Novel Indicators for INFRAstructure at RISK

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Background and Consortium

- **Funding Vehicle**
  EU 7th Framework Programme

- **Work Programme**
  2013 Cooperation Theme 6-Environment

- **Call Topic**
  Env.2013.6.4-4

  *Towards stress tests for critical infrastructure against natural hazards*

- **Duration & Budget**
  October 2013 – September 2016
  €2.8 million
Motivation

• Increasing number of natural hazard events due to:
  ➢ Climate Change
  ➢ Increased land occupation
  ➢ Eastwards expansion of the EU
  ➢ Human activity

• Increase preparedness and resilience
  ➢ Effective Road & Rail Transport Network
  ➢ Increased Traffic
  ➢ Ageing Infrastructure
  ➢ Budgets / Resources
**Definition of stress test**

- Stress tests refer to the assessment of a particular system performance under a specific set of adverse conditions.

- The outcome of stress tests can be used to inform decisions on intervention on infrastructures components, contributing to the resilience of critical transport networks.

- The stress output consists of an outcome probability distribution conditional to the proposed stress scenario.

- Typical stress outcome metrics are the costs of physical repairs to the network, delay times for network users, loss of connectivity, financial losses.
Project Focus

- **Low probability, high consequence natural hazard events**
  - Earthquakes, floods and landslides
- **European road and rail infrastructure**
- **Risk quantification**
  - Physical damage, transport delays, economic loss
Case study base

Road Infrastructure

Rail Infrastructure
**Challenges/ Solutions**

- 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)?
Project Outputs

- Knowledge Base Repository and Risk Profiling
- Multi-risk Assessment Framework
- Multi-risk Vulnerability and resilience framework
- INFRARISK Decision Support Tool
- Training Course for Infrastructure Owners/Decision Makers
Risk Profiling

Inventory of Critical Infrastructure in the EU

Major Global Infrastructure Failures

Focus on critical elements of Ten-T transport infrastructure

https://infrarisk.datagraft.net/
Output: Map based Graphic User Interface
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
Stress test framework

- Set up risk assessment
- Determine approach
- Define system representation
- Determine parts of system to be analysed in more detail
- Estimate risk
- Evaluate risk
- More analysis required
- Resulting in decision to conduct more analysis, modify system, or do nothing

Process encourages only obtaining as much information as required.
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 $\rightarrow$ GF)
- **Subsequent events**: flood follow by an earthquake (FL + EQ $\rightarrow$ GF)

Multi-risk fragility framework should be consistent for all these cases.
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)
Hazard scenario definition

- Seismic Hazard Model (Stress Test)
- Example GM field
  - SHARE Active
  - Low attenuation ground motion
  - 10,000 year return period
  - 90% fractile
- Linked to ‘critical network element’
  - Betweenness centrality method
Landslide hazard

- Use of Random Forest method to determine rainfall thresholds for slope failure given landslide susceptibility.

Validation results: $R^2=77.15$

Landslide classification- Bologna
Italian Case Study

**Earthquake-triggered landslides**

- Rigid sliding block approach
  - Landslide yield acceleration values ($k_y$)
Multi-risk vulnerability and resilience framework

<table>
<thead>
<tr>
<th>Asset system</th>
<th>Hazard types</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$H_1 \ldots H_i \ldots H_k$</td>
</tr>
<tr>
<td>$C_1$</td>
<td>$x$</td>
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<tr>
<td>$\ldots$</td>
<td>$\ldots$</td>
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<td>$C_i$</td>
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<tr>
<td>$C_n$</td>
<td>$x$</td>
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Harmonization through functional consequences

Harmonized system-level damage states

Hazard-specific component fragility curves

$P_{Ci}(DS \mid IM_{Hj})$

Bayesian Network

Inference from hazard IM evidence

Hazard-independent fragility model

Joint probability of system damage states
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Harmonized fragility functions

<table>
<thead>
<tr>
<th>Failures modes</th>
<th>Earthquake</th>
<th>Ground failures</th>
<th>Floods</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>- Ground shaking</td>
<td>- Slope failure</td>
<td>- Submersion</td>
</tr>
<tr>
<td></td>
<td>- Rock fall</td>
<td>- Rock fall</td>
<td>- Scour</td>
</tr>
<tr>
<td></td>
<td>- Settlement</td>
<td>- Settlement</td>
<td>- ...</td>
</tr>
</tbody>
</table>

Tunnels
- Component 1
- ...
- Component i
- ...
- Component 1
- ...
- Component i
- ...

Bridges
- Component 1
- ...
- Component i
- ...
- Component 1
- ...
- Component i
- ...

Road segments
- ...
- Component i
- ...
- Component 1
- ...
- Component i
- ...

Component fragility curves

Bayesian Network

Multi-risk fragility

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From physical damage to functionality loss

- Relation between each component damage state and a set of loss metrics (e.g. functionality loss, restoration time, etc.), through an expert elicitation process

Loss metrics:
- Functionality loss
- Type of intervention
- Cost/Duration of intervention
- Functionality loss during intervention

Harmonization of the effects of different hazard types at the consequence level

- Loss metrics are then used to estimate the system performance (e.g. though network/traffic analysis)
Functionality models at component level

Expert-based survey

Functionality models for downtime duration and functional losses

Current limits:
- Limited amount of data points
- No ‘seed’ questions

Statistical treatment (‘pooling’)
Derivation of functionality loss curves

- Solving of the Bayesian Network for increasing values of IM
- Observing the updating of the probabilities for the system states

- Observing the updated probability at node SYS provides access to joint probabilities of occurrence:
Agent-Based Model for infrastructure at risk

- Development of an agent-based natural hazard risk analysis approach for Infrastructure systems

**Data**
- Social-economic data
- OD data
- OD data
- Infrastructure (bridge, tunnels) data
- Road network in disaster area
- Earthquake data

**Model**
- Economic Model
  - ABM
    - Traffic Simulation model
    - Infrastructure response simulation model

**Application**
- Italy cities GDP loss evaluation
- Italy traffic time delay
- Bologna road vulnerability dynamic map

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Agent-Based Model for infrastructure at risk

• Three layers in the ABM:
  • **Disaster and physical infrastructure layer**
    • This layer simulates disaster events as well physical road network, so that scenarios of the road network situation in the context of disasters can be visualized. At this layer road, nodes, links, tunnels and bridges are set as agents.

  • **Traffic flow layer**
    • This layer simulates the traffic flow on the road network. Road networks are the infrastructure serving for transport. Therefore, road network performance is evaluated by the condition of traffic flow. At this layer, traffic flow can be set as one agent.

  • **Economic assessment layer**
    • This layer assesses the direct economic loss of physical road network due to disasters as well as indirect economic loss caused by travel delays.
Case-study – Application to the Bologna area

- ABM of the road network (bridges, tunnels) around Bologna
- Developed with the NetLogo ABM platform
- Simulation of the physical infrastructure network (road system) and its responses to seismic events
- Visualization of random scenarios

Simulation of traffic flows under natural hazards and evaluating the economic impact of risk reduction measures
Case-study – Application to the Bologna area
Case-study – Application to the Bologna area

Network Vulnerability – Travel Delays

• Regional traffic analysis
  ➢ NEXTA traffic modelling software
Case-study – Application to the Bologna area

Network Vulnerability – Travel Delays

• Regional traffic analysis
  - NEXTA traffic modelling software
  - Origin-Destination data obtained from Italian 2011 census data to represent traffic demand
Case-study – Application to the Bologna area

Network Vulnerability – Travel Delays

- Regional traffic analysis
  - NEXTA traffic modelling software
  - Origin-Destination data obtained from Italian 2011 census data to represent traffic demand
  - Simulation of post-event traffic
Consequences

Set up Risk Assessment → Determine Approach → Define System → Estimate Risk → Evaluate Risk

Network Vulnerability – Travel Delays

• National traffic analysis
  - NEXTA traffic modelling software
  - Wider impacts
Consequences

Set up Risk Assessment ➔ Determine Approach ➔ Define System ➔ Estimate Risk ➔ Evaluate Risk

Network Vulnerability – Travel Delays

• National traffic analysis
  - NEXTA traffic modelling software
  - Wider impacts
  - Origin-Destination (O-D) data obtained from ETIS project to represent traffic demand
Italian Case Study

Set up Risk Assessment → Determine Approach → Define System → Estimate Risk → Evaluate Risk

- Monte Carlo sampling method
  - Epistemic uncertainty
- Direct consequences
  - Total network repair cost
Italian Case Study

Set up Risk Assessment → Determine Approach → Define System → Estimate Risk → Evaluate Risk

- Monte Carlo sampling method
  - Epistemic uncertainty
- Direct consequences
  - Total network repair cost
- Indirect consequences
  - Average increase in travel time

Regional scale

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Italian Case Study

- Monte Carlo sampling method
  - Epistemic uncertainty
- Direct consequences
  - Total network repair cost
- Indirect consequences
  - Increase in average travel time
National level

Economic impact estimation
Traffic condition simulation
National level scale
Infrastructure disruption scenario
Wider Economic impact evaluation

Bologna Weekly GDP Loss per capita after the earthquake (Euro)

Non-disaster area cities weekly GDP during an earthquake event

Weekly GDP loss percentage

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Italian Case Study

- Adequacy of risk assessment
- Determine outcome of stress test
  - Risk acceptability
  - Interventions (i.e. repair works)
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

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

\[ \Rightarrow \] 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
Model application on evaluating the factor of restoration time to the economic loss

Histogram of the road network recovery time given different bridge restoration time

Emilia-Romagna region cities GDP Loss

Other cities GDP Loss
INFRARISK: Novel Indicators for Identifying Critical Infrastructure at Risk from Natural Hazards

Decision Support Tool

Infrarisk.it-innovation.soton.ac.uk
Training Course

Training Video

1  INFRARISK Project Introduction
2  INFRARISK Stress Testing Procedure
3  INFRARISK Decision Support Tool
4  INFRARISK Croatian Case Study – ORT Application

https://www.youtube.com/channel/UCK4VKDQzosT7FwgDtaSRWiA/videos
Project Impacts

• **Improvement of risk management approaches**
  Incorporating an exhaustive and rigorous treatment of the deep uncertainties involved in rare extreme events, probabilistic methodologies, and cascading effects.

• **Improvement of operational tools and procedures**
  Incorporating an INFRARISK decision support tool and operational evaluation methodology that can support decision making in a “stakeholder friendly” and transparent way.

• **Understanding the limitations of existing measures**
  Assessing the resilience margins of CI through the developed stress test framework and improving the awareness of the consequences of such events.

• **Contribution to European risk governance of CI**
  Stress test results will help to revise transport standards and management to create more harmonised and consistent technical approaches contributing as well with useful knowledge to disaster risk prevention policies.

• **Increased capacity at stakeholder level**
  Operational Analysis Framework considering cascading hazards, impacts and dependent geospatial vulnerabilities with practical software tools and guidelines and training course provisions.
Conclusions

- CI failures are a function not only of the extreme event but also of the primary failure type of an infrastructure element or system which could lead to cascading failures in local and regional interdependent systems.
- Stress tests are central to resilience analysis for extreme rare events. Stress tests allow for the identification of relevant measures that are needed to assure continuity of services in cases where scarcity of data from such events cannot provide a reliable prediction of similar future events.
- Through the use of a Bayesian network approach and Agent Based Modelling framework we can reproduce the chain of events and consequences triggered by a natural hazard scenario accounting for the uncertainties at each step.
- The close correlation between traffic flow and regional economy and therefore traffic flow data is ideal for quantitative evaluation of the economic impacts of infrastructure disruption due to natural hazards for the purpose of investment in infrastructure resilience.
Novel Indicators for identifying critical INFRAstructure at RISK from Natural Hazards

Website

www.infrarisk-fp7.eu

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