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NEW TRENDS IN EARTHQUAKE ENGINEERING: SEISMIC RESILIENCE ESTIMATION

BY

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Abstract. With the continuous growth of the number of people all over the world, as well as of the number of buildings, the possible losses which result following a disastrous event have also increased. For diminishing these losses, specific measures must be taken before and after the disruptive event, with the purpose of increasing communities' resilience. The most devastating event is considered to be the earthquake, not only because of the vibratory motion, but also because of the secondary hazards which may occur afterwards. This paper presents the means used nowadays for estimating the seismic resilience in an urban area. Firstly, a state-of-the-art of the seismic resilience concept is presented, followed by several methods used to assess and compute seismic resilience, *e.g.* PEOPLES Resilience Framework, REDi Rating System. Assigning a value or a level for a community's or structure's seismic resilience is of major importance, providing later on the possibility of monitoring the resilience's evolution in time and designing effective post-seismic management plans.

Keywords: seismic resilience; urban area; disruptive event; losses.

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1. Introduction

Throughout time, natural hazards have affected many cities all around the world, causing material damages and human life losses. The hazard which is considered to have the biggest impact upon both society and built environment is the earthquake. In a few minutes this type of event can wipe off entire areas, leaving behind only debris and victims. The danger is given not only by the vibratoury motion, but also by the secondary hazards which may appear, due to the facilities systems' failures or to the poor soil site characteristics, e.g. fires, landslides, land failures, floodings. If the society is not prepared to counteract these effects in case of major seismic events, then the distruction of the area is imminent and it can have repercussions not only in the social and structural field, but also in the economic domain. In these type of cases, the recovery process is slow and requires a lot of resources. In order to prevent these situations, the concept of resilience in the earthquake engineering field has been researched, with the purpose of diminishing as much as possible the losses caused by seismic events. Obtaining an acceptable level of seismic resilience implies suggesting and implementing some economic, organizational, social and structural measures within a community.

2. Seismic Resilience. Concept Definition

Crawford Stanley Holling was the first one to introduce the concept of "resilience" in research, in his studies from 1973, concerning ecology (Holling, 1973). Since then, this concept started to be used in many other fields, like social sciences, economy and engineering. Although analyzing the resilience of a system is fundamental in order to improve it, the interest in this concept has increased only in the last decade. During this period, several quantification methods and definitions of its characteristics have been proposed.

One of the difficulties in the analysis of the resilience concept is the fact that it should take into account aspects regarding various fields. For example, in case of seismic resilience, aspects related to the engineering, social and economic fields should be considered, due to the fact that a change in any of these fields influences another. Therefore, not only the characteristics and the means of computation are hard to find, but also a definition which reflects the meaning of the concept.

Following the analyses on the definitions given for the resilience concept, it can be observed that they are divided into two major categories. The first category insists on the post-event situation and on the recovery process, *e.g.* Longstaff *et al*., (2010), Adger (2000), while the second category takes into account also the system's state before the disruptive event's occurrence, *e.g.* DHS (2010), CARRI (2015), National Academies (2012), Bruneau *et al*.

(2003). In the seismic resilience case, it is important to consider both situations, *i.e*. pre- and post-event, because a thoroughly analysis of the state of the system before the earthquake's occurrence can reveal the weak points, leading to measures which can decrease the seismic risk in the region of interest. For an urban area, such measures may imply making the seismic standards in accordance with the hazard existent in the area, creating risk management plans, using seismic protection systems in building design, and implementing strict laws regarding dwellings' insurance. These measures are included in the stage of preparation for the seismic event and have as effect the increasing of the seismic resilience level.

Having as basis the definitions for the resilience given in the literature (Longstaff *et al*., 2010, Subcommittee on Disaster Reduction, 2005; National Academies, 2012; Bruneau *et al*., 2003; Adger, 2000; DHS, 2010; CARRI, 2015; McCloskey, 2014; Washington State Seismic Safety Committee, 2012) and applying them for a seismic event in an urban area, the seismic resilience could be defined as the capacity of a society located in a seismic vulnerable region to take preventive measures for decreasing both the seismic risk and the probability of secondary hazards' occurrence; then to absorb efficiently the seismic shock, with a minimum loss in system functionality; and finally to organize effective recovery actions which do not cause a negative impact on the community.

Following the analysis on the seismic resilience (Bruneau *et al*., 2003) suggested four dimensions for this concept: *technical*, *social*, *economic* and *organizational*. The capacity of the structures to absorb the shock of the earthquake without exceeding a certain damage level is included in the *technical* dimension. The *social* dimension reports to the measures taken within the community by the public administration or/ and by various organizations, e.g. non-governmental organizations, with the purpose of decreasing the negative impact upon the citizens, caused by the earthquake. The *economic* dimension deals with the capacity of the society to limit the economic losses, emerged after the seismic event, by adopting specific measures before and after the earthquake. The *organizational* dimension refers to the organizations' ability to take precautionary measures for diminishing the negative effects of the disruptive event and, afterwards, to organize themselves in an efficient manner so that the recovery period to be as small as possible and the resources used not to exceed a certain imposed limit.

Starting from the dimensions proposed by Bruneau *et al*., (2003), Renschler *et al*., (2010), developed them for obtaining a better perspective on the categories of systems/values, which influence the seismic resilience level in a community, and incorporated them inthe PEOPLES Resilience Framework. Within this model, seven dimensions of the concept are proposed, between them existing an interdependency: *Population and Demographics*, *Environmental/ Ecosystem*, *Organized Governmental Services*, *Physical Infrastructure*, *Lifestyle and Community Competence*, *Economic Development*, *Social-Cultural Capital*. Each of the dimensions proposed in the PEOPLES Resilience Model has a significant role in the recovery process of the society (Renschler *et al*., 2010).

Bruneau *et al*., (2003), suggested some properties which could be associated with the seismic resilience concept and which should be taken into account when creating a general plan for increasing the seismic resilience in an urban area: *robustness*, *redundancy*, *resourcefulness* and *rapidity*. The first property, *robustness*, is considered as being the capacity of the system to resist the earthquake's action, as well as the secondary hazards which may appear, without affecting its functionality. From the definition given for *robustness*, it can be stated that this property is included not only in the technical dimension, but also in the economic and social ones, due to the fact that the damages which occur inside a system influence the community's economy, and impact in a negative way the population. *Redundancy* – part of the technical dimension – is defined as the extent to which the system, or its components can be replaced, or their functions can be taken over by other systems/ components, after a seismic event, so that the system can perform as it did initially. *Resourcefulness* – part of the organizational dimension - characterizes the capacity of identifying the problems emerged after a seismic event, then of establishing the priorities and of using the available resources in an efficient manner in order to restore the initial functionality of the system. *Rapidity* defines the capacity of meeting the objectives as soon as possible, in order to diminish the possible losses. Having these characteristics, the *rapidity* can be included in the organizational and social dimensions (Bruneau *et al*., 2003; Tsionis, 2014).

Each of these properties is used in a certain stage of the process of increasing the resilience. Therefore, *robustness* and *rapidity* are the properties linked with the desired result obtained after improving the seismic resilience, whereas the *redundancy* and *resourcefulness* are the means of increasing the seismic resilience level (Tsionis, 2014).

3. Methods for Seismic Resilience Assessment

3.1. Analytic Estimation of Seismic Resilience

The concept of seismic resilience is very useful when creating post-disaster management plans, or when conceiving a plan of action that may increase the system's resistance to the seismic event. However, taking into account the various dimensions it implies and their interdependence, it becomes difficult to manage all the measures taken for increasing the resilience and to analyze the final result. The solution is to find some methods for numerically estimating the concept. This would allow analyzing the resilience evolution in time, for a specific area, as well as comparing two systems/ communities.

In the literature, there are some suggestions in what concerns the computation of the seismic resilience. The proposed formulas are based on the evolution in time of the functionality value, following a seismic event. The functionality function depends on the infrastructure's condition and the services provided within the community. If the quality of these services or of the infrastructure diminishes, then automatically the functionality degree decreases as well. On the other hand, the recovery process is characterized by an increasing of the functionality value. Fig. 1 highlights the evolution in time of the functionality function, $Q(t)$, after the seismic event's occurrence, describing, in this manner, the general concept of seismic resilience.

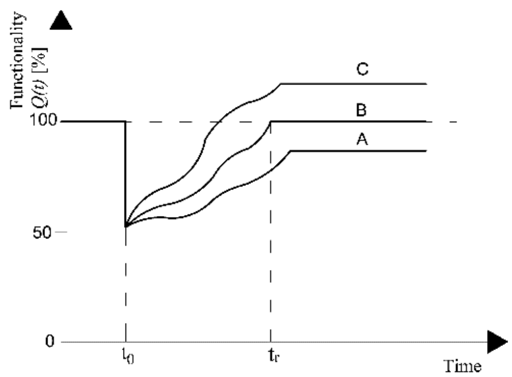


Fig. 1 – Seismic resilience graphic representation
Source: adapted after Bruneau *et al.* (2003) and Cimellaro *et al.* (2010).

When a seimic event occurs, at time t_0, the system's functionality drops suddenly, as it can be seen in Fig. 1, from the level of 100% to an inferior level, depending on the capacity of the community/ system to absorb the earthquake's shock. The disaster is usually followed by a recovery period, until t_r, which should lead to obtaining a functionality level equal to the initial one, as in graphic B, or higher, as in graphic C. However, there are cases when the society is not well prepared, or the resources are limited, the result being a longer recovery period, or a final functionality level inferior to the initial one, i.e. graphic A.

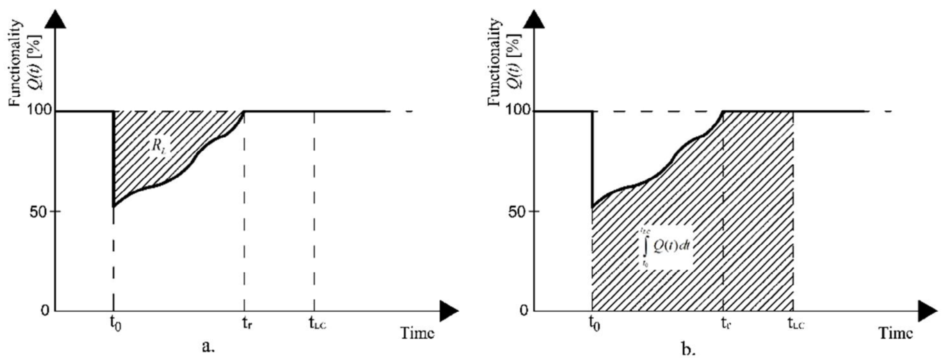
One of the first formulas proposed for quantifying the seismic resilience concept is the one given in Bruneau *et al.*, (2003), presented in eq. (1), where the authors compute the resilience loss. Graphic B from Fig. 1 is a general representation of the chart based on which the formula was conceived.

$$R_L = \int_{t_0}^{t_r} \left[100 - Q(t)\right] \mathrm{d}t \,. \tag{1}$$

According to eq. (1) and Fig. 1, (Bruneau *et al.*, 2003) computed the resilience loss as the area above the functionality function graphic, as it is presented in Fig. 2 *a* (Cimellaro *et al.*, 2008, 2010) suggested a method to evaluate directly the resilience value, by computing the area found beneath the functionality function graphic, with eq. (2):

$$R = \frac{1}{t_{LC} - t_0} \int_{t_0}^{t_{LC}} Q(t) \mathrm{d}t \,. \tag{2}$$

Eq. (2) is, at the moment, the most used formula for computing the seismic resilience of various systems, *e.g.* road networks, structures (Tsionis, 2014), and, unlike eq. (1), it considers a larger time interval in the analysis, as it is illustrated in Fig. 2 *b*.



a *b*

Fig. 2 – Resilience quantification methods;
a – Bruneau *et al.* (2003) ; *b* – Cimellaro *et al.* (2008, 2010).

As it can be seen in Fig. 2 *b*, the time period considered in the computation is extended after the recovery process' end, at time t_r, with $t_{LC} - t_r$. This extension had to be made in order for the seismic resilience final value to be in accordance with reality. If this solutions would have not been used, then a decreasing of time t_r would have led to a diminishing in the resilience value *R*, which does not reflect reality (Tsionis, 2014). The time interval $t_{LC} - t_0$ corresponds to the system's life cycle or operating life, as proposed by Cimellaro *et al.* (2008).

A form of the functionality function *Q(t)*, shown in eq. (3), is offered by Cimellaro et al. (2010), and it is applied in assessing the seismic resilience of hospitals (Tsionis, 2014; Cimellaro *et al*., 2010).

$$Q(t)=\left[1-L(I,t_r)\right]\left[H(t-t_0)-H(t-t_r)\right]\times f_{\text{rec}}(t,t_0,t_r) \qquad (3)$$

where: $L(I,t_r)$ is the loss function corresponding to a seismic event of intensity *I*, *H*(…) – the Heaviside step function, $f_{\text{rec}}(t,t_0,t_r)$ - recovery function, whose formula depends on the analyzed system.

The recovery function depends on the manner in which this process develops in time. In the beginning, there is a period of time intended for organizing the recovery activities and resources, i.e. idle period, its length depending on the level of seismic resilience within the community, being smaller for a prepared society. Following this idea, two types of recovery functions can be obtained: *exponential* – for a small idle period, but a high initial recovery speed, which decreases as the intended functionality level is close to be reached –, and *trigonometric* – for a large idle period, which is afterwards balanced by a high recovery speed. There is also a third type of recovery, i.e. *linear,* which is usually used when there are no specific informations regarding the way in which the recovery process is developing. This case is associated to a medium-prepared community, which deals with a seismic event. All three cases are illustrated in Fig. 3 (Tsionis, 2014; Cimellaro *et al*., 2010).

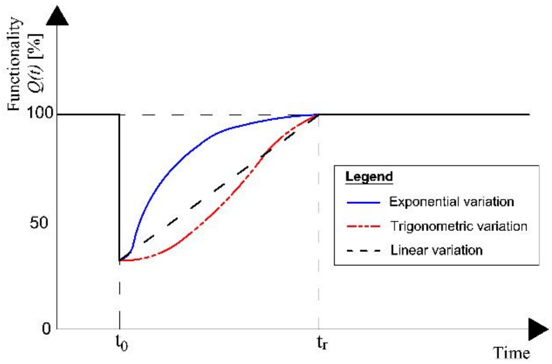


Fig. 3 – Recovery functionality curves
Source: adapted after Cimellaro et al. (2010) and Tsionis (2014).

3.2. Seismic Resilience Indices

As it has been stated above, seismic resilience is a complex concept which is influenced by a high number of factors, belonging to several domains, *e.g*. economy, environment, infrastructure, population. Because of this complexity it is difficult to process the information, to select the important data and then to introduce it in some formulas, which could give useful values in the seismic resilicence computation. Finding a way to solve this problem has become the purpose of many researchers, because a solution would provide the possibility of making approximations in what concerns, for example the manner in which people act after a disastrous event, which influences also the economic field. Moreover, by having centralized the data concerning the infrastructure and the level of the seismic resilience in this domain, it is possible to highlight the vulnerable elements of the built environment and road network, respectively. Having these results, emergency management plans could be designed and the evolution of the resilience improving process could be monitored.

Table 1
Indices for Infrastructure and Built Environment
Source: Cutter *et al*. (2008) and Renschler *et al.* (2010)

Category	Indices
Residential buildings	- the value of all residential properties - the medium age of the existent buildings - building density - number of building permits for the new buildings
Commercial and industrial buildings	- commercial/ industrial companies income - number of commercial/ industrial companies - number of banks - number of hotels
Lifelines	- number of schools, hospitals, fire stations, police stations - number of hospital beds - student hostels capacity - stadia's capacity - number of emergency centers
Transportation infrastructure	- number of airports, railway stations and their capacity - length and capacity of the existent roads - number and capacity of bridges
Monuments	- number of churches, museums - number of public parks

The solution given by the researchers was to part the existing data into fields, and for each one to assign an index, which describes the domain and influences the final value of the resilience. Within PEOPLES Resilience Framework, a series of indices have been suggested, which characterize each dimension considered in the model. For example, for the index related to the *Pysical Infrastructure* domain, the model bases its computation on the number of safe buildings, the number of emergency shelters, the number of commercial buildings and the number of hospitals in the area. Another example could be for the *Economic Development* dimension, in which case are considered the unemployment level, the industrialization degree, the population education level and the number of loans. This list can continue depending on the intended detail level, on the location for which the seismic resilience is evaluated, and the availability of the information. Table 1 presents a series of indices which can be used in the seismic resilience assessment of the infrastructure and the built environment, based on CARRI Research Report and the PEOPLES Resilience Framework.

3.3. Seismic Resilience Level Appraisal for Structures

For making a realistic analysis of a community's seismic resilience level and then providing efficient methods for improving it, it is required also to obtain data regarding the structures' resilience. This could be done by applying the REDi Rating System, which provides also a guide for increasing the seismic resilience level of a building. REDi proposes three resilience tiers: *Silver*, *Gold* and *Platinum*, each of then having several objectives presented in Table 2 (Almufti & Wilford, 2013).

Table 2
Resilience Tiers' Objectives, Specific for the Design Earthquake
(Almufti & Wilford, 2013)

Rating tier	Objectives			
	Re-occupancy	Functional recovery	Direct financial loss	Occupant safety
Platinum	Immediate	< 72 h	< 2.5%	Improbable inhabitants' injury caused by element failure
Gold	Immediate	< 1 month	< 5%	Improbable inhabitants' injury caused by element failure
Silver	< 6 months	< 6 months	< 10%	Possible inhabitants' injury caused by falling components or by non-structural collapse

In order for a structure to be assigned a certain resilience tier, it must fulfil several requirements, which have as purpose the protection of the inhabitants during and after the seismic event. One common requirement which is requested for each of the three tiers is the design of emergency exits inside the structures, which should provide protection during the earthquake. *Platinum* and *Gold* tiers imply a superior design, which allows only minimum damages, while *Silver* classified structures may experience a higher degree of damage, which would later require some additional costs for repairing works and hireing of engineers/workmen. The *Platinum* tier has some additional requisite to those requested by the *Gold* tier. In this respect, the building should be equipped with provisional emergency systems that can replace the utility systems, if they are damaged during the seismic action. Moreover, the influence of the surroundings is taken into account, *e.g.* access blocking, setting as requirements the limiting of this type of risks.

For classifying a building, REDi Rating System takes into account the fulfillment of several criteria, which are assigned to a specific seismic resilience evaluation category, *i.e.* organizational resilience, building resilience, ambient resilience and loss assessment. A high level of organizational resilience is assigned to buildings for which post-seismic emergency plans have been drafted, thus preventing utilities' disruption. In addition, this type of resilience would require also that, during the recovery period, the companies could continue their activities at least at an acceptable level. The criteria associated to building resilience are related to achieving a specific seismic resistance degree for the structural and non-structural elements. Ambient resilience is connected to the events caused by the earthquake, external to the structure, and which have a negative influence on the building's functionality. Through loss assessment, an estimation can be done regarding the economic feasibility of the measures proposed for the increasing of the seismic resilience level.

REDi Rating System provides a useful tool for assessing the losses caused by the seismic events, namely the Performance Assessment Calculation Tool (PACT), developed by the Federal Emergency Management Agency FEMA. This program offers the possibility of obtaining the damage degree of the building components, as well as the downtime and cost (Almufti & Wilford, 2013).

4. Final Remarks

The importance of a community's seismic resilience assessment is becoming evident as the population density and the number of structures increase. This study presents information regarding the seismic resilience concept and the methods used nowadays for its evaluation. The research in this field is still under way, but there are already several approaches which can be used in order to assess the seismic resilience of a certain region. CARRI and PEOPLES Resilience Framework offer some methods of general assessment, laying the basis for future research. For an individual assessment of a building, the REDi Rating System is one of the solutions which can be used, providing not only the possibility of a structure's seismic resilience estimation, but also of designing a new structure for a specific seismic resilience level, in accordance with the owner's financial means.

The final purpose, for improving the seismic resilience, is to design a method, which takes into account all variables and which can be used in any region, regardless of its economy, population, organization, or building types. Only in this manner, researchers would be able to evaluate the real state of a community by comparing it with others and by monitoring its evolution in time.

REFERENCES

Adger W.N., *Social and Ecological Resilience: are they Related?*, Progress in Human Geography, **24**, *3*, 347–364 (2000), DOI: 10.1191/030913200701540465.

Almufti I., Wilford M., *REDi Rating System: Resilience-based Earthquake Design Initiative for the Next Generation of Buildings*, Resilience Based Design Initiative, 2013, http://publications.arup.com/Publications/R/REDi_Rating_System.aspx.

Bruneau M., Chang S.E., Eguchi R.T., Lee G.C., O'Rourke T.D., Reinhorn A.M., Shinozuka M., Tierney K., Wallace W.A., Winterfeldt D., *A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities*, Earthquake Spectra, **19**, *4*, 733–752 (2003).

Cimellaro G.P., Fumo C., Reinhorn A., Bruneau M., *Seismic Resilience of Health Care Facilities*, Proc. of the 14th World Conference on Earthquake Engineering WCEE, Beijing, China, 2008, http://www.iitk.ac.in/nicee/wcee/article/14_S21-001.PDF.

Cimellaro G.P., Reinhorn A.M., Bruneau M., *Seismic Resilience of a Hospital System*, Structure and Infrastructure Engineering, **6**, *1–2*, 127–144 (2010), doi: 10.1080/15732470802663847.

Cutter S.L., Barnes L., Berry M., Burton C., Evans E., Tate E., Webb J., *Community and Regional Resilience: Perspectives from Hazards, Disasters, and Emergency Management*, *CARRI Research Report I.* Community and Regional Resilience Initiative CARRI, Oak Ridge, TN, 2008, http://www.resilientus.org/wp-content/uploads/2013/03/FINAL_COLTEN_9-25-08_1223482263.pdf [Accessed, 12.03.2016].

Holling C.S., *Resilience and Stability of Ecological Systems*, Annual Review of Ecology and Systematics, **4**, *1*, 1–23 (1973).

Longstaff P.H., Armstrong N.J., Perrin K., Parker W.M., Hidek M.A., *Building Resilient Communities: A Preliminary Framework for Assessment*, Homeland Security Affairs, **6**, *3*, 1-23 (2010).

McCloskey J., *Final Report: Increasing Community Resilience Through Integrated Earthquake Science*, Scoping Workshop for China-UK Cooperation: Developing Collaborations in the Natural and Social Sciences in the area of Geohazards, Increasing Resilience to Natural Hazards (IRNH) programme, National Environment Research Council, 2014, http://www.nerc.ac.uk/research/funded/programmes/resilience/mccloskey/ [Accessed, 28.02.2016].

Renschler C.S., Frazier A.E., Arendt L.A., Cimellaro G.P., Reinhorn A.M., Bruneau M., *Developing the 'PEOPLES' Resilience Framework for Defining and Measuring Disaster Resilience at the Community Scale*, Proc. of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering, July 25-29, 2010, Toronto, Ontario, Canada, Paper No. 1827, Earthquake Engineering Research Institute (EERI), Red Hook, NY: Curran Associates, Inc.

Tsionis G., *Seismic Resilience: Concept, Metrics and Integration with Other Hazards*, Joint Research Centre, Publications Office of the European Union, Luxembourg, doi:10.2788/713724, 2014.

* * * *Department of Homeland Security Risk Lexicon*, DHS, Risk Steering Committee, US Department of Homeland Security, Washington, DC, 2010, http://www.dhs.gov/xlibrary/assets/dhs-risk-lexicon-2010.pdf.
* * * *Disaster Resilience: A National Imperative*, National Academies, The National Academies Press, Washington, DC, doi:10.17226/13457, 2012.
* * * *Grand Challenges For Disaster Reduction. A Report of the Subcommittee on Disaster Reduction*, Subcommittee on Disaster Reduction, National Science and Technology Council, Committee on Environment and Natural Resources, 2005, http://www.sdr.gov/documents.html [Accessed, 12.01.2016].
* * * *Resilient Washington State: A Framework for Minimizing Loss and Improving Statewide Recovery after an Earthquake. Final Report and Recommendations*, Washington State Seismic Safety Committee, Emergency Management Council, Washington, D.C., 2012, http://mil.wa.gov/uploads/pdf/seismic-safety-committee/RWS%20final%20report.pdf [Accessed, 10.03.2016].
* * * *What is Community Resilience?*, CARRI, Community and Regional Resilience Institute, http://www.resilientus.org/about-us/what-is-community-resilience/ [Accessed, 27.12.2015].

NOI TENDINȚE ALE CERCETĂRILOR ÎN INGINERIA SEISMICĂ: ESTIMAREA REZILIENȚEI SEISMICE

(Rezumat)

Dezvoltarea, fără precedent, din zonele urbane a tipologiei constructiilor, dar şi concentrarea densității populației, poate conduce la pierderi materiale şi umane semnificative, înregistrate în urma unui eveniment seismic extrem. În vederea evitării pierderilor de vieți omeneşti şi reducerii celor de natură economică, având ca efect îmbunătățirea rezilienței seismice a comunităților din zone cu hazard seismic ridicat, este necesară considerarea anumitor măsuri atât a priori, cât şi după producerea unui eveniment seismic. În acest articol se prezintă o sinteză comparativă a metodelor de estimare a rezilienței seismice într-o zonă urbană, subiect de actualitate în cercetarea din domeniul ingineriei seismice. Într-o primă parte a articolului se prezintă stadiul cercetării privind reziliența seismică, iar în partea a doua sunt analizate câteva dintre metodele utilizate în evaluarea rezilienței seismice, printre care se consideră PEOPLES Resilience Framework şi REDi Rating System. Ascocierea unui anumit nivel al rezilienței seismice pentru o comunitate ofera posibilitatea de a monitoriza ulterior evoluția rezilienței în timp, creând oportunitatea conceperii şi abordării unor planuri eficiente de management a situațiilor de urgență, care să conducă la îmbunătățirea siguranței vieții în zona urbană considerată.