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Assessment of a city's performance under different earthquake scenarios

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Abstract

The seismic performance assessment of an urban system can help raise awareness and improve a community's preparedness for extreme earthquake events. Addressing this issue, the authors' first attempt at a quantitative evaluation of a city's performance in the event of an earthquake is presented in this paper. The assumed city model comprised of four main urban components (buildings, transportation infrastructure, social community, and open spaces) takes into consideration their relationships and interactions. A set of preliminary analyses on the test model were performed using the GIS tools and graph theory. The analysed model was generated based on the combination of real (city layout, buildings' heights and footprints, road network configuration and length) and fictitious data (earthquake scenarios, structural fragility of the investigated building stock, the use of a building, etc.). In the main part of the study, several scenarios of possible earthquake events with various degrees of intensity and with different locations of damaged buildings were considered, and the assessment of a city's performance in terms of connectivity and accessibility (the graph theory measure of global efficiency) was carried out. The impact of building debris on the roads as a result of the earthquake damage and/or the collapse of nearby buildings and their non-structural components was included in the analysis as well by applying the measure of a building's impact radius and assessing the road traffic disruptions. Furthermore, certain practical results in relation to the analysed urban system were taken under observation and are discussed in the paper (travel time, affected population when considering the day-/night-time scenarios, etc.). The proposed framework has proven to be a viable tool for identifying network weaknesses and quantifying the loss of the city network functionality.

Key words: urban system modelling, earthquake scenarios, city performance assessment, GIS, graph theory

1 Introduction

A city's performance depends on the properties of a complex urban system that direct urban growth and development. However, due to various dangers that threaten a city's performance, lasting prosperity cannot be fully guaranteed without enhancing the overall urban resilience. Despite the low probability of a severe earthquake event, the consequences could be fatal in terms of casualties, economic loss, and downtime. Moreover, as an earthquake is a rare event, society is unable to develop an adequate perception of seismic risk before a major earthquake occurs [1], which has been further substantiated by recent events in Zagreb and Petrinja [2, 3]. In order to avoid the worst-case scenarios and limit the extent of damage, more attention must be paid to raising public awareness of the importance of risk reduction and increasing the seismic resilience of urban systems.

A comprehensive assessment of a city's seismic performance should capture the complexity of an urban system including its main components (buildings, transportation infrastructure, social community, and open spaces) and the interactions between them [4]. Therefore, a city's performance cannot be evaluated using one single measure; it is supposed to include several approaches and indicators of seismic urban performance which can be observed in scientific literature [5]. Studies on seismic fragility of buildings and critical elements of road infrastructural facilities (e.g. bridges) are based on nonlinear methods for seismic analysis of structures. For the performance assessment of an entire infrastructural network, criteria and algorithms of graph theory are commonly used [6, 7]. The social vulnerability index, SoVI [8], serves as the basis for several studies on social community resilience [9, 10]. Despite the recognized importance of open space for the seismic resilience of cities, a lack of quantitative research into its influence on the resilience of the entire urban system in case of an earthquake could be observed [11]. Combined qualitative and quantitative approaches are commonly applied when assessing the impact of open spaces on urban seismic performance [1, 12, 13].

The challenge of further research is to assess the seismic performance of a socio-spatial system as a whole while considering the interactions between different urban networks [4]. Different risk indices attempt to comprehensively evaluate an urban system; however, despite addressing different components, they fail to capture the interactions between them. The impact of buildings on the transport infrastructure network in the form of the impact radius of adjacent damaged buildings is presented by Argyroudis et al. [14, 15]. The comprehensive treatment of urban seismic resilience is tackled by studies that consider the urban system as a network and evaluate its performance quantitatively by using graph theory indicators and algorithms. Such an approach is utilized by Cavallaro et al. [16], who model the city as a hybrid social-physical network (HSPN). HSPNs represent a model featuring a mathematical graph from various points (buildings and their inhabitants) and (transport) connections between them. The measure of global efficiency [17] evaluates the functionality of the system based on the relationships between the individual elements, but it fails to take into account the overall health of the system in terms of the quantity and quality of these elements. To address this issue, the purpose of the presented preliminary study performed on the assumed test model was to test different measures and indicators in order to comprehensively assess the seismic performance of an urban system.

2 Description of the assumed city characteristics

The assumed model of the investigated urban system comprised of four main urban components refers to the layout of the selected part of Ljubljana (Figure 1). For the purpose of this research, which is essentially a study of feasibility of graph theory algorithms and GIS applications for a comprehensive city performance evaluation in the case of an earthquake event, the model was generated based on the combination of real (city layout, buildings' heights and footprints, road network configuration and length) and assumed data. As the aim of the study was not to assess a particular area of the city, most of the data were defined fictitiously (structural fragility of the investigated building stock, the use of a building, the road network category, the number of inhabitants, etc.) in order to focus on the investigated methodology and avoid time-consuming data compilation. All quantities of urban components in the initial (non-seismic) state are presented in Table 1, 3rd column (S0).

Figure 1. Four main urban components of the test model based on real, semi-real and assumed data

Factual data in relation to the buildings and road infrastructure, which are easily accessible on-line, were obtained from the Surveying and Mapping Authority of the Republic of Slovenia (GURS) and the Open Street Map (OSM) databases. The obtained data regarding the building stock were fragmented to reflect various building areas and subsequently simplified by merging different building parts into one single unit when they were in contact and of similar height. Factual data in relation to the building stock include building footprints and heights and serve as the basis for calculating the data in connection to the area, for instance the number of floors and users. For all four considered types of buildings (Figure 1), the structural material, the age of construction, and the type of structural system were assumed. The seismic fragility of buildings was classified into four categories (i.e. fragility classes) which coincide with the assumed seismic scenarios (see Section 3). The fragility classes were evenly distributed across the building stock (Figure 2), taking into account the centrality of the nearest road connection [18] and the height of buildings. Buildings of medium height adjacent to the road connections with moderate centrality were associated with higher seismic fragility. Each building type was assigned a value of importance (V_i) (see Eq. (6)), which plays a crucial role for a city's efficient performance (Figure 1). The buildings were classified according to their type as important buildings (health care facilities and rescue stations (V_i = 5), government and administrative facilities, educational facilities and shops selling essential goods (V_i = 4), sports, cultural, and religious buildings (V_i = 3)), residential buildings (V_i = 2), or ancillary (V_i = 0) and other buildings (V_i = 1).

The factual transportation infrastructure data cover the configuration of road network and the calculated length of individual segments. Road categories (1, 2, 3), their width (20, 15, 10 m respectively) and average travel speed (30, 20, 10 km/h respectively) in normal conditions were assumed depending on the location in the road network (Figure 1). Four bridges included in the model are also regarded as built facilities with assumed seismic fragilities, while road traffic disruptions due to earthquake damage to the adjacent buildings were analysed as part of each seismic scenario.

The complex structure of the social community depends on several uncertainties regarding the current location of the population. In this study, social community was modelled according to the number of users of an individual building and was, therefore, composed of citizens (i.e. users of residential buildings) as well as other users, including daily migrant workers, weekly visitors, or seasonal tourists. As the data regarding the number of inhabitants in individual buildings are not freely available, an assumption was made on the basis of the average value per square meters of the total floor area (1 inhabitant/30 m^2) [16]. Total capacity of the system provides the maximum possible number of all people located at any given time in all buildings included in the system, whereas the capacity of residential buildings represents the number of residents. As this is a purely theoretical situation, a realistic scenario should consider the fact that a great portion of inhabitants and other users is located outside, in open spaces. Therefore, day-time and night-time scenarios were adopted to allocate the citizens and visitors. It was assumed that during the day, 20 % of people were at home, and 80 % of important and other buildings were occupied, while at night-time, residential buildings were 98 % occupied, and important/other buildings were 1 % occupied. Percentages only reflect the occupancy of a particular type of building and cannot be summed into a total number of inhabitants.

When an earthquake occurs, open spaces usually stay intact and may, therefore, serve as safe places for the evacuation of the affected population. Moreover, they can provide spare capacity for system recovery and have the potential for transforming a city into a more resilient urban space. However, not all open spaces are suitable to be used as evacuation sites or temporary shelters. The most important factors when choosing the safe places for evacuation or shelters are their capacity, open space infrastructure, its natural features, and accessibility as the proximity of home is crucial for the affected people [9]. The capacity for emergency evacuation must comply with the required 1 refugee/3.5 m^2, while the capacity for temporary settlements is supposed to be 1 inhabitant/45 m^2 [19], which includes roads and communal infrastructure as well. In the presented study, the capacity requirements for temporary settlements were decreased to 1 inhabitant/15 m^2 as we used smaller open spaces to address evacuation and recovery needs and assumed that communal infrastructure was still available for use.

3 Mathematical modelling and earthquake scenarios

For a comprehensive city performance assessment, the test model comprised of the aforementioned urban components was created in the GIS environment. A city's performance includes the overall health of the urban system and its efficiency in terms of connectivity and accessibility of different urban functions. For calculating the global efficiency, a graph model of the selected urban system was generated. According to graph theory, a mathematical graph is composed of nodes (vertices) and connections (edges). Therefore, every element of a building's component was transformed into nodes by applying the GIS centroid creation function. After that, all building nodes were connected to the nearest (orthogonal) road connection to create a mathematical graph model (Figure 2a). The same process was repeated when creating a graph model of open spaces and buildings. In graph theory, one of the most popular algorithms refers to the shortest path between individual elements, which is also the basis for the betweenness centrality and the global efficiency measure (Eq. (2)) [11]. Betweenness centrality indicates the importance of individual connections or network intersections by calculating the shortest paths that run across the considered connection or intersection (Figure 2a) [18]. In the present study, different variations of global efficiency (i.e. global efficiency of all buildings (GE), global efficiency between residential and important buildings (GE_{RIB}), and global efficiency between residential buildings and open spaces (GE_{RBOS})) were calculated using the Wolfram Mathematica software. In order to complement the measure of global efficiency, the indicator of "richness", which includes some specific values of overall health, is proposed by Eq. (6). When considering a specific component, e.g. buildings, every building was evaluated according to its capacity (i.e. the number of users) and value, which refers to the type of use (see Section 2).

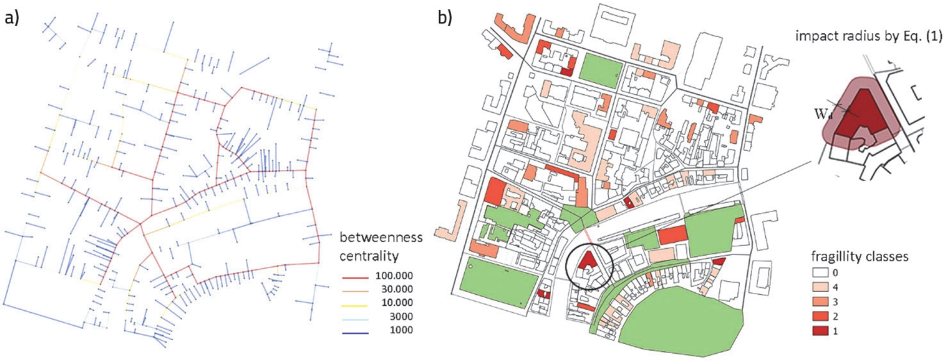

Figure 2. a) Graph of the analysed city area with the betweenness centralities of road connections; b) Fragility classes of bridges and buildings with their impact radii

Four scenarios (S1-S4) of possible earthquake events with regards to the intensity and location of damaged buildings were assumed, while the initial state of the model prior to an earthquake represents the scenario S0. In each scenario according to the associated seismic fragility, certain buildings were presumed to be seriously damaged and unsafe for use. For instance, in seismic scenario S1 with the lowest intensity, only buildings in the category of seismic fragility 1 were affected (i.e. collapsed or unsuitable for safe use), while in seismic scenario S2, buildings of seismic fragility 1 and 2 were affected, and in seismic scenario S3, buildings of seismic fragility 1, 2, and 3 were affected. In the S4 scenario featuring the highest intensity, only buildings in the category of seismic fragility 0 remained unaffected. Affected buildings have an impact on the nearby road connections measured by the impact radius (the estimation of the collapsed building debris). It was calculated for each affected building according to the simplified relation (model B) proposed by Argyroudis et al. [14]:

$$W_d = \sqrt{W^2 + \frac{2 \cdot k_v \cdot W \cdot Y}{\tan c}} - W \qquad (1)$$

where W_d is the debris width that is extended further than the initial width of the building (W), k_v is the ratio between the collapsed volume (V_t) and the original volume (V_o) of the building, Y is the building height, and c the inclination of the collapse. In this study, the values $k_v = 0{,}3$ and $c = 30°$ were used for all buildings. The impact radius of the affected buildings also includes non-structural damage to buildings (e.g. falling façade elements) as this is a significant factor in building resilience when a slight structural damage occurs. In the GIS environment, after calculating the impact radii of affected buildings, the analysis of the impact radius on the adjacent road connections was performed. Where more than 50 % of a road connection was covered by the building debris, the connection in question was regarded as being interrupted. If the connection was covered between 0 and 50 %, it was assumed to be merely disrupted, meaning that the travel speed was reduced by half.

To evaluate the performance of the test model under different conditions, the described analysis was carried out for every seismic scenario. In addition to the global efficiency and the overall health of the system, certain practical results were analysed. These include the shortest path to the hospital (or other important buildings of choice), the affected population considering day-/night-time scenarios, and the use of open spaces for evacuation and recovery purposes.

4 City performance assessment

The core of the research was the city performance assessment on the basis of the assumed urban model described in the previous sections. The overall health was evaluated on the basis of four basic urban components and their elements' properties (Table 1). The type and number of affected buildings in each seismic scenario were determined according to seismic fragility, while impairment of other components depends on the affected buildings and their impact radius. It was presumed that the open spaces remain unaffected. Four scenarios ranging from the S1 with minimal loss (only 1,3 % of the entire building stock was affected) to moderate earthquake intensity (S2 and S3) and a severe earthquake event causing extensive damage to the built environment (S4) were analysed and compared to the initial state (S0). A 15 % decrease in the number of built structures was observed in the most devastating scenario (S4), while other two affected components, road infrastructure (a 25 % decrease) and social community (a 30 % decrease), suffered an even greater loss (Figure 3a). It turned out that the impact on the population was significantly greater than just the loss of buildings, which depends on the selected type of buildings, their total floor area, and the fragility class. Nevertheless, regardless of the scenario choice, the loss of interdependent components tends to increase substantially.

Moreover, day- and night-time scenarios, which consider the number of people present at a given time, were analysed as well (Figure 3b). The numbers of unaffected people were lower than the total capacity of all buildings as the same residents are either at home, in important/other buildings, or in open spaces. Daily migrations to as well as outside the considered system were also taken into account. Differences between day- and night-time scenarios are dependent upon the selected type of the affected buildings as during the daytime, more people would be affected at work, while at night, more victims are expected in residential buildings. Consequently, the number of people who were left homeless has a strong correlation with the night-time scenario (see the overlapping curves in Figure 3b). The affected population needs a space that can be used for evacuation purposes and temporary shelters, and this is where open spaces can be utilised (Figure 3b). In scenario S1, one open space (OS1) (see Figure 1) can be sufficient for meeting all the needs of the affected residents. Two open spaces (OS1 and OS2) are needed to accommodate all refugees in scenario S2. In the event of more severe earthquakes (S3 and S4), all open spaces must be included in the process of evacuation and recovery of the affected urban system. However, not all open spaces are equally appropriate. Therefore, further studies should include a comprehensive qualitative and quantitative evaluation of the open spaces to predict the most effective recovery scenarios.

Table 1. Basic values of main urban components representing the overall health of the city and their changes in different seismic scenarios

Urban components		S0	S1	S2	S3	S4
buildings	total buildings	369	364	354	338	314
	important buildings	20	20	19	16	15
	residential buildings	226	221	212	201	181
	ancillary and other buildings	123	123	123	121	118
road network	total network [m]	6605	6284	6122	5805	4921
	category 1 [m]	1760	1760	1705	1634	1541
	category 2 [m]	2272	2093	1986	1790	1293
	category 3 [m]	2573	2431	2431	2385	2087
social community	total capacity	29163	28751	27163	25372	20502
	day-time scenario	14658	14575	14037	13160	10453
	night-time scenario	14316	13913	12965	12051	10084
open spaces	used for evacuation	0	OS1	OS1	OS1	OS1-OS2
	used for temporary shelters	0	OS1	OS1-OS2	OS1-OS5	OS1-OS8
	area for temporary shelters [m^2]	0	10794	21042	34636	130080

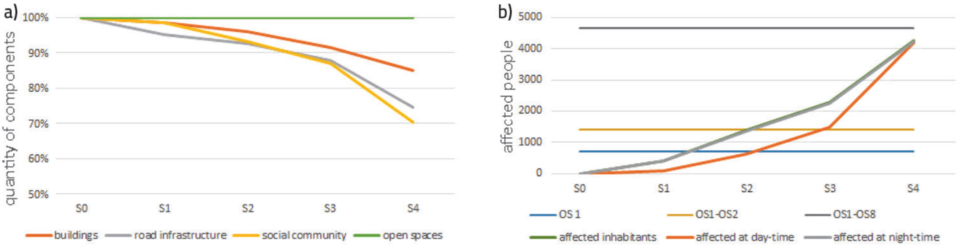

Figure 3. a) Urban components' quantity variations through all analysed seismic scenarios; b) Requirements of the affected people vs. open space capacities for temporary settlements

To assess the performance in terms of mutual accessibility of urban elements, the measure of global efficiency (GE) was adopted and supplemented according to the aforementioned needs. Three variations of GE were analysed, the basic GE, GE_{RIB}, and GE_{RBOS} (see Section 3):

$$GE = \frac{1}{N\left(N-1\right)} \sum_{i \neq j \in N} \frac{1}{d_{ij}} \tag{2}$$

$$GE_{RIB} = \frac{1}{RB \cdot IB} \sum_{\substack{i \neq j \\ i \in RB,\, j \in IB}} \frac{1}{d_{ij}} \tag{3}$$

$$GE_{RBOS} = \frac{1}{RB \cdot OS} \sum_{\substack{i \neq j \\ i \in RB,\, j \in OS}} \frac{1}{d_{ij}} \tag{4}$$

where N is the total number of all buildings and d_{ij} is the shortest path between a pair of nodes (lengths in [m]), RB is the number of residential buildings, IB denotes the number of important buildings, and OS is the number of open spaces.

As shown in Figure 4a, all three variations of GE revealed a sharp drop in efficiency, between 50 % and 65 %. On the other hand, the measure of global efficiency between residential buildings and open spaces GE_{RBOS} indicates a slight increase of efficiency in scenario S1. According to its definition, GE takes into consideration the relationships between all pairs of nodes in the system but does not address the "overall health" in terms of quantity and quality of these elements. If some of the buildings collapse in an earthquake, their nodes are excluded from the graph and not considered in the evaluation, which could, in some cases, result in improved connectivity between the remaining nodes. Therefore, the authors' proposal is to upgrade the basic global efficiency measure by taking into account the additional factor of "richness", which considers the overall health of the system as well. To address this issue, all three variations were supplemented using the factor of "richness" (r) (see Eqs. (5-6)), which tends to prevent such anomalies (Figure 4b):

$$GE^{+} = \frac{1}{N\left(N-1\right)} \sum_{i \neq j \in N} \frac{1}{d_{ij}} r_{all} \tag{5}$$

$$r = \sum_{i \in N} V_i U_i \tag{6}$$

where r_{all} represents the richness of all buildings, V_i is the value of an individual building (see Section 2), and U_i denotes the number of users of the building.

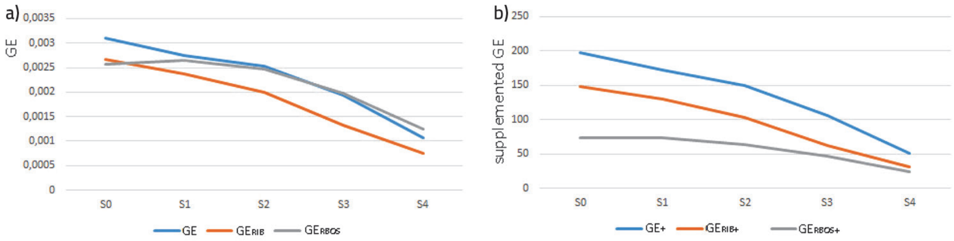

Figure 4. A city's performance for each seismic scenario in terms of variations of: a) basic global efficiency (GE) measure; b) supplemented GE

The presented model also enables us to carry out certain targeted analyses with practice-oriented results. In an emergency situation, the accessibility to critical infrastructure, such as hospitals or rescue stations, is crucial. To evaluate the accessibility of a selected important facility, the analysis of the shortest routes was performed (Figure 5). According to the estimated extent of collapsed building debris, the complete as well as partially disrupted connections were taken into consideration to identify the fastest route and calculate the shortest travel time. Since the analysed area is relatively small and compact, the travel times where the connections are functioning are short enough to allow for an efficient provision of emergency aid. When assessing a larger urban area, it would be recommended to consider a 15-minute city concept [20] even in the phase of emergency following a catastrophic event.

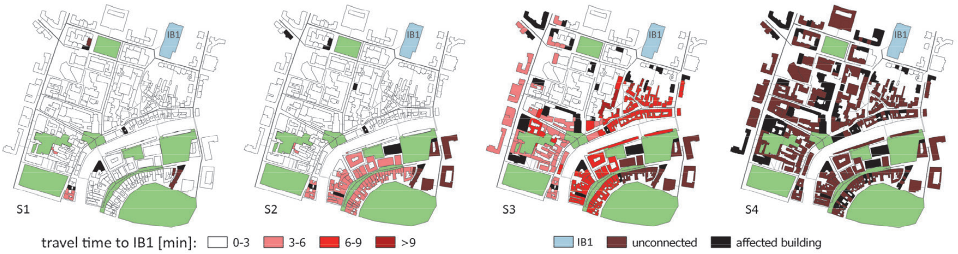

Figure 5. The shortest travel time from each building to a selected important building (IB1) in scenarios S1-S4

5 Conclusions

A preliminary study of an assumed urban system's seismic performance assessment was presented in this paper. The aim of the study was to test measures and indicators as part of a comprehensive evaluation that includes the overall health (i.e. the quantity and quality of individual components) and global efficiency of the assumed city model. This study serves more as a demonstration of the proposed methodology and its potentials for seismic resilience assessment than an actual case study with realistic results that may be applied as part of risk mitigation strategies.

The proposed framework has proven to be a viable tool to identify network weaknesses and quantify the loss of city network functionality. It has turned out that a relatively small proportion of collapsed buildings results in a significant loss of functionality, which further increases the importance of prevention and preparedness of an urban system for severe seismic events. However, in light of all the applied limitations, the model needs further development. As the limitations of global efficiency have been recognized in previous studies [16], a supplementation in terms of the correction coefficient (*r*) was suggested in this paper, serving merely as a form of preliminary research that needs to be continued and improved. For example, further study on open spaces evaluation and the assessment of their interaction with residential buildings is planned. Finally, the proposed model should be implemented in a real case study using realistic data and circumstances.

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