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STRUCTURAL VULNERABILITY AND RISK ASSESSMENT IN SEISMIC AREAS

BY

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Abstract. The seismic hazard and risk analysis represents an important research domain and it acts as a connector between the earthquake engineering new advances and the sustainable development of the society.

Romania is one the European countries with the highest seismic potential. Within this context, the seismic hazard analysis is an essential component for the seismic hazard mapping, for the seismic risk scenarios design and analysis, for preparing the seismic risk mitigation and reduction strategies, on one hand, and for the development of the post-disaster interventions, as well as the recovery and reconstruction activities, on the other hand.

This paper generally presents the natural hazards for Romania and the necessity of studying their effects. Some examples are used to highlight the earthquake effects upon vulnerable structures.

The main procedures for seismic risk analysis and the standards provisions for the structural vulnerability assessment along with their advantages and disadvantages are then summarized.

Keywords: seismic hazard maps; seismic intensity scale; pushover analysis; capacity spectrum method; fragility curves.

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1. Seismic Hazard

Seismic risk analysis includes the following main stages: macro and micro analysis of the seismic hazard, on one hand and vulnerability and risk assessment, on the other. The hazard represents a potentially destructive physical event, phenomenon, or human activity that can cause loss of life, destruction of property, or environmental degradation in a specific period of time (Barbat *et al.*, 2006a).

The hazards include latent conditions that can become future threats of different origins, either natural or human-induced processes. Each potentially destructive event is characterized by its location, intensity, frequency and probability. The seismic hazard can be described by a variety of parameters which characterize the ground movements, such as amplitude of the peak ground acceleration, earthquake duration, Fourier response and response spectrum, differential movements or depending on the effects of earthquakes on structures and the soil response (Gupta, 2002). The seismic hazard map of Romania used for the ultimate limit state design of buildings describes the peak ground acceleration variation for a recurrence period of 225 years, as shown in Fig. 1 (P100-1/2013).

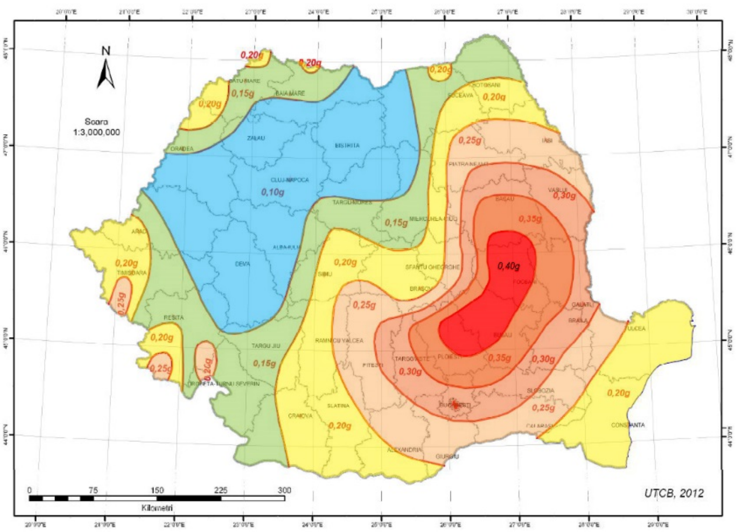


Fig. 1 – Seismic hazard map of Romania (https://mobee.infp.ro/despre-cutremurele-din-romania/harta-cutremurelor-din-romania).

The importance of seismic hazard assessment can be easily understand considering its many applications, as presented in Fig. 2 (MP-026-04). By far, the most important application is considered the seismic hazard mapping (Anderson and Trifunac, 1977; Lee and Trifunac, 1987; Trifunac, 1990).

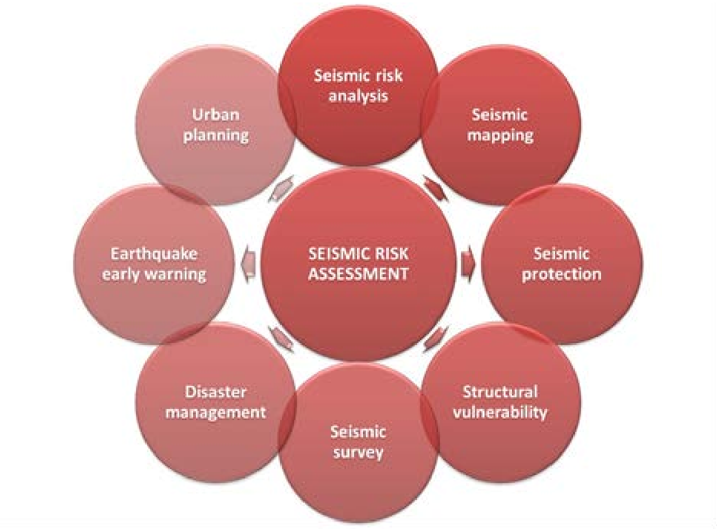


Fig. 2 − Seismic risk assessment.

Geomorphological hazards include soil collapses, landslides, and avalanches. Landslides represent mass movements of soil under the direct influence of gravity. In our country, the largest areas with landslides are found in the Sub Carpathians, the Transylvanian Depression, the Moldavian Plateau and in the Eastern Carpathians. Figure 3 shows the hazard map regarding the landslides in Romania.

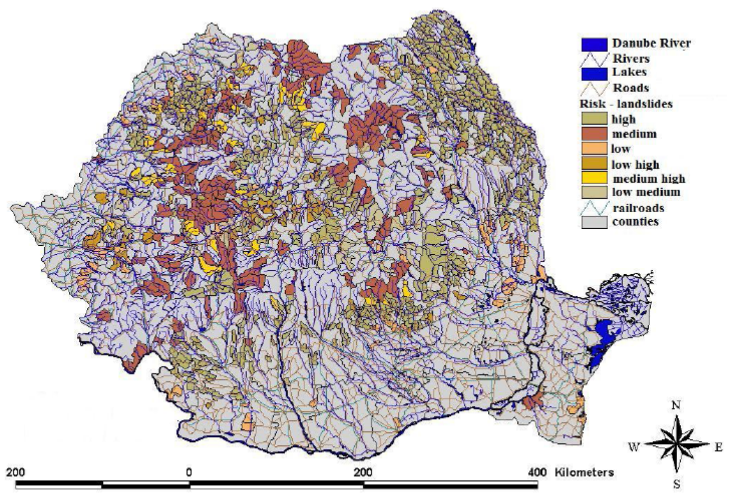


Fig. 3 − Landslide hazard map of Romania (575/2001 law).

Floods are widespread hydrographic hazards, causing extensive property damage and human losses. Figure 4 represents the map of flood risk in Romania, developed by the Romanian Institute of Geography. It can be seen that most events take place along the Danube River, and usually have serious economic and social consequences.

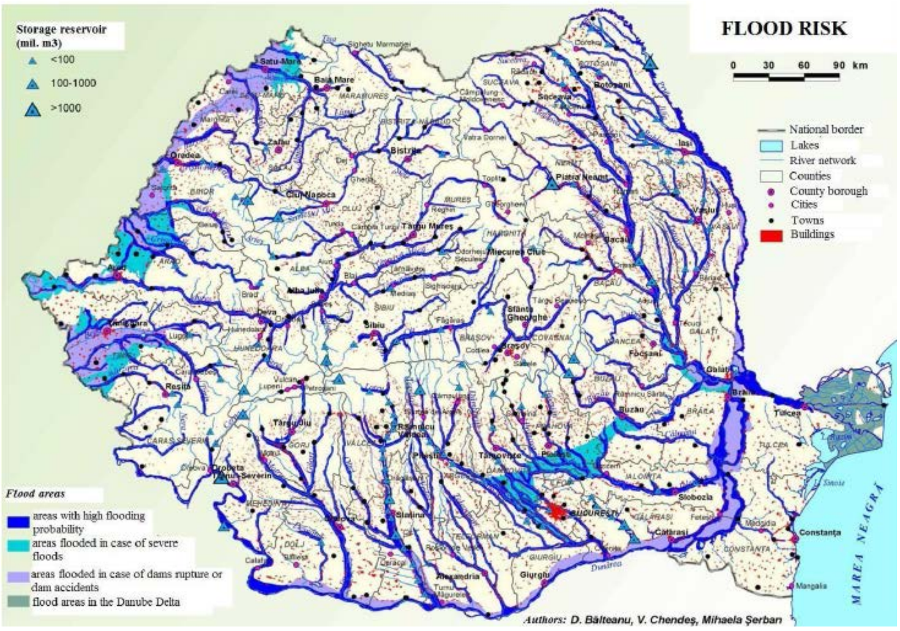


Fig. 4 − Flood hazard map of Romania (Bălteanu *et al*., 2013).

Seismic hazard assessment can be performed deterministically or probabilistically. For the deterministic approach, the parameters of the earth movements are approximated for the maximum possible earthquake in the studied location and is consistent with the seismic history of the site (Barbat *et al.*, 2006a). The probabilistic approach integrates the effect of all possible earthquakes in different locations, for a specific period of time, taking into account the uncertainties and the random nature of events (Lee and Trifunac, 1985; Gupta, 2002). The probabilistic approach approximates the soil movements with a certain safety degree, allowing to compare the risk in different regions of a country.

The results of the seismic hazard or risk analyses are used to make decisions such as: design method, rehabilitation criteria, financial planning for losses that may occur following an earthquake, emergency intervention plans, post-earthquake recovery and long-term recovery of an area affected by natural disasters. Such decisions are most correctly obtained by considering both deterministic and probabilistic approaches (McGuire, 2004).

2. Seismic Vulnerability Assessment

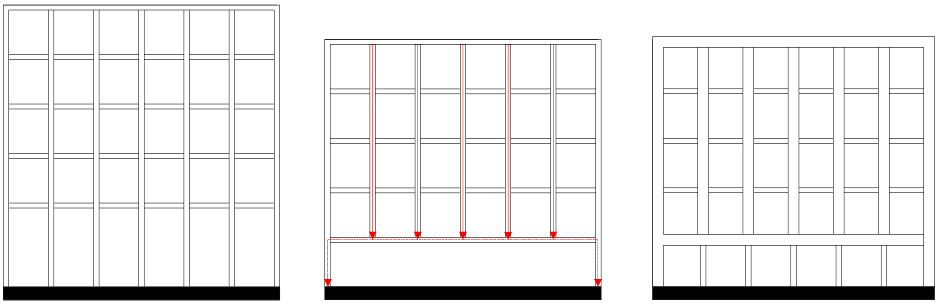
The seismic vulnerability of a structure refers to the intrinsic predisposition of the exposed elements to be affected or susceptible to damage, following an event of known intensity (Barbat *et al.*, 2006b). The structural vulnerability is a measure of the damage state that a building subjected to a seismic movement with a known intensity can suffer. The dynamic response of a structure subjected to seismic actions is complex and depends on various parameters: the precise characteristics of earth movements, the extent to which the structure can deform, the strength of materials in the structure, the construction works quality, the damage state of structural elements and structure, the interaction between structural and non-structural elements, etc. Most of these factors can be approached, but never known exactly (Banu *et al.*, 2012a).

The observed seismic vulnerability represents the damage state of the structure assessed by visual inspection after an earthquake. The predicted seismic vulnerability is computed based on anticipations of a future earthquake, considering possible destruction of the most exposed objectives.

The seismic vulnerability depends mainly on human action, but also on the degree of structural damages and on the decrease of the structure's strength, as a result of cyclic exposure to various factors. The general tendency is for the vulnerability to increase in time (Banu *et al.*, 2012a). Among the degradation factors for reinforced concrete structures are: improper choice of materials; design errors; inadequate supervision and control during the execution stage; chemical corrosion and external physical and/ or mechanical factors (Pastia *et al.*, 2014). Some of the conceptual errors of structures are: soft story at the ground floor, intermediate soft floors, irregular structural configuration and stiffness differences on the construction height (Kay, 1992).

Stress concentration and improper load transfer to the foundation lead to the development of "weak" floor. The term is used for structures that have a less stiff ground floor, compared to the higher levels. Such weak levels subsequently cause damages at any level of the structure, but given that all the loads are transferred to the ground floor, the discontinuities between the ground floor and the upper floors cause much more serious damage (FEMA 454).

The reduced number of columns at the ground floor level due to architectural reasons leads to the structural collapse during earthquakes. The development of plastic hinges at the top or bottom of the columns generates failure mechanisms with the concentration of plastic deformations at the ends of the columns, the collapse being imminent (Bachmann, 2003). Figure 5 shows three cases, which lead to the formation of weak ground floor.



(*a*) (*b*) (*c*)

Fig. 5 – Weak ground floor: (*a*) flexible ground floor; (*b*) discontinuous load transfer; (*c*) heavy upper structure.

In Fig. 6 some examples of structures seriously damaged after an earthquake due to weak ground floor are presented.

(*a*) (*b*)

Fig. 6 – (*a*) Collapsed block of flats due to the ground floor columns failure (Taiwan, 1999); (*b*) Ground floor failure mechanism (Italy, 1976).

Fig. 7 – Examples of damaged structures due to an intermediate soft story (Japan, 1995).

When the bracings are dimensionally reduced or neglected on the height of the structure, or if the horizontal strength of two consecutive floors is significantly different, a soft intermediate floor mechanism is achieved, Fig. 7.

The complexity of nowadays structural functionalities, correlated with the significant decrease of the free space for buildings, frequently lead to buildings with very complex in plan structural systems. These structures develop stress concentrations in the joint area and different structural behavior of each section. Figure 8 outlines the occurrence of torsion, as the mass and stiffness centers position do not coincide. To solve this kind of problems either the building construction as simpler rigid bodies is used, or the consolidation of the building's corners with special elements (Banu *et al.*, 2012b).

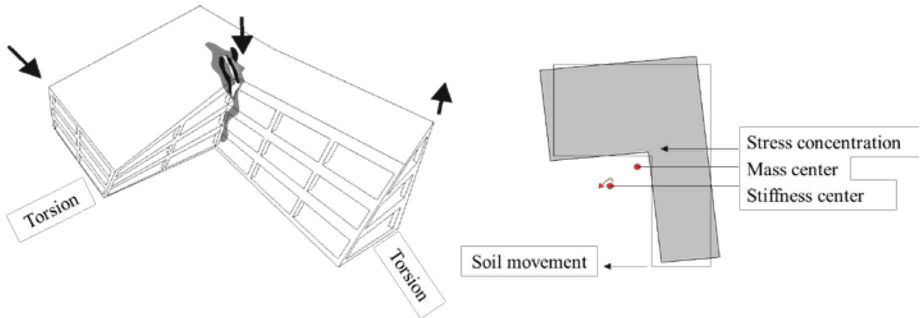


Fig. 8 – Effects of in plane irregular configuration.

Fig. 9 – Ground floor failure mechanism of Olive View Hospital
(San Fernando, California, 1971).

The discontinuous bracings negatively affects the load transfer to the foundation, weakens the strength of the structure and reduces the bracings ductility. Olive View Hospital is one of the severely damaged structures following the 1971 earthquake in San Fernando, California, and it represents a case of extreme discontinuities, Fig. 9. The vertical configuration of the main building has two weak levels consisting only of frames, on top of which four stiffer levels made of frames and structural walls rest.

The physical vulnerability of a structure in an urban area can be assessed by: descriptors or qualitative variables, indexes of physical vulnerability or capacity curves (Banu *et al.*, 2012b).

A qualitative descriptor classifies structures according to their vulnerability class, such as: low, medium, high or A, B, C, etc. The European Macroseismic Scale (EMS 98) is the basis for assessing seismic intensity in European countries. Developed on the basis of the Medvedev-Sponheuer-Karnik scale from 1964, it first occurred in 1988, and was later improved to its current form. Compared to earthquake magnitude scales, which express the seismic energy dissipated by the earthquake, the EMS 98 intensity scale expresses the extent to which a building was affected by an earthquake. The EMS 98 scale has 12 divisions covering the entire range of earthquakes, from imperceptible to strong earthquakes, which lead to global collapse and is based on three factors: people, objects and structures (Grünthal, 1998).

Capacity curves are graphical representations of the force-displacement relationship, which describe the behavior of the structure in case of an earthquake and they are obtained by nonlinear static analyses.

Static nonlinear methods (SNM) do not need all the input data, required by the dynamic nonlinear analysis (DNM). In the case of SNM, the structure is subjected to an increasing lateral load, according to a standard model, until a local or global failure mechanism is formed. SNM identifies the critical elements in the structure during a seismic action, namely the elements that require additional measures in the design process (Pavel *et al.*, 2016). Despite differences between the analysis methods, research has shown that the results obtained by SNM are comparable to those from DNM.

The pushover analysis (PA), a static nonlinear method, is used in assessing the seismic performance of existing structures, but also for their design. PA is considered an appropriate method for performance-based design (PBD) of structures, being presented in various seismic design codes. The results of the PA are used to evaluate the structural capacity, plotting the variation of the top of the structure displacement, with respect to the base shear. This graph is known as the capacity curve or pushover curve (Nour el-din Abd-Alla, 2007).

The assessment of expected physical damage, which quantifies the average damage to a particular structure or infrastructure, based on a specific hazard scenario and structural vulnerability, can be determined using: the probable damage matrix (Eleftheriadou and Karabinis, 2008); the vulnerability functions (Văcăreanu *et al.*, 2015) and the fragility curves.

3. Seismic Risk Analysis

The risk analysis consists in measuring the probability and magnitude of threats causing harmful consequences, or expected losses (deaths, injuries, destruction of property, destruction of lifestyle, economy or environment), as a result of interactions between natural or man-made hazard and vulnerable conditions. Seismic risk assessment is performed based on seismic hazard and structural vulnerability analyses.

The seismic risk assessment is based on pushover analyses which include: the capacity spectrum method, the coefficients method and the N2 method. Different versions of the capacity spectrum method are presented in ATC-40 and in the Japanese standard (JBDPA, 2004), while some alternatives of the N2 method are found in FEMA-273, FEMA-356 and EC 8.

The capacity spectrum method (CSM) allows the graphical comparison between the capacity of the structure and the requirements of the seismic action (Fajfar, 1999; Lin *et al.*, 2004). The strength of the structure is represented by a force-displacement curve, obtained from the pushover analysis. The requirements of the seismic action are transcribed by the graph of the response spectrum. Both curves are represented in a graph, in spectral coordinates (Albanesi *et al.*, 2002), as in Fig. 10, where S_a is the pseudo-spectral acceleration and S_d is the spectral displacement. The point of intersection, evaluates the expected performances and the maximum response of the structure for a considered earthquake. This graphical method highlights the relationship between the capacity of the structure and the requirements of the considered earthquake.

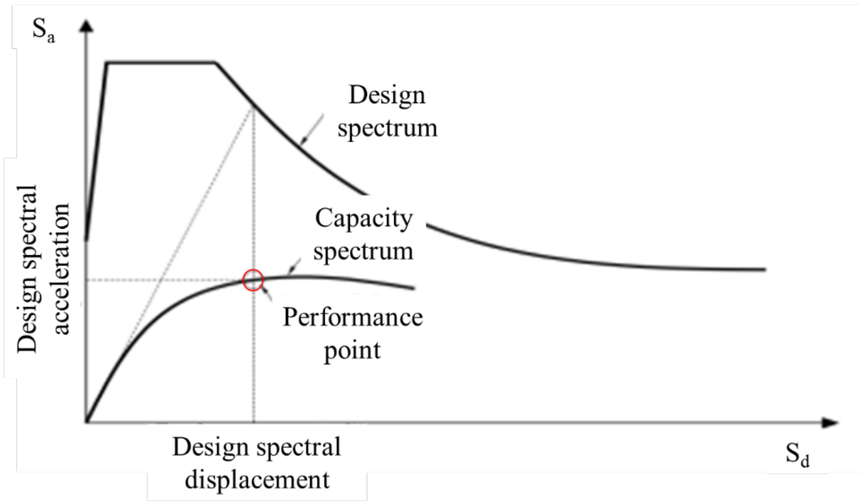


Fig. 10 – Graphical representation of the capacity spectrum method.

The main advantage of CSM is the possibility to visualize the relationship between the capacity of the structure and the necessary conditions for a possible earthquake, which can highlight several conceptual behaviors (Fajfar, 1999). Disadvantages include: the lack of a theoretical principle to justify the relationship between hysteretic energy dissipation and equivalent viscous damping, it is an iterative approach to evaluate viscous damping, equivalent to the linear system, which requires a long time to compute (Albanesi *et al.*, 2002) and it uses a fixed distribution for the lateral forces.

The N2 method proposed by Fajfar (Fajfar, 1999) combines the pushover analysis of a multiple degree-of-freedom (MDOF) model with the spectral analysis of an equivalent single degree-of-freedom (SDOF) system, thus solving some of the disadvantages of CSM. This method was developed in the mid-1980s, based on a hysterical model proposed by Saidii and Sozen (Saidii and Sozen, 1981).

Lately, the seismic risk is represented by fragility curves, which express the probability that a damage index, *d*, for the structure to reach or exceed a specific degradation state, *ds*, as a function of a parameter quantifying the seismic action intensity. This quantifies the distribution (in a probabilistic or statistical way) of the structural damages, caused by the earthquake, in correlation with the initial parameters of the structure, Fig. 11.

The fragility curves characterize a single type of structural systems and they are determined using: empirical or observational methods, methods based on expert opinions (ATC-13, 1987; ATC-40, 1996), analytical methods and mixed methods.

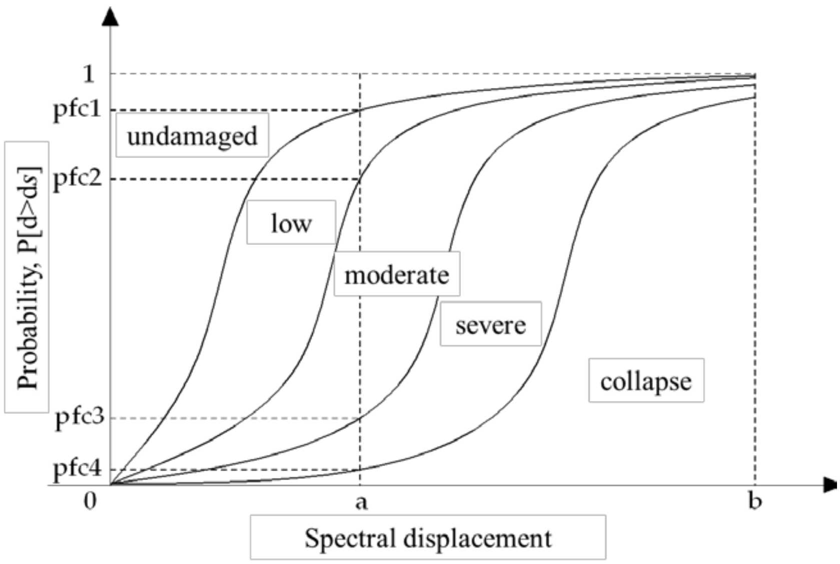


Fig. 11 – Fragility curves representation.

For an easier interpretation of the structural behavior under seismic action, vulnerability curves can also be drawn. Such representations are useful for risk assessment in urban areas, and libraries with such curves can be obtained for a variety of structures.

4. Conclusions

The structural damages due to the seismic action represent unfavourable effects of the physical state of a building which may affect both structural and non-structural elements. The seismic risk analysis directly connects the seismic hazard assessment results, deterministically or probabilistically obtained, to the fragility/ vulnerability features of buildings and different damage state levels can be this way established for various types of structures.

The current paper presents the parameters used in the seismic hazard and risk analyses and the necessity of performing them in order to evaluate the vulnerability levels of structures. Some of the factors making the structures vulnerable when they are constructed in seismic areas are also summarized. This way it is highlighted that the on-site data recording is of great importance to carry over any seismic risk assessment. A reliable seismic risk analysis needs accurate details on the year of construction, the construction materials, the type of structure, the area, the structure purpose, the existing state of damage of the structural elements due to any previous natural hazards happened along a structure life time and so on. Some of the conceptual errors of structures such as soft story at the ground floor, intermediate soft floors, irregular structural configuration and stiffness differences on the construction height are presented by means of various examples of damaged structures after an earthquake event.

The seismic risk assessment can be conducted based on results of the seismic hazard and structural vulnerability analyses. The main structural codes procedures of performing the seismic risk analysis are briefly discussed, such as the capacity spectrum method (CSM), the coefficients method and the N2 method. Their specific set of advantages and disadvantages, also summarized here, allows the more suitable choice for one of them.

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EVALUAREA VULNERABILITĂŢII STRUCTURALE ŞI A RISCULUI ÎN ZONELE EXPUSE ACŢIUNII SEISMICE

(Rezumat)

Analiza hazardului seismic şi a riscului seismic constituie un important domeniu de cercetare şi funcţionează ca un element de legătură între noile progrese din ingineria seismică şi dezvoltarea continuă a societăţii.

România este una dintre ţările europene cu cel mai ridicat potenţial seismic. În acest context, analiza hazardului seismic constituie o componentă esenţială pentru elaborarea hărţilor de hazard seismic, pentru proiectarea scenariilor şi analiza de risc seismic, pentru stabilirea strategiilor de prevenire şi reducere a riscului seismic, pe de o parte, iar pe de altă parte pentru pregătirea intervenţiilor post-dezastru, precum şi a activităţilor de recuperare şi reconstrucţie.

Acestă lucrare prezintă în general care sunt tipurile de hazard natural întâlnite în România şi necesitatea de a studia efectele acestora. Prin intermediul câtorva exemple, sunt evidenţiate efectele cutremurelor asupra structurilor vulnerabile.

Apoi sunt expuse modalităţile principale de analiză a riscului siesmic şi prevederile normativelor în ceea ce priveşte evaluarea vulnerabilităţii structurale, împreună cu avantajele şi dezavantajele pe care le presupune utilizarea acestora.