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A multi-hazard risk assessment methodology, stress test framework and decision support tool for resilient critical infrastructure

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Abstract

Natural hazards can cause serious disruption to societies and their transport infrastructure networks. The impact of these extreme events is largely dependent on the resilience of societies and their networks. The INFRARISK project is developing a reliable stress test framework for critical European transport infrastructure to achieve higher network resilience to low probability extreme events. The project considers the spatio-temporal processes and the propagated dynamic uncertainties associated with extreme natural hazard events, such as earthquakes, floods and landslides. Integrated risk mitigation strategies are employed to consider multi-hazards, as well as cascading hazard events. The project is developing an operational framework using an online INFRARISK Decision Support Tool (IDST) to advance decision making approaches, leading to better protection of existing transport infrastructure. The framework will provide greater support to the next generation of European infrastructure managers to analyse the risk due to extreme natural hazard events. To demonstrate the overarching risk assessment methodology developed in the project, the methodology is applied to a road network in the region of Bologna, Italy and a rail network extending from Rijeka to Zagreb in Croatia; both of which comprise portions of the European TEN-T network. INFRARISK is funded by the European Commission's FP7 programme, Grant Agreement No. 603960. Further information can be found at www.infrarisk-fp7.eu.

Keywords: Transport infrastructure; Natural hazards; Stress testing; Risk assessment.

1. Introduction

Extreme and rare natural hazard events can have a devastating impact on societies and their networks. In recent decades, the complex interdependencies of European infrastructure networks have been highlighted through cascading and escalating failures during extreme events. For example, the floods experienced in central Europe in

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August 2002 resulted in the deaths of approximately 150 people and an estimated €150 billion worth of damage (Toothill, 2002). Germany and the Czech Republic were worst affected, experiencing damage to approximately 250 roads and 256 bridges, as well as electricity failures, disruptions to telecommunication links, disruptions to gas services, and contamination of water. Furthermore, the 2009 L'Aquila earthquake in Italy resulted in the deaths of over 300 people, over 10,000 damaged buildings, several damaged bridges, as well as earthquake-triggered landslides (Miyamoto, 2009). To ensure the preparedness and the resilience of societies and their infrastructure networks to such extreme events, effective risk assessment and mitigation methodologies are required.

The INFRARISK project (*Novel Indicators for Identifying Critical Infrastructure at Risk from Natural Hazards*) is developing a multi-hazard risk assessment methodology to perform stress testing for European transport infrastructure networks due to low probability, extreme events. The stress test framework will enable infrastructure owners and managers to assess European transport infrastructure networks, prioritising interventions in order to improve the resilience of the wider infrastructure network and, therefore, minimise the impacts of extreme natural hazard events. As part of the project, an online INFRARISK Decision Support Tool (IDST) is being developed that will provide the next generation of infrastructure owners and managers with the necessary tools to manage their transport networks.

The INFRARISK project is focused upon nodal 'land-links', e.g. roads, highways and railroads, and the associated structural components (e.g. bridges, tunnels, road pavements). The hazards considered include earthquakes, landslides and floods, as well as the associated triggering effects (e.g. earthquake-triggered landslides). The project considers the complex interdependencies of multi-hazards and their cascading effects, and their impacts on transport infrastructure networks. The spatial and temporal vulnerabilities of transport networks to extreme natural hazard events are incorporated into the methodology.

The INFRARISK project is funded by the European Commission's FP7 programme, Grant Agreement No. 603960. It commenced in September 2013 and is three years in duration. The consortium consists of a multi-disciplinary team that gathers 11 partners from 7 European countries: Roughan and O'Donovan Ltd., the Swiss Federal Institute of Technology in Zurich, Dragados SA, Gavin and Doherty Geosolutions Ltd., Probabilistic Solutions Consult and Training BV, the Spanish National Research Council, University College London, PSJ, Stiftelsen SINTEF, Ritchey Consulting AB, and the University of Southampton. It is led by Roughan and O'Donovan Ltd., one of Ireland's largest civil and structural engineering consultancies. Overall, the consortium comprises three research institutes/organisations, two higher education institutes, one large industry and 5 small-to-medium enterprises.

2. Research Focus

The focus of the INFRARISK project is the on the development of a stress test framework to establish the resilience of critical European transport networks to rare, extreme natural hazard events. This will aid decision making regarding the protection of existing transport infrastructure networks and the development of robust infrastructure networks for the future. In the framework of the INFRARISK project, the TEN-T road and rail core networks (Figure 1) and their structural elements (e.g. bridges, tunnels and road pavements) are considered to be critical infrastructure in the context of the European transport network.

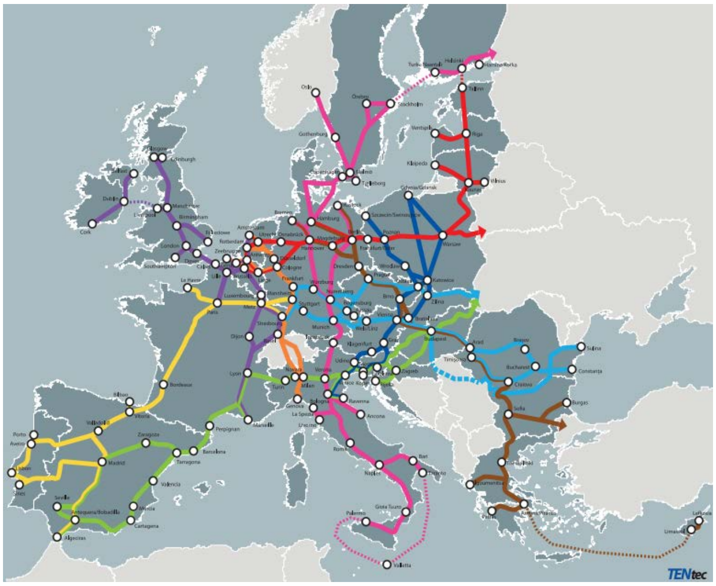

Fig. 1. European TEN-T Network

2.1. Hazards

The extreme hazards considered in the INFRARISK project are earthquakes, floods and landslides. The interactions and cascading effects associated with these hazards are illustrated in Figure 2. Although extreme hazard events are not relatively frequent in many parts of Europe, their occurrence can have devastating consequences on transport infrastructure networks, consisting of physical damage to the network and functional disruptions at local and/or regional level, resulting in significant societal and economic losses.

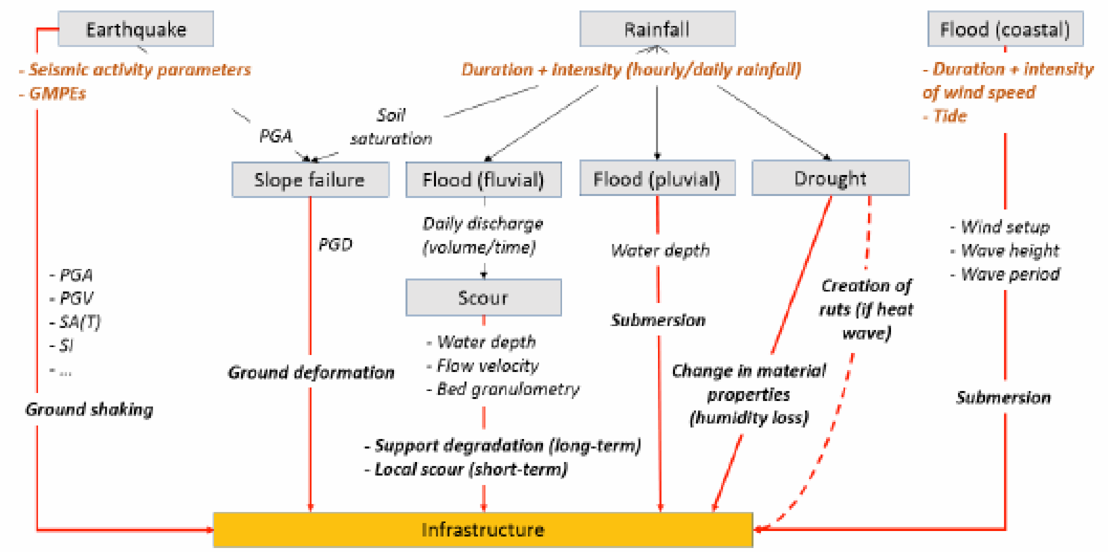

Fig. 2. Various hazards considered within INFRARISK framework

Within the INFRARISK risk assessment methodology, initially each hazard is analysed individually to quantify the hazard intensity level at a given site of interest for a given source or triggering event (D'Ayala & Gehl, 2014). For seismic hazards, a probabilistic seismic hazard assessment (PSHA) approach is adopted (Baker, 2013). PSHA is concerned with the evaluation of the likelihood of strong motion intensities, which may cause damage to infrastructure, as well as causing disruption to economic and social activities (Atkinson & Goda, 2013). PSHA offers an effective approach for analysing the seismic risk to spatially distributed infrastructure networks since various earthquake events, their resulting ground motions, and their associated probabilities of occurrence may be considered. INFRARISK uses Monte Carlo simulation to evaluate the low probability ground motions, which considers the aleatoric and epistemic uncertainties associated with seismic ground motions.

Flood hazards are defined as a rise in water level that causes an overflow of inland and/or tidal waters onto normally dry land areas. The INFRARISK project considers both coastal and rainfall related floods (see Figure 2). To determine the flood hazard, one of two approaches may be employed depending on data availability: 1) the Probable Maximum Flood (PMF) method, 2) estimation of the probability of a certain flood for a given return period based on empirical, statistical or hydrometeorological data.

Within the INFRARISK framework, landslide hazards are defined as the probability of occurrence of a landslide of a given magnitude within a specified period of time (Commission on Landslides, 1990) whereby a landslide is described as a shallow mass movement of soil down a slope. A geotechnical approach is adopted in INFRARISK to conduct the landslide hazard assessment whereby the stability of a slope is evaluated according to the mechanical condition of the slope (Park, et al., 2013). Both rainfall-triggered and earthquake-triggered landslides are considered in INFRARISK and the vulnerability of road sections to landslides is analysed. For rainfall-triggered landslides, precipitation describes the intensity measure of the hazard, in terms of slope saturation, rainfall intensity and rainfall duration. For earthquake-triggered landslides, Peak Ground Acceleration (PGA) is used to define the hazard intensity measure since slopes are considered as infrastructure components rather than a hazard within the framework of the project.

3. Multi-Hazard Risk Assessment Methodology

The occurrence of earthquake, floods and landslide hazards, the response of the infrastructure network's structural components (e.g. bridges, tunnels, road segments) and the response of the transport activities to a network disruption vary both spatially and temporally. The proposed INFRARISK multi-hazard risk assessment methodology explicitly considers the spatial and temporal correlation between the extreme natural hazard events and the functional interdependencies of the network objects. To store this data, an integrated spatio-temporal database (STDB) is employed in the project (Cheng & Taalab, 2014). The INFRARISK multi-hazard risk assessment methodology follows the generalised risk management process illustrated in Figure 3 (Adey, et al., 2014). The proposed methodology is developed specifically for road and rail infrastructure networks; however the methodology may be adopted for other network types.

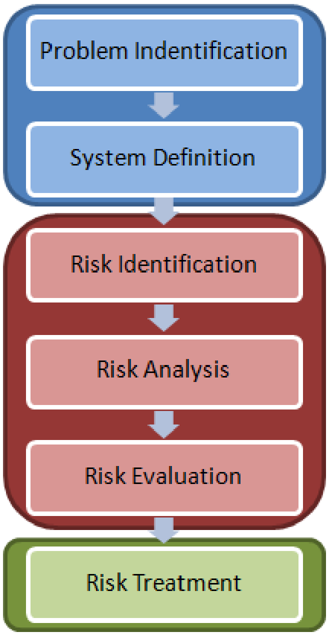

Fig. 3. Outline of INFRARISK risk assessment methodology

3.1. Problem Identification

The initial step involves identifying the problem, e.g. the infrastructure network to be examined, the associated hazards and the overall objective of the risk assessment.

3.2. System Definition

The next stage of assessment requires the system to be defined in terms of the system boundaries. To do so, specification of the spatial boundaries of the system is required, which consists of the geographical boundaries of the network, hazard events, and where the consequences may occur. In addition, it is necessary to define the temporal boundaries of the system. This involves defining the time period over which the risk is to be assessed, the number and size of intervals into which this period should be divided, and whether the system representation is static or dynamic. The system elements must also be defined. These may include the following: source events (e.g. tectonic plate movement, rainfall); hazard events (e.g. earthquakes, floods); infrastructure events (e.g. yielding of a bridge reinforcement bar, a bridge collapse); network events (e.g. closure of a freight corridor due to a tunnel collapse); societal events (e.g. 10% of goods are not delivered due to the closure of a freight corridor). Finally, it is necessary to define the relationships between system elements (e.g. determining the amount of water coming into contact with a bridge during a flood).

3.3. Risk Identification

Once the problem and system elements have been defined, it is necessary to identify the associated risks. This involves the development of a set of scenarios to represent all combinations of the system elements.

3.4. Risk Analysis

To analyse the risk, the next step involves estimating the probability of occurrence of the scenarios and determining the associated consequences for each scenario. To do so, either a qualitative or a quantitative approach (or both) may be adopted. A quantitative approach provides the more accurate estimate of the probabilities of occurrence using a statistical analysis or probabilistic modelling (e.g. event tress, fault trees, Bayesian networks, Monte Carlo simulation).

3.5. Risk Evaluation

The risk associated with the network being analysed must then be evaluated in terms of the perception of stakeholders and decision makers.

3.6. Risk Treatment

Finally, where the risk levels are unacceptable, the risks must be treated by implementing appropriate interventions.

4. Stress Test Framework

Stress testing may be defined as the process of determining the ability of a network to maintain a certain level of effectiveness under unfavourable conditions. For transport infrastructure networks specifically, stress testing may be employed to determine the resilience of the network to extreme hazard events. The INFRARISK project is performing stress testing for transport infrastructure network according to advanced simulation models. The stress tests involve evaluating the results of the multi-hazard risk assessment methodology according to specified criteria (Avdeeva & van Gelder, 2014). Within the INFRARISK stress test framework, there are three possible outcomes if the network fails the stress test: 1) a more detailed analysis is to be conducted for part of the network and no further stress tests are required, 2) a more detailed analysis is to be conducted for part of the system and further stress tests are required, 3) interventions may be specified to improve the infrastructure network.

5. INFRARISK Decision Support Tool

An online tool, referred to as the INFRARISK Decision Support Tool (IDST), is being developed as part of the project (Meacham & Sabeur, 2014) (Melas & Sabeur, 2015). This will integrate the overarching stress test framework and the various workflow processes involved. The IDST will consist of a user-friendly Graphical User Interface. Users of the IDST, such as infrastructure owners and managers, can apply the INFRARISK stress test framework to any transport network of interest provided that the relevant data is uploaded. Figure 4 illustrates the welcome page of the IDST v1.0.

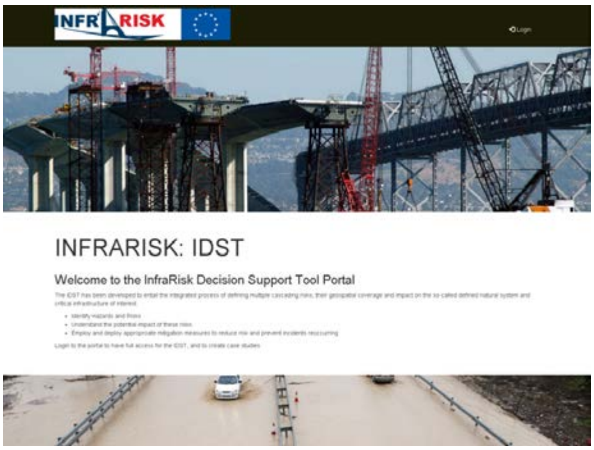

Fig. 4. INFRARISK Decision Support Tool (IDST) v1.0 welcome page

To demonstrate the systematic application of the overarching stress test framework, the IDST will provide access to generated databases and results for two European case studies that are being examined as part of the INFRARISK project (Ni Choine & Martinovic, 2014). The first case study consists of a road network in Northern Italy in the vicinity of the city of Bologna (Figure 5a), which is subjected to earthquake and earthquake-triggered landslide hazards. The second case study comprises a planned rail network in Croatia connecting the port of Rijeka to Zagreb (Figure 5b) that is currently at design stage and which is subjected to flooding and flooding-triggered landslide hazards. Both networks form part of the European TEN-T core network. An overview of the application of the INFRARISK multi-hazard risk assessment methodology to the selected Italian road network is provided herein.

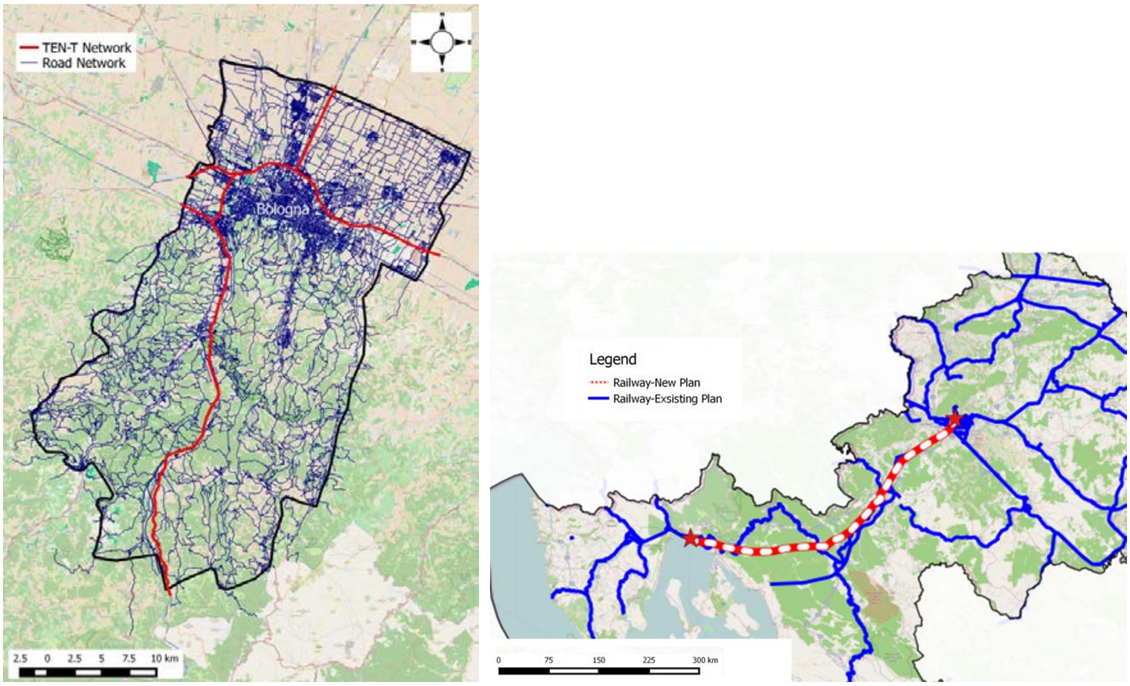

Fig. 5. INFRARISK case study (a) Italian road network (b) Croatian rail network

5.1. INFRARISK Case Study: Italian Road Network

The area considered for the Italian road network in the region of Bologna in Northern Italy is approximately 990km^2 and is exposed to earthquake and earthquake-triggered hazards. Within this region, 340 bridges and 30 tunnels were identified and information regarding their structural attributes was obtained according to specified parameters (Hancilar & Taucer, 2013). In addition, road segments were classified according to the road type (e.g. primary, secondary). Based on this information, earthquake fragility curves could subsequently be assigned to each structural element (e.g. bridges, tunnels, road segments) to indicate the probability of exceeding a specified damage state according to the ground motion intensity level (e.g. Peak Ground Acceleration).

To assign earthquake fragility curves for bridges, 45 typologies were initially identified based on the structural data collected. A database of bridge fragility curves (Pitilakis, et al., 2014) was subsequently consulted to identify fragility curves for each of the typologies. For tunnels, a similar approach was adopted whereby five typologies were identified and an existing database (Argyroudis & Kaynia, 2013) was consulted.

To assign fragility curves to road sections due to earthquake-triggered landslides, it was necessary to determine the landslide yield accelerations (k_y) for the region (Pitilakis, et al., 2011). To do so, the INFARISK project employed a sliding block displacement approach (Saygili & Rathje, 2009) whereby the yield acceleration (k_y) of the sliding block represents the horizontal acceleration that results in failure of the slope. The yield acceleration values (k_y)

were calculated according to the local topography, geotechnical properties, an assumed failure depth and the percentage saturation of this failure surface. Values of k_y were calculated for a 10m x 10m resolution grid for the Italian case study region (Figure 6) based on a digital elevation model and a geological map of the region. Fragility curves were subsequently assigned to the road network at 10m intervals, in terms of PGA, using the method described by (Pitilakis, et al., 2011). Example fragility curves for a road segment due to an earthquake-triggered landslide are illustrated in Figure 7 for three damage states (slight, moderate and extensive/complete).

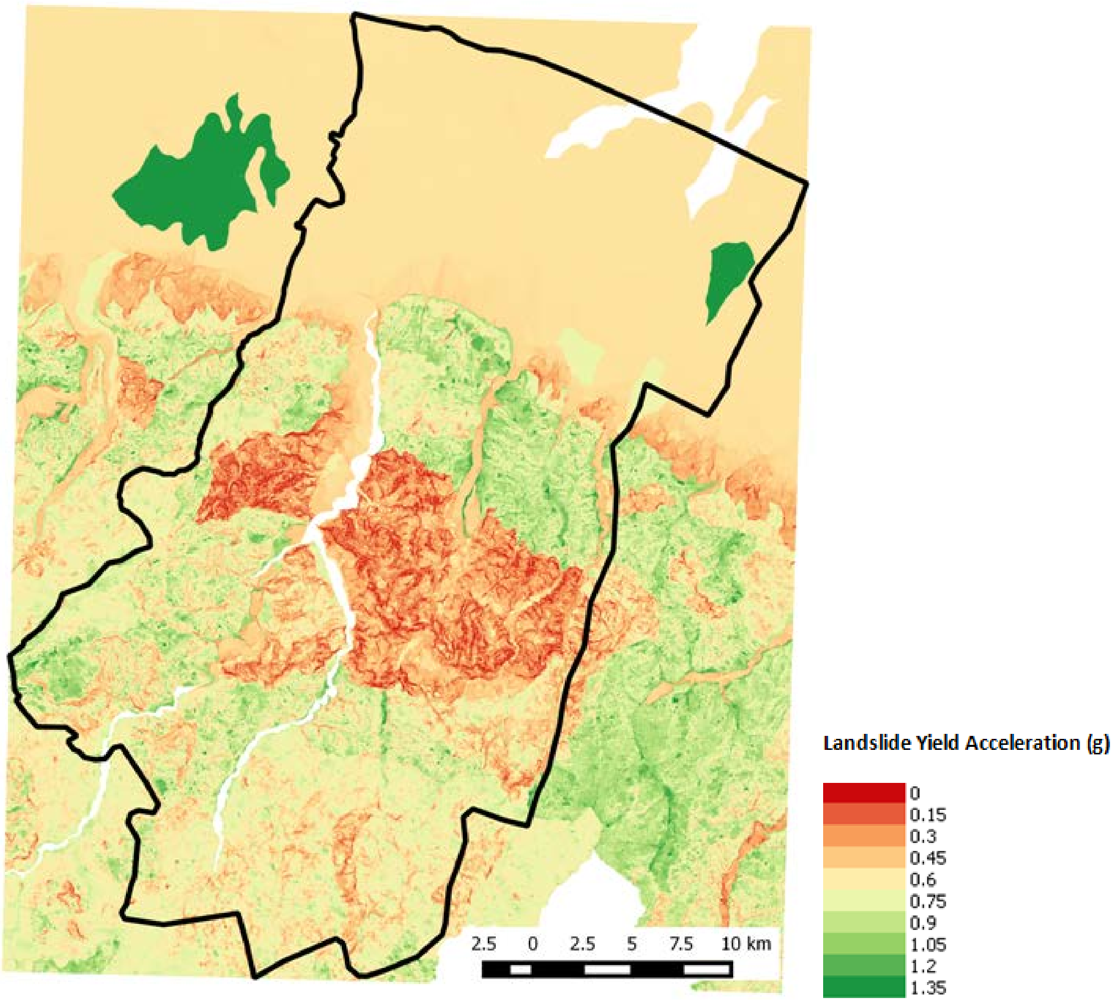

Fig. 6. GIS raster map displaying landslide yield accelerations values (k_y) for Italian road case study

The seismic hazard for the region may be estimated according to a database of ground-motion (GM) fields obtained using a Monte Carlo simulation method that correspond to a variety of low probability earthquake scenarios. The GM fields are used in conjunction with the fragility curves to determine the damage state of the network for a given earthquake scenario. The direct and indirect consequences associated with the network may then be calculated. In the framework of the INFRARISK project, 'direct' consequences refer to the cost of physically restoring the network to the level of service that existed prior to the natural hazard event and, therefore, these losses are considered to be directly attributable to the infrastructure manager. 'Indirect' consequences refer to the costs associated with any further network or societal costs associated with the occurrence of the natural hazard (e.g. lost working time due to additional travel time due to network disruptions).

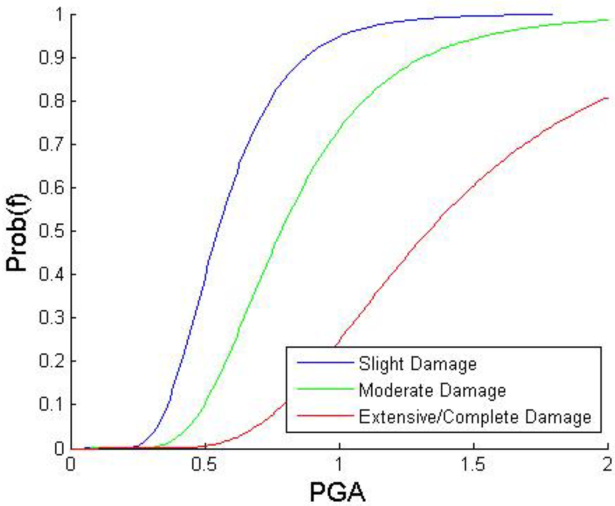

Fig. 7. Example earthquake fragility curves for an 'urban' roadway segment due to landslides (k_y = 0.2).

6. Discussion and Conclusions

The aim of the INFRARISK project is to develop a stress test methodology that facilitates the improved risk assessment and resilience of critical infrastructure networks through the development of a user-friendly online decision making tool. The multi-hazard risk assessment methodology requires the context to be initially established through the identification of the problem and the definition of the system. Next, a risk assessment is performed according to the identification, analysis and evaluation of the risks. Finally, the risk is treated by implementing appropriate intervention measures. This methodology fits within the encompassing INFRARISK stress test framework to determine the resilience of the overall network to low probability, extreme natural hazard events. This framework, as presented using on online IDST will provide transport infrastructure owners and managers with a decision making tool to manage the risks associated with extreme natural hazard events and to improve the resilience of transport infrastructure networks.

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References

Adey, B., Hackl, J., Heitzler, M. & Iosifescu, I., 2014. *Infrarisk Deliverable D4.1 Preliminary Model, Methodology and Information Excahange*, s.l.: European Comission.

Argyroudis, S. & Kaynia, A. M., 2013. Fragility Functions of Highway and Railway Infrastructure. *Geotechnical, Geological and Earthquake Engineering*, pp. 299-326.

Atkinson, G. M. & Goda, K., 2013. Probabilistic seismic hazard analysis of civil infrastructure. *Handbook of*

Seismic Risk Analysis and Management of Civil Infrastructure Systems, pp. 3-28.

Avdeeva, Y. & van Gelder, P., 2014. *Infrarisk Deliverable D6.1 Stress Test Methodologies,* s.l.: European Commission.

Baker, J. W., 2013. *Probabilistic Seismic Hazard Analysis,* s.l.: s.n.

Cheng, T. & Taalab, K., 2014. *Infrarisk Diliverable D5.1 Integrated Spatio-Temporal Database,* s.l.: European Commission.

Commission on Landslides, I., 1990. Suggested noemclature for landslides. *Bulleton of the International Association of Engineering Geology 41,* pp. 13-16.

D'Ayala, D. & Gehl, P., 2014. *Infrarisk Deliverable D3.1 Hazard Distribution Matix,* s.l.: European Comission.

Hancilar, U. & Taucer, F., 2013. *Guidelines for typology definition of European physical assets for earthquake risk assessment*, s.l.: European Commission.

Meacham, K. & Sabeur, Z., 2014. *Infrarisk Deliverable D7.1 IDST System Specification v1.0,* s.l.: European Commission.

Melas, P. & Sabeur, Z., 2015. *Infrarisk Deliverable D7.3 IDST System v1.0,* s.l.: European Commission.

Miyamoto, G. R., 2009. *L'Aquila Italy M6.3 Earthquake April 6, 2009,* s.l.: Miyamoto.

Ni Choine, M. & Martinovic, ,. K., 2014. *Infrarisk Deliverable D8.1 Critical Infrastructure Case Studies,* s.l.: European Commission.

Park, S., Choi, C. & Kim, J., 2013. Landslide susceptibility mapping using frequency ratio, analytic hierarchy process, logistic regression, and artificial neural network methods at the Inje areas, Korea. *Environmental Earth Sciences 68,* pp. 1443-1464.

Pitilakis, K., Crowley, H. & Kaynia, A. M., 2014. SYNER-G: Typology Definition and Fragility Functions for Physical Elements at Seismic Risk. *Geotechnical, Geological and Earthquake Engineering 27.*

Pitilakis, K. et al., 2011. *Physical vulnerability of elements at risk to landslides: Methodology for evaluation, fragility curves and damage states for buildings and lifelines,* s.l.: s.n.

Saygili, G. & Rathje, E. M., 2009. Probabilisticall based seismic landslide hazard maps: An application in Southern California. *Engineering Geology 109 (3-4),* pp. 183-194.

Toothill, J., 2002. *Central European Flooding August 2002,* s.l.: An EQECAT Technical Report.