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RESILIENCE OF ROAD NETWORKS TO EARTHQUAKES

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Abstract

This paper deals with the assessment of intercity road networks resilience to earthquake loading. The motivation for this work is the fact that, as recent strong earthquakes have highlighted, the integrity of key transportation components, such as bridges, tunnels and geotechnical works has a great impact on the ability of the network to restore its original functionality and to limit the overall loss incurred by the community. The latter is defined as the direct structural, damage-related, loss as well as the indirect loss associated with the prolonged traffic disruption and the wider socio-economical consequences in the affected area. The above aspects of seismically-induced loss are particularly pronounced in cases of developed societies with extended and coupled intercity infrastructure wherein the interdependency between citizens and functionality of the numerous critical road components is extended.

Quantifying therefore, the ability of the road network to withstand, adapt to, and rapidly recover after a disruptive event is a challenging issue of paramount importance towards holistic disaster management. Along these lines, this paper presents a comprehensive, multi-criterion framework for assessing road network resilience to earthquakes and mitigating the time-variant loss experienced by the community after an earthquake event. In order to reflect the multi-layered nature of loss, a set of novel, qualitative, time-variant metrics is herein introduced, while quantitative indicators are used for cumulatively assessing the total loss incurred throughout the entire recovery period. The above probabilistic framework consists a holistic risk management tool for making informed decisions both pre- and post- a major earthquake event, thus prioritizing the pre-disruption strengthening schemes and accelerating the inspection and recovery measures, respectively. The methodological framework and its associated indicators are developed analytically but are also transformed in the form of a user friendly, GIS-based freeware available to the engineering community.

Keywords: network resilience, seismic risk; bridges; traffic analysis; risk management

1. Introduction

Intercity networks are a vital component of prosperity in modern, dense populated societies by facilitating mobility for people, goods and services. Their smooth and undisruptive operation is a crucial factor that ensures the efficient disaster response and recovery after extreme events such as earthquakes, landslides and floods. Recent earthquakes worldwide have caused extensive damages primarily to seismically sub-standard road components [1], [2] and led to significant loss to the community from an economic, social and environmental point of view [3].

The potential loss associated with future seismic events can be estimated by a seismic risk analysis that is coupling the vulnerability to the hazard of the area of interest. The assessment of seismic risk for the case of multiple-component systems that extent in a wide geographical area, such as intercity road networks, introduces a number of significant challenges that hinder the reliable estimate of the potentially induced loss. One of the most difficult and to some extent subjective part in the assessment procedure is the holistic quantification of loss ascribed to both network damage and malfunction impact. The example of 2011 Tohoku Earthquake that caused $319 billion of direct loss and $619 billion of indirect loss underlines the enormous impact of seismic events in urban environments [4]. At a road network level, the direct loss is related to the repair of the damaged network [5], if one neglects, for the sake of monetarization the priceless loss of human life. On the other hand, indirect loss refers to the induced effect on road network functionality and the subsequent travel time increase, disturbance of the citizens' social and professional life, business interruption and additional transportation cost [6–8].

Another important aspect of the problem is that, while direct loss depends on the damage of individual network components (i.e., bridges, tunnels, geotechnical works and slopes affecting roads), indirect loss estimation is less straightforward. This is because damage in one critical component influences the functionality of the entire network but also because the post-event traffic flow has been altered during the crisis period compared to their everyday routine for both behavioral and practical reasons. Indirect loss is amplified by the fact that the reduced network functionality may substantially impede the emergency response, the recovery activities and the rehabilitation process as a whole following a major earthquake event. The interdependence between modern life activities and the difficulty in identifying and quantifying loss pertaining different sectors (e.g. economy, society, environment) adds further to the complexity to the indirect loss estimation which, in contrast to the one-off direct loss, evolves with time. In an attempt to incorporate the indirect loss as part of risk analysis process, the interaction between structural failure and social, financial and environmental consequence has attracted scientific attention over the last few years.

An additional challenge introduced to the seismic risk assessment of road networks is the reliable estimate of seismic hazard. This is because a road network spans over a wide region in contrast to a single structure where hazard is site-specific. As a result, the critical network components (i.e. bridges, tunnels etc.) are exposed to different levels of seismic hazard and also the earthquake-induced damage and traffic redistribution are effectively scenario-based [9].

For all the above reasons, a comprehensive road network risk estimation framework has to be able to assess all the above explicit and implicit consequences, while addressing the network resilience [10], that is, its ability to withstand external forces, adapt to post-event circumstances and quickly recover its pre-earthquake state [11–15]. A number of studies have proposed frameworks in support of loss mitigation strategies to be adopted before or after an earthquake event. At pre-earthquake level, the aim is to identify the most efficient retrofit strategy among a pool of alternatives [16–18]. At the post-earthquake level, risk management refers to response agencies preparedness, repair process planning and minimization of earthquake consequences [19–21]. The pre- and post-earthquake risk management levels are strongly interconnected in the sense that every pre-earthquake activity has an impact to the post-earthquake response while most of the post-earthquake level strategies are planned before the occurrence of the earthquake.

The objective of this paper is to develop a holistic probabilistic approach for the multi-criterion management of the seismic risk of road networks that considers the interaction between damage, functionality and traffic, and can be used to improve the network resilience after a major earthquake event. It is also to combine, adjust or propose several quantitative and qualitative loss metrics to assess the direct and indirect cost, as well as the wider social, financial and environmental consequences as a function of earthquake recurrence period. All the indicators introduced are based on an uncertainty integration formulation that takes into account the prevailing uncertainties (i.e., those associated with the seismic performance of critical network components, seismic hazard and event-based traffic analysis). Ultimately, the same loss indicators are used as multiple criteria for the optimal road risk management. The study concludes with a short description of the software developed and a brief overview of a characteristic case study.

2. Loss Estimation Framework

2.1. Network Description

The methodology proposed herein, the outline of which is illustrated in Fig. 1, initiates with the description of the road network topology [22], the pre-earthquake traffic conditions and the location and properties of the key network components (in most cases bridges and overpasses, geotechnical works, tunnels and slopes). Every network intersection and every network location from which the drivers are originated or are heading to is considered a *node*, while two successive nodes are connected with a *link*. A pre-earthquake traffic load and a traffic capacity are assigned to every link. After the topological representation of the road network and the traffic assignment, the characteristics of the most vulnerable components of the network are described. Wherever possible, *classes* of structures with similar geometrical characteristics (hence similar vulnerability) are used.

2.2. Uncertainty integration

The uncertainty integration stage consists of three intermediate stages, namely, fragility analysis, seismic hazard analysis and traffic analysis.

2.2.1 Seismic fragility of road networks

Fragility curves express the probability of exceeding predefined Damage States (DS) given a seismic intensity level, expressed by means of an appropriate, efficient and sufficient, intensity measure (IM), typically peak ground acceleration or spectral acceleration among others. Fragility curves are usually plotted assuming a lognormal distribution function [23–25]:

$$P_{DS_t/IM=im} = \Phi\left[\frac{1}{\beta_t}\ln\left(\frac{im}{im_{mt}}\right)\right] \tag{1}$$

where

Φ : is the standard normal cumulative distribution function

im_{mt} : is the median threshold value of the IM associated with damage state *t*

β_t : the lognormal standard deviation of the IM associated with damage state *t*

A set of four Damage States (DS 1 to DS4) is used to define the fragility of every key component class, corresponding to minor, moderate, extensive damage and collapse. Given the component classification, a set of fragility curves is assigned to every single key component of the network. Given the intensity measure value at the location of each critical component (bridge, tunnel etc), the probability that the component will experience damage corresponding to DS1-4 can be directly computed from the limit-state exceedance probabilities:

$$\begin{gathered} P_{DS_0/IM} = 1 - P_{S\geq DS_1/IM},\, P_{DS_1/IM} = P_{S\geq DS_1/IM} - P_{S\geq DS_2/IM} \\ P_{DS_2/IM} = P_{S\geq DS_2/IM} - P_{S\geq DS_3/IM},\, P_{DS_3/IM} = P_{S\geq DS_3/IM} - P_{S\geq DS_4/IM},\, P_{DS_4/IM} = P_{S\geq DS_4/IM} \end{gathered} \tag{2}$$

2.2.2 Seismic Hazard Analysis

The spatial variation of the IM of interest along the road network is derived from a seismic hazard analysis. It is recalled that the conventional probabilistic seismic hazard assessment (PSHA) integrates an earthquake occurrence model (in time and space) and the corresponding source characteristics with a ground motion prediction relationship. The uncertainties related to hazard (earthquake occurrence, source rupture, wave propagation, and site effects) are comprehensively accounted by integrating hazard contributions over all earthquake sources capable of generating ground motions of non-negligible damage potential.

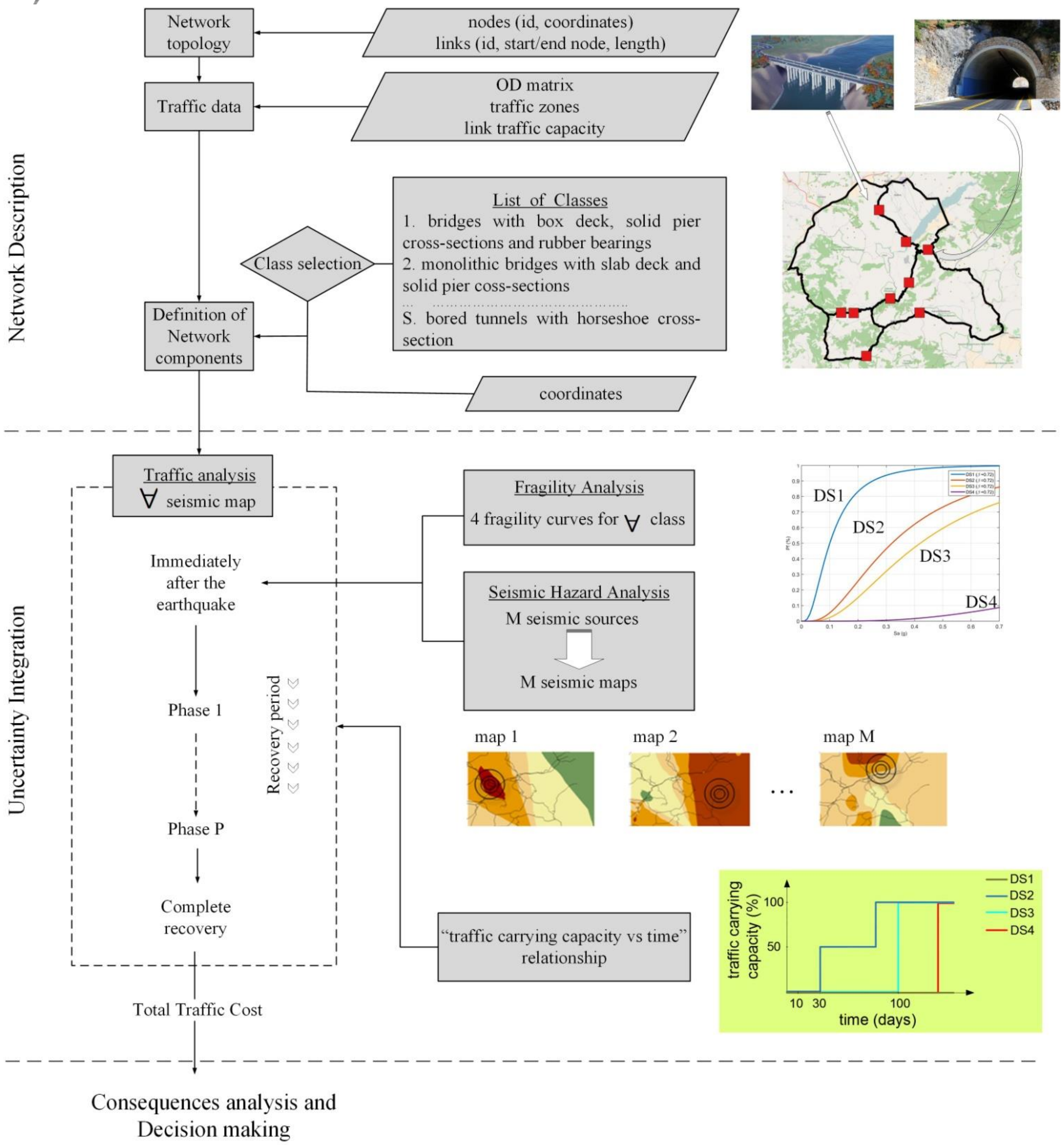

Fig. 1– Loss estimation workflow

Notably, the integration of seismicity from different earthquake sources that is expressed in the form of conventional seismic hazard maps, is not compatible with the inherent nature of 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 (i.e., a specific source with a given probability of generating spatially correlated IMs) [26,27]. In order to address this issue, an extension of the simple-scenario approach in proposed herein. More specifically, the proposed seismic hazard analysis is similar to the standard PSHA but in this case, given the source-specific recurrence relationship, hazard is computed independently for every seismic source without aggregating the multiple seismic sources. For every source therefore, ground motion maps are generated associated to specific return periods (namely 100, 475, 980 and

1890 years). Subsequently, the corresponding IM is derived at the location of each critical road network component. Naturally, for every return period, *M* number of ground motion maps are generated out of *M* earthquake sources identified.

2.2.3 Traffic Analysis

Having generated the *M* different seismic maps a corresponding set of traffic scenarios is then developed, under the assumption that immediately after an earthquake a critical network component (bridge, tunnel etc) may either retain the 100% of its traffic carrying capacity (i.e., remain intact) or completely lose its traffic carrying capacity by being closed. The functionality of all network components is expressed in the form of a binary matrix $\tilde{T}_r$, wherein each one of the *i* critical components, takes a value of either 1 (fully functional) or 0 (closed) based on whether the damage induced exceeds a critical damage state (in this case "moderate" damage, DS_{cr}=DS2), given the IM at the site of the particular component *i*, as computed by the m^{th} seismic map (one for each active source), which is associated with the k^{th} earthquake scenario (i.e., 100, 475, 980 and 1890 years) as shown in Fig.2:

$$\tilde{T}_r = \begin{cases} 1 \;\; if \;\; P_{i,k,m}[D \geq DS_2] \,|\, im_{i,k,m} < 0.5 \\ 0 \;\; if \;\; P_{i,k,m}[D \geq DS_2] \,|\, im_{i,k,m} \geq 0.5 \end{cases} \tag{3}$$

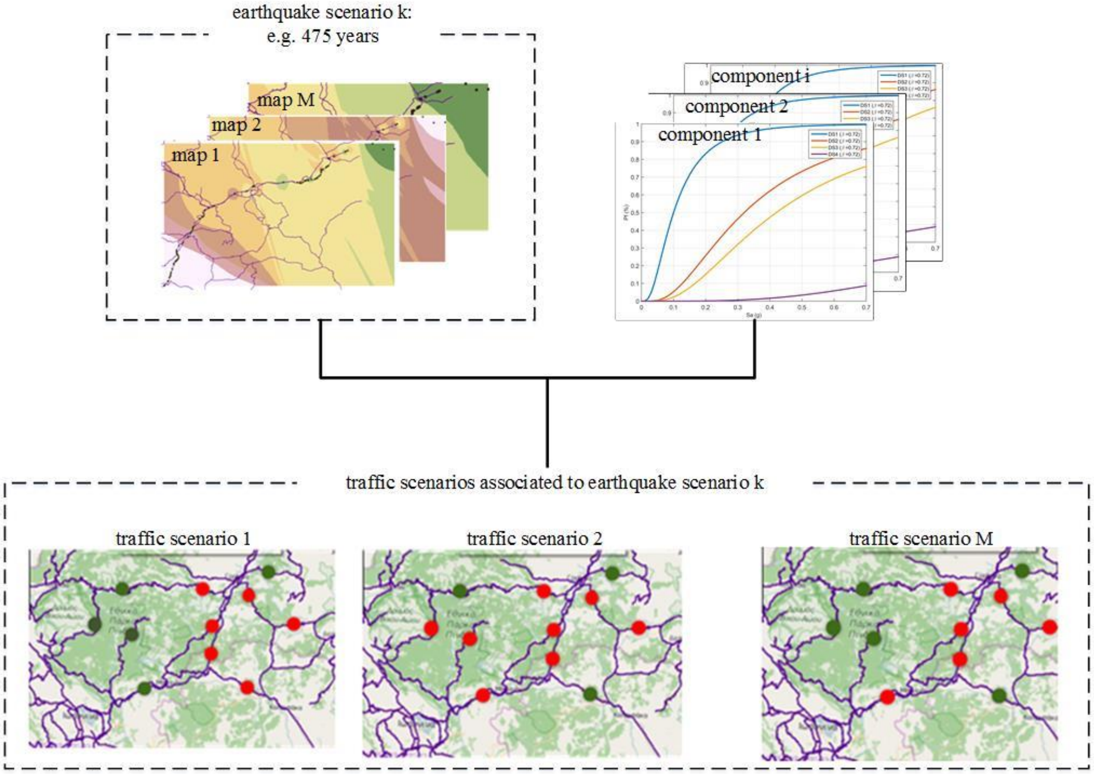

Fig. 2– Generation of the group of *M* traffic scenarios associated to sample earthquake scenario *k*

This assumption effectively implies that the functionality state of the key network components is semi-probabilistically treated, as the extent of damage is assessed probabilistically ($P_{i,k}[D > DS_2]$) but the relevant consequence (i.e., open or closed) is defined deterministically. A more comprehensive approach would involve a complete Monte Carlo analysis wherein the terms of the functionality matrix would be associated with the corresponding probability of occurrence. Given the functionality matrix and the distribution of closed and open links among the road network, every traffic scenario is decomposed to several phases that evolve in time based on the stepwise opening of the critical components throughout the recovery period. The latter decomposition of the initial (immediately after the earthquake) traffic scenario to *p* distinct post-earthquake phases depends on the recovery "traffic carrying capacity vs. time" relationship, which is of course different for each component (bridge, tunnel etc) and in turn depends on the level of damage each structure suffered. Evolution from one recovery phase to the following is assumed to be made when all components along each road network link *j* are either open or re-opened to full service.

3. Consequences Analysis

To assess the earthquake impact on the functionality of the road network and the resilience of the affected area, a set of quantitative and qualitative indicators are proposed, their main difference being that the first quantify the cumulative direct structural and traffic cost per seismic scenario, while the latter reflect the evolution of wider consequences over the recovery period attributed to seismic events from multiple sources for each seismic scenario.

3.1 Qualitative indicators

By developing the complete set of $(k \cdot m \cdot p)$ post-earthquake traffic phases the increase in travel time is derived along with the associated *additional* (travel) cost. The latter is expressed in monetary units per time unit (e.g. euros per day) and evolves in time, being gradually deceased until it is diminished upon re-establishment of the full network functionality (Fig. 3). In this study, the additional travel cost is derived according to Goodwin [28]:

$$EC_p = D_p \cdot VOT \tag{4}$$

where:

$$D_p = \sum_{j=1} (V_{jp} t_{jp} - V_{j0} t_{j0})$$

EC_p : is the additional cost due to traffic conjunction during phase *p* (per time unit)
VOT : is the value of time meaning the cost of the time that a traveler spends on his journey
D_p : is the total delays during phase *p*
V_{jp} : is the traffic load in network link *j* during phase *p*
t_{jp} : is the travel time in network link *j* during phase *p*
V_{j0} : is the traffic load in network link *j* before earthquake occurrence
t_{j0} : is the travel time in network link *j* before earthquake occurrence

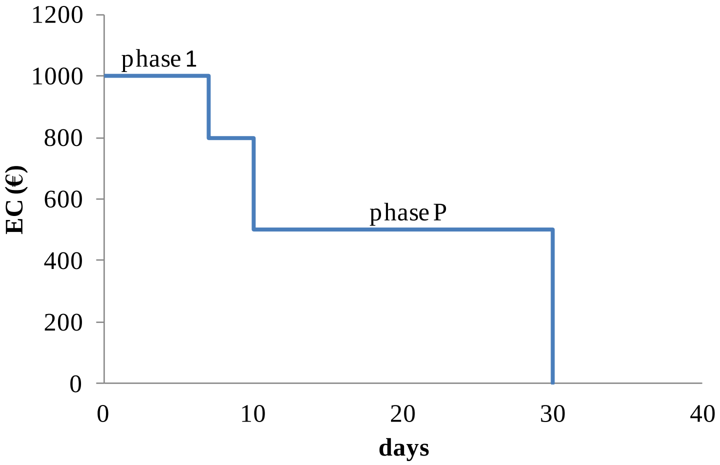

Fig. 3 – Sample "Additional cost vs. time" graphical representation correlated to a specific traffic scenario

To further quantify the impact of the network functionality in the region of interest, a *Consequences vector* $\left\{ECO_p, CON_p, ENV_p\right\}$ is introduced. This is a three-component vector used for cumulatively assessing earthquake loss to the financial life of the affected area, the connectivity among various Points of Interest (POI) and the environment. This vector is composed by three loss factors which vary between 0 and 1. The lower the factor (i.e., closer to zero) the higher the consequences. As anticipated, immediately before the earthquake the values of all the three factors are 1, drop suddenly when the earthquake event occurs and are gradually restored to 1 by the end of the recovery period. As mentioned, the *Consequences vector* is populated by three distinct factors:

The *economic loss factor* ECO_p is used to express the increase in the transportation and travel cost, the disturbance in the productive activities, the decrease in the tourist business and generally the earthquake consequences that have an economic impact to the society [3], [29]. It is wider than the additional travel cost of Eq. (4) but is again based on Goodwin's approach and on the assumption that the economic consequences are proportional to the increase of travel time. The factor value for every phase of the recovery period is given by Eq. 5 where the denominator sum does not include terms that refer to network links that are closed during phase *p*.

$$ECO_p = \frac{\sum_{j=1}^{ntot} (V_{j0} \cdot t_{j0})}{\sum_{j=1}^{ntot} (V_{jp} \cdot t_{jp})} \tag{5}$$

where:

n_{tot} : is the total number of network links
V_{j0} : is the traffic load of network link *j* during the normal traffic-condition period
t_{j0} : is the travel time in network link *j* during the normal traffic-condition period
V_{jp} : is the traffic load of network link *j* during phase *p*
t_{jp} : is the travel time in network link *j* during phase *p*

The *connectivity loss factor* CON_p refers to the consequences due to loss of access to points of interest. The POIs are structures or areas that it is crucial to be accessible after an earthquake such as hospitals, power stations, administrative buildings, ports and border checkpoints among others. It is noted that this index solely considers the accessibility and not the traffic load or travel time to each destination [30]. The calculation of the *connectivity loss factor* is based on the assumption that network functionality loss in a region where POIs are located affects the accessibility to the particular POIs. To derive the CON_p it is necessary to define the number of POIs per traffic zone, so that a zone with a higher number of POIs can take higher weighting in the equation. Only zones that contain at least one important location are taken into account:

$$CON_p = \frac{\sum_{z=1}^{S} (\gamma_{zp} \cdot N_k)}{\sum_{z=1}^{S} K_z} \tag{6}$$

where:

$\gamma_{zp} = \frac{L_{z0} - L_{zp}}{L_{z0}}$: is the accessibility factor in traffic zone *z* during phase *p* of the recovery period
L_{z0} : is total network length in traffic zone *z*
L_{zp} : is the total length of the network links that belong to traffic zone *z* and experience a functionality loss during phase *p*
N_z : is the total number of important locations located at traffic zone *z*
S : is the total number of traffic zones that include important locations

The *environmental loss factor* ENV_p assesses the consequences to environmental-sensitive areas due to an increase of traffic after an earthquake and the associated gas emissions, noise pollution and heavy vehicle transport [31]. Such areas may be national parks, protected forests and regions with wild life passing routes. The calculation of the factor relies on the definition of the links that are environmentally sensitive. Environmentally sensitive links may be the links that cross environmentally sensitive areas but also other links that have a high environmental impact themselves.

$$ENVp = \frac{\sum_{j=1}^{J} l_j}{\sum_{j=1}^{J} a_{pj} \cdot l_j} \qquad (7)$$

where:

α_{pj} : is the ratio between the traffic load at network link *j* during phase *p* to the traffic load to that link has during the normal traffic period

l_j : the length of the environmentally sensitive network link *j*

J : the total number of the environmentally sensitive network links

The graphical representation of the *Consequences vector* $\left\{ECO_p, CON_p, ENV_p\right\}$ as function of time represents the evolution of earthquake financial, social and environmental impact until the functionality of the road network is fully restored..

3.2 Quantitative indicators

The total cost associated with each earthquake scenario *k* (i.e., 100, 475, 980 and 1890 years) is the sum of the cumulative direct cost of structural damage within the network and the earthquake-induced total traffic cost. More precisely, every damage state that a critical component may experience is associated to a structural repair cost ratio defined as the repair cost over the total construction cost of a specific network component (bridge, tunnel etc). It is necessary to define such repair cost ratio indices for all four damage states prior to the analysis for each component class. Based on the repair cost ratio index and the probability of attaining every damage state for each critical component *i*, the estimated Total Structural Cost TSC_k due to seismic scenario *k* is given by:

$$TSC_k = \sum_{i=1}^{N} D_{i,k} \qquad (8)$$

where:

$$D_{i,k} = TBC_i \cdot \sum_{1}^{M} (RCR_1^i \cdot P_{DS1}^{i,k,m} + RCR_2^i \cdot P_{DS2}^{i,k,m} + RCR_3^i \cdot P_{DS3}^{i,k,m} + RCR_4^i \cdot P_{DS4}^{i,k,m})$$

TBC_i : is the total cost of re-constructing critical component *i*

$RCR_1^i, RCR_2^i, RCR_3^i, RCR_4^i$: are the repair cost ratios corresponding to DS1 to 4

$P_{DS}^{i,k,m}$: is the probability that the damage of the critical component *i* exceeds DS1 to 4 due to the contribution of seismic source *m* to earthquake scenario *k*

M : the total number of the identified earthquake sources

N : the total number of critical network components

The traffic cost correlated to each traffic scenario *m* is the additional cost during the entire recovery period of that traffic scenario, and as such, it is the sum of the product of each phase duration, times the corresponding additional traffic cost. The total traffic cost correlated to a seismic scenario *k* (TTC_k) is the mean of the *M* traffic costs associated to that seismic scenario as defined in eq. (4):

$$TTC_k = \frac{\sum_{m=1}^{M} \sum_{p=1}^{P} EC_{m,p} \cdot t_{m,p}}{M} \qquad (9)$$

where:

$t_{m,p}$: is the duration of phase *p* of traffic scenario *m*

The total road network cost due to seismic scenario *k* is defined as sum of the total structural cost and the total traffic cost:

$$TNC_k = TSC_k + TTC_k \qquad (10)$$

Since every seismic scenario has a specific return period (and relative annual excedeence probability) the TNC_k is the estimated total network cost corresponding to the return period of earthquake scenario k.

4. Software development

The above holistic probabilistic framework has been materialized as a standalone, GIS-based interactive freeware including open-source traffic assignment engine DTALite [32] and has been made available to the engineering community (www.retis-risk.eu).

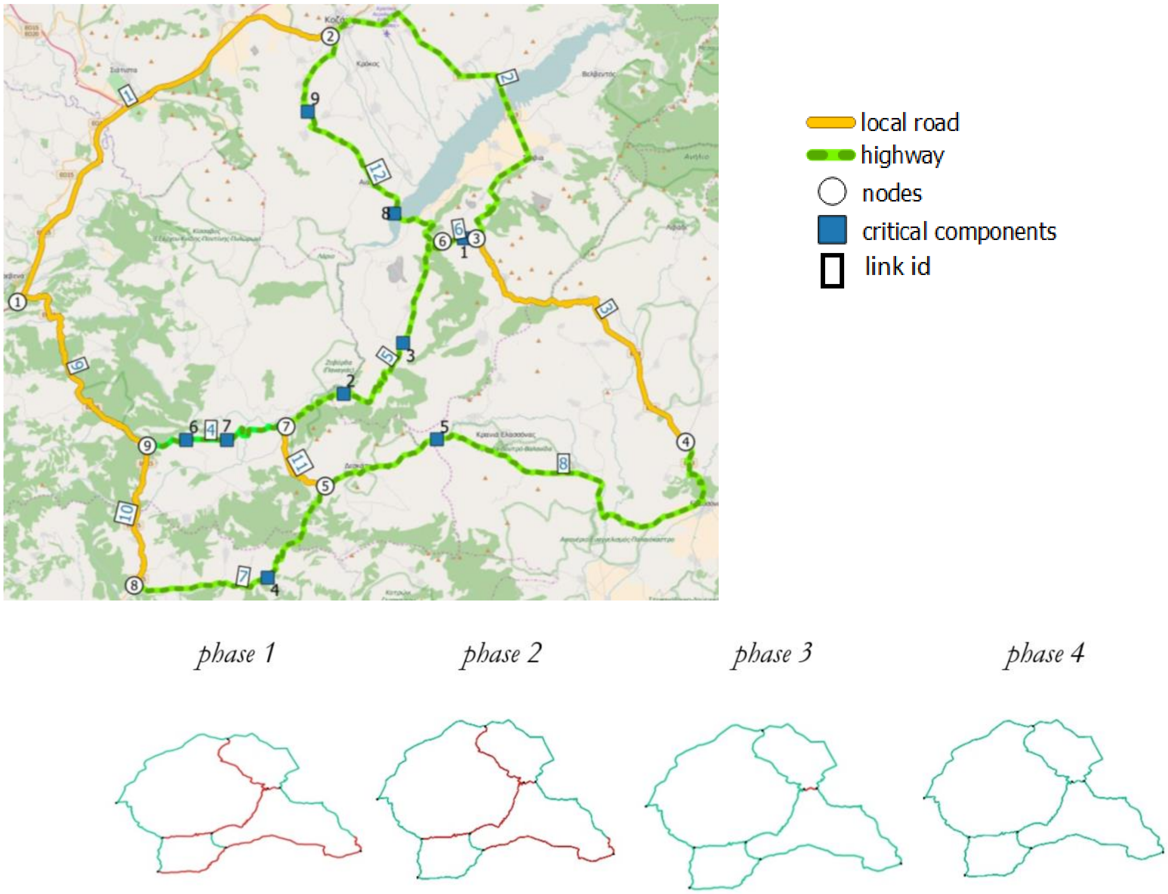

Fig. 4 – Case Study network topology (top) and progressive restoration of network functionality (bottom)

5. Case study

The same software and framework has been applied to a simple, idealized, road network that consists of 12 uni-directional links. A total number of 9 critical components (Fig.4) classified into 3 general classes (class 1: seismically isolated bridges, class 2: monolithic bridges, class 3: tunnels) where assumed to be distributed along the network. The traffic demand originating from nodes 9 and 8 towards nodes 3 and 4 was prescribed assuming that all drivers choose the fastest route, 9-7-6-3 and 8-5-4 (i.e., the shorter paths with the higher speed limits). Four earthquake scenarios (periods of recurrence of 100, 475, 950 and 1890 years) were considered, each one composed by two seismic maps, (i.e., triggered by two seismic sources). A traffic carrying capacity-time relationship and a repair to cost ratio [33] were assigned to each one of the 9 key network components.

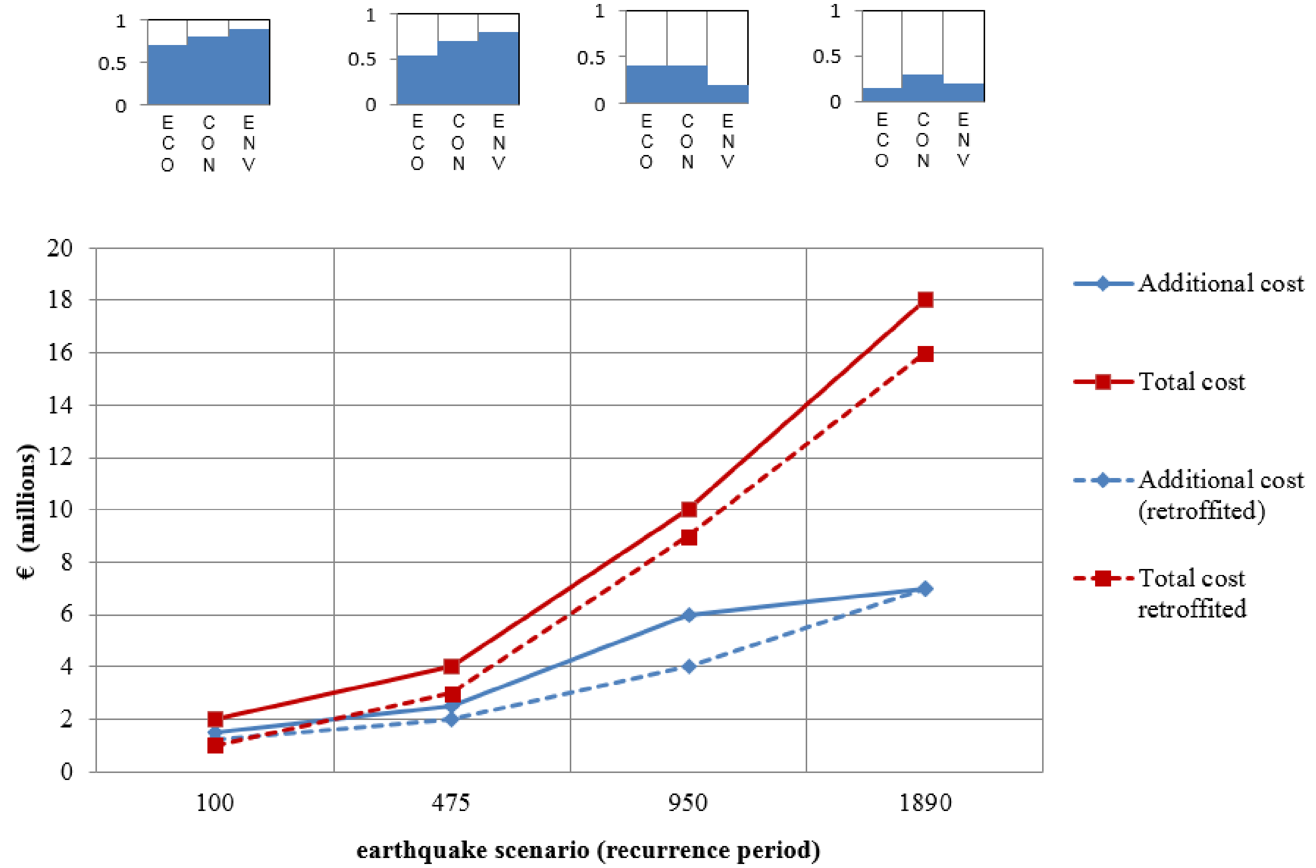

Fig. 5 – Decision-making diagram

6. Decision making

Road management is a two-level process involving pre-earthquake, prioritized strengthening of key road network components [3,34,35] as well as post-earthquake risk management. Having defined the qualitative and quantitative indicators associated with each seismic scenario the network stakeholders have the ability to selectively intervene towards risk mitigation and network resilience. Prior to the earthquake, this may be achieved by identifying tailored retrofit of the components with the most profound adverse impact on the network functionality. The retrofit of selective bridges, overpasses, tunnels and other geotechnical works is reflected on the updated fragility curves, which in turn lead to the mitigation of the overall seismic risk of the road network, the reduction of the life-cycle cost and the significant improvement of the network resilience. This is evident in Fig. 5, where both the additional traffic and the total cost are significantly reduced in case of well-tailored retrofit for all seismic scenarios examined. On the other hand, post-earthquake risk management can be substantially improved by spotting the most probable weak links along the network and driving the recovery efforts to the corresponding locations during the crisis period immediately after a strong earthquake event. The holistic framework presented herein may also be used for reducing the time interval between the onset of the earthquake and the initiation of repair works. In light of available shake maps, the *M*, scenario-based, seismic maps produced can be updated with the actual spatial distribution of seismic demand (i.e., IM), thus significantly improving the prediction of potentially damaged network components and optimizing the recovery actions of the first few hours

7. Conclusions

In this study, a framework is presented for the multi-criterion assessment and management of road networks' seismic risk involving an integrated vulnerability, hazard, traffic and network analysis. Several qualitative and quantitative indicators are introduced considering the time-variant nature of loss incurred by the community, from the onset of the earthquake throughout the entire recovery period until the full functionality of the network is restored. The holistic estimate of the direct (structural) and indirect (traffic) monetary loss as well the wider social, financial and environmental impact of seismic events with different period of recurrence is a precious decision-making tool for the stakeholders involved in mitigating the seismic risk of the road network and ensuring resilience after a major earthquake event. The same framework can be used to identify the optimum pre-earthquake retrofit measures of key network components (mainly bridges, overpasses, tunnels and slopes) that can have a major impact in improving the network resilience and reducing downtime at the minimum possible cost. It may also be used for identifying the most probable weak links of the road network in an area affected by a strong earthquake event during the first critical hours of the recovery period, thus improving the efficiency of the remedial measures.

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