INTERNATIONAL SYMPOSIA FOR NEXT GENERATION INFRASTRUCTURE

Real-time multi-hazard risk of interurban highway networks

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Abstract

Highway networks are the most important civil infrastructure in highly developed countries. Recent earthquakes evidenced that some structural and geotechnical components of a highway network such as bridges and tunnels may be particularly vulnerable to strong motions. Network seismic risk is the probability that the network will incur a certain level of loss given its components vulnerability and the earthquake hazard to which they are exposed. Apart from direct loss, damage to network components may cause prolonged traffic disruption, which in turn results in large indirect loss in the affected area. Network resilience is a key concept in network seismic risk assessment since it can express the extent of both direct and indirect loss as well as the system's ability to quickly recover its pre-earthquake state. This paper aims to present a methodology for the multi-criteria, resilience-based assessment of the possible loss that a highway network may experience due to seismic events with different probability of recurrence and subsequent intensity measure distributions over the network region. It also proposes a framework for qualitatively and quantitatively assessing the time-variant loss that a highway network may experience from the onset of the earthquake throughout the recovery period, using resilience-based and scalar quantities, respectively. The above indicators also consist a useful risk management tool at pre-and-post-earthquake level. At pre-earthquake level, they can be used for the identification of the optimum retrofit scheme, among a pool of alternatives, on the basis of two conflicting factors, namely the initial investment cost and the future network loss mitigation. At post-earthquake level, the emergency and recovery actions that lead to the minimum post-earthquake network loss can be defined. In the proposed approach, the two aforementioned levels of highway risk management are interdependently considered towards the adoption of an efficient loss mitigation plan.

Key Words

Resilience, Seismic Risk, Multi-hazard Assessment, Highway Networks

1. Introduction

Intercity transportation networks constitute a vital component of prosperity in modern, dense populated societies by facilitating the mobility of people, goods and services. Their smooth and undisruptive operation is crucial for ensuring sustainability after extreme natural disasters such as earthquakes, landslides and floods. Natural disasters, e.g. earthquakes, have caused extensive damage worldwide primarily to seismically sub-standard road or highway components (i.e., bridges, overpasses, tunnels etc)[1], as well as to adjacent geotechnical works that influence road functionality (e.g. slopes). These

[1] Shen, Y., Gao, B., Yang, X., Tao, S.: Seismic damage mechanism and dynamic deformation characteristic analysis of mountain tunnel after Wenchuan earthquake. Eng. Geol. 180, 85–98 (2014).

damages have led to enormous direct and indirect losses to the affected areas[2]. *Direct* loss is related to the repair of the damaged components[3], if one for the sake of quantification, neglects the priceless loss of human life, while *indirect* loss refers to the reduced functionality of the road network and the subsequent increase of travel time, the disturbance to social and professional life, business interruption, additional transportation cost and environmental implications[4]. Direct and indirect loss associated with future events affecting highway networks and their secondary roadways is assessed probabilistically[5,6], by coupling structural/ geotechnical vulnerability[7] with the hazard at the site(s) of interest[8,9], as well as the altered traffic flow[10] and the wider economic, social and environmental consequences of both infrastructure failure and traffic diversion.

Figure 1: Earthquake-induced (left, middle) and flood-induced damage (right) in road networks.

Key in assessing the community loss is the concept of network *resilience*[11] that encompasses the dimensions of network *capacity*, *redundancy* and *recovery time* to express its ability to withstand and adapt to a natural disaster, while being able to recover and restore the services offered quickly. Following the basic idea placed by Bruneau et al.[12] a number of different resilience definitions and studies aim to conceptualise resilience. A number of general models have been developed[13,14] that may be applied to different kinds of complex systems such as hospitals[15], natural gas, water distribution[16], energy[17] and infrastructure networks[18]. Due to the interdependency and complexity of roadway networks, however,

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[12] Bruneau, M., Chang, S.E., Eguchi, R.T., Lee, G.C., O'Rourke, T.D., Reinhorn, A.M., Shinozuka, M., Tierney, K., Wallace, W.A., Von Winterfeldt, D.: A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. Earthq. Spectra. 19, 733–752 (2003).
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as well as their extension in large geographical areas, *quantification* of resilience and, most importantly, *informed decision-making* based on the resilience metrics, face several challenges that have hindered the practical application of such innovative concepts in existing roadway networks.

One major difficulty is that, first, **direct and indirect loss of road networks are correlated** since damage in one network component influences the functionality of the entire network, which subsequently may impede the emergency response, the recovery activities, the rehabilitation process and the accessibility of critical transportation (ports, airports, train) or operation of energy facilities. The interdependence between modern life activities and the uncertainty in identifying and quantifying losses pertaining to different sectors (e.g. economy, society, and environment) adds further to the complexity of the indirect loss estimation[19,20] and therefore has not yet been assessed in a reliable, computationally efficient and quantitative manner. Moreover, in contrast to the immediate direct loss, **indirect loss evolves with time** following the gradual restoration of standard (i.e., pre-earthquake) functionality. For these reasons, only a wider network perspective that includes the analysis of consecutive recovery phases can capture the time variation of the indirect loss and provide a reliable approach for its overall estimate throughout the entire recovery period. Time has an additional effect on infrastructure resilience as **ageing** of transportation infrastructure affects not only the initial state of functionality Q of the pre-disaster roadway network but effectively determines the immediate resilience drop of functionality to the residual (robustness) level right after the natural disaster, a fact that is also commonly overlooked. Figure 2 illustrates how network functionality drops from an initial state Q(0)=100% to $Q(t_{0E1})$ after the first event, gradually recovers back to 100% at time $t_{0E1}+t_{RE1}$, until it drops again to $Q(t_{0E2})$. Clearly, different pre-event measures to higher or lower robustness (residual functionality) levels and different recovery measures can lead to faster or slower post-disaster recovery.

The **time dimension** of resilience, further implies that **traffic analysis** is integral in the computation of roadway network functionality, a fact that has three major implications: (a) the **computational cost** is almost prohibitive given that traffic redistribution needs to be repeated in a Monte Carlo scheme for every different case of network state (i.e., open and closed critical links) to comply with a fully probabilistic treatment of risk, (b) the origin-destination (OD) matrix that controls the traffic flow is dynamic, in other words, the **drivers' behaviour is event-dependent,** meaning they tend to alter their destination after a disaster and divert towards home, shelter or emergency facilities) and (c) the risk associated with natural hazards is either very difficult to be reliably assessed in advance, as for example in case of **flooding** which **gives little warning**[21] or cannot be evaluated using conventional approaches. For example, **probabilistic seismic hazard analysis (PSHA) is not applicable** because, in contrast to a single structure analysis where hazard, defined as the probability of exceeding a given intensity measure, is site-specific, a road network spans over a wide region, thus resulting in key network components (i.e. bridges, tunnels etc.) that are exposed to different levels of seismic demand simultaneously. Overall, both in case of an earthquake where the spatial distribution of a seismic Intensity Measure (IM, such as peak ground acceleration or spectral acceleration among others) attenuates from the source to the sites of interest, and in case of a flood or landslide where operation of critical roadway network links can be disrupted, the damage distribution within the network varies in space and time and subsequently, the **traffic redistribution is also event-dependent**.

[19] Lounis, Z., McAllister, T.P.: Risk-Based Decision Making for Sustainable and Resilient Infrastructure Systems. J. Struct. Eng. F4016005 (2016).
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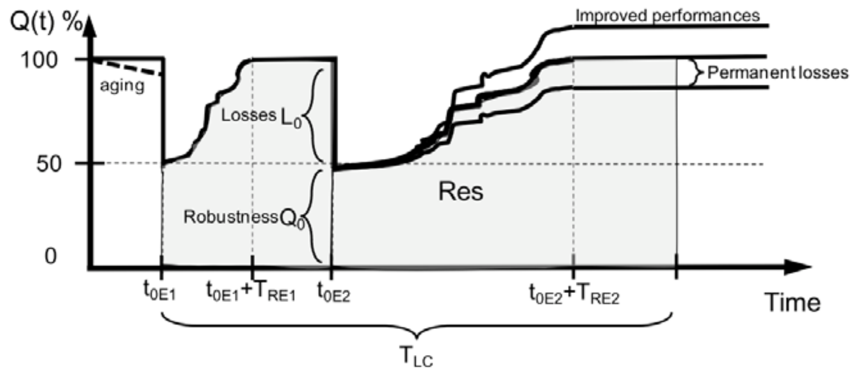

Figure 2: Schematic representation of disaster resilience[22]

An additional challenge is that the resilience of roadway networks should also consider **the cross correlation of hazards and their effects**. In fact, even though natural hazards are primarily uncorrelated, their secondary effects can be highly correlated. Earthquakes, for instance, may cause flooding of a coastal area by triggering a tsunami or a landslide into a lake or river.

At a third level, the damage caused by one hazard may also affect the capacity of the roadway network components to resist the effects of other hazards: reinforced concrete bridge piers exhibiting even minor cracking due to seismic loading without being adequately repaired, are more prone to corrosion which is accelerated in cases of flood or heavy rain. Fluvsial floods may also lead to scour which can then weaken pier foundations. Increase of water table can influence the soil strength along a bridge and subsequently the stiffness and damping at its supports, hence reducing their safety factor towards future seismic events. Along these lines, multi-hazard, multi-damage[23], integrated fragility curves are needed for the different components of road networks.

Facing the above challenges, this paper discusses the fundamental concepts and the first steps for **developing a robust, multi-hazard, quantitative decision making framework** for the management of road network resilience to natural hazards that treats all the prevailing uncertainties[24] associated with hazard, critical component damage, pre- and post-disaster drivers' behaviour and network functionality, with a balanced degree of sophistication. Leading to a matrix of resilience indices and an open GIS-based software, the framework will permit stakeholders to adapt their pre-disaster strategy to meet specific resilience-based objectives thus minimizing loss and optimizing functionality after a natural disaster. Below, the first holistic application is presented integrating structural vulnerability and hazard assessment, as well as traffic and consequence analysis for the case of a single hazard (i.e., related to earthquake loading).

2.Application for a single hazard case

2.1 Overview

Retis-Risk (www.retis-risk.eu) is a holistic framework developed for the seismic risk assessment and resilience enhancement of interurban roadway networks[25]. Utilizing a software tailored to the developed

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[23] Taskari, O., Sextos, A.G.: Multi-angle, multi-damage fragility curves for seismic assessment of bridges. Earthq. Eng. Struct. Dyn. 44, 2281–2301 (2015).

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[25] Sextos, A. G., Kilanitis, I., Kyriakou, K., and Kappos, A. J. Resilience of road networks to earthquakes., 16th World Conference on Earthquake Engineering, Santiago, Chile, 9-13 January (2017).

methodology, its application is presented herein for the case of the interurban roadway network of the Western Macedonia prefecture, in Greece. To illustrate the importance of post-disaster planning, two risk management strategies are considered and comparatively assessed; the first based on the identification and retrofit of the key components with the highest impact to network resilience and a second one, solely focusing on the improvement of recovery planning. The study is based on the actual data concerning network topology and traffic conditions which were collected and processed. Network bridge fragilities were taken into account in a refined manner utilizing a novel bridge-specific fragility methodology[26]. The subsequent steps of the methodology are summarised below. A more detailed presentation of assumptions, data and results can be found elsewhere[27].

2.2 Road Network Topology

"Εγνατία Οδός", often translated as Via Egnatia A2, is a recently constructed highway that extends from the western port of Igoumenitsa to the eastern Greek–Turkish border running a total of 670 km (420 mi). Egnatia Highway crosses the prefecture West Macedonia consisting the backbone of its road network, which is also complemented by several secondary roads that serve to the regional transportation needs (Fig. 3). For the purposes of this pilot application both the main highway of the region under study and the secondary road system with speed limits lower than 90km/h are modelled with a total number of 263 bidirectional links and 283 traffic nodes for the purposes of this analysis.

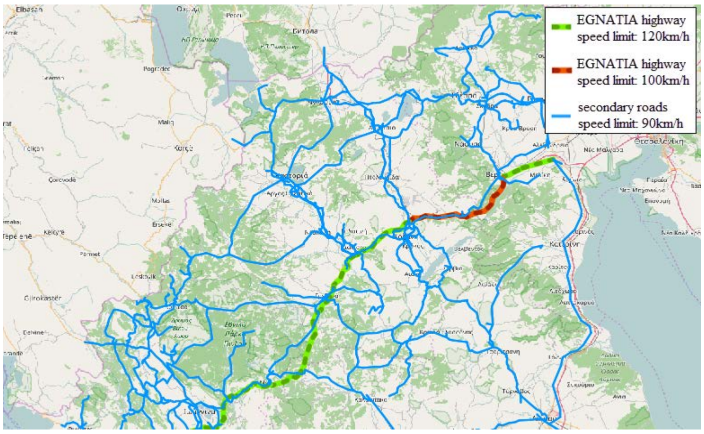

Figure 3: Case study road network

2.3 Key components of the network system

The set of *key network components*, that is, the structures whose failure may lead to road closures, is the first to be identified. Key components are assumed to be the bridges, overpasses, slopes and tunnels across the network. Given the structure of the interurban system studied, bridges and tunnels exist along the Egnatia highway only. Overpasses of the secondary network are also neglected for simplicity given their smaller size, simpler structural systems and minor effect to the overall network resilience. However, in principle, their vulnerability can be accounted for both by the methodology and the software developed, which are structure, size and importance-independent.

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[26] Stefanidou, S.P., Kappos, A.J.: Methodology for the development of bridge-specific fragility curves. Earthq. Eng. Struct. Dyn. 46, (2017).

[27] Sextos, A. G., Kilanitis, I., Kappos, A. J., Pitsiava, M., Sergiadis, G., Margaris, V., Theodoulidis, N.,et al. Seismic resilience assessment of the western Macedonia highway network in Greece, 6th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering M. Papadrakakis, M. Fragiadakis (eds.) Rhodes Island, Greece, June 15–17 (2017).

A total number of 148 key components were identified within the network system studied. Since the traffic along each network link is bi-directional, each identified key component comprises of two identical branches with a unique ID number per pair.

2.4 Pre-earthquake traffic conditions

An Origin-Destination (OD) matrix is used to describe the travel demands in the network for all possible combinations, extracted from a relevant study carried out by the stakeholder. Given the travel demands and the additional input of the traffic capacity of every network link, pre-earthquake traffic flows over the whole network are calculated according to Zhou et al.[28] It is noted that the OD matrix used herein, refers to travel demands during the typical hour of a normal day and thus appropriate scaling factors are applied to the results whenever daily traffic data are deemed.

2.5 Structural stock value, repair cost ratio, "traffic capacity-time" relationship

A re-construction cost was calculated for each one of the 74 dual branch key components assuming a value of 17.000€/m for the (twin) bridges and overpasses and 20.000€/m for the tunnels. Based on the length of each component, the total structural stock value of the network portfolio is approximately assessed to 630 million euros. Moreover, a damage state-specific repair cost ratio was defined for all the key components according to Basoz et al.[29] assuming ratios of 0.03, 0.25, 0.75 and 1 for Damage State 1 (DS1) to Damage State 4 (DS4), respectively. A closure period of 0, 7, 150 and 450 days is further assigned to the four damage states, DS1 to DS4, was assigned to all key network components, assuming that after this period 100% of the traffic carrying capacity is regained.

2.6 Seismic hazard analysis

The integration of seismicity from different earthquake sources that is expressed in the form of conventional seismic hazard maps, is not applicable for the case of the post-earthquake traffic distribution, as the latter depends on the individual probability of operation of each network key component, which is in turn dependent on the specific seismic scenario examined and the corresponding spatial distribution of the Intensity Measures (IM) of interest[30,31] [12], [13]. For this reason, hazard is herein assessed independently for each one of the *m* seismic sources potentially affecting the network and for a set of *n* different return periods. Along these lines, eleven seismic sources (m=11) were identified, located either within the case study area or in its vicinity. For every fault, ground motion maps associated with the k=4 return periods, namely 100, 475, 980 and 1890 years, were generated leading to a sample of kxm maps depicting the spatial distribution of intensity.

2.7 Fragility analysis

For every bridge and overpass key component of this study, a set of four fragility curves was generated for the four damage states considered, DS1 to DS4, corresponding to minor, moderate, extensive damage and collapse, respectively (Fig. 4). Bridges and overpasses are organized in classes of identical fragility, while for important bridges of the network a bridge-specific methodology is followed involving nonlinear static and incremental dynamic response history analysis. The stock of the 28 twin tunnels of the network

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[28] Zhou, X., Taylor, J., Pratico, F.: DTALite: A queue-based mesoscopic traffic simulator for fast model evaluation and calibration. Cogent Eng. 1, 961345 (2014).
[29] Basoz, N., Kiremidjian, A.S., King, S.A., Law, K.H.: Statistical Analysis of Bridge Damage Data from the 1994 Northridge, CA, Earthquake. Earthq. Spectra. 15, 25–54 (1999).
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[31] Sokolov, V., Wenzel, F., Jean, W.-Y., Wen, K.-L.: Uncertainty and Spatial Correlation of Earthquake Ground Motion in Taiwan. Terr. Atmos. Ocean. Sci. 21, 905–921 (2010).

was grouped into one gross tunnel fragility class also illustrated in Fig. 4 based on fragility relationships expressed in terms of peak ground velocity.

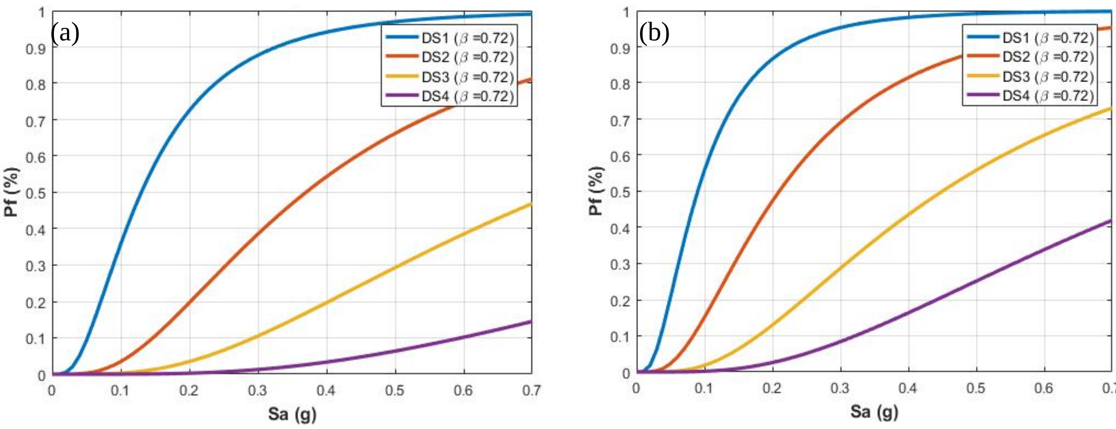

Figure 4: Bridge-specific fragility curves: bridges b1, b2 and b3 (charts a-c). General tunnel-class fragility curves (chart d)

In order to be consistent with the PGA-based maps developed, a transformation of PGV to PGA was performed according to Wald et al.[32]. Given the PGA value at the location of the key components, the probability that each component will experience damage corresponding to Damage States 1 to 4 was derived as follows:

$$
\begin{aligned}
&P_{DS_0/PGA} = 1 - P_{S \geq DS_1/PGA}, P_{DS_1/PGA} = P_{S \geq DS_1/PGA} - P_{S \geq DS_2/PGA} \\
&P_{DS_2/IM} = P_{S \geq DS_2/IM} - P_{S \geq DS_3/IM}, P_{DS_3/IM} = P_{S \geq DS_3/IM} - P_{S \geq DS_4/IM}, P_{DS_4/IM} = P_{S \geq DS_4/IM}
\end{aligned} \tag{1}
$$

Figure 5 illustrates a sample fragility map showing the most probable Damage States of each key component on the basis of the probabilities computed by eq. (1) for the PGA values calculated for the seismic source “Kozani” and the return period of 475 years.

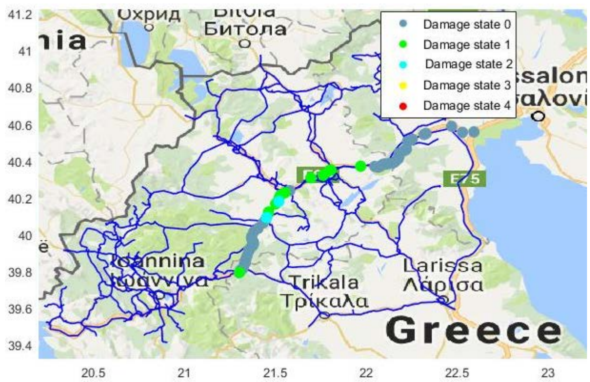

Figure 5: Sample fragility distribution map showing the most probable DS for every key component.

[32] Wald, D.J., Quitoriano, V., Heaton, T.H., Kanamori, H.: Relationships between peak ground acceleration, peak ground velocity, and modified mercalli intensity in California. Earthq. Spectra. (1999).

2.8 Traffic Analysis

Having generated 11 different seismic maps for each return period, a corresponding set of traffic scenarios is then developed, under the simplifying assumption that immediately after an earthquake a key network component may either retain the 100% of its traffic carrying capacity (i.e., remain intact and hence, fully operational) or close and completely lose its traffic carrying capacity. Along these lines, each one of the 74 key components is assumed with a binary response, associated to a value of either 1 (fully functional) or 0 (closed) based on whether the damage induced exceeds a critical, moderate level of damage (DS_{cr}=DS_2). Given the individual Damage State probabilities computed by eq. (1), a Monte Carlo (MC) analysis is employed and 10 initial traffic scenario samples, each one consisting of a scheme defining open and closed network links, are associated to every PGA map. Hence, a group of 11x10=110 initial traffic scenarios is generated for each one of the four earthquake return periods. Every initial traffic scenario is then decomposed to several **phases** that evolve in time based on the stepwise opening of the key components throughout the recovery period as shown in Figure 6.

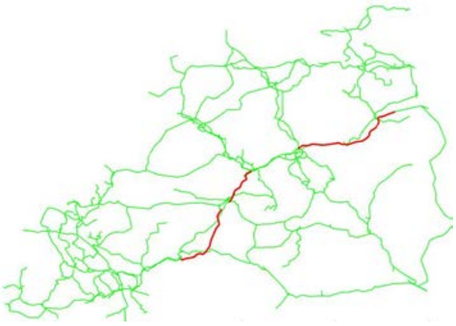

Figure 6: Closed links for the recovery phase of the first 7 days, for the 475y map of "K" seismic source.

2.9 Seismic risk assessment of the "as-built" network

The total cost associated with each earthquake event *k* (*k* taking values from 1 to 4 for the 100, 475, 980 and 1890 years return period), is the sum of the cumulative direct cost of structural damage within the network and the indirect, earthquake-induced total traffic cost. Based on the repair cost ratios defined and the probability of attaining every damage state, the **Estimated Structural Cost *$ESC_{k,m}$*** due to earthquake *k* stemming from source *m* is derived for the *i*=74 key network components as:

$$ESC_{k,m} = \sum_{i=1}^{74} D_{i,k,m} \quad (2)$$

where: $D_{i,k,m} = TBC_i \cdot (RCR_1 \cdot P_{DS1}^{i,k,m} + RCR_2 \cdot P_{DS2}^{i,k,m} + RCR_3 \cdot P_{DS3}^{i,k,m} + RCR_4 \cdot P_{DS4}^{i,k,m})$ (3)

TBC_i : is the total cost of re-constructing key component *i* calculated based on its length (Table 1) and the re-construction cost per meter values defined in section 2.5, {$RCR_1^i, RCR_2^i, RCR_3^i, RCR_4^i$}={0.03, 0.25, 0.75,1} are the repair cost ratios that correspond to damage states DS1 to DS4, and $P_{DS}^{i,k,m}$: is the probability that the damage of the key component *i* exceeds DS1 to DS4 for the case of n_{samp} seismic source *m* and an event return period *k*

The earthquake-induced **traffic cost (*TC*)** is calculated for every Monte Carlo simulated traffic scenario. This cost refers to the *additional* traffic cost during the entire recovery period of that particular traffic scenario (seismic source *m* and an event return period *k*), and as such, it is the sum of the product of each phase duration, times the corresponding additional travel cost [33].

3 RISK MANAGEMENT STRATEGIES

For every Monte Carlo-sampled initial traffic scenario that is decomposed into phases, a plot showing network functionality evolution throughout the recovery period is generated. Every vertical branch of such a plot is associated to the opening of one or more links and respectively to one or more *critical key components* that are the last link components to open for the traffic (i.e. components that define the opening time of the whole link in case of a series of components comprising a link). A retrofit scheme therefore is developed for the particular bridges leading to updated fragilities or reduced probability of failure for the same Intensity Measure. The updated fragilities were in this case approximately derived by multiplying the mean threshold value of the corresponding "as-built" components by 1.3, for all DSs. A second risk management strategy consisting of improved post-earthquake response expressed through an improved traffic carrying capacity-time relationship was also considered. In this case, closure periods were assumed to be lower due to better recovery planning and were updated to 0, 4, 100 and 300 days instead of 0, 7, 150 and 450 days for Damage States 1 to 4, respectively.

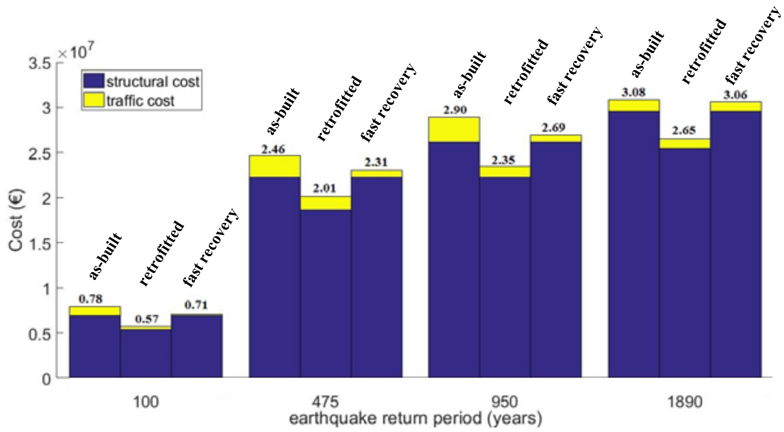

Figure 7: Expected costs for the four seismic scenarios for the case of the "as-built" network and the two risk mitigation stategies

Figure 7 depicts the resulting estimated structural, traffic and total cost for different earthquake return periods for the case of the "as-built" network as well as the two risk management strategies (i.e., bridge retrofit or improved recovery planning) due to the seismic maps derived from the critical seismic source, as identified in Section 6. Retrofit of selected key components is found to be more effective compared to the recovery plan enhancement for all the examined return periods. This is because, in this particular network, structural cost, which is essentially unaffected by an improved recovery, is the much higher than traffic cost. However, both risk management strategies contribute to a non-negligible, yet small (5-18%), extent to the the estimated total network cost reduction again due to the high resilience and low expected loss of the "as-built" network.

[33] Sextos, A. G., Kilanitis, I., Kappos, A. J., Pitsiava, M., Sergiadis, G., Margaris, V., Theodoulidis, N.,et al. Seismic resilience assessment of the western Macedonia highway network in Greece, 6th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering M. Papadrakakis, M. Fragiadakis (eds.) Rhodes Island, Greece, June 15–17 (2017).

4 STUCTURAL HEALTH MONITORING FOR (NEARLY) REAL TIME RISK ASSESSMENT

To further explore the possibility to update the intensity measure estimates with actual recordings after a major seismic event, a resilient structural health monitoring (SHM) scheme was installed to G9 bridge of the Egnatia motorway[34] (Fig.8). The system is based on serial/optical fiber data transfer from the data loggers to a local communication center, hybrid wired/cellular/satellite gateways from the local center to the end user, and uninterruptable power supply unit-based back up energy sources. The innovative elements this installation are the redundant end user gateways and the use of satellite communication that can provide crucial independence from terrestrial telecommunication networks. Nearly real-time data transmission can significantly improve the prediction of potentially damaged network components and optimize the recovery actions of the first few hours. This pilot instrumentation is deemed a useful demonstration of the potential towards real-time estimation of seismic risk.

Figure 8: Layout of the monitoring scheme installed to G9 Egnaria Motorway bridge

5 CONCLUSIONS

In this paper an application is presented of the Retis-Risk framework (www.retis-risk.eu) for the pilot case of a road network in Greece exposed to seismic risk as the first step of a holistic methodology for the real time, multi-hazard assessment of interurban highway networks. After defining the network topology and pre-earthquake traffic conditions vulnerability of bridges and overpasses were taken into account in a refined way through the use of bridge-specific fragility curves. Tunnel fragility was also accounted for in the form of a general fragility class. The structural and traffic cost due to earthquakes of certain return periods was assessed for the existing network of the specific prefecture. The resilience of the network was found to be considerable mainly due to the recent construction of the high standard Egnatia Highway studied. For demonstration purposes, two alternative risk management strategies were also examined involving both a tailored retrofit scheme and an improved recovery planning strategy, the first being more effective by reducing loss by approximately up to 18%. This pilot study is deemed a useful example of the applicability of the Retis-Risk framework in assessing the seismic (and further, multi-hazard) risk of interurban networks that can significantly enhance the informed decision-making of stakeholders, particularly of networks with a number of sub-standard key components and a more complex structure of interconnected roads.

[34] Sergiadis, G., Hadjidimitriou, S., Charisis, V., Panetsos, P., and Chrysanidis, T. A structural health monitoring data managing scheme with resiliency to seismic events: implementation on a road network bridge, 5th ECCOMAS Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, Crete, Greece (2015).