Conceptual Framework for the Seismic Risk Evaluation of Transportation Networks in Romania

Dragos Toma-Danila, Iuliana Armas and Carmen Ortanza Cioflan

Abstract The assessment of seismic risk for transportation networks is a difficult task, due to its complexity, hard to get detailed data, lack of methods with low uncertainties and difficulty of defining inter-relations. Through this paper we identify viable ways of analysing the seismic risk of transportation networks in Romania, considering the availability and characteristics of specific data, the possibilities of adapting external knowledge and recently developed methodologies. Until now there was no coherent and complex approach in Romania for this task, referring to the bigger picture. Therefore, we propose an integrative framework that incorporates GIS capabilities (like the ones provided by the ArcGIS Network Analyst Toolbox) and test it for Bucharest. This framework can provide answer to important questions, like "which are the critical segments of networks" or "what could the implications of connectivity loss be?" in case of an earthquake. The approach relies on using fragility functions for critical structures like bridges and tunnels, on empirical formulas for estimating damage level, traffic flow characteristics or connectivity analysis. Results are depicted through multiple performance indicators.

Keywords GIS · Infrastructure · Earthquakes · Vulnerability

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1 Introduction

Each major earthquake has the capability to produce a large amount of damage over a wide extent, in a very short amount of time. The transportation networks play a vital role—both immediately after an earthquake, and also long time before it occurred; they constitute support for the fast intervention and for the recovery efforts. Therefore, their functionality and capability to satisfy traffic demands is a key aspect in reducing human and economic losses.

The impact of large scale natural disasters like earthquakes on infrastructures has two clear dimensions: temporal and spatial. These dimensions have their place in a Geographical Information System (GIS). Beside these there is also the perspective of the actor involved: national institution, citizen, financial system, NGO or others.

Generally, the vulnerability of transportation networks can be analysed at two main levels:

- Structural level—the focus is on the physical (direct) vulnerability of a components
- Functional level—the functional vulnerabilities of the network and the indirect implications are analysed

According to Pinto et al. (2011), a fundamental distinction among the studies related to the seismic performance of road or transportation networks can be made, based on the importance of the role played by the network itself. Therefore, three main categories have been identified:

- Basic: the attention is focused on the functioning of the network in terms of pure connectivity.
- Advanced: the scope of the study is widened to include consideration of the network capacity to accommodate traffic flows.
- Complex: aims at obtaining a realistic estimate of the total loss, whether direct or indirect; economic interdependencies are accounted for.

In general, the simpler the category, the smaller the uncertainties. Simulating the behaviour of transportation networks during an earthquake is a very difficult task and multiple uncertainties and high error thresholds are normal. Still, in the last decades important progress was made into this interdisciplinary field of study, making the models more accurate. Projects like Hazus or Syner-G united resources available at their time (also created new ones) and lead to the development of dedicated tools and methodologies for the analysis of the seismic risk of transportation networks (like roads, railroads, gas pipes or electrical power lines). Theoretical frameworks have been proposed—in the enumerated projects or in papers like Du and Nicholson (1997), Werner et al. (2006), Jansuwan (2013), Miller et al. (2015) and others. These framework's concepts have to be adapted to the national specific of different countries.

Romania is a country that was and will be affected by major earthquakes; the most hazardous seismic source is the Vrancea Area, located in the curvature of the

Carpathian Mountains, approximately 150 km away from Bucharest. Here, in the last century occurred 4 earthquakes with moment-magnitude (Mw) greater than 7 (in 1908, 1940, 1977 and 1986), at depths between 90 and 150 km. Due to this intermediate-depth interval, high intensities and considerable damage to buildings and infrastructure were recorded far from the epicentral area, up to 300 km away. Bucharest was one of the most affected cities, especially during the 1940 and 1977 earthquakes. There are also other crustal seismic sources like Fagaras-Campulung, Banat or Shabla (in the north-eastern Bulgaria), which can produce earthquakes large enough to generate local and regional damage.

As it happens everywhere, when major earthquakes occur, the focus of society is mainly upon the damaged buildings (since most people die due to building collapse, and not solely the seismic waves), the immediate saving of lives and recovery efforts. In an ever more complex system, the role of transportation networks and the need for it to be functional is ever more important; as complexity can be considered directly proportional with vulnerability, we expect that future earthquakes will highlight more and more the tangled dependencies in our societies, all tied through infrastructure.

One of the starting questions of this paper can be: "was the behaviour of transportation networks during earthquakes really an issue in Romania?". Due to the focus on other aspects, few information is nowadays available regarding how earthquakes affected transportation networks and what the implications were. We certainly know that it wasn't like in California (when the 1989 Loma Prieta and 1994 Northridge earthquakes struck) or Japan (as during the Kobe earthquake on 1995). However, there are still records that some railroads, bridges, road surfaces, pipelines or electrical power lines were affected; in 1977, the railroad employees worked in the very hours after the earthquake to restore the connections. The Otopeni International Airport was also affected and quickly repaired, due to its vital role. In Bucharest, the centre of the city was mostly affected; 32 high-rise buildings collapsed partially or totally, and debris was not an issue in blocking a large number of roads. Although fires were quickly put out, electricity was off for hours. Nowadays we have to be caution and realistic, since many things changed and during future events the rule of the game could be different, because:

- Times have changed. If in the communist era (until 1989) the road traffic was reduced, nowadays it became a major problem; official records (from the Romanian Direction for Driving Licenses and Vehicle Registration Statistics) show that there are more than 1.12 million cars registered in Bucharest (more than 1 car at 2 people) and 6 million cars in total in Romania (which has 22 million people). In case of an earthquake occurs at an unfortunate hour, the traffic jams would greatly increase the intervention times in urban areas—most affected. It is a question of minutes and hours to have a chance of saving people trapped under debris.
- The damage could be much greater; experts included 373 buildings in Bucharest in the seismic risk class I (Bucharest General Municipality 2015), meaning that they could collapse to any major earthquake. And many other buildings still not

evaluated are clearly endangered. There are more than 30,000 buildings constructed without considering seismic effects on buildings.

- Economic activities and recovery efforts are strongly influenced by the disruptions of transportation networks; considering globalisation, the extent of good's circuit and the dependencies on constant flows of materials from distant origins, each delay time can have serious repercussions.

So under this considerations, would the transportation networks be reliable and not risky? We believe that an investigation has to be performed. Especially since in Romania there are so few initiatives that analyse the safety of transportation networks during earthquakes. One of the main legal obligations is the analysis of structures (mainly bridges), according to national normative (such as CD 138-201), but from here to seismic risk there is a long way. The recent research papers that we've found regarding the analysis of not only a singular structure from an engineering point of view (like in Racanel 2015 or Sartori 2012), but a network view, were Ciutea and Atanasiu (2014; with sparse references to road network's seismic risk) and Toma-Danila (2013). We consider that nowadays, with the aid of technology and international scientific knowledge, the few data available for transportation networks in Romania can be put to use, through a specifically designed schema capable of integration within a GIS, which we describe and partially test in the following chapters.

2 Proposed Framework

The conceptual framework that we propose is based on the fundamental idea that the loss of connectivity is the main issue that has to be evaluated (also in terms in implications), since its role is major in the escalating risks. In the framework development we focused on determining logical sequences that link hazard and vulnerability, determining initially the structural and functional behaviour of transportation networks and ultimately the socio-economic influences.

What makes the analysis of the networks special in a seismic context is the fact that the structural damage can have a clear expression for specific targets (link between earthquake engineering and geography); hotspots can be identified and also the modification of the socio-economical patterns (effects on the origin-destination pairs) has a considerable effect right after the event and for a significant period of time.

One of the key input data required is the definition of the network, with its components, subcomponents and attributes that can reflect the vulnerability state (from a seismic point of view, but also seen as capacity to accommodate traffic and new configurations). Some of the elements that can be considered for road networks are presented in Fig. 3. Of course, the spatial dimension has to be specified, and the resulted geodatabase should respect network specifications in order to make it
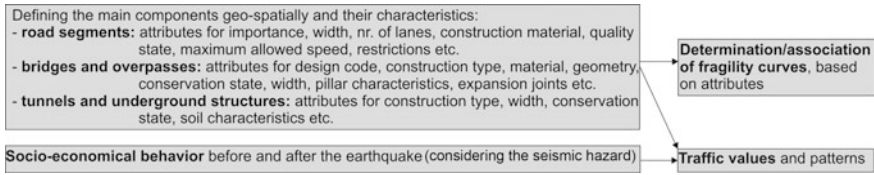
Fig. 1 Proposed definition chart for a road network, applicable to seismic risk assessment

useful. For example, the Network Analyst Module of ArcGIS that we also use in the case study requires beside location (that has to be interconnected) other attributes (such as maximum speed, importance or relative elevation), in order to allow modelling the network behaviour appropriately.

For pipelines (or electrical) networks, the elements can consist of main pipelines (power lines) with attributes like technical state, material, diameter, flow capacity etc., and special buildings (pumping or transformation stations, reservoirs etc.) that can be analysed through fragility curves, for example.

Figure 1 shows some of the main criteria to be considered when defining the components of road networks; by knowing all these aspects, important considerations regarding the behaviour of the network during an earthquake can be emitted. The use of fragility functions is a common practice in seismic risk assessment. These functions (also named fragility curves, from the graphical representation) facilitate the numerical expression of a structure's probability to be in a vulnerable state (defined more or less subjective), for a certain ground movement parameter or intensity value. A fragility function can be seen as the cumulative distribution function of the capacity of an asset to resist an undesirable limit state (Porter 2015). The research in transportation networks lead to the definition of specific functions for components like bridges, tunnels or even embankments. Many fragility functions are gathered in the HAZUS Software and the SYNER-G project deliverables. There is no warranty that these functions are applicable elsewhere then they were determined or that they are highly reliable, however they can roughly provide the damage probability for a certain type of component. The design of new fragility curves is always an option (for long bridges is generally performed), but the process is quite complicated and hard to validate in natural conditions. Seismic fragility curves for bridges and tunnels usually require values of peak ground acceleration (PGA), intensity or peak ground deformation (PGD$_f$). Building analysis can also require spectral acceleration values for capacity curves. Embankment, tunnels or pipeline fragility curves require mostly peak ground velocity (PGV). Obtaining seismic damage probabilities is an important step in the analysis, since it reflects the direct damage on transportation networks. Without fragility curves, an empirical assessment can be achieved through formulas like the ones developed by Anbazhagan et al. (2012) or Kaynia et al. (2011). These formulas link intensity or permanent displacement to a certain damage state, based on real observations. In all cases, knowing detailed attributes for the components is important.
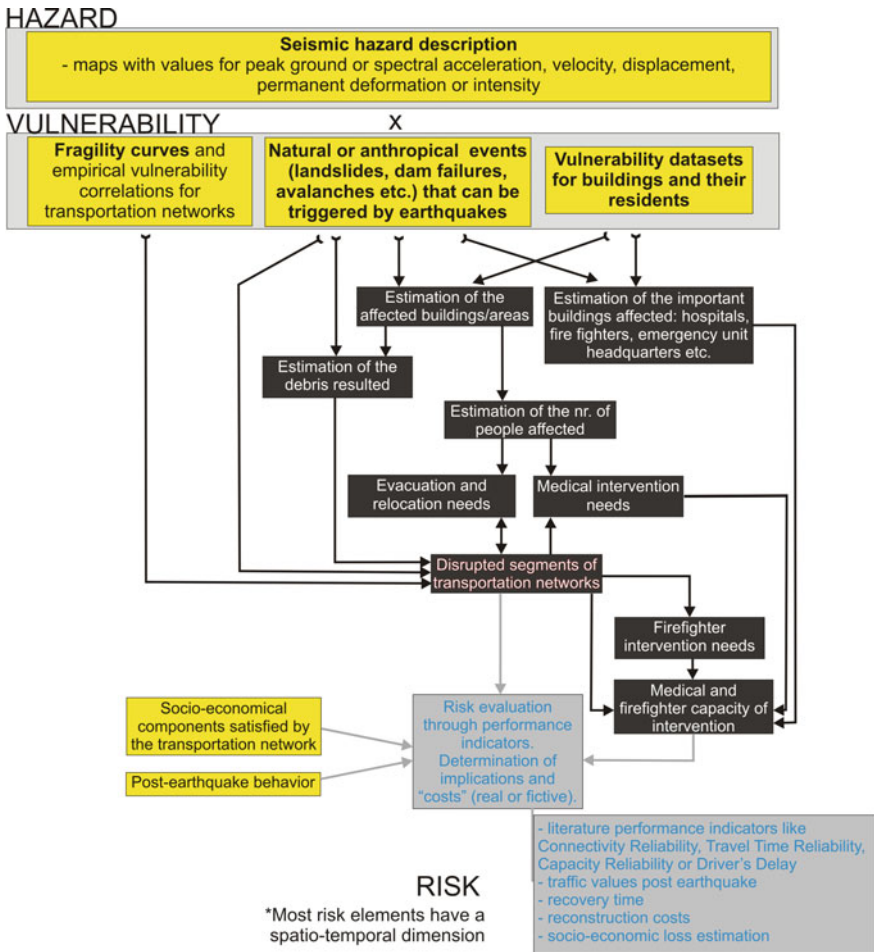
Fig. 2 Conceptual framework for analysing the seismic risk of transportation networks, for a specific seismic event

When an earthquake occurs, the socio-economic behaviour modifies dramatically; for example, people abandon buildings and, due to the failure of communication systems, try to reach home or other safe places; emergency intervention actors fill the streets; some businesses boom and others enter conservation states. Therefore, traffic values and patterns modify. It is best to model these modifications, since they greatly reflect in the computation of fictive costs translatable into risk indicators.

The framework proposed in Fig. 2 leads to trip generation, distribution and traffic assignment (origin-destination pairs) in order to check the capacity of the network to accommodate the demand, in post-earthquake context, and the risks that might occur. The framework focuses on the need for emergency intervention, from
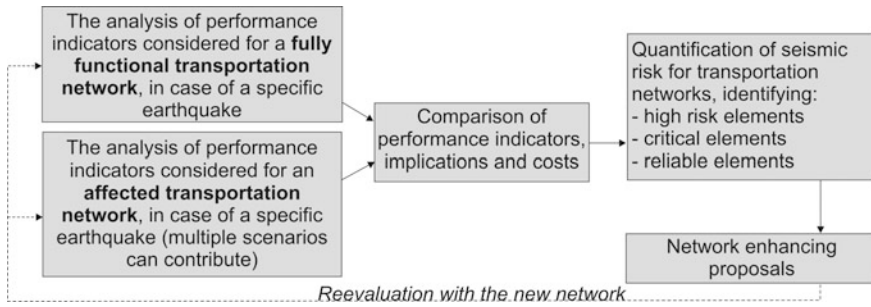
Fig. 3 Conceptual framework for quantifying the overall seismic risk and testing new proposals

fire fighters or ambulances, since the intervention times are vital for saving human lives, and if the road networks affect these times, they pose great risks. Performance indicators regarding connectivity and reliability (expressed in several transportation network papers like Asakura and Kashiwadani 1991; Chen et al. 1999 or Shinozuka et al. 2003) can be used in order to quantify the overall performance of the network and allow direct comparisons with other network configurations. The computation of costs (whether real, like money spent per km or fictive, like minutes of delay) is also important. Although hard to contain, the socio-economic risk can be estimated through different empirical models that express economic losses or life expectancy for people trapped under debris (Coburn and Spence 2002) as a function of time, for example. For network components (bridges, tunnels, km of highway) reconstruction costs can be derived based on building costs, also for different damage states.

Figure 3 presents the quantification of risks, after evaluating individual scenarios with the flowchart in Fig. 2. Basically, a comparison is performed between performance indicators obtained for the undamaged network and the damaged one, desirably at segment level in order to identify specific critical or reliable elements. Through this schema, improved network configurations can also be tested.

3 Framework's Applicability to Romania

Due to its flexible character, the proposed framework can be applied (although with a lower confidence level) to areas where there is few data regarding the vulnerability of transportation networks, such as Romania. Nowadays, technology has led to a massive increase of datasets (including GIS data) and their public dissemination over internet. Although quality is one of the concerns when dealing with big data or free data, at least road and railway networks can be determined usefully—from a geographic point of view and with basic characteristics. In this chapter we analyse the availability of hazard and vulnerability data for Romania, considering the new capabilities of getting the needed data.

3.1 Data Availability

3.1.1 Seismic Hazard Data

The seismic hazard of the Romanian territory has been the subject of multiple studies that used probabilistic (Ardeleanu 2010; Sokolov et al. 2008; Mantyniemi et al. 2003; Musson 2000), deterministic (Marmureanu et al. 2010) or neo-deterministic methods (Cioflan 2006). The current national seismic design code (P-100/2013) presents maps at national level with design PGA values for 225 years return period and 20 % probability of exceeding in 50 years and response spectrum corner periods (1.6, 1.0 and 0.7 s, each with corresponding elastic respond spectrum). Together with other considerations, regulations and recommendations, this code can contribute to expressing the seismic hazard and vulnerability of transportation networks (although it's focus is mainly on buildings and individual structures).

Acceleration and intensity maps are of great use in the proposed framework and for Romania they are available, whether from the references presented above or from (near real-time) ShakeMaps and other products of the Romanian Seismic Network, operated by NIEP. Specifically for Vrancea intermediate-depth earthquakes, several ground motion prediction equations have been developed (like Sokolov et al. 2008; Vacareanu et al. 2015), providing PGA, SA, PGV or intensity values (Sokolov et al. 2008) at bedrock or surface. There are also available microzonation maps at city level, for Bucharest (Marmureanu et al. 2010) for example. Therefore, seismic hazard scenarios are obtainable, but their uncertainties are not to be neglected, since major Vrancea earthquakes are far from being understood in detail and can and have shown unpredictability (Cioflan 2006).

3.1.2 Transportation Network Data

In Romania, official GIS data regarding basic transportation networks such as important roads and railroads is not yet public and downloadable. Probably, through the INPIRE directive this is going to change, however until then we investigated other ways of obtaining GIS data with respect to the scheme in Fig. 1.

Knowing the geographical location of the network's subcomponents is one of the basic requirements when analysing the vulnerability or risk of a network. The need of knowing the spatial distribution (considering also the connectivity aspect) is vital for the analysis. Since the seismic hazard is spatially distributed, so the network must be. Romanian roads are viewable on internet websites and services (GoogleMaps, BingMaps, YahooMaps etc.) or in GPS software and actually allow interactivity. However, how can they be used in a custom seismic analysis (without digitisation by hand)? OpenStreetMap data seems to be the top choice nowadays, when requiring data that can be downloaded and manipulated (in a non-commercial purpose). Its advantages lie in the fact that is under an open license, millions of
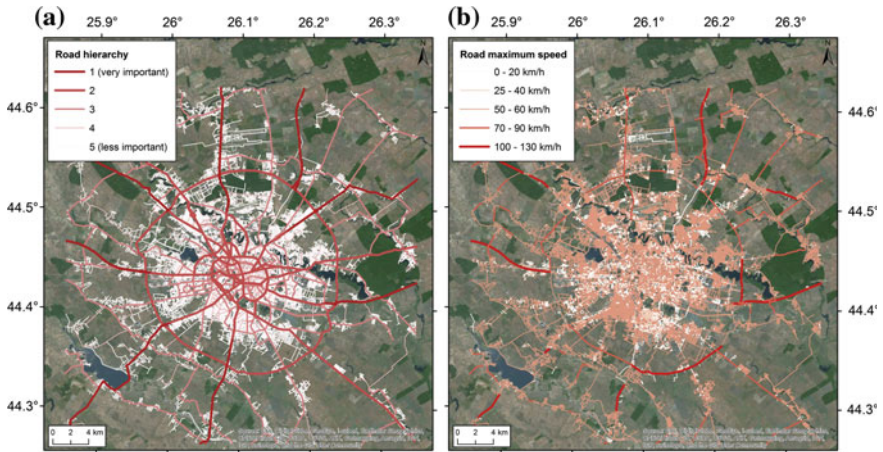
Fig. 4 Maps for different attributes: **a** hierarchy; **b** maximum speed limit, for the Bucharest road network obtained from OpenStreetMap data and processed in ArcGIS according to the Network Analyst Module specifications

collaborators from all over the world update it regularly and respect standardised procedures. We downloaded a dataset for Bucharest and we were not disappointed (as in the case of other webGIS resources that provided to basic information, inaccurate, incomplete or obsolete); the road dataset is complete (up to the smallest streets) and up-to-date, the connectivity of the segments is good and there are also very useful attributes. Also, there are tools that allow shapefile conversion, in order to use the data with the Network Analyst Module of ArcGIS. Among the attributes that enhance the modelling of the road network are relative elevation references (allowing bridges, overpasses, tunnels to not interfere with ground level roads etc.), maximum speed limits, names, importance (hierarchy) or one way and car restrictions (Fig. 4). All these data and attributes contribute to the development of a customisable road network that further requires other attributes that offer the perspective of seismic vulnerability and risk: association of fragility curves, integration of traffic values (before and after the earthquake), origin-destination pair definitions, direct and indirect seismic damage etc.

As mentioned before, fragility curves can be used for the seismic vulnerability definition of individual structures, such as bridges or tunnels. In Romania, no fragility curves were defined until now; however, in the literature there can be found suitable correspondents. Within the Syner-G Project there was compiled a world-wide library of fragility curves for bridges, tunnels or embankments, which can be used if appropriate. For bridges there are for example 6 European alternatives. Many other curves, specific to USA, are available from the Hazus-MH software.

The National Company of Motorways and National Roads (CNADNR) elaborated a normative regarding the criteria of determining the viability state of road bridges (CD 138-201), which particularizes for different construction materials (concrete, reinforced concrete, precompressed concrete, metal or composite) the aspects linked to the seismic action on the structure. A set of instructions for determining the technical state of bridges (AND 522-2002), tied to the normative aforementioned, is also in use. According to it, bridges can be classified into different technical states, requiring different levels of interventions. For the vulnerability evaluation of road network elements and tunnels there are also other regulations (CD 155-2001 and AND 601-2010). These regulations can be very useful in the assessment of transportation network's risk, but until now we haven't been able to receive reports based on these regulations and technical classifications (and we are unsure whether they also exist).

Traffic values for the roads of Romania are the subject of the General Circulation Census, which had its last editions in 2000 and 2010. The public information consists of Daily Annual Mean Traffic Values per category of vehicles (vehicles/24 h), for every national road individually and for all county or communal roads, as mean. Although useful for a wide area analysis (especially for areas outside of cities), these values are irrelevant for big cities like Bucharest, that we analyse further. The national authority that has the task of collecting road traffic values (also in charge of the census) is the Centre for Road Technical Studies and Informatics (CESTRIN), but data has to be paid in order to be used, and the costs are great (partially justified when considering the classical methods of collecting traffic data, with sensors, microwave radars, acoustic and video measurements or others, described in Leduc (2008). Fortunately, new technology—GPS and smartphones offers now a breakthrough and aid greatly in the process of crowd-sourcing for traffic values. Services like Google Traffic or BingMaps Traffic allow map generation for live traffic, based on the times spent in traffic by users of the company's apps, transmitted automatically to big data servers. We tested Google Traffic in Bucharest; giving that many Romanians use smartphones (in 2014, 34 % of Romanians had a smartphone according to Initiative Media 2015), almost all roads excepting very local ones had live traffic values. The service can also show mediated values for different times of the day and week. Although GoogleMaps can use these traffic values to predict origin-destination times, due to the fact that no downloadable data is available yet, the processing cannot be easily replicated in other systems. However, for the case study in this article we georeferenced images illustrating the Monday morning traffic, extracted the classes of traffic: slow, medium and fast, and used it as influence on maximum speed limits in our custom road network.

For other transportation networks such as water-supply and waste-water networks, fire-fighting system, electric power network or natural gas system, the framework can also be applied, but the public data is extremely limited in Romania.

A collaboration with companies in charge of these networks, that also possess the data considered restricted, is however achievable, giving also the requirements of the Seveso Directive.

3.1.3 Other Significant Data

As presented in the framework, it is not only necessary to know, for example, if a bridge is affected and that the risk of losing it reflects only in reconstruction costs. If the functionality of the road network is greatly affected by the loss of that bridge, than the losses are far bigger. In order to assess the indirect impact of the damage, most methodologies in transportation networks require origin-destination (O-D) pairs over the network's segments (or traffic flow definition). Right after an earthquake, one of the basic O-D pair formed is between emergency intervention teams and affected areas. Later on, implications in terms of disrupted businesses, delay times, additional costs generated (by detours or more traffic) etc. can be evaluated.

In Romania is hard to anticipate what the affected areas (destinations for the road networks) will be, since right from the beginning, intermediate-depth earthquakes in Vrancea have the tendency of producing wide-spread damage with inconstant directivity (Cioflan 2006); the 1940 earthquake produced more damage in Moldova whether the 1977 earthquake produced more damage in Bucharest and Muntenia. In the recent years, at NIEP it was implemented a near real-time system for Estimating the Seismic Damage in Romania (SEISDaRo). Its results could be used (and were used, in Toma-Danila 2013) as data for different risk scenarios for transportation networks. Also, the Bucharest General Municipality (and other cities) keeps a list of buildings (Bucharest General Municipality 2015) enrolled in different seismic risk classes (I for the most endangered). These buildings were used in the case study of this paper.

Other data that is significant for the proposed framework and can be partially available for Romania is data referring to hospitals, fire stations, Emergency Units or shelters in case of disasters. Socio-economic aspects (commuters, businesses, supply demands etc.) and their links with transportation networks is also desirable, but not easy to find.

3.2 Bucharest Case Study

The risks in an area with collapsed buildings increases significantly, if the place becomes inaccessible. The recent Nepal earthquake (2015) showed exactly this aspect. Beside casualties, earthquakes can easily cause fires (mainly due to gas

leaks). In this demonstrative case study we evaluated for basic scenarios the times for intervention in a possibly affected Bucharest. We applied parts of the conceptual framework defined in this paper to datasets from sources specified above, to evaluate the risk of delays for emergency intervention forces (fire fighters and ambulances) in Bucharest. We considered a Vrancea earthquake with Mw > 7.4 that had as effect the collapse of all buildings evaluated by experts as being in the seismic risk class I, and multiple failure situations for road segments, based on traffic values and debris caused by expected to collapse buildings (modelled as 500 m. buffers; if height or volume information for this buildings would be available, specific methods for debris calculation could be employed, such as the ones from RISK Iran or Risk-UE Projects).

The analysis is performed mainly in ArcGis with the aid of the Network Analyst Module, for a complete network of Bucharest's streets, taken from OpenStreetMap and refined based on the attributes specified in Sect. 3.1.2. The analysis procedures consist of applying route, service area and O-D cost matrix procedures. As origin points we used the emergency hospital locations (excluding children hospitals and distinguishing between them based on the Health Ministry's classification) and also fire stations. Since this case study is a proof of concept and we had no data regarding the capacity of each hospital/fire station and also the demand of intervention, we used only indicators reflecting unique/primarily intervention times. In a seismic context it would be of great interest to see what happens in a supersaturated system (that is also influenced and influences the behaviour of transportation networks).

The traffic conditions considered were no traffic and Monday morning traffic (when the city is very crowded). The travel times consider the speed of an ambulance or fire truck with acoustic signals (therefore with priority in traffic and no waiting times at traffic lights).

Figure 5a shows that in no (or very light) traffic conditions, each building should be quickly accessible by ambulances. Also, in Monday morning traffic (Fig. 5b) the times would generally be smaller than 5 min. But if damaged buildings would block the adjacent roads, intervention times for the city centre would exceed 8 min (Fig. 5c). And this times double if victims are to be returned to the closest hospital. In case of a major earthquake, the priority destinations for victims are the top hospitals; we considered the accessibility to these hospitals only, and Fig. 5d shows that in Monday morning traffic conditions and no blocked roads, there are minimum intervention times up to 8 min (to destination). Figure 5 also shows the closest hospitals to buildings, based on travel times.

In Fig. 6a we represented the intervention times for fire trucks, in Monday morning traffic. As it can be seen, the maximum time is of 10 min, mostly for all Bucharest, due to the good spatial distribution of fire stations. Figures 5 and 6 could be combined in a model based on weigh overlay in order to express the risk for each building to be accessed by intervention forces. In this paper we chose not to create
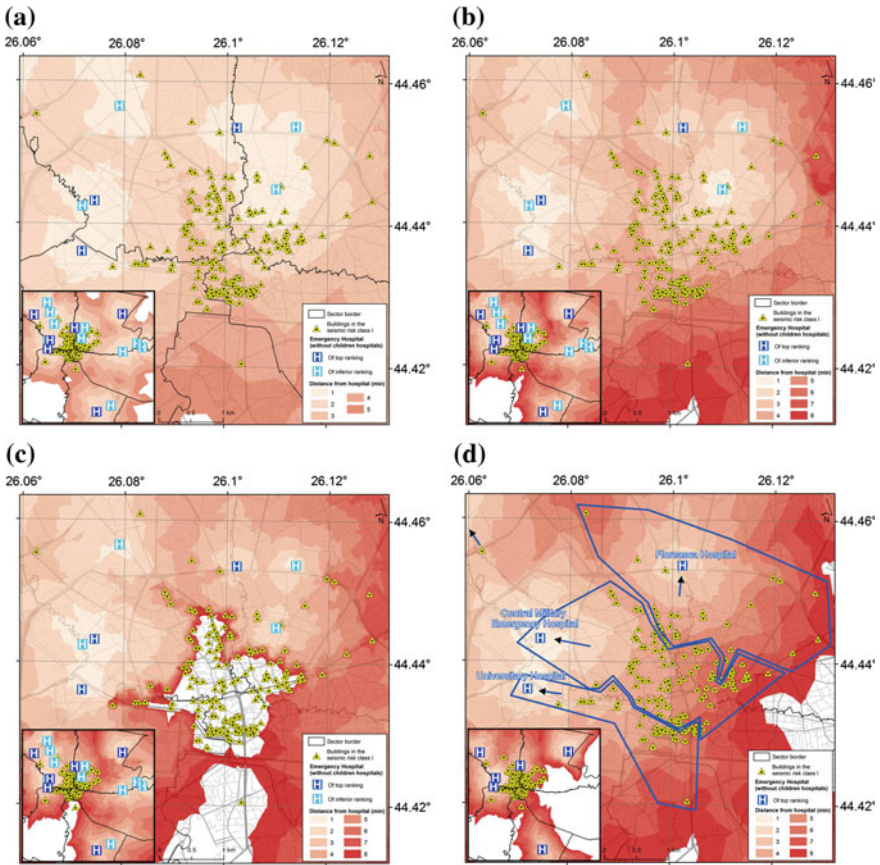
Fig. 5 Intervention time zones for ambulances from hospitals to possibly affected buildings (in seismic risk class I), for different scenarios: **a** no traffic, **b** morning traffic, **c** morning traffic and blocked streets due to buildings collapse (100 m buffer around buildings) and **d** morning traffic, but only top ranked emergency hospitals (according to the Health Ministry classification), showing also the quickest to reach hospitals to buildings with high seismic risk

such a model due to the few scenarios considered. We believe that Monte-Carlo simulations could greatly help in testing the significance of specific road segments in the process of satisfying the traffic demands imposed on it.

Figure 6b answers the question: how affected are the routes that cross the city (N-S) if buildings in the city centre collapse (and block the streets)? As it can be seen, there are plenty of alternatives and the additional time required is not so considerable (as it would probably be in case of non-urban locations).
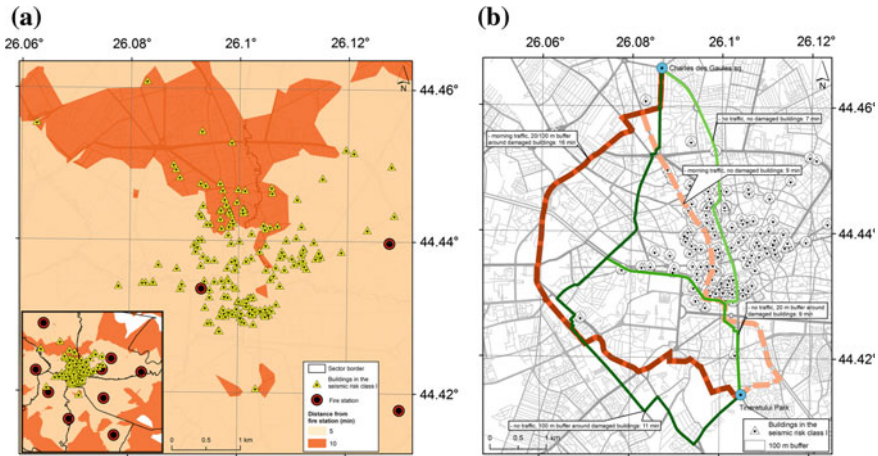
Fig. 6 a 5 and 10 min intervention zones for fire-fighters, considering the fire stations in Bucharest and the morning traffic; it is considered that each station has at least one fire truck, and no other aspects regarding the firefighting capacities are considered; **b** Fastest routes between northern and southern Bucharest for emergency intervention vehicles, considering various scenarios: no traffic or morning traffic, collapsed/not collapsed buildings in seismic risk class I, determining street blockage (computed through 20 and 100 m buffers). Routes show that there are reliable alternatives of crossing the city, with few time differences

4 Conclusions

In this paper we proposed a conceptual framework that allows the analysis of the seismic risk of transportation networks, considering inter/intra dependencies between components and the direct and indirect effects of seismic events. Our goal was to make this framework adaptable to different datasets, more or less complex (as in the case of Romania). GIS proves to be the binder of apparently heterogenic data related to hazard and vulnerability aspects, in an environment that respects the spatio-temporal dimension of the analysis. The framework shows how multiple disciplines can contribute to the characterisation of network risk.

Although without a significant background in Romania, the topic of the paper, as we demonstrated, can be nowadays tackled; by using public information (mostly available for road networks) or other data sources from national authorities, the risks of transportation networks can be quantified (currently in a simplified manner). The availability of useful seismic hazard data for Romania is an important aspect. This study is a first step in trying to understand what the seismic losses in Romania could be, due to network failure and effects.

The case study for Bucharest demonstrates the applicability of the framework to Romania. In case of high traffic and collapse of many buildings in the city centre during a major Vrancea earthquake, it would take more than double to transport injured people to the nearest hospital than normal. The number of trips required

would be considerable, raising the question if hospitals near the city centre can deal with a great amount of casualties. Results also showed that there are good alternatives for detour routes. Although promising, due to the basic inputs of the analysis, results must be treated with care: no post-earthquake traffic, no description of intervention capacities or no assessment of seismic road damage (only empirically, through debris) were considered. We are aware of the limitations, but future studies will add significance to the model. The framework could be of great interest when applied to broader areas (county level), where distance problems, direct and indirect seismic effects and blockage implications like detours are more significant for the analysis of transportation network risks.

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