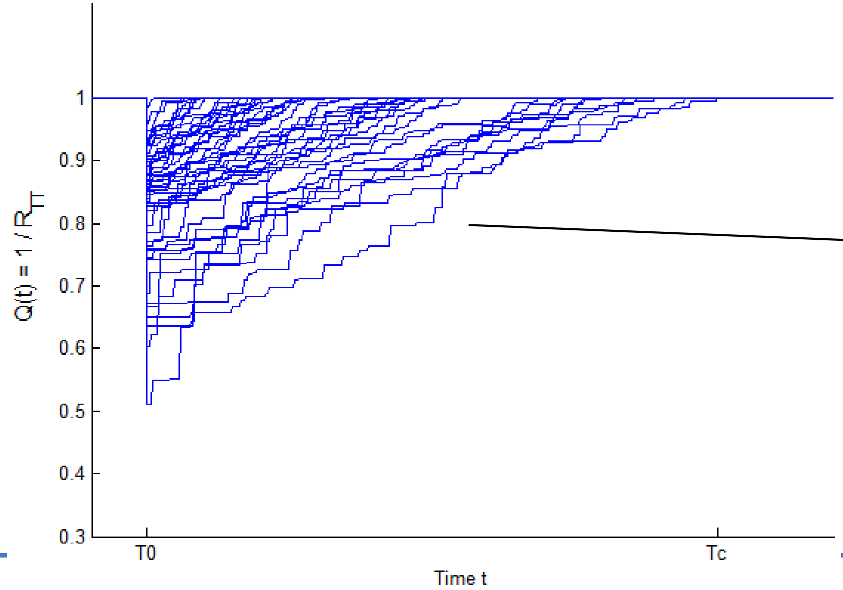
$$R_{TT} = \frac{1}{n}\sum_{i=1}^{n}\frac{TT_{i,d}}{TT_{i,0}}$$

- Proposed measure for remaining functionality:

$$Q(t) = \frac{1}{R_{TT}}$$

- Definition of the resilience index:

$$R = \int_{t=0}^{T_C}\frac{Q(t)}{T_C}\,dt$$

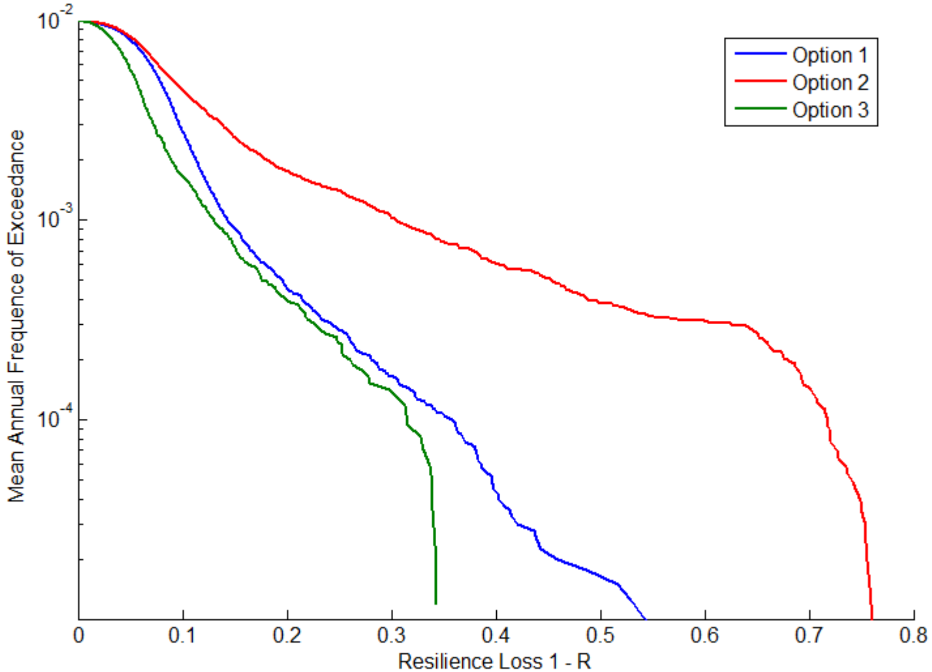


Each sampled damage scenario leads to a different resilience index
➔ probability distribution?

Evaluation of restoration strategies

- Assumption : only one repair team available (restoration sequence)
- Three restoration schemes are evaluated:

  1. Work in priority on the bridges with heaviest functional losses
  2. Work in priority on the bridges with lightest functional losses
  3. Work in priority on the bridges that have the highest impact on the network performance



Conclusions

- Merits of Bayesian Networks to assess joint probabilities of occurrence and to decompose complex events at smaller scales (from system to components and vice-versa)
- Component-level damage mechanisms provide a better resolution of the functional consequences
- Efficient and innovative seismic hazard approach to handle low-probability extreme ground motions and derive associated deterministic scenarios
- The two procedures above can be successfully sued to determine network physical damage scenarios
- Need to improve the knowledge of functionality models for various failure modes
- Functionality curves may be derived for other hazard types since they provide a harmonized ‘damage’ scale
- Application to a real-life network is underway

www.infrarisk-fp7.eu

This project has received funding from the European Union's Seventh Programme for research, technological development and demonstration under grant agreement No. 603960