RAPORT DE PROIECT

CERCETARE POSTDOCTORALĂ – 2021
ACADEMIA OAMENILOR DE ȘTIINȚĂ DIN ROMÂNIA (AOSR)

Titlul proiectului:
Analiza timpilor de intervenție în situații de urgență, ținând cont de implicațiile cutremurelor asupra rețelelor rutiere

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Obiectivele proiectului:

1. Îmbunătățirea planurilor de pregătire în situații de urgență prin dezvoltarea unei metodologii capabile de automatizare, destinate analizei timpilor de intervenție în caz de cutremur
2. Testarea acestei metodologii pe București, ținând cont de implicațiile directe și indirecte ale unui cutremur asupra rețelei rutiere

Descrierea muncii de cercetare

Cutremurele sunt unele dintre cele mai periculoase fenomene naturale de pe Glob, ele având capacitatea de a produce o cantitate semnificativă de pagube pe un teritoriu extins într-un interval de timp foarte scurt. Rețelele de transport joacă un rol vital atât imediat după cutremur (constituind suport pentru intervențiile rapide ale salvatorilor), cât și mult timp după acesta (când eforturile de revenire trebuie deservite în mare parte prin intermediul lor). De aceea, capabilitatea rețelelor de transport de păstrare a funcționalității și de adaptare la noi fluxuri și configurații reprezintă aspecte fundamentale în reducerea pagubelor umane și economice. Rețelele de transport rutiere joacă un rol foarte important în reducerea pagubelor, ele asigurând de regulă accesul mijloacelor de intervenție și reconstrucție – care sunt de altfel majoritar de tip auto. În condițiile în care cutremurele majore provoacă pagube semnificative în special în medii urbane dar și blocaje rutiere post-seism, toate ducând la disfuncționalități majore în ceea ce privește accesibilitatea rutieră atât de necesară, cât de mare poate fi impactul asupra timpilor de intervenție din partea pompierilor sau ambulanțelor? Analiza a multiple scenarii posibile dar și crearea unor soluții automate bazate pe date transmise din teren de la echipamente IoT, care să faciliteze identificarea unor rute sigure sau vitale, este un lucru dezirabil care poate duce la reducerea numărului de victime printr-o intervenție mai promptă.

Bucureștiul este una din capitalele europene cu cel mai mare risc seismic - datorită nivelului ridicat al hazardului seismic având ca sursă principală zona Vrancea, influenței efectelor locale, expunerii mari a populației dar și vulnerabilității seismice ridicate a clădirilor. Cutremurele mai recente ce au avut loc în Vrancea (cele din 10 Noiembrie 1940, Mw 7,7 și din 4 Martie 1977, Mw 7,4) au dus la pagube progresiv mai semnificative, demonstrând necesitatea unei pregătirii mai adecvate în situații de urgență, atât din punct de vedere a siguranței clădirilor cât și a capacității de intervenție a salvatorilor. Din păcate, situația actuală nu este una încurajatoare, dincolo de problemele ce țin de clădiri adăugându-se și o nouă provocare: presiunea traficului rutier, cu influență majoră asupra timpilor de intervenție.

Metodologia dezvoltată continuă munca începută în cadrul inițiativei Network-Risk toolbox (http://www.infp.ro/index.php?i=nri), publicată în Toma-Danila et al. (2020) și Toma-Danila (2018). Pentru analiza timpilor de intervenție au fost exploatate funcționalitățile unui Sistem Informațional Geografic (GIS) – în special software-ul ArcGIS și extensia sa dedicată analizei rețelelor de transport: Network Analyst. Acesta facilitează integrarea datelor cu privire la rețele rutiere, asigurând reprezentarea geografică a datelor dar și respectarea regulilor cu privire la conectivitate. Datele cu privire la rețeaua rutieră din București au fost preluate din cadrul inițiativei deschise OpenStreetMap, fiind creat un modul dedicat integrării facile a acestora în

ArcGIS. Pentru identificarea vulnerabilităților cu privire la rețeaua rutieră în caz de cutremur, ce influențează timpii de intervenție, au fost considerate aspecte cu privire la:

- vulnerabilitatea clădirilor și infrastructurii;
- potențialul de blocare a segmentelor de drum datorită molozului rezultat în urma prăbușirii clădirilor cu risc seismic ridicat (date oficiale de la Administrația Municipală pentru Consolidarea Clădirilor cu Risc Seismic fiind utilizate);
- traficul anterior și posterior unui cutremur (identificat prin modelări empirice dependente de timp), fiind utilizate date tipice de trafic din inițiative din cadrul TomTom.

Comparativ cu studiile anterioare, în acest proiect a fost adăugată funcționalitatea de analiză dependentă de timp. De asemenea, noi locații pentru unitățile de intervenție sau destinații medicale (spitale) au fost adăugate, ținându-se cont în analiză și de numărul de vehicule disponibile în modelarea timpilor de intervenție totali și indicatorii de performanță rezultați. Aspecte ce țin de posibilitatea utilizării de către aceste vehicule a unor linii dedicate (precum liniile de tramvaiau fost integrate – acestea având atât în realitate cât și în simulare un impact benefic.

Metodologia generează hărți cu privire la zonele de „deservire" – accesibile în diferite minute în condiții ante- și post-seism, rute de deplasare rapide sau sigure dar și zone cu probabilitate mare de blocare. Ținând cont și de locațiile de intervenție dar și distribuția potențială a clădirilor prăbușite și victimelor generate, evaluări cu privire la nivelul de risc indirect pot fi realizate, metodologia și rezultatele fiind de mare utilitate în îmbunătățirea Concepției Naționale de Răspuns Post-Seism.

Rezultate

Principalul rezultat al acestui proiect este realizarea și trimiterea către publicare, într-o revistă indexată ISI/Webofknowledge cu factor de impact mare (Frontiers in Earth Sciences – Factor de impact 3,498; AIS 1,192; special issue „Integrated Disaster Risk Management: From Earth Sciences to Policy Making"), a materialului următor în limba engleză. Așa cum este menționat și în acesta, metodologia și o parte din date vor fi accesibile și pe site-ul INFP (http://www.infp.ro/network-risk), în cadrul toolboxului Network-Risk.

Dovada trimiterii către publicare:

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Time-dependent framework for analyzing emergency intervention travel times and risk implications in case of earthquakes. Bucharest case study

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Abstract

Earthquakes can generate a significant amount of casualties and economic damage within seconds. The lack of rapid and coordinated emergency intervention as well as a limited distribution of search and rescue resources can contribute to much greater losses. In this paper we develop a methodology built upon the ArcGis network analyst module, able to account for post-earthquake conditions. By combining i) direct seismic damage information with ii) models to determine road obstruction potential, iii) traffic information and time-dependent post-earthquake modeling, iv) the contribution of traffic-independent lanes for emergency vehicles but also v) emergency intervention facilities (hospitals or fire stations) and consideration of their capabilities, this methodology can provide important support for the management of emergency intervention but also for risk reduction planning. Main results consist of maps showing travel times for various scenarios and moments after an earthquake, inaccessible areas, vital access roads or highly important facilities. As case study we chose Bucharest, one of Europe's most endangered capitals considering the seismic risk level. The city was and could be considerably affected by earthquakes in the Vrancea Zone, being characterized by a high number of vulnerable buildings and by one of the greatest typical traffic congestion levels in the world. Compared to previous network studies for Bucharest, the approach in this paper is more complex and flexible, providing means for real-time integration and time-dependent analysis. Given that results are considered for the National Conception of Post-Earthquake Response, we present how they are shaped in order to accommodate practical procedures.

Key words: earthquake; seismic risk; time-dependent; emergency; network; infrastructure.

Introduction

Transportation networks are strategically crucial to the post-shock recovery and resilience. As demonstrated by several recent real-world seismic events (among which Wenchuan, China, 2008; Haiti, 2010; Maule, Chile, 2010; Tohoku, Japan, 2011; Gorka, Nepal, 2015 or Central Italy, 2016), road networks have turned out to be vulnerable both directly and by influence, contributing to significant additional losses. Problems can vary depending on location (urban vs rural), scale (structural or systemic) and damage type (direct or indirect). Of particular relevance to the improvement of emergency intervention management is the time-dependent status of the systems considered and the quality and quantity of information relating to such status. This usually increases and changes in nature as time from the disruptive event elapses, but can also be affected by secondary events as time progresses, overlapping the immediate response and recovery phases. An adaptive time-dependent framework for analyzing emergency intervention travel times will enable relevant stakeholders to identify specific risks of interest, and formulate relevant coordinated demands for preparedness and response actions.

In order to mitigate the risks due to non-rapid response, a good understanding of intervention capabilities as well as travel times under various conditions is needed. The possibility of integrating live data regarding traffic, incidents or the status of emergency facilities and vehicles – taking advantage of recent technological progress (from IoT devices to big data analysis), should be one of the key inputs to consider in methodological development. By analyzing multiple studies in the field, among which Hackl et al. (2018), Hirokawa and Osaragi (2016), Jenelius and Mattson (2015), Miller (2014), Pinto et al. (2012) or Franchin et al. (2006), as well our evaluation of recent experiences, we identified some of the main types of aspects to consider in modeling emergency intervention travel times after earthquakes:

- **medical treatment facilities** (such as hospitals), characterized by location, structural or functional vulnerabilities (including back-up systems in case of emergencies or reach-time to work place for personnel), specialties (more or less relevant for specific emergencies), staff characteristics, number of beds, equipment, ambulances etc;
- **facilities for emergency intervention** (such as fire-stations or operative centers), characterized by location, structural or functional vulnerabilities, number and type of vehicles (with various fire-extinguish capabilities), staff characteristics, equipment etc.
- **directly affected infrastructure components** (from bridges to traffic-lights - also due to blackouts) **and road incidents**, all with implications on traffic flow; these could be reported in the various applications currently available such as Waze or Google Maps, making a real difference, if data communication would still be functional;
- **affected areas** where intervention might be needed, **number of potentially affected people, demand for specific rescue forces and on-site accessibility for rescue vehicles**;
- **identification of roads potentially obstructed by building debris**, based also on street characteristics (Figure 1a and b shows the problems in Bucharest right after the March 4, 1977 earthquake);
- **the potential effects of aftershocks and the multi-hazard and multi-risk dimension**;
- **traffic pattern changes**: a modelling of initial traffic values and post-earthquake modifications (using the previously mentioned aspects), which can be related also to multiple causes such as the people desire to ensure that their relatives or assets are safe, people evacuating affected areas or entering them with rescue or transit purposes, people in need to reach their jobs as responsible in emergency situations etc. In many cases, post-earthquake traffic is characterized by the violation of circulation rules. For a real account of the situation, live data crowd-sourced or from emergency vehicle's GPS devices, traffic monitoring cameras and devices would facilitate a good understanding of the modifications and proper traffic management decisions, as well as validation for traffic models. The analysis could also account for various traffic management decisions.

Given that hospitals play one of the most important roles in post-earthquake situations - on them depending the save of many lives in express need of medical care, we consider as a necessity to focus on these facilities and travel times away and toward them. Recent experiences in our case study area - Bucharest (but also in many other areas), highlight important aspects to consider, regarding the risks of medical treatment facilities:

- **structural and non-structural damage of hospitals, as well as limited patient treatment capacity and shortage of medical personnel are significant threats**. These can make a hospital nonfunctional at some point after the earthquake and lead to the necessity of a viable alternate solution. That is why in an important performance indicator should refer to the availability of other hospitals to take over the rescue effort. As real experiences in Bucharest, we mention that after the March 4, 1977 Vrancea earthquake, the 1500 patients of the Floreasca Clinical Emergency Hospital needed to be evacuated one day after the earthquake, given that after rapid structural inspection the building was considered unsafe (Figure 1c and d).
- **not all hospitals can cure typical wounds due to earthquakes**. As Hotz et al. (2010) shows, for the Haiti earthquake in 2010 the most common injury diagnoses due to earthquakes are fractures/dislocations, wound infections, and head, face, and brain injuries. The most common injury-related surgical procedures were wound debridement/skin grafting, treatment for orthopedic trauma, and surgical amputation. In case of fires due to earthquakes, also burns will need to be treated.
- **the mistreating of patients with medical problems** (example: the case of patients with severe burns affected by nosocomial infections, after the Colectiv Club fire in Bucharest – Marica, 2017)
- **the chaos in and around the hospitals could be a significant problem, right after earthquakes**. In the case of Floreasca Clinical Emergency Hospital, located close to affected areas, in the first hour following the 1977 earthquake road access was very difficult and had to be handled by volunteers (Buhoiu, 1977); also the COVID-19 pandemic showed this feature during the peak of its waves (Figure 1g).
- **additional risk in the context of the COVID-19 pandemic.** Some hospitals or some of their sections are devoted in this period to the treatment of COVID-19 patients only. Many hospitals are overcrowded especially during surges, so the collapse and potential fire outbreak (with increased vulnerability due to substances for ventilation) could lead to multiple victims - not to mention the loss of vital medical personnel. In the COVID-19 period, fires occurred in 11 hospitals in Romania (Milonean, 2021), especially in the intensive care units – without the contribution of earthquakes. In case of hospital evacuation, the limited relocation capabilities, the potential mix of patients and the neglecting of pandemic rules (sometime forced by the circumstance) can lead to a significant increase of COVID-19 cases. Hygiene problems can also be a major issue. The recent experience of the March 2020 earthquake in Croatia was documented to not have caused a significant increase in COVID-19 cases following the event (Čivljak et al., 2020), although many hospitals needed to be evacuated, among the patients being 22 persons with the new virus. The Haiti earthquake in August 2021 showed a different facet: that a large number of medical facilities destroyed (66 in Grand'Anse, Nippes and Sud, following this event) can lead to lack of access to basic services – for 34% of the people in earthquake affected-areas (Bagaipo and Janoch, 2021) and as such to limited vaccination rates; the consequences are yet to be evaluated. The analysis of the Epirus and Samos earthquakes but also the Evia flood and Ianos storm in Greece, in 2020, has shown no major contribution

to the increase in the number of COVID-19 cases (Mavroulis et al., 2021), but as authors mention, various circumstances and number of casualties can have high impact on the rate.

Figure 1 Damage due to the March 4, 1977 earthquake in Romania, leading to the blockage of streets (a and b; source: Malide Cristian/muzeuldefotografie.ro) and to Floreasca Clinical Emergency Hospital evacuation (c and d). The figure also presents actual problems in Bucharest: vulnerable buildings (e) and traffic congestion (e and f), the importance of delimited tramway lines accessible also to emergency vehicles (f) and ambulance queue formed in front of the Floreasca Clinical Emergency Hospital due to multiple COVID-19 cases (g; source: Lapovita Ana)

As cities, their infrastructures and the means of transportation constantly change, as well as risks in the context of increased exposure, climate change or unstoppable and unpredictable hazards such as earthquakes, triggering more and more other hazards, travel time analysis and their implications is a continuous effort. Many cities have been significantly affected by earthquakes – Bucharest, capital of Romania, being one of them. However, so much has changed since the previous major events in the Vrancea Zone, on November 10, 1940 (Mw 7.7) and March 4, 1977 (Mw 7.4) – the latest leading to the collapse of 32 moderate and high-rise buildings in the city, the death of 1424 persons (90% out of the national total) and a 70% percentage of the total economic losses. Traffic is now a significant problem (Figure 1e and f) - Bucharest being ranked 18th by Tom-Tom (2020), out of 416 world-wide cities, in terms of typical congestion level. The very high seismic vulnerability of many buildings (including hospitals and fire stations), accompanied by limited access for emergency intervention in many areas due to the high number of cars parked illegally (Figure 3), could be the recipe for a greater disaster. Recent studies (such as Toma-Danila et al., 2020, Toma-Danila, 2018 and Ianos et al., 2017) have showed the need to improve emergency intervention access and planning in Bucharest. Through this article we make additional steps toward a standardized and flexible time-dependent analysis, with applicability in legal procedures and near-real time implementation. New modeling components such as delimited access routes recently introduced (Figure 1f), a greater dataset of vulnerable buildings in Bucharest, more reliable traffic data from TomTom, a detailed dataset regarding hospitals and their importance in case of earthquakes as well as a quicker procedure for integrating OpenStreetMap road data and traffic values (with applicability to many other study areas).

The analysis, contributing to a new version of the Network-Risk toolbox (with the previous presented in Toma-Danila et al., 2020), relying on ArcGIS with the Network Analyst extension, contributes to improving the emergency intervention management in Romania; it reflects the need for less vulnerable and new hospitals, traffic management planning in post-earthquake situations and buildings consolidation. It is also shaped to fit the needs of the future revised National Conception for Post-Earthquake Response – an operational procedure issued by the General Inspectorate for Emergency Situations in Romania, aimed to ensure a proper planning of intervention in post-earthquake conditions. As an additional objective, our analysis can be used to support or not the time frame mentioned in the National Law 95/2006, which states that the organization of qualified first aid services must ensure a maximum reach time (counted from the emergency call time) not exceeding 8 minutes in urban areas, for more than 90% of cases, and 12 minutes in rural areas, for more than 75% of cases, can be performed.

Methods and data

Flowchart of the methodology

When trying to develop a decision-support system improving emergency management based on the analysis of travel times, multiple inputs need to be considered. As Figure 2 shows, we consider in our framework the following inputs:

- road network: we expand on this type of transportation network given that it is still the most used for the emergency intervention access. However, it could easily be replaced by railways or waterways. Off-roads can also be defined as well as multi-modal transportation.
- traffic scenarios: whether typical, specific or real-time data;
- data regarding buildings and infrastructures damaged in various degrees by the mainshock and aftershocks (estimated or validated), but also by other types of hazards (such as tsunamis or landslides);
- the implication of building and infrastructure damage (as well as triggered hazards) on road network functionality loss, through an evaluation of debris potential to block the roads and changes in traffic patterns;
- various facilities (hospitals, fire stations) with different functionalities but also resilience indicators;
- various emergency units' availability over time and restrictions (such as width of a street for access);
- origins and destinations for economic activities, in order to further calculate the economic impact of network disruptions.

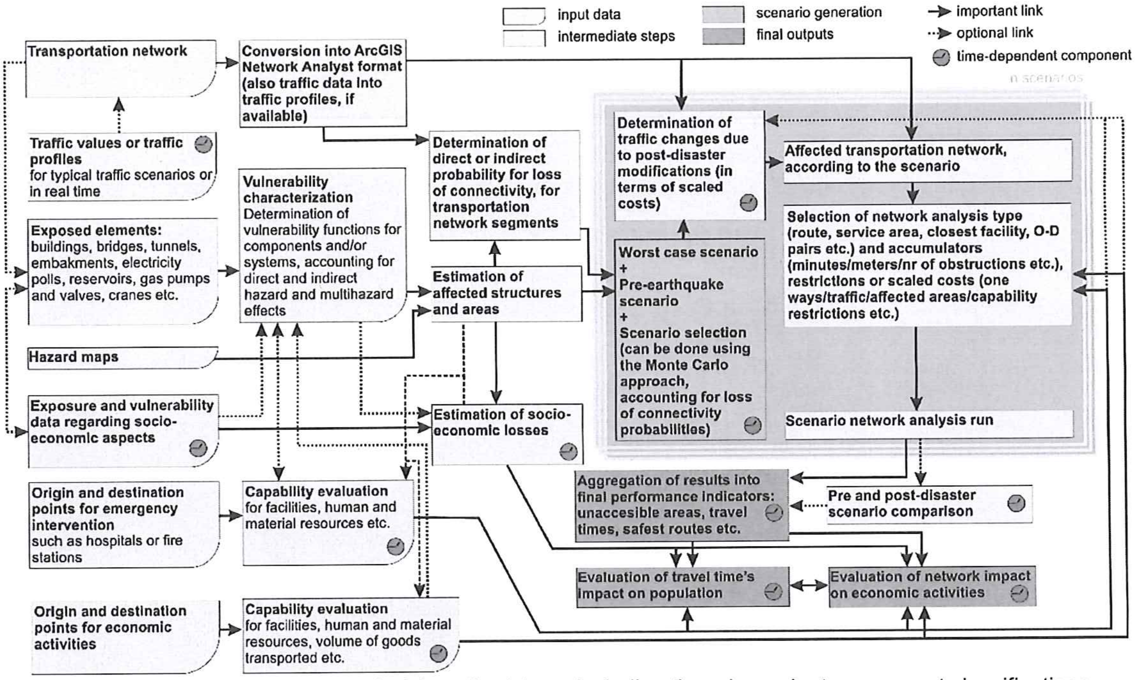

Figure 2 Flowchart of the Network-risk methodology, including time-dependent component classifications

The framework in this article expands and improves the capabilities of the free Network-risk toolbox (both versions can be found at Toma-Danila and Tiganescu, 2021). Novelties of version 2, making it also significantly different from other frameworks such as Rohr et al. (2020), Hirokawa and Osaragi (2016) or Pinto et al. (2012), comprise of:

- the use of the historical traffic feature (ESRI, 2021; compared to using individual columns for cost computations), therefore providing an easier time-dependent analysis– both easy to define using traffic profiles and continuous (enabling simulations for earthquakes at any hour with limited amount of parameter recalculations);
- a new approach for calculating which road segments that are partially of fully blocked by building debris;
- for network analysis, we now recommend and use the concept of barriers and scaled costs, which is more straight-forward than the previous ways of using special columns with times for each time interval and additional cost definitions (which could still be used however for tasks such as counting how many difficult to cross areas will be encountered);
- a computer-assisted methodology for converting rapidly free OpenStreetMap road data into the ArcGIS network format.

The Network-Risk toolbox is designed for ArcGIS with the Network Analyst extension, which is a popular commercial choice for complex network modeling. Among the recent studies relying on it, partially similar to our approach, we mention Rohr et al. (2020), Shahabi and Wilson (2014) or Sevtsuk and Mekonnen (2012). ArcGIS uses as shortest-path routing algorithms the widely used Dijkstra algorithm (ESRI, 2021), which provides a good balance between computational time and accuracy (Fan and Shi, 2010); optimized approaches such as hierarchy preferences are a good feature for testing large network datasets. The integration of other algorithms such as A*, Bellman-Ford, Floyd–Warshall or Johnson would be a good addition for research – ArcGIS's Python script compatibility setting good premises. We chose

ArcGIS due to its already available spatial analysis and network modeling functionalities but also GIS representation capabilities, which allowed us to test multiple input data setups, but also because it eases the use and customization for other interested researchers. ArcGIS's Network Analyst extension also has the option to use live traffic – using speeds from dynamic traffic format (DTF) files. Nevertheless, our framework could be also embedded using QGIS or Matlab's graph and network algorithms.

Input Data for Bucharest

The data which we were able to use in this study consists of:

- OpenStreetMap (OSM) vector road network of Bucharest and surroundings (Figure 2) from October 2021, reprocessed in ArcGis Network Analyst format through a semi-automated procedure described in the Network-risk toolbox manual (Toma-Danila and Tiganescu, 2021). Compared to our previous studies (Toma-Danila et al., 2020 or Toma-Danila, 2018), which used OSM road data from January 2016, October 2021 data has some important additions such as the A3 highway, the Nicolae Grigorescu passage or the Ciurel Passage. The chosen road network extent is also greater, allowing the analysis of many cities close to Bucharest and with significant dependencies toward it. Given that emergency intervention vehicles can legally use in the last years the asphalted specially delimited tramway lines (Figure 1f), which creates a separate and generally safe (therefore faster) alternative access route, we identified and included these segments in the road network (Figure X).
- Typical traffic is still a major issue (TomTom, 2020) – also in the COVID-19 period, in which, except for lock-down periods, people used cars more often given the increased exposure in public transport vehicles. Measures taken in the last years such as stricter regulations for parking space in the city center, opening of underground parking lots and installation of pavement blockers have reduced the amount of traffic lanes blocked by illegal parking, but still there are significant issues limiting the road's functional space (too many cars and to less care about the law). As typical traffic data we used Area Analysis Data from TomTom Traffic Statistics available via TomTom's MOVE portal (TomTom, 2021), averaged for the 1 to 21 April 2019 (with orthodox Easter being on 28 April 2019 so no major influence of holidays being induced). Data was available only for the 1-3 Local Time (LT), 8-10 LT and 16-18 LT intervals. To differentiate between weekdays and weekends we used as proxy 0.6 respectively 1.2 multiplication factors to average speeds, deduced also by result comparison with Google Maps typical traffic queries for representative routes. Given that TomTom road data is different from OSM data (and less detailed, including only important roads), we used the *near* function in ArcGis to associate the closest average speed values to the OSM road segments (for segments closer than 200 meters). For other segments we applied the OSM maximum speed and for tramway road-accessible segments we used the 50 km/h speed. In order to generate 24/7 profiles in ArcGIS, we used the TomTom values but also used local knowledge and Google Maps traffic verification for some time intervals.

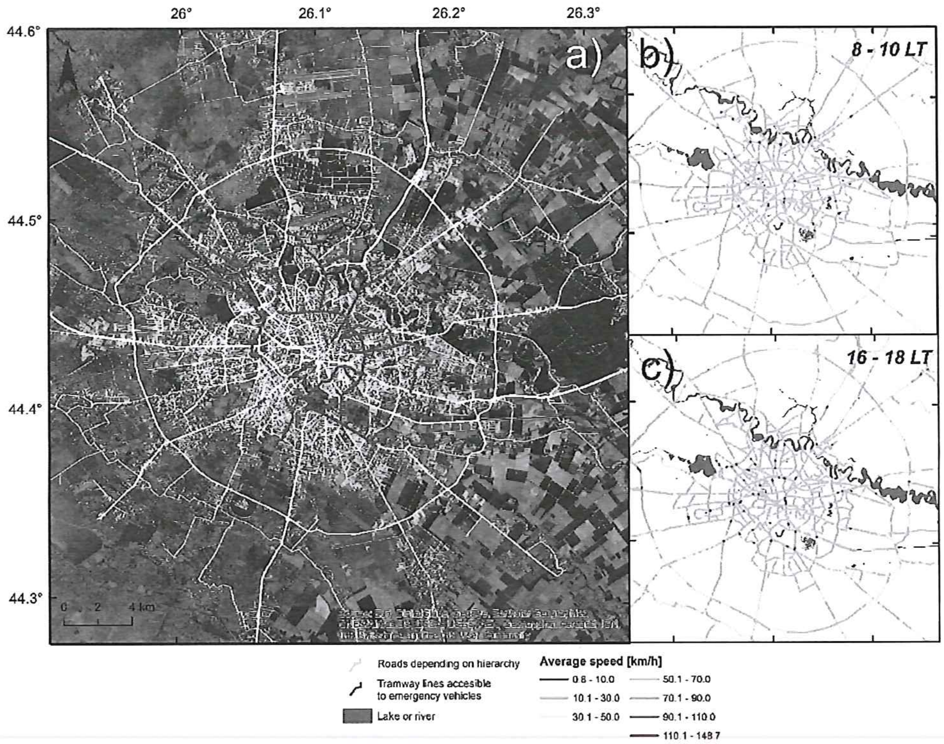

Figure 3 OSM road network for Bucharest and surroundings, used in this study (a) and typical traffic values according to TomTom data (b and c), showing the TomTom less complex road network, comprising of higher hierarchy roads

- A new dataset regarding all hospitals (both public and private) in Bucharest and Ilfov county nearby – a significant extension from the dataset used in previous studies such as Toma-Danila (2018) and Toma-Danila et al. (2020). This also provides information regarding treatment capabilities (also in earthquake emergency situations). Based on it and the feedback from people involved in disaster medicine we provide a classification of hospitals in terms of importance in case of earthquakes, considering both treatment capacity, available personnel, their experience and real typical destinations for ambulances. For some hospitals, an evaluation of seismic vulnerability is provided. Currently, among the hospitals acknowledged by expertise to have significant seismic vulnerability in Bucharest (ISUBIF, 2021) are the Bagdasar-Arsenie Emergency Hospital, the Gorgos psychiatry hospital (Titan) and Bucur Maternity - in seismic risk class (SRC) I - greatest probability to collapse), the Fundeni Clinical Institute's B building with SRC II housing 1000 patients and 2000 medical personnel and the Floreasca Hospital's A building - in SRC II (still considerable collapse probability). Many hospitals were not yet expertise.
- Location of residential buildings individually evaluated by engineers and categorized in SRC I and II (maximum SRC being IV) or urgency categories (older classification) on official lists from the Municipal Administration for the Consolidation of Buildings with Seismic Risk (AMCCRS), georeferenced by RE:RISE and geo-spatial.org (2021). These are not all highly vulnerable buildings in Bucharest, still they provide a good coverage for building typologies which were most affected during the 1977 earthquake – high-rise reinforced concrete buildings built before 1940. As the National Census in 2011 shows, there are at least 31430 residential buildings older than 1947. Out of these, 295 have at least 6 floors - category shown to be highly vulnerable during the 1940 and 1977 Vrancea

earthquakes (Toma-Danila and Armas, 2017). 263 are on the AMCCRS list – 115 being in SRC I, 110 in SRC II and 15 in SRC III – 23 being consolidated. Additionally, 26349 buildings constructed between 1947 and 1960 are also in Bucharest. The first compulsory seismic design code being instituted in 1963.

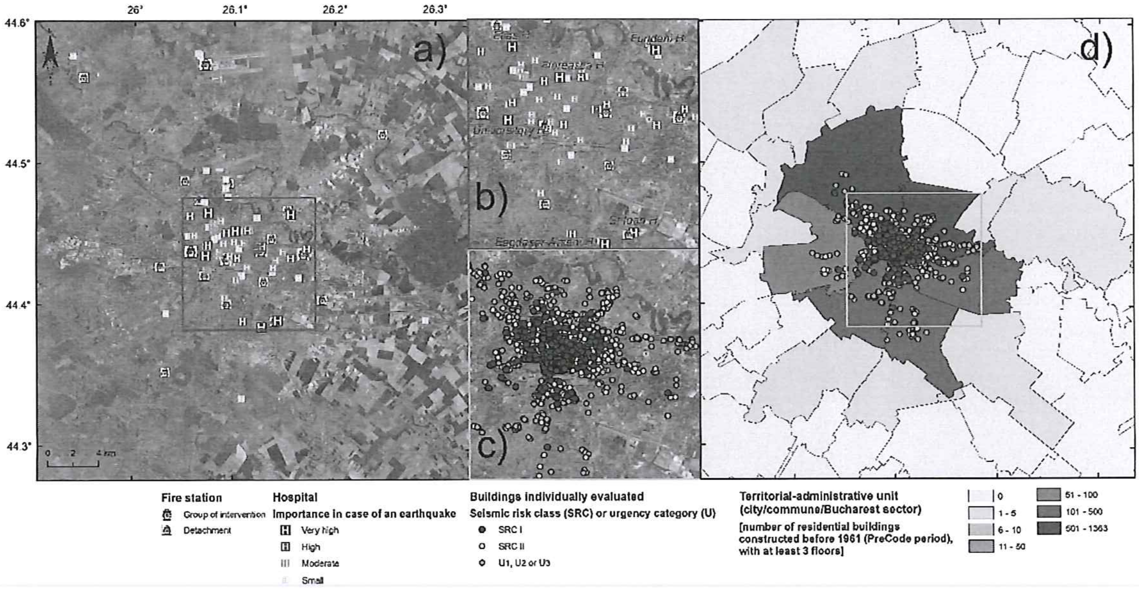

Figure 4 Location of hospitals and fire-stations (a) and residential buildings with SRC I, II and in urgency categories as well as number of residential buildings constructed before 1961, with at least 3 floors, according to the 2011 National Data Census, at city/commune/sector level (d). The zoom windows (b and c) show the city center and the names of very important hospitals (b)

- For determining the road obstruction potential due to building collapse, we calculated the debris footprint of buildings in SRC I and II and in urgency categories. We used the empirical equation in WP6 of the RISK-UE Project (as mentioned in Franchin et al., 2011), which was determined based on the observations done after the Kocaeli 1999 earthquake for collapsed RC buildings (representative typology also for Bucharest): debris footprint (in meters) = ⅔ * number of floors. This provided satisfactory results, as Figure 5 shows and also easy implementation for multiple scenarios runs. By converting road polylines into polygons based on their number of lanes and hierarchy (when important roads are drawn separately for both ways in the database, polygons could become larger than in reality), we were able to partially automate the process of detecting full or partial obstruction due to building debris by using the ArcGIS erase and intersect functions and identification of duplicate segments afterward (given that some road segments completely blocked by debris split into segments) or missing segments (which can be re-added as completely blocked segments). More complex equations, considering also adjacency of buildings or debris footprint for different building damage states, such as Argyroudis et al. (2015), Zanini et al. (2017) or Yu and Gardoni (2021) will soon be tested in a different paper, also with on-field analysis.

Figure 5 An example of results of the automatic determination of fully or partially blocked road segments due to building debris (d) for a central area near the Coltea Hospital, and exemplification of the real situation (a, b, c – source: Google Street View). Scaled costs calculated using Table 1 are also represented (e and f)

- For bridges, tunnels and passages in Bucharest we did not have damage potential reports available; by applying typical fragility functions from the Syner-G Project, we showed in Toma-Danila et al. (2020) that limited complete damage is expected in Bucharest – as also the 1977 earthquake showed. However, by using visual inspection and warning issued also in mass-media, some structures can be considered prone to seismic damage to a greater degree: the Constanta passage but also Basarab passage, which is relatively new but poorly maintained and due to its long span can have both structural and traffic problems leading to blockage. We tested what could be the travel time impact if these structures collapse.

In order to facilitate the replicability, improvement and integration of data in other studies, both OSM Bucharest network road data in the ArcGIS network format and data regarding hospitals in and near Bucharest can be retrieved from Toma-Danila and Tiganescu (2021).

Modeling post-earthquake traffic

This task is one of the most difficult given the many modeling parameters and uncertainties. Detailed procedures have been tested through the time, in studies such as Feng et al. (2020) or Aydin et al. (2018), but still validation with real post-earthquake data is limited. Among the complex systems we mention MATSIM or Simulation of Urban Mobility (SUMO), which was recently used in Costa et al. (2020), but also the Freeways video game (Captain Games, 2017) which provides interesting insights on the problem and solutions. All post-earthquake traffic modeling results can be incorporated in our methodology – in the form of polygons with various scaled costs increasing the time needed to travel in a specific area. For this study we chose to test a basic yet flexible methodology, following the next steps:

a) selection of buildings affected by the earthquakes (MonteCarlo approach can be used, as in Toma-Danila et al., 2020);
b) determination of road segments affected by debris completely or partially;
c) calculation of service areas around these segments in terms of meters. If desired, a differentiation between completely and partially affected segments can be made - as traffic might be more influenced near completely blocked road segments. We used service areas of 100, 200, 300, 400 and 500 m.
d) calculation of service areas around hospitals, with variable meter distance depending on hospital importance. We used 200 m for most important hospitals and 100 m for the others.
e) use of the ArcGIS *union* function to merge all service area polygons (explode multipart features if needed) and assign scaled cost values in a specific column. We used the costs in Table 1, after consultations with emergency stakeholders (future incidents – not necessarily earthquakes – could help validate these assumptions, so we will find new solutions for determining analytically these costs). In polygons with multiple scaled costs from different sources we calculated the maximum scaled cost and added an additional cost depending on scaled costs from multiple sources of traffic. Then we summed all potential values (with minimum 4 and maximum 11 and for values greater than 7.5 we added to the maximum value 0.5 and for values between 6.5 and 7.4 we added 0.3.

Table 1 Scaled costs considered for Bucharest

Moment after the earthquake	**Service Area Facility**	**Scaled costs in the service area of:**				
		100 m	**200 m**	**300 m**	**400 m**	**500 m**
First two hours after	Completely blocked segments	3.5	3	2.5	2.2	2
	Partially blocked segments	2.5	2.2	2	1.8	1.6
	Important hospitals	3	3			
	Less important hospitals	2				
Next 6 hours	Completely blocked segments	3	2.5	2.2	1.8	1.5
	Partially blocked segments	2	1.8	1.6	1.4	1.2

	Important hospitals	2.5	2.5			
	Less important hospitals	1.5				

f) run of Route, Service Area, Closest Facility or O-D cost matrix analysis for hospitals of various importance, with scaled costs for the previously determined service area polygons. Also add to these polygons lines/polygons for road segments affected by buildings: completely blocked segments as restrictions and partially blocked segments with a scaled cost of 5 for the first two hours after the earthquake and 3 for the next hours.

Results for Bucharest

Our study aims to show the general public and stakeholder potential risks due to poor road network connectivity after major earthquakes expected to affect Bucharest greater than in 1977. Also, our study aims to contribute directly to improving emergency intervention management, fitting within the National Conception for Post-Earthquake Response. As such, we organize our results in subchapters providing direct answers to questions often asked by emergency responders and planners.

Which areas could become inaccessible?

By using service area analysis with detailed generation of polygons, for a greater-than-expected sole break (we used 300 minutes), areas inaccessible to reach can be identified. For the generation of Figure 6 (and most of the next figures), we considered a worst-case scenario in which all buildings in SRC I, II and urgency categories are considered to be affected, even though in reality the chances are quite few – at least for complete collapse; however it is to be kept in mind that beside buildings on the AMCCRS list there are much more vulnerable buildings in Bucharest, as demonstrated above. Given that we had two classifications of building debris impact (fully or partially blocking the roads), we run the analysis and represented the results differently. Given the methodological limitations (the empirical equation for debris area calculation, not considering the adjacency of other buildings – epistemic uncertainty, as Figure 5b shows for a segment considered to be partially blocked), but also aleatory uncertainty, it is safer to consider a wider extent of the inaccessible area and not just the red polygons. In this way, a significant potentially inaccessible area in eastern part of the city center can be identified, but also other areas relatively great in size (the minibox of Figure 5).

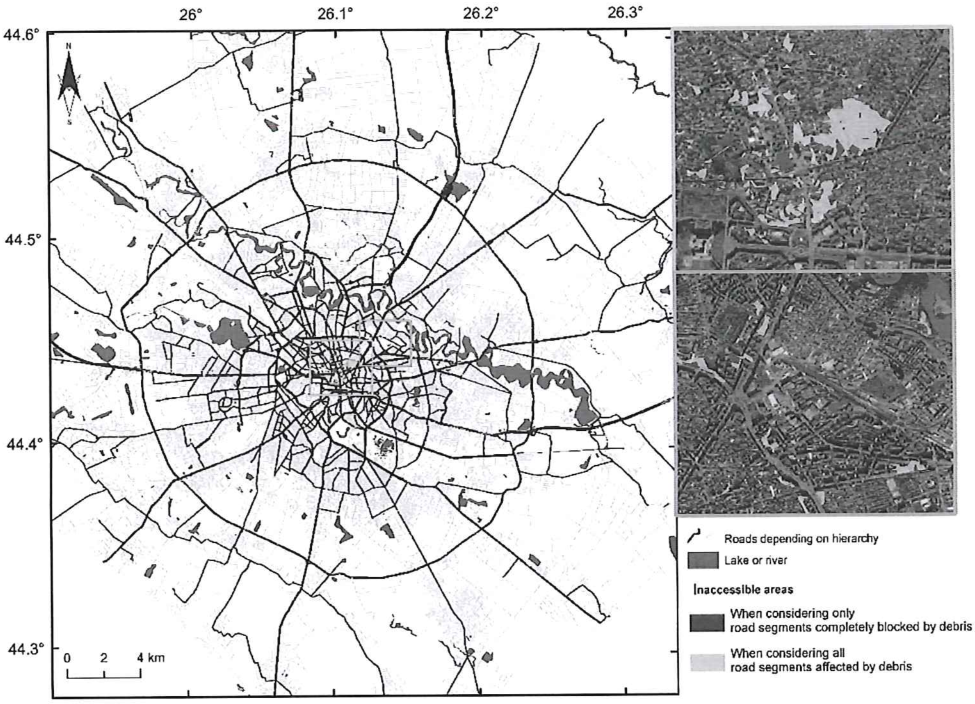

Figure 6 Map showing the potentially inaccessible areas, for the worst-case scenario – all SRC I, II and urgency categories buildings collapsing

How long would it take for ambulances and fire trucks to reach a location (or vice versa)?

Results of our methodology can show which areas are harder to reach by firefighters or ambulances - therefore having an increased potential of fire spreading or risk for emergency victims (when making correlations with graphs such as the golden-hour medicine time – Hekimoglu et al., 2013 or Goncharov, 1997).

Although our analysis can be performed for any time interval, we chose for this article the following representative scenarios, in order to reflect both the city's maximum risk compared to minimum:

- Earthquakes occurring at 2 (AM) LT and 8 (AM) LT, on a typical weekday;
- Time-dependent snapshot of the situation 3 hours after the earthquake (at 5 and 11 LT)
- For the same time intervals, we computed travel times in no earthquake conditions, in order to facilitate comparison (Figure 7);
- Service Area analysis was performed with hierarchy enabled (given that preference for main roads is most possible also for moderate or large-size emergency intervention vehicles), no one-way restrictions, generalized polygons, toward facilities for hospitals of very high and high importance in case of earthquakes (Figure 7) and away facilities for fire-stations (Figure 8).

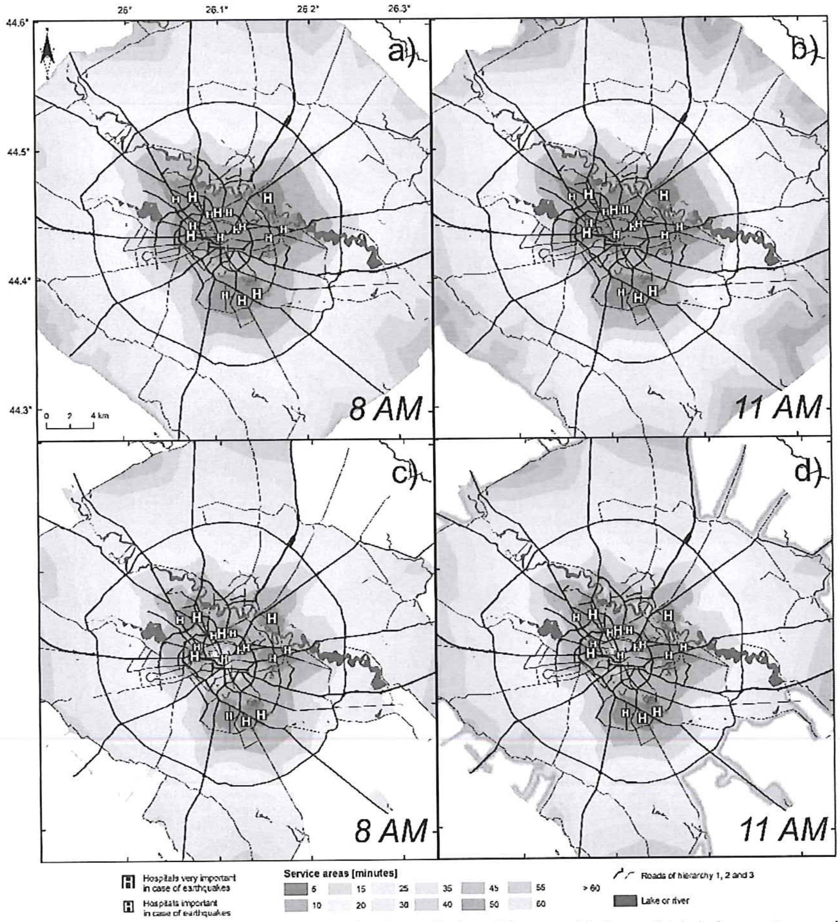

Figure 7 Maps showing Service Area times for hospitals with very high and high importance in case of earthquakes, in pre-earthquake (a and b) and post-earthquake (c and d) conditions, for an earthquake occurring at 8 LT on a typical weekday

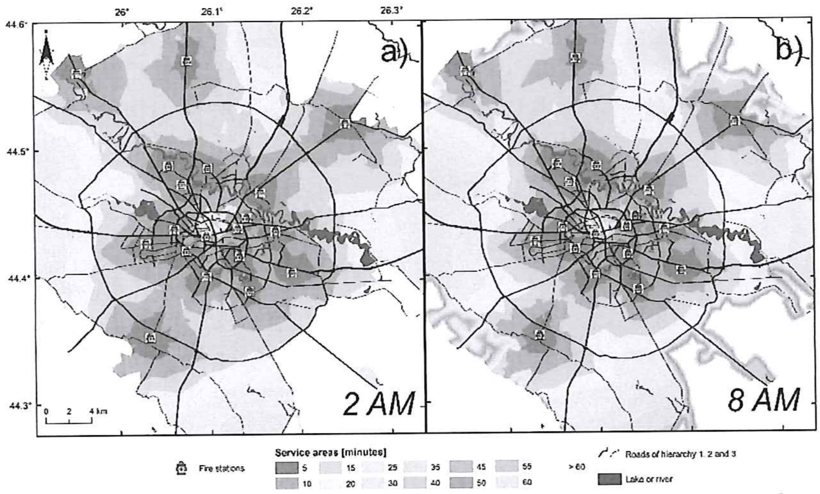

Figure 8 Maps showing Service Area times for fire stations, in post-earthquake conditions, for an earthquake occurring at 2 LT (a) and at 8 LT (b) on a typical weekday

In order to show the importance of safe routes for emergency intervention vehicles (such as the tramway line segments in Bucharest), we performed a Service Area analysis for the highly important emergency hospital Floreasca, located near such safe routes. Figure 9 shows the time-travel differences between using and not using these safe routes, for the earthquake occurring at 8 LT described earlier.

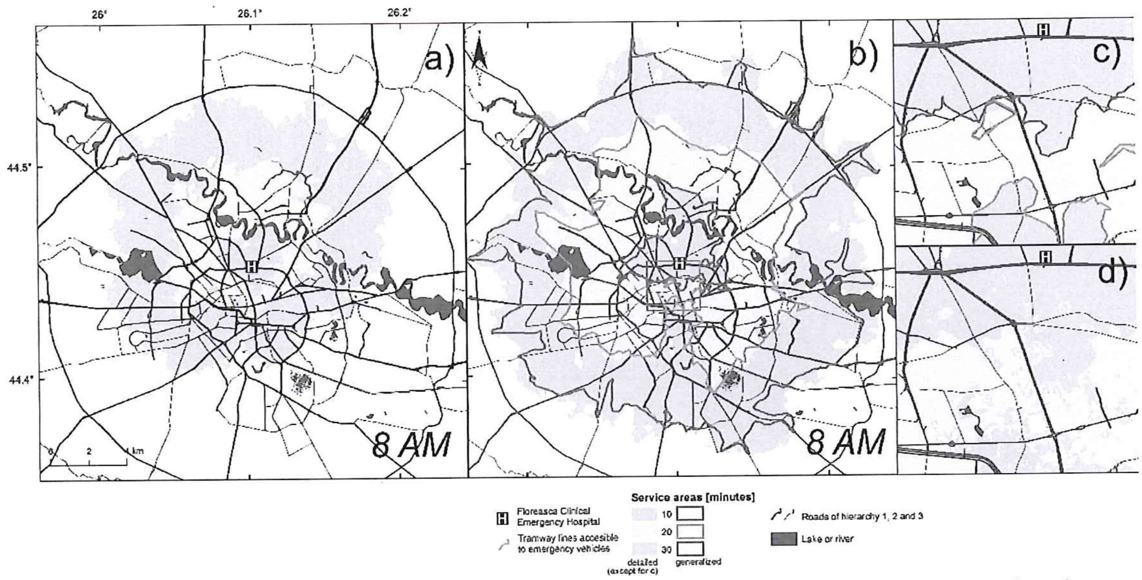

Figure 9 Maps showing service areas for the Floreasca Clinical Emergency Hospital, in post-earthquake conditions, for an earthquake occurring at 8 LT on a typical weekday, without (a) and with (b) the asphalted specially delimited tramway lines. The zoom maps show service areas polygons created by ArcGIS with the generalized (c) and detailed (d) option

As reflected by Figure 9, the generalization of Service Area polygons in ArcGIS smooths the shapes (and also improves the computational demands) but results fail to show small road segments becoming not accessible due to building debris and sudden increases in traffic values. For decision makers, an additional layer such as the one in Figure 6 should be overlayed.

Most vulnerable areas in case of an earthquake, due to limited connectivity, can be identified by service area analysis. Various emergency facilities and their characteristics can be considered (such as treatment capacity), but also considerations regarding second or third best available choices, as indicators of backup and resilience. Maps showing systemic resilience can be developed, using an index such as the one in Toma-Danila et al. (2020). In this study we however chose to present, in the context of time-dependent analysis, an example based on Closest Facility analysis and timeline graphs (Figure 10) for a highly representative area: Calea Victoriei, in front of the 95 and 101adjacent buildings with SRC I, which were affected by the 1940 and 1977 earthquakes and which are located in the city center, near many other vulnerable buildings. Both the area and representative routes can be seen in Figure 11.

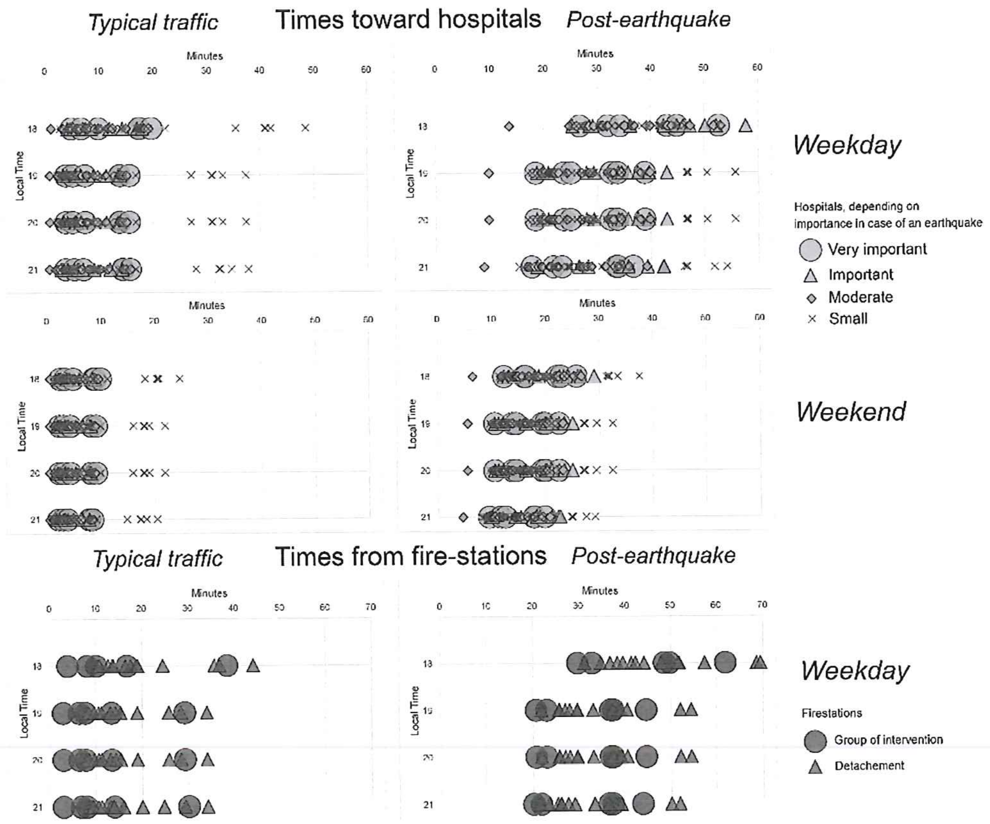

Figure 10 Graphs showing the time between the Calea Victoriei 95-101 location and hospitals and fire stations, for typical traffic (at 18 – 21 LT on a typical weekday and weekend) and post-earthquake traffic, for an earthquake occurring at 18 LT

Which would be the most important roads in emergency situations?

For identifying which are the most traveled road segments in order to provide the quickest access to facilities (we used in our analysis all hospitals), we recommend the following steps in ArcGIS:

- Perform Closest Facility Analysis on a greater than 1 number of facilities to find;
- Run the *identity* function, between road segments and results of the Closest Facility Analysis
- Perform a query to keep only common segments
- Run the *summary statistics* function in ArcGIS for counting how many overlapping segments exist
- Make a join between the road network and the resulted table to map the values.

For a demonstration, we considered for the analysis two representative locations as incident point: Calea Victoriei 95 – 101 (in the city center) and Iuliu Maniu Bd. 55 in the Militari neighbourhood, near the Veteranilor Market, an area not close to hospitals but where a high-rise building collapsed during the 1977 earthquake and others are on the AMCCRS lists. The first location is near inaccessible areas, still our analysis shows that, for our worst-case scenario, routes are available to all hospitals. Figure 11 shows routes critical (considering also hierarchy) for minimum access times to hospitals can be seen. For reasons of space, we did not differentiate or weighted depending on hospital importance, showing also second-best routes and a graph comparison such as in Figure 10, but the potential of this type of analysis can be seen. Some branches, with darker colours, are clear – indicating a route important for access to multiple hospitals. There are also similar routes between Figure 11 a and b; for multiple locations, a count of multiple routes would be very useful.

This procedure could be also relevant for multiple routes calculated between affected buildings and closest hospitals or fire stations, as it was done in Toma-Danila et al. (2020).

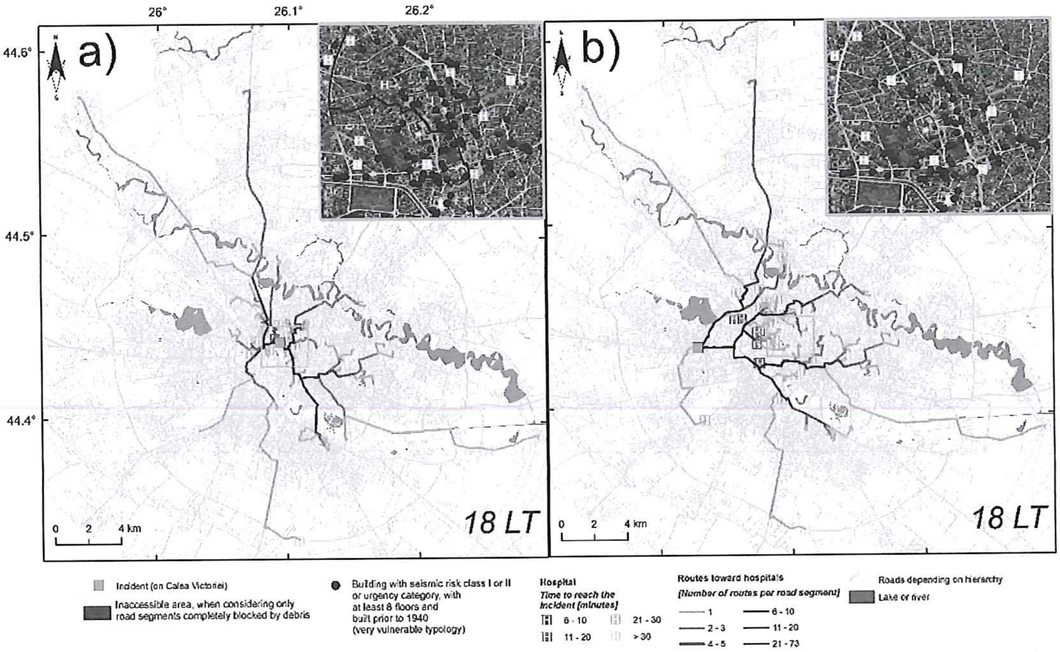

Figure 11 Maps showing safest and fastest routes toward hospitals, for two representative locations: Calea Victoriei 95 – 101 (a) and Iuliu Maniu Bd. 55 (b), in the case of an earthquake occurring at 18 LT on a typical weekday. Maps also show the number of roads overlapping per road segment.

Bridges, tunnels and passages are important structures which enable a fast connection, crossing or bypassing critical points. If these, due to direct damage or other incidents (such as accidents), would become unsafe, what would be the implications on travel times? By using route analysis, we tested what would happen in low traffic condition, without any other post-earthquake scaled costs, if the Constanta and Basarab passages would be closed. As mentioned earlier, these structures have a relatively high potential of disruption in case of an earthquake. It can be observed that minimal transit times increase greatly in the case of the Constanta passage (with more than 5 minutes and more than double the distance) – showing that this is a critical point. In the case of the Basarab passage, there are more than 2 minutes of extra time; also, multiple routes, slightly higher in times, are available given the greater density of roads. However, post-earthquake traffic and the first-hours chaos could greatly increase the times.

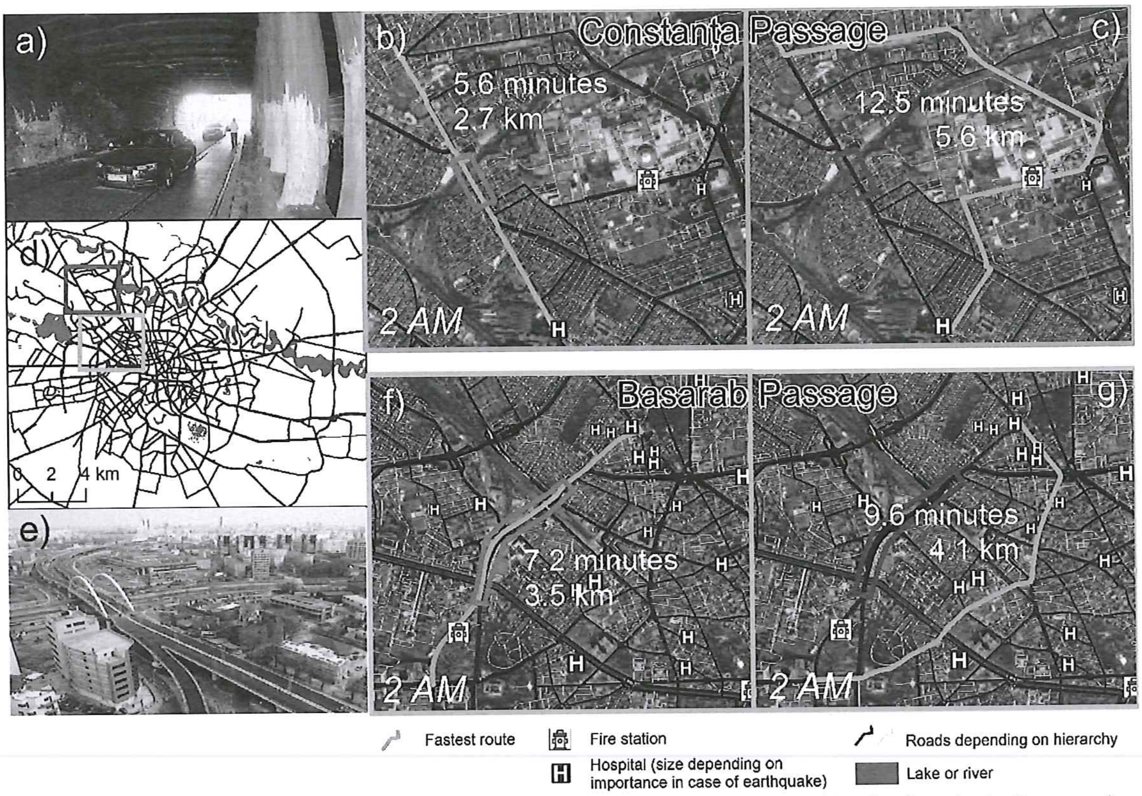

Figure 12 Maps showing the time between representative points, when connected by the Constanta Passage (a, b) and Basarab Passage (e, f) and not connected by these structures (c and g), in no earthquake conditions, at 2 LT on a typical weekday

Discussion

Scenarios for decision-based risk mitigation measures can be tested using our framework: imposing of traffic restrictions, opening or reopening of specific road segments (at different times after the earthquake) considering also for example expert-based evaluation of the process of post-earthquake structural safety inspection.

Our results can contribute to the development of systemic vulnerability functions reflecting for example the delay potential in case of various earthquakes or functions reflecting hospital resilience (for example, for various time windows and earthquake loss scenarios, a function reflecting the number of patients, considering travel times). These could be developed in future studies, although due to the complexity of the modeling and the multiple sources of uncertainty, as well as the continuously updating input data, we think that the scenario-based approach presented in this paper can be more suitable for emergency management planning and in near-real time situations.

In order to enable near-real time implementation, it would require to embed (preferably automatically) in our framework:

- Real traffic data, from providers such as Waze or from monitored emergency vehicles.
- Continuous updates of affected areas and how many emergency vehicles and of which type they require (can be also taken by drones).
- Continuous updates regarding hospital number of patients.

For time-dependent and real-time data integration capabilities, additional challenges can arise:

- **real data, regarding affected buildings and infrastructure or traffic incidents, continuously updates**, therefore new information must be easily integrated; this data can also refer to the evolution of rescue activities and need of additional forces on sites, results of rapid structural inspection, repair works and their evolution, emergency facilities lack of functionality etc.
- **no data doesn't necessarily mean that the situation is good**; in earthquake situations for example, the "doughnut effect" (Bossu et al., 2017) should be accounted for, otherwise less affected areas could be prioritized for intervention in the detriment of severely affected areas.
- **multiple sources of data need to be easily transferable in a network-modeling system**; for example, in case of traffic data, different road datasets not joinable with between them (and a mistreating of from-to and to-from data) can lead to wrong travel times.
- **computational demands for complex network models could be extensive**, therefore a selection of computational time-effective performance indicators needs to be performed.
- The impact of management actions (such as building instrumentation, mobile hospital deployment or establishment of dedicated emergency intervention routes) should be considered both in simulation and in real time.

Which would be the hospitals in high demand?

Some hospitals, due to their location close to affected areas but also due to treatment capacity and acknowledgment in the mental perception of citizens could be, in the first hours after an earthquake, much more crowded than others. This would be the case of the Floreasca and University Clinical Emergency Hospitals, which are both renowned institutions in emergency medicine and close to the city center. As Figure 9 shows, Floreasca Hospital (but also disaggregated data of Figure 7 for both hospitals) has a relatively good time coverage of all of Bucharest for the considered scenario, meaning that within an hour or two after the earthquake it could become overcrowded. Also, central locations such as Coltea Hospital would be highly busy – given the adjacency to the vulnerable city center and many hard-to-reach areas. In this area, the installation of a mobile hospital would be a good option and our type of analysis can and has served to the identification of reliable locations (Armas et al., 2020).

Given that in the western part of the city there are no hospitals with at least moderate importance capabilities in case of earthquakes (with higher reach time as shown by Figure 7), the need to build a hospital in this area is major, considering also the high seismic loss estimates shown in Toma-Danila and Armas (2017) and the multiple vulnerable buildings shown especially in the Militari neighbourhood in Figure 4.

Conclusions

In the last years, multiple studies have started to analyze the direct and indirect implication of earthquakes on road networks, with a focus on the emergency intervention travel times between hospitals and affected areas. However, not many of them accounted for the time-dependent evolution of the situation, setting also premises for near real-time implementation. In this article we make steps forward, creating and testing a flexible framework which relies on already available and widely used GIS software (ArcGIS with Network Analyst extension). The framework links various relevant aspects reflected by previous studies but also in real situations, such as traffic issues in post-earthquake situations, the impact of building debris on road networks but also characteristics of emergency facilities such as hospitals – important to consider as also reflected by the COVID-19 period and important in order to address the resilience potential. By using traffic profiles, scaled costs and restrictions to influence the typical traffic times we showed an easier yet satisfactory way of incorporating evolutionary traffic modelling and road blockages in the analysis.

As showed in this article, some of the outcomes of our framework, especially when implemented in near-real time, are:

- Play an important role in post-earthquake traffic management, indicating roads that need to be accessible and areas where police intervention is needed to allow a decrease of travel times between affected areas and vital hospitals.
- Let rescuers know which hospital they should send victims and on which route.
- Play a role in decision making, enabling the understanding of which hospitals to upgrade and where to place mobile hospitals not just in terms of adjacency to affected areas but also considering easy access to it.

Results will contribute to a better National Conception for Post-Earthquake Response, indicating the actual risks due to high travel times in emergency situations but also aspects to consider for reducing these risks: the need of consolidation (for residential buildings but also for hospitals and infrastructure elements), of traffic management and of increased capacities for vital hospitals or the building of new facilities in specific areas (such as western Bucharest).

Given that the risk of Bucharest is significant but not easy to evaluate, also due to limited data available, we provide through this study also relevant GIS datasets regarding roads (based on OSM data), hospitals and fire stations. Also, through the version 2 of the Network-Risk toolbox (Toma-Danila and Tiganescu, 2021) we introduce a partially-automated and rapid methodology for the conversion of this data in ArcGIS format, which will facilitate the implementation of our analysis in many other case study areas.

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