

Proposal for Holistic Assessment of Urban System Resilience to Natural Disasters

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Abstract. Urban system is a complex mix of interdependent components and dynamic interactions between them that enable it to function effectively. Resilience of urban system indicates the ability of a system to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner. In the relevant literature, most studies consider individual components separately. On the other hand, the purpose of this paper is to assess the urban system as a whole, considering all relevant components and their interactions. The goal is a study of possibilities for holistic evaluation of urban system resilience to natural disasters. Findings from the preliminary study are presented: (i) the definition of urban system and categorization of its components, (ii) a set of attributes of individual components with impact on disaster resilience of the entire system and (iii) review of different methods and approaches for resilience assessment. Based on literature review and extensive preliminary studies a new conceptual framework for urban resilience assessment is proposed. In the presented paper, a conceptual model of urban system by abstraction of its components as nodes (buildings), patches - specific nodes with spatial properties (open space), links (infrastructures) and base layer (community) is created. In the suggested model, each component is defined by its own quantitative attributes, which have been identified to have an important impact on the urban system resilience to natural disasters. System is presented as a mathematical graph model. Natural disaster is considered an external factor that affects the existing system and leads to some system distortion. In further analyses, mathematical simulation of various natural disasters scenarios is going to be carried out, followed by comparison of the system functionality before and after the accident. Various properties of the system (accessibility, transition, complexity etc.) are going to be analysed with graph theory. The final result is going to be an identification of critical points and system bottlenecks as basis for further actions of risk mitigation.

1. Introduction

Natural disasters are periodically recurring adverse events. In case of natural disasters, not only structures and their users but also a performance of the entire system is affected. Destructive effects of extreme natural events cannot be fully prevented as it is difficult to influence their occurrence. On the other hand, it is possible to be prepared for them by trying to partially prevent or at least mitigate their effects. Sufficiently prepared urban system is capable of maintaining the basic system performance in time of an extreme event and also of enabling a quick and efficient recovery of the entire system immediately after it.



The term 'resilience' derives from the Latin word 'resiliere', which means to “bounce back” [1]. The concept was first put forward in the science of mathematics and physics, where indicates the capability of the material or system to return into the balance after being displaced [2]. Later, the use of the term spread to other scientific fields (ecology, materials science, psychology, economics and engineering). The United Nations generally defines the concept of resilience as the ability of system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, through the preservation and restoration of its essential basic structures and functions [3]. In the field of architecture and urban planning Godschalk [4] defines a resilient city as a sustainable network of physical systems and human communities, capable of surviving and functioning under extreme stress.

Most current investigations are focused on the socio-economic vulnerability of the urban system [3, 5–9] or structural weakness of its physical components [10–16]. On the other hand, there are few studies that treat the urban system as a whole. Most of them are offering conceptual framework with guidance towards a more resilient urban system without concrete tools and methods for assessment of resilience [4, 17]. Duzgun et al. [18] offer a vulnerability assessment of multiple urban components (community, buildings, accessibility to critical services) individually but do not include their interactions. Carreño et al. [7] and Salgado-Galvez et al. [8] propose composite risk index including different parameters but ignore transportation networks and system connectivity.

The purpose of this paper is to assess the urban system as a whole, considering all relevant components and their interactions. The main goal is a study of possibilities for holistic evaluation of urban system resilience to natural disasters by extensive literature review. The paper tends to answer the following research questions: What is an urban system and what are its components? Which components influence the urban resilience the most? What are the attributes of individual components with impact on the urban system resilience to natural disasters? How to assess the resilience of the entire urban system?

2. Urban system and its components

Complex urban system is composed of interdependent networks formed of different physical and social urban components. There are dynamic interactions between individual components that enable efficient system performance [4, 17]. Physical components act as the body of the system, its skeleton, veins and muscles. Social components function as the brain of the city, directing its activities, responding to its needs, and learning from its experience [4].

Open space is an important component that influences the resilience of urban system [8, 19, 20, 21]. Urban streets, road connections, squares, parks, etc. represent the space for activities and urban processes, consequently enabling the functionality of the urban system. Large open spaces within the urban fabric, the so-called “urban voids” (e.g. vacant land, river and lake edges) that are unsuitable for the construction and loosely programmed represent essential resources and reserves in the case of a disaster. Despite the fact that some studies recognize their importance, there is a lack of research of their impact on the resilience of the entire system.

Urban system can be described in several ways, depending on the importance of individual components. In this initial phase of our research, we propose the division of the urban system on the four basic components, which significantly affect the resilience of the system in the event of natural disasters (figure 1): buildings, open space, infrastructure and community. Buildings are physical skeleton of the urban system that is united in the whole by open space and powered by infrastructure. Finally, community is a lifeblood and a soul of the system. However, it should be noted that the proposed division could be spread by additional component(s) depending on the aim and priorities of the urban

system analysis. The authors of the current paper agree that the whole relevant urban content could be captured by the proposed four components.

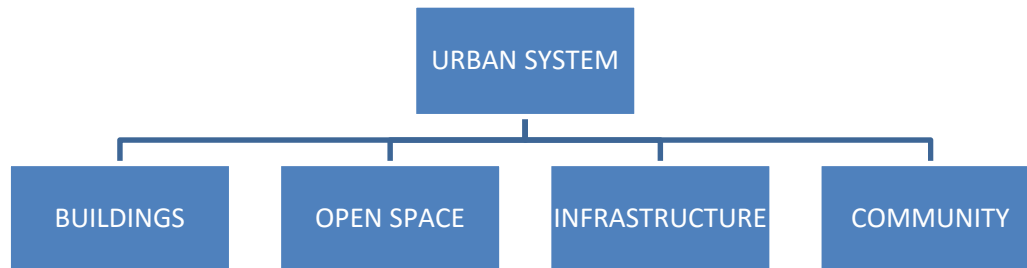


Figure 1: Proposed division of the urban system

Not all disasters have the same effects on the urban system. Different types of disaster have different impact on each component. For example, a 19th-century 5-storeyed building with masonry structure and without basement could be extremely vulnerable to earthquake, but could suffer no significant damage in the case of inundation. Therefore, specific attributes for individual components dependent on the type of natural disaster should be used. In this paper, the focus is placed on severe seismic motion. According to this, a selection of attributes for each component is proposed.

2.1. Buildings

In the proposed concept, buildings are divided in two subcomponents: key important facilities (emergency, health care, administrative facilities, buildings of public services and supply, economic, educational, cultural and sports facilities) and other buildings. Not all buildings are of the same importance for the urban system resilience to natural disasters. As the name says, key important facilities have greater impact on urban resilience than other buildings. But there are also differences among key important facilities. They could be ranked by relevance to emergency response or system recovery. Emergency and health care facilities are recognized as the most important in the phase of response (especially for protection of human lives) immediately after the disaster occurrence. Administrative facilities, buildings of public service and supply, economic and educational facilities are important in a phase of preparedness and recovery. Cultural and sports facilities are recognized as important for system performance but not critical in the phase of emergency response and recovery. However, very important cultural facilities are also the historic and architectural heritage buildings, which are often particularly vulnerable to natural disasters (e.g. earthquakes) and thus a special attention should be paid to them [22, 23].

There are several building attributes that influence the resilience. In our proposal, they are classified into three categories: capacity curves, spatial characteristics and building characteristics. A capacity curve (in earthquake engineering literature also often called a pushover curve) provides information of a structural capacity which depends on building structural system, structural material, stiffness, number of storeys, building's height, age of structure, etc. It provides representation of both the displacement and the force capacity of a building in terms of roof drift and base shear, respectively. Using simple concepts in structural dynamics the quantities could be transformed into spectral displacements (S_d) and spectral accelerations (S_a) (figure 2). Additionally, in order to reduce the computational effort, the actual capacity curves could be idealised (in multi-linear curves). Once the capacity curve for selected building is calculated, the seismic response of the analysed building could be simply assessed in terms of demand displacements and forces, ductility demands, damage states etc. For the seismic structural damage measure, several damage indices can be found in the relevant literature. The main idea of describing the state of damage of the structure by a damage index is to combine the cumulative and spread structural damage into just one number on a defined scale.

Spatial characteristics are site conditions, distance to the nearest buildings, plot ratio, free area percentage, etc. Buildings characteristics are type of foundations, having basement or not, being waterproof or not, having green roof or not, program or use of buildings, time dependant occupancy, etc.

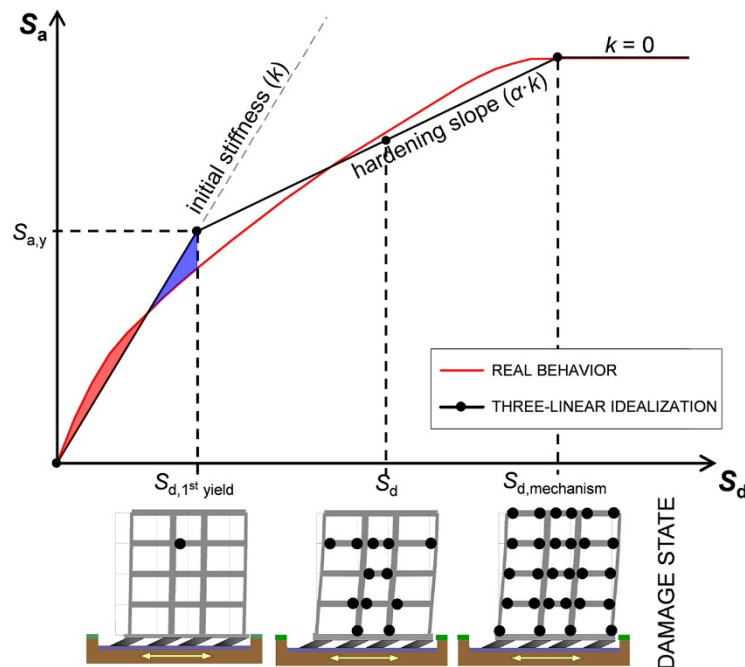


Figure 2: Actual and idealized capacity curve of base-isolated structure [24, 25]

2.2. Open space

Green surfaces (parks, tree avenues, gardens, urban forests, water surface and arable land), built surfaces (squares, street surfaces) and undeveloped areas are forming an open space between buildings. It could have positive or negative influence on urban resilience depending on the type of natural disaster. In the case of earthquake occurrence open space represents a place for evacuation and essential resources for recovery process. It is a space of movement and continuing processes, which enable enhancement of system performance after a disaster. An extreme earthquake could affect open space by soil liquefaction or earthquake faults, but usually it has no direct impact on open space. Damaged or collapsed buildings could affect the quality of open space and impair the connectivity of the system. On the other hand, open space could be severely affected by inundations. Unregulated water surfaces represent a risk for other urban components and for the entire system.

Open space attributes that influence the resilience to natural disasters are: site conditions (terrain, soil quality, climate), area size and area quality (elements, composition). Key important open space attributes with impact on urban system performance are connectivity and accessibility of open space.

2.3. Infrastructure

Infrastructure includes transportation infrastructure and other technical infrastructures (gas, electrical, telecommunication networks, water supply and sewage system). Infrastructure could be also a part of open space or buildings, but in our proposal, it is treated separately because of its special characteristics. The main purpose of infrastructure is supply support and connectivity of other urban components and system as a whole.

Attributes of transportation infrastructure considered in resilience assessment are road hierarchy, travel cost (measured in time), average speed, average daily traffic and key important transportation components (bridges, tunnels, crossroads, underpasses) [14, 18]. Key important transportation components could be described as similar to important buildings by capacity curves and spatial characteristics. In the case of key important transportation components, the relevant attributes of spatial characteristics are distance to the nearest buildings and site conditions, while others (plot ratio and free area percentage) could be omitted. Connectivity and accessibility of infrastructure are measured by mathematical graph theory using different network measures [26]: cyclomatic number, alpha index, beta index, gamma index, average degree, cyclicity, diameter, average Shimbel index, betweenness centrality, etc.

2.4. Community

Community is formed by people and organizations. This component is crucial for system response and recovery in the case of natural disasters. Agile and conscious population with financial stability would react better in crisis situations than weak, poor and uneducated one. Attributes of population with impact on urban resilience are age, employment, education, ethnicity, economic situation, family structure, migration and information access [5, 9].

Well-organised community is capable of quick and efficient self-recovery. Beside this, strong community organizations are driving force for the recovery of other components and the entire urban system. Community organizations include emergency services (fire brigade and rescue teams), healthcare services (hospitals, pharmacies and health centres) and government services. In a pre-disaster phase, organizations implement risk mitigation actions [27]: prediction (hazard monitoring and forecasting, hazard evaluation and mapping, vulnerability and risk assessment), hazard preparedness (training and education on risk management; community preparedness and training; simulation, updating and test of interinstitutional response; endowment of equipment, tools and infrastructure), planning (risk consideration in land use and urban planning; updating and enforcement of safety standards and building codes; rehabilitation and reconstruction planning, emergency response planning and implementation of warning systems), system enhancement (hydrographical basin intervention and environmental protection; implementation of hazard-event control and protection techniques; housing improvement and human settlement relocation from disaster prone-areas; reinforcement and retrofitting of public and private assets), financial support (implementation of social safety nets and funds response; housing and private sector insurance and reinsurance coverage).

3. Possibilities for assessment of urban system resilience to natural disasters

According to the literature review, there are various possibilities for resilience assessment. Urban resilience including phase of preparedness, response and recovery, could be described by resilience function shown in figure 3 [10, 13] and calculated by general equation (1). Resilience function shows system performance (P) through different time units, before the event (phase of preparedness), in the time of event (phase of response) and after the event (phase of recovery). P_0 indicates the system performance before the natural disaster (at time t_0) while P_1 indicates the level of system performance immediately after the natural disaster (at time t_1). Smaller decline of the curve at the event and steeper curve after the event indicates greater resilience (R) of the system (which could be quantitatively measured by the area under the curve). Curve A indicates the system capable to return to the same level of functionality as before the disaster. Curve B indicates the system capable to enhance the level of functionality compared to the level before the disaster. Curve C indicates the system not capable to return to the same level of functionality as before the disaster.

Beside this, it is also possible to calculate the resilience from different parameters to get the composite resilience index [3, 5, 6]. Network connections can be transformed to a mathematical graph model. System properties and interactions between individual components could be assessed by mathematical

algorithms from graph theory [14–16, 26]. When displaying the existing situation and analysing results, there are often used Geographic Information System (GIS) tools [7–10, 14, 15, 18, 28]. GIS enables spatial analysis by mapping different value of chosen indicators (e. g. social vulnerability and hazard) and combining them to get the final result map (e. g. vulnerability map).

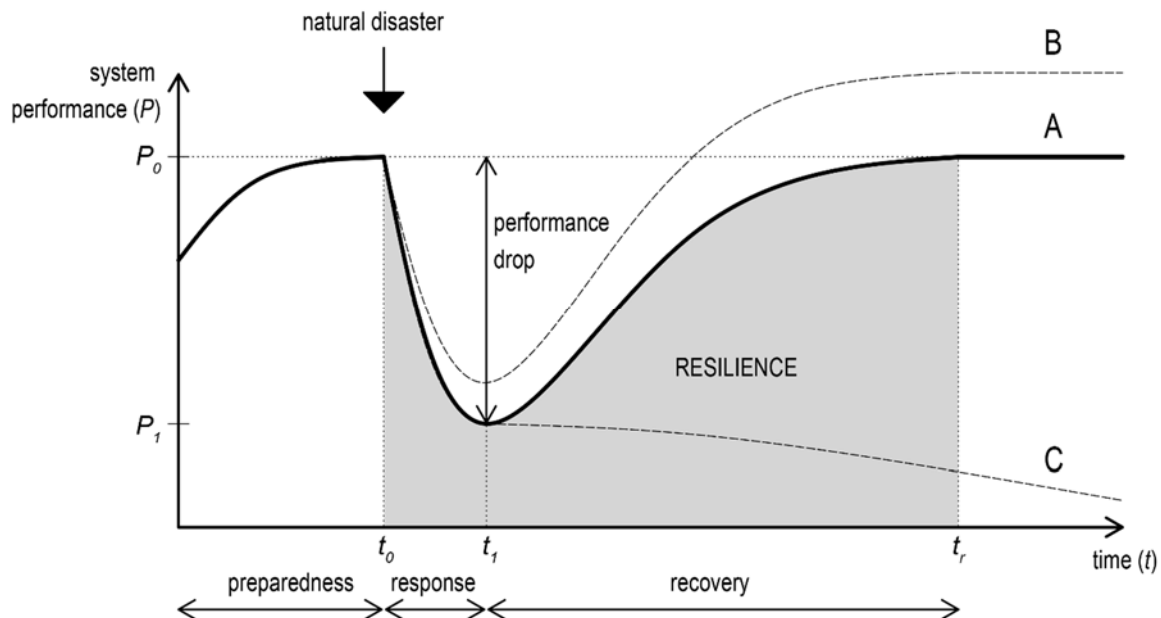


Figure 3: Resilience function

$$R = \int_{t_0}^{tr} P(x)dt \quad (1)$$

where:

- R – urban system resilience,
- $P(x)$ – performance at time x ,
- t_0 – time of the natural disaster,
- t_r – measurement time after the natural disaster.

4. Holistic assessment of urban system resilience to natural disasters

Interactions between individual components and their influence on the resilience of the entire urban system are difficult to assess with a single evaluation method. In order to embrace the complexity of the urban system, a combination of different methods and approaches should be used. In this section, findings from extensive literature review of urban resilience assessment in the case of natural disasters are presented. The main method of resilience function is proposed to be supported by individual measures of system performance by using graph theory and composite index.

The urban system could be represented as mathematical graph model by abstraction of its components as nodes (vertices), patches (specific nodes with spatial properties) and links (edges) (figure 4). Buildings are represented as nodes (key important facilities) and patches (other buildings). Open space is modelled by patches, while infrastructure is presented as links (transportation infrastructure and other technical infrastructure) and nodes (key important transportation components). Community is treated as base layer of the urban system.

Key important facilities, open space, transportation infrastructure and community are recognized as the most important urban system components in relation to the resilience of the whole system. The lack of such urban qualities has proved to be fatal for city system as seen on several examples of strong

earthquake motions in the past and recent time. Other components (other buildings and technical infrastructure) could be applied in similar ways as previously described key important components.

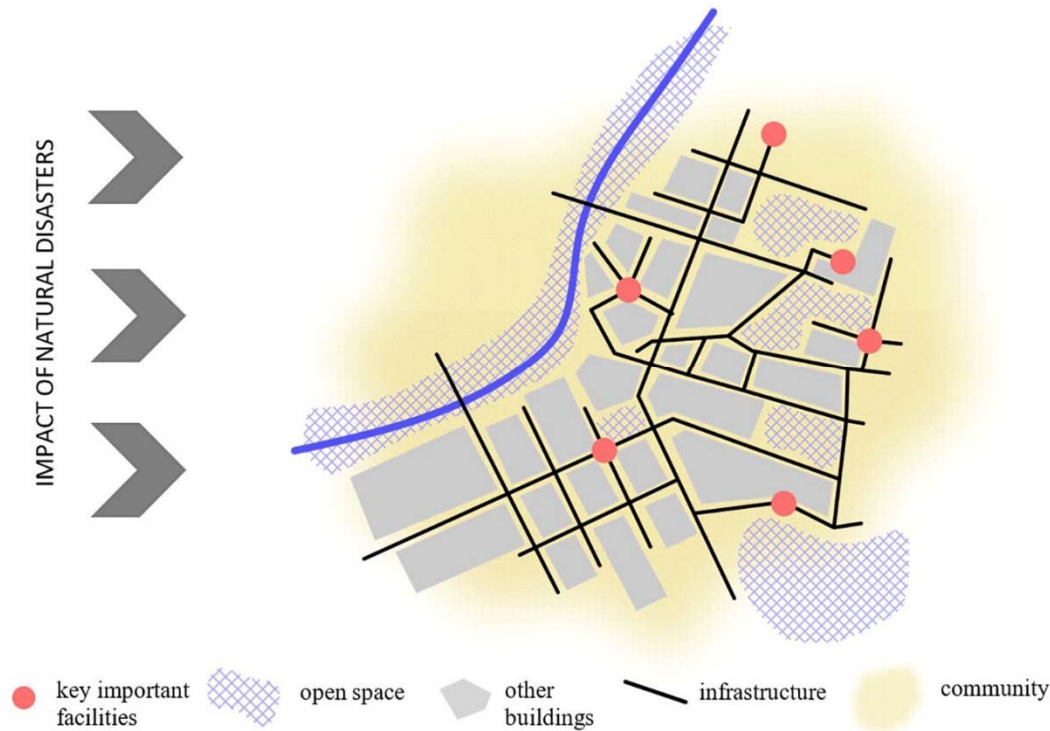


Figure 4: Urban system as a graph model

A set of attributes, with impact on urban resilience to natural disasters described in section 2, belongs to each component. These attributes could be measured by parameters typical for the individual component (e.g. structural stiffness for buildings, area for open space, flow rate for infrastructure, population density for community, etc.). Natural disaster is considered an external factor that affects the existing system and leads to some distortion. In order to analyse several scenarios of the selected natural disaster (e.g. earthquake), simulations of various events with different intensity (e.g. peak ground acceleration) should be performed (e.g. applying nonlinear dynamic analysis). The performance drop of single component is calculated as a change of composite index composed by quantitatively evaluated attributes. For example, key important facilities are defined by attributes, such as structural capacity curves (including information of a structural system and material, stiffness, number of storeys, building's height, age, etc.), spatial characteristics (including site conditions, distance to the nearest buildings, plot ratio, free area percentage) and buildings characteristics (including type of foundations, having basement or not, being waterproof or not, having green roof or not, program or use of buildings and time dependant occupancy). Combined parametric value is the composite index of a key important facility performance. Using different weighting methods, the value could be also weighted according to the expert stakeholder priorities or urban decision maker preferences.

Performance of the entire urban system in terms of connectivity, accessibility and complexity is calculated by mathematical algorithms from graph theory. System performance before and after the accident is compared to get the performance drop. Performance of the entire urban system and performance of individual component before an extreme natural event is considered to be equal to 100 %. The focus is placed on performance drop after the event and not on absolute value of the performance.

Finally, the performance maps for selected indicators are also going to be elaborated with the aid of GIS tools. The evaluation process mentioned above describes the response phase of resilience (see figure 3).

In further research the phase of preparedness and recovery could be assessed. Preparedness would be measured as performance before the disaster occurrence in absolute value. The performance of single component is calculated composite index. The value obtained from the parameters evaluated before the accident is the indicator (composite index) of key important facilities performance. In the next step of the procedure (i.e. assessment of the total system performance) it is used as the input data for mathematical calculations of graph theory. All results in the phase of preparedness are going to be presented in absolute value. On the other hand, assessment of the recovery phase requires extensive data of system capacities depending on available resources, preparedness of the society, politics, financial resources, etc. Having obtained these data, it is possible to predict a recovery time, speed of recovery (shape of the curve) and final degree of system functionality. The final result tends to be an identification of critical points and system bottlenecks as a basis for further actions of risk mitigation.

5. Conclusions

Urban system is a complex system of interdependent networks formed of different urban components and dynamic interactions between them that enables an efficient system performance. The following components have been recognized to have a substantial influence on the urban resilience in the case of selected natural disaster: key important facilities, open space, transportation infrastructure and community.

Different types of disaster have different impact on urban system and each component. Therefore, specific attributes for individual component should be used depending on the type of natural disaster. Attributes of key important facilities are structural capacity curves, spatial characteristic and building characteristics. For the description of the open space the following attributes are proposed: site conditions (terrain, soil quality, climate...), area size, area quality (elements, composition), connectivity and accessibility. Attributes of transportation infrastructure are road hierarchy, travel cost (measured in time), average speed, average daily traffic, connectivity and accessibility. Key important transportation components (bridges, tunnels, crossroads, underpasses) are treated similarly to buildings by capacity curves and spatial characteristics. Attributes of community with impact on urban resilience are age, employment, education, ethnicity, economic situation, family structure, migration, information access, quality of emergency services, quality of healthcare services, quality of government services and implementation of risk mitigation actions.

For holistic assessment of urban system resilience to natural disasters, a method of resilience function supported by graph theory and composite index is proposed. The urban system could be presented as mathematical graph model by abstraction of its components as nodes (vertices), links (edges) and patches (specific nodes with spatial properties). To each component belongs a set of attributes, which have been recognized to have a substantial impact on the urban resilience in the case of investigated natural disaster. By quantitative evaluation of the considered attributes and their parameters in two different states (before and after the accident), the basis for the assessment of the total system performance is provided. System performance before and after the accident is assessed to get the performance drop. The final goals are identification of critical points within an urban system and final mapping of the system performance using GIS tools.

The proposed conceptual framework presented in the paper is our initial result of the preliminary analysis. The currently performed analyses address test models where the earthquake resilience of the selected small urban systems is being assessed. Further studies require holistic earthquake resilience evaluation of a more complex (real) urban system considering the actual data and local priorities.

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