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GIS-ORIENTED METHOD FOR ELABORATION OF PROBABILISTIC EARTHQUAKE SCENARIOS

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SUMMARY

The probabilistic earthquake scenarios are the latest generation of scenarios in which a probabilistic approach is used for seismic hazard and vulnerability assessment. An integral GIS-oriented method for elaboration of probabilistic earthquake scenarios (hereafter noted as PES-RDM method) is developed. It can be used: 1) To assess the seismic vulnerability and performance of buildings in urban regions; 2) To define the probability of occurrence of the estimated damages/losses; and, 3) To propagate consistently the uncertainty in the estimation through its global convolution in the last phase. The principal steps of the PES-RDM method are: 1) Definition of hazard-consistent earthquake; 2) Preparation of a buildings typology matrix; 3) Methods for fragility and performance analysis with two estimation levels; 4) Elaboration of probabilistic earthquake scenarios; 5) Integration of different modules of the PES-RDM method into GIS environment. The PES-RDM method is used to estimate the expected damages and performance of buildings in the urban region of the city of Bitola, Macedonia, which is exposed to moderate to high seismicity (m_{max} = 5.58 ± 0.10 and λ_o = 0.07 ± 0.03), and prevailed by traditional buildings constructed at the end of XIXth and the first half of the XXth century. Eight probabilistic earthquake scenarios with return periods of 43, 72, 475 and 970 years and 84% and 50% probability of occurrence are elaborated for the city of Bitola. Since the traditional buildings are dominating (> 60% of the total number of buildings) the buildings vulnerability in the Bitola urban region is estimated as extensive, however it implies to significant economical losses from future earthquakes, with negligible level of morbidity and mortality of the population.

INTRODUCTION

In the last decades, besides the significant efforts being done to mitigate the destructive effects of future earthquakes, they continue to be a serious threat to the world due to the enlarged concentration of population and property. The strong earthquakes that happened in the past revealed the fact that the modern societies may be seriously affected by them to extent of decreasing even temporary interrupting of the social development. In order to increase the seismic safety, i.e. to decrease the level of unacceptable seismic risks, it is necessary to apply a multidisciplinary approach in various social domains. The seismic

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mitigation as a part of the emergency management is considered as the most appropriate group of measures to be undertaken for the stated needs. Their long-term goal is to create a society resistant to earthquakes, i.e. to transform unacceptable into acceptable risks. The preparedness of the society to mitigate the expected consequences of future earthquakes and successful response should be based on relevant assessments.

The elaboration of earthquake scenarios is the most frequently used method for assessment of the effects of future events. The global indicator of their efficiency is the favorable cost/benefit range. Currently, the earthquake scenarios are widely used not only to assess the expected seismic vulnerability of the urban regions, but also to estimate their seismic performance and response capacity. In the elaboration of earthquake scenarios the application of geographical information systems and remote sensing is remarkable.

Up to present times the commonly used earthquake scenarios are the deterministic and hybrid ones. The probabilistic earthquake scenarios are the newest generation of scenarios in which a probabilistic approach is used for seismic hazard and vulnerability assessment. It is considered that they give more reliable assessment, if compared to deterministic and hybrid scenarios and may be used to define the margins of the social vulnerability and performance in case of an earthquake.

CONCEPTS AND STRUCTURE OF GIS-ORIENTED METHOD FOR ELABORATION OF PROBABILISTIC EARTHQUAKE SCENARIOS

An integral GIS-oriented method for elaboration of probabilistic earthquake scenarios (hereafter noted as PES-RDM method) is recently developed, Trendafiloski [10]. It can be used: 1) To assess the seismic vulnerability and performance of buildings in urban regions; 2) To define the probability of occurrence of the estimated damages/losses; and, 3) To propagate consistently the uncertainty in the estimation through its global convolution in the last phase.

The main characteristics of the method are the following:

- Flexibility - due to its modular nature, the method itself posses an open architecture with high level of flexibility; and,
- Compatibility - high level of conceptual compatibility exists between the method modules.

The PES-RDM method is structured into four modules (Fig. 1).

Module 1 refers to determination of hazard-consistent earthquakes for predefined seismic hazard return periods using extended seismic hazard analysis. This concept provides a possibility to estimate the distribution of the seismic hazard parameters with a uniform risk index and doesnot eliminate the generic information for the contribution of particular magnitudes and distances to the seismic hazard level at particular site. The final results of the extended seismic hazard analysis are the hazard-consistent response spectra for particular site which are used as seismic demand in vulnerability and performance estimation.

Module 2 of the PES-RDM method refers to the typological inventarization of the buildings. The building typology matrix (BTM) is constructed taking into consideration the following parameters: 1) principal structural system (material and structure); 2) nonstructural elements; 3) buildings height (low, mid and high rise) or mean predominant structural period; and, 4) level of seismic protection (codes). For the stated needs RISK-UE BTM is adopted, Lungu [7].

An original concept for two levels vulnerability assessment is included in **Module 3**. Its main part are the methods for developing fragility curves and damage probability matrices.

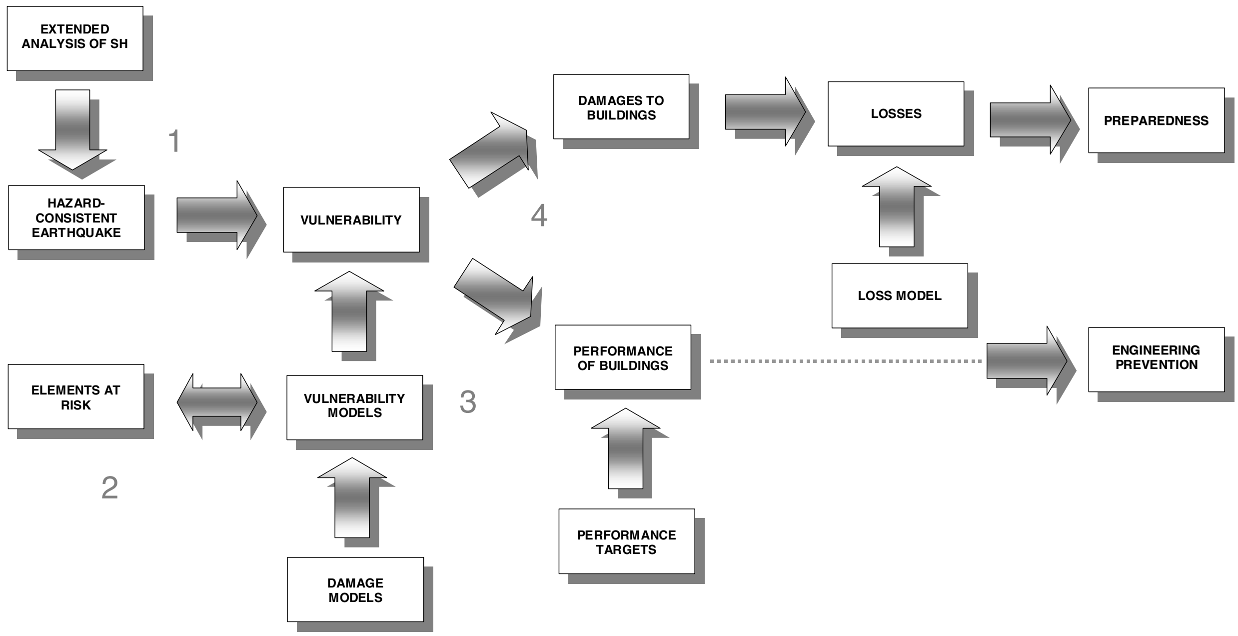


Fig. 1. PES-RDM Method Structure

Module 4 includes an approach for elaboration of probabilistic earthquake scenarios with predefined return periods (43, 72, 475 and 970 years) and 84% and 50% probability of occurrence. It can be used for estimation of the expected buildings damages as well as their performance.

Because of its modular structure, the PES-RDM method can successfully be incorporated in the geographical information systems (GIS).

METHOD FOR EXTENDED SEISMIC HAZARD ANALYSIS

A method for extended seismic hazard analysis to be used for computing hazard-consistent seismic demand is recently developed and included in PES-RDM, Trendafiloski [10]. The principal steps of this method are the following: 1) delineation of the seismic sources; 2) estimation of the seismic activity parameters through complex management of earthquake catalogue; 3) definition of hazard-consistent events using quadriparametric seismic hazard disaggeregation for predefined seismic hazard return periods; and, 4) computing hazard-consistent seismic demand spectrum as an attenuation of the hazard-consistent magnitude and distance.

The analyses should be performed for each seismic zone separately and the seismic hazard parameters are estimated as mean values. Hence, the disaggragates of the seismic hazard define a physically realizable event, i.e. the event is placed within the borders of the seismic zone and the hazard-consistent magnitude belongs to the range of the minimum (level of completeness of the catalogue, m_o) and maximum expected magnitude (m_{max}). The proposed concept, based on the estimation of the mean parameters of hazard-consistent earthquakes, is compatible with the methods for fragility analysis.

Hazard-consistent earthquake

The hazard-consistent earthquake is defined with the following parameters: 1) hazard-consistent magnitude (energetic quantificator of the event) and 2) hazard-consistent epicenter (location of the event). The hazard-consistent epicenter is determined in polar coordinates (hazard-consistent distance and angle).

In order to define the parameters of the hazard-consistent earthquake, a procedure for quadriparametric disaggregation of the seismic hazard is recently proposed, Trendafiloski [10]. It does a probabilistic re-evaluation of the magnitudes and the distances which contribute to the seismic hazard level at certain location and defines the parameters of the event as mean values of the conditional probability distribution, Ishikawa [4]. The quadriparametric disaggregation refers to hazard-consistent magnitude $\overline{M}(p)$, distance $\overline{\Delta}(p)$, angle $\overline{\Theta}(p)$ and predominant period $\overline{T}(p)$.

$$\overline{M}(p) = \frac{\sum_i \sum_j m_i \, P(Y \geq y(p) \mid m_i, \delta_j) \, P_k(m_i) \, P_k(\delta_j)}{\sum_i \sum_j P(Y \geq y(p) \mid m_i, \delta_j) \, P_k(m_i) \, P_k(\delta_j)}$$

$$\overline{\Delta}(p) = \frac{\sum_i \sum_j \delta_i \, P(Y \geq y(p) \mid m_i, \delta_j) \, P_k(m_i) \, P_k(\delta_j)}{\sum_i \sum_j P(Y \geq y(p) \mid m_i, \delta_j) \, P_k(m_i) \, P_k(\delta_j)}$$

$$\overline{\Theta}(p) = \frac{\sum_i \sum_j \Theta_i \, P(Y \geq y(p) \mid m_i, \delta_j) \, P_k(m_i) \, P_k(\delta_j)}{\sum_i \sum_j P(Y \geq y(p) \mid m_i, \delta_j) \, P_k(m_i) \, P_k(\delta_j)}$$

$$\overline{T}(p) = \frac{\sum_i \sum_j T(m_i, \delta_j) P(Y \geq y(p) \mid m_i, \delta_j) \, P_k(m_i) \, P_k(\delta_j)}{\sum_i \sum_j P(Y \geq y(p) \mid m_i, \delta_j) \, P_k(m_i) \, P_k(\delta_j)}$$

where $P_k(m_i)$ and $P_k(\delta_j)$ are probabilistic mass functions of the magnitude and epicentral distance, $T(m_i, \delta_i)$ is an attenuation relationship for the predominant period.

The hazard-consistent predominant period $\overline{T}(p)$ appears as an additional condition in determination of the epicenter of the hazard-consistent earthquake. The epicenter of the event defined by the quadriparametric disaggregation is an event which cause seismic motions at particular site with predominant period $\overline{T}(p)$.

Hazard-consistent seismic demand

The PES-RDM method introduces the hazard-consistent seismic response spectrum as seismic demand to be used for fragility analysis. It is defined as response spectrum at certain location caused by the hazard-consistent earthquake, Trendafiloski [10] and refers to mean elastic acceleration spectrum $\overline{S}_{A,el}(T, p_o)$

$$\overline{S}_{A,el}(T, p_o) = f_T\left[\overline{M}(p_o), \overline{\Delta}(p_o) \mid \overline{T}(p_o)\right]$$

where f_T is attenuation of spectral accelerations, p_o is seismic hazard level.

The proposed spectrum takes into consideration the type of soil conditions and its frequent characteristics are dependent on the hazard-consistent earthquake parameters, particularly to the hazard-consistent magnitude when local seismic sources are analyzed. The maximum spectral acceleration refers to the spectral acceleration corresponding to the mean predominant hazard-consistent period of the ground motion.

FRAGILITY ANALYSIS AND ELABORATION OF EARTHQUAKE SCENARIOS

Two levels vulnerability estimation is included in PES-RDM method. Level 1 fragility analysis estimates the conditional probability of being in or exceeding a certain damage state using the excitation parameter - peak ground acceleration. Level 2 fragility analysis refers to the estimation of the conditional probability of being in or exceeding a certain damage state using the structural response parameter - spectral displacement at the top of the building.

A unified system of four damage degrees is adopted for both estimation levels. These damage degrees are noted as: 1) slight; 2) moderate; 3) extensive damages; and, 4) collapse.

Semi-empirical fragility functions

A method for developing semi-empirical fragility functions and damage probability matrices is provided for Level 1 fragility estimation.

It is based on the implicit vulnerability model incorporated in EMS-98 (qualitative damage matrices), vulnerability classes and indices, Grünthal [3].

The damage probability matrices are modeled with binomial distribution

$$p_k = \frac{5!}{k!\,(5-k)!}\, d^k (1-d)^{5-k}$$

where p_k is probability of occurrence of damage degree k (k = 0, 1, 2, 3, 4, 5); d is a parameter of the binomial distribution.

The parameter of the binomial distribution d represents "an average damage" and its correlation with the seismic intensity (I) and the vulnerability indices (I_v) is modeled by trigonometric function as follows, Lagomarsino [6]

$$d = 0.5 + 0.45\left\{\arctan\left[0.55\left(I - 10.2 + 0.05\, I_V\right)\right]\right\}$$

The critical input parameter in the proposed method is the vulnerability index (I_v). For its calculation a technique for calibration of the vulnerability index with the data from past earthquakes and existing vulnerability functions in Republic of Macedonia is proposed. This technique provides high level of flexibility and applicability of the method to various building types including the old traditional buildings.

The semi-empirical fragility functions are modeled using cumulative lognormal probability distribution

$$P\left[ds \mid PGA\right] = \Phi\left[\frac{1}{\beta_{ds}} \ln\left(\frac{PGA}{PGA_m}\right)\right]$$

where PGA is peak ground acceleration at which there is a conditional probability p of being in or exceeding the damage state ds; PGA_m is the median value of PGA; β_{ds} - standard deviation of the PGA natural logarithm; and Φ is the standard normal cumulative distribution.

Analytical fragility functions

A method for developing the analytical fragility functions and damage probability matrices is proposed for Level 2 fragility estimation.

It is based on nonlinear dynamic analyses of structures and statistical data processing for the global damage index and the corresponding spectral displacement at the top of the building. It uses: 1) one-dimensional shear-type model for nonlinear dynamic analyses; 2) representative set of seven earthquakes for 25 acceleration levels (0.02 g - 0.55 g); 3) bilinear hysteretic model; and, 4) Park & Ang damage model, Williams [11].

The analytical fragility functions are modeled by cumulative lognormal distribution

$$P[ds \mid S_d] = \Phi\left[\frac{1}{\beta_{ds}} \ln\left(\frac{S_d}{\overline{S}_{d,ds}}\right)\right]$$

where S_d is spectral displacement at the top of the building at which there is a conditional probability p of being in or exceeding the damage state ds; $\overline{S}_{d,ds}$ is the median value of the spectral displacement at the top of the building; β_{ds} is a standard deviation of the natural logarithm of the spectral displacement for damage state ds; and Φ is the standard normal cumulative distribution.

The parameters of the fragility functions are calculated with nonlinear regression analysis of the discrete values of the conditional probability of reaching or exceeding a certain damage index $P[DI \geq DI_K]$ and the mean value of the spectral displacements in the selected intervals, Trendafiloski [10].

$$P[DI \geq DI_K] = 1 - \Phi\left[\frac{DI_K - DI_{av}}{\sigma_{DI}}\right]$$

where DI_{av} and σ_{DI} are the mean value and the standard deviation of the damage index that corresponds to the spectral displacements interval; DI_k = 0, 0.1, 0.25, 0.4 and 1.0.

The damage probability matrix is modeled with bounded standard normal distribution

$$P[ds] = \frac{\Phi\left(\frac{DI_{K+1} - DI_{av}}{\sigma_{DI}}\right) - \Phi\left(\frac{DI_K - DI_{av}}{\sigma_{DI}}\right)}{\Phi\left(\frac{DI_n - DI_{av}}{\sigma_{DI}}\right) - \Phi\left(\frac{DI_1 - DI_{av}}{\sigma_{DI}}\right)}$$

where ds is a damage state, DI_k is a damage index for the damage state k; DI_{av} and σ_{DI} are the mean value and standard deviation of the damage index; DI_n = 2.0 and DI_1 = 0.0.

Elaboration of probabilistic earthquake scenarios

Three levels of earthquake scenarios with 84%, 50% and 16% probability of occurrence are proposed taking into consideration the adopted probabilistic model for fragility analysis. The earthquake scenario with 16% probability of occurrence is considered as conservative estimation and consequently the scenario with 50% probability of occurrence is adopted as upper margin of the estimation.

The mean zero period spectral acceleration $\overline{S}_A(T=0, p_o)$, i.e. peak ground acceleration, is used as a seismic demand for probabilistic earthquake scenarios of Level 1 fragility estimation as follows:

$$\overline{S}_A(T=0, p_o) = f_{T=0}\left[\overline{M}(p_o), \overline{\Delta}(p_o) \mid \overline{T}(p_o)\right].$$

Spectral displacement at the top of the building is used as seismic demand for earthquake scenarios of Level 2 fragility estimation. This parameter is calculated as hazard-consistent inelastic displacement as follows:

$$\overline{S}_{D,inel}(T_{str}, p_o) = f_{DM}(\mu, T_{str})\,\overline{S}_{D,el}(T_{str}, p_o)$$

where $\overline{S}_{D,el}(T_{str}, p_o)$ is hazard-consistent elastic spectral displacement; $f_{DM}(\mu, T_{str})$ is spectral displacement transfer function, Miranda [8]; T_{str} is the building predominant period; and, μ is ductility demand.

The PES-RDM method proposes a procedure for estimation of the building seismic performance by the application of performance coefficients. It uses the concepts of performance based earthquake engineering proposed by SEAOC Vision 2000, Bertero [1]. The performance coefficients are defined as percent (%) of the total number of a particular building type which doesnot fulfill the predefined performance target.

They are determined as a sum of the estimated damages to buildings of a particular building type according to the following relationships

$$p_0 = \sum_{i=1}^{3} d_i \qquad p_1 = \sum_{i=2}^{3} d_i \qquad p_2 = d_3 \qquad p_3 = 0$$

where d_i are the estimated damages for damage degree i (in %).

The performance coefficients p_0, p_1, p_2 and p_3 refer to earthquake scenarios with return period of 43, 72, 475 and 970 years. The state $p_i > 0$ is defined as an unacceptable level of buildings seismic performance.

PROBABILISTIC EARTHQUAKE SCENARIOS FOR THE CITY OF BITOLA

The PES-RDM method is used to estimate the vulnerability and performance of buildings in Bitola urban region which is characterized by moderately high seismicity ($m_{max} = 5.58 \pm 0.10$ and $\lambda_o = 0.07 \pm 0.03$) and prevailed by traditional buildings constructed at the end of XIXth and the first half of the XXth century. The magnitude frequency for the seismic source Bitola-Florina is modeled with doubly truncated Gutenberg-Richter exponential distribution (Fig. 2).

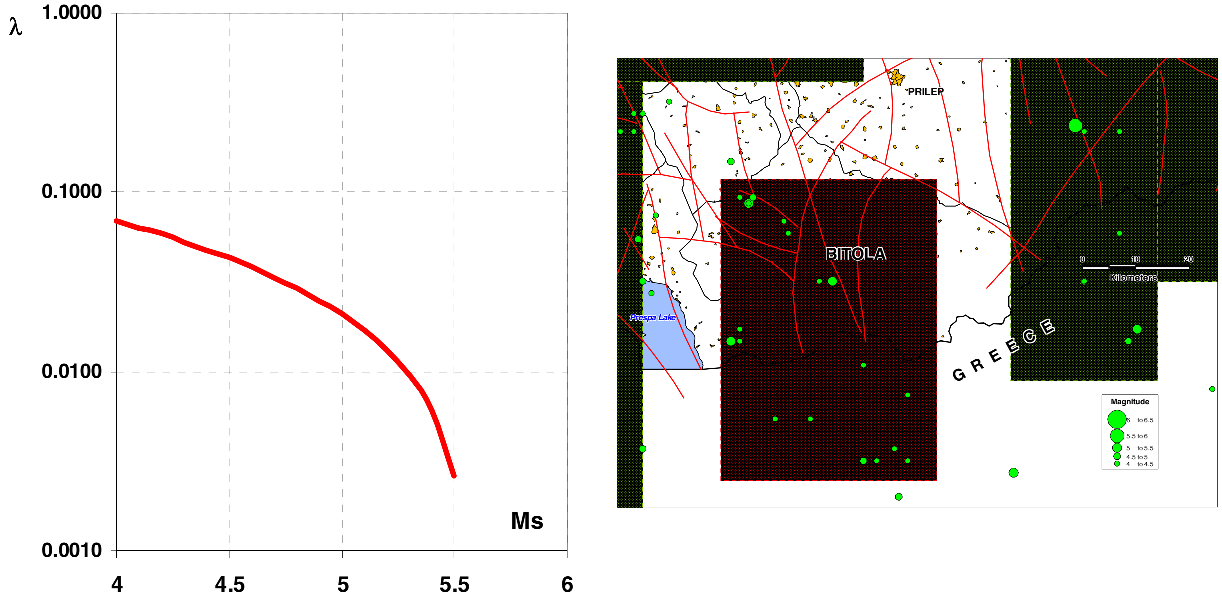


Fig. 2. Magnitude-frequency Distribution for the Seismic Source Bitola-Florina

The hazard-consistent earthquakes for the city of Bitola are determined for return periods of 43 (E43), 72 (E72), 475 (E475) and 970 (E970) years for the local seismic source Bitola-Florina, due to the fact that it contributes the most to the city seismic risk level (Fig. 3).

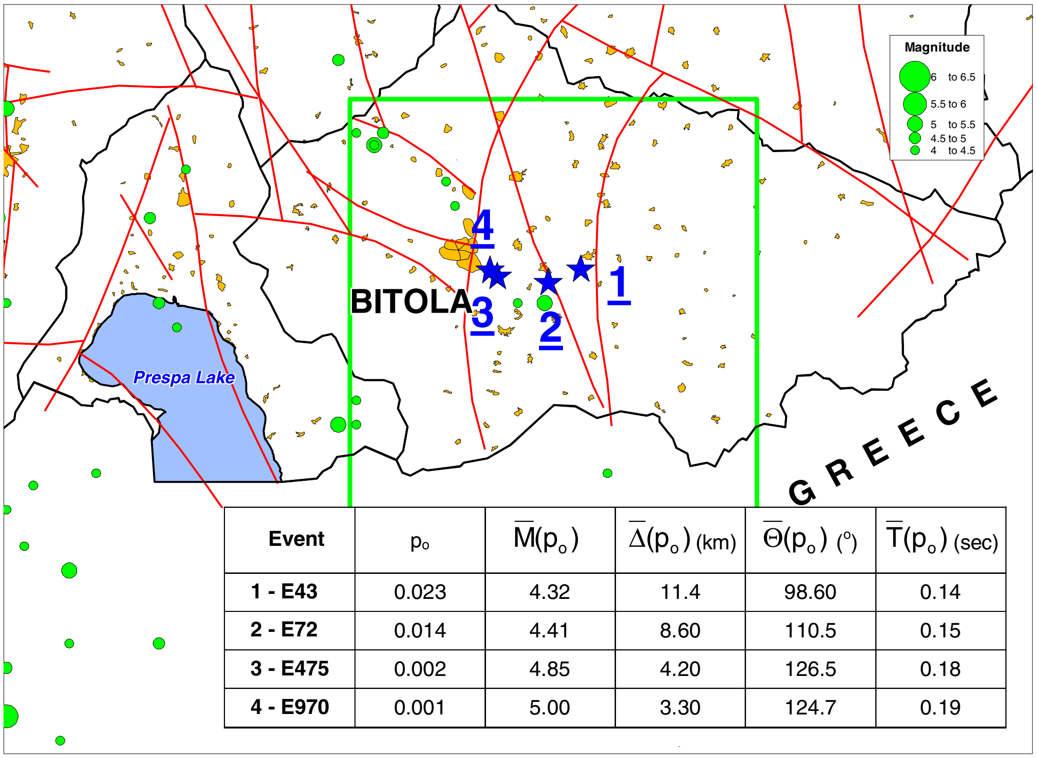
In accordance with the RISK-UE BTM the following predominant building types are identified in the Bitola urban region:

- masonry buildings: 1) simple stone masonry (M1.2); 2) bondruck structures (BK); 3) brick masonry bearing walls with wooden floors (M3.1); 4) brick masonry bearing walls with RC floors (M3.4); and, 5) overall strengthened brick masonry (M5).
- reinforced concrete buildings: 1) RC moment-resisting frames (RC1); and, 2) RC dual system - RC frames and shear walls (RC4).

The parameters of the semi-empirical fragility curves and calibrated vulnerability indices pertinent to the predominant building typology in Republic of Macedonia that are used for the City of Bitola BTM are presented in Table 1.

Table 1. Parameters of the semi-empirical fragility functions

BTM	Iv	Slight		Moderate		Extensive		Collapse	
		PGA_m	β	PGA_m	β	PGA_m	β	PGA_m	β
M1.2	45	0.109	0.50	0.176	0.51	0.283	0.55	0.537	0.59
BK	42	0.119	0.50	0.192	0.51	0.302	0.55	0.586	0.60
M3.1	40	0.126	0.50	0.203	0.51	0.327	0.55	0.621	0.60
M3.4	30	0.169	0.40	0.271	0.51	0.437	0.55	0.834	0.60
M5	20	0.225	0.50	0.362	0.51	0.582	0.55	1.120	0.65
RC1	20	0.225	0.50	0.362	0.51	0.582	0.55	1.120	0.65
RC4	10	0.300	0.50	0.482	0.51	0.776	0.55	1.499	0.66



Event	p_o	$\overline{M}(p_o)$	$\overline{\Delta}(p_o)$ (km)	$\overline{\Theta}(p_o)$ (°)	$\overline{T}(p_o)$ (sec)
1 - E43	0.023	4.32	11.4	98.60	0.14
2 - E72	0.014	4.41	8.60	110.5	0.15
3 - E475	0.002	4.85	4.20	126.5	0.18
4 - E970	0.001	5.00	3.30	124.7	0.19

Fig. 3. Hazard-consistent Earthquakes for the City of Bitola

Eight probabilistic earthquake scenarios: S43(84/50), S72(84/50), S475(84/50) and S970(84/50) are defined. They refer to return periods of 43, 72, 475 and 970 years and 84% and 50% probability of occurrence, respectively.

The earthquake scenarios with 50% probability of occurrence are adopted as upper margin of the vulnerability and unacceptable behavior of the buildings in the Bitola urban region.

The center of gravity of the damage histogram for scenarios with 50% probability of occurrence is shifted for one damage degree higher for (Fig. 4):

- buildings type M1.2 for S43-50 if compared to S43-84;
- buildings type M1.2, BK and M3.1 for S72-50 if compared to S72-84; and,
- for all types of buildings for S475/970-50 if compared to S475/970-84.

For the elaborated earthquake scenarios with 84% probability of occurrence, the highest vulnerability level is expected to traditional buildings (type M1.2, BK and M3.1). The cumulative damages for these types of buildings are estimated at 1-2% for scenario S43-84, 5-10% for S72-84, 40-50% for S475-84 up to 60-70% for S970-84. The maximum estimations for damage degree 4 (collapse) are low within the range of 3-6% for scenarios S475-84 and S970-84.

Low vulnerability level is estimated for the modern RC buildings (type RC1 and RC4) as well as the buildings constructed of overall strengthened masonry (type M5). For these types of buildings the cumulative damages are estimated in range of 8-16% for S475-84 and S970-84.

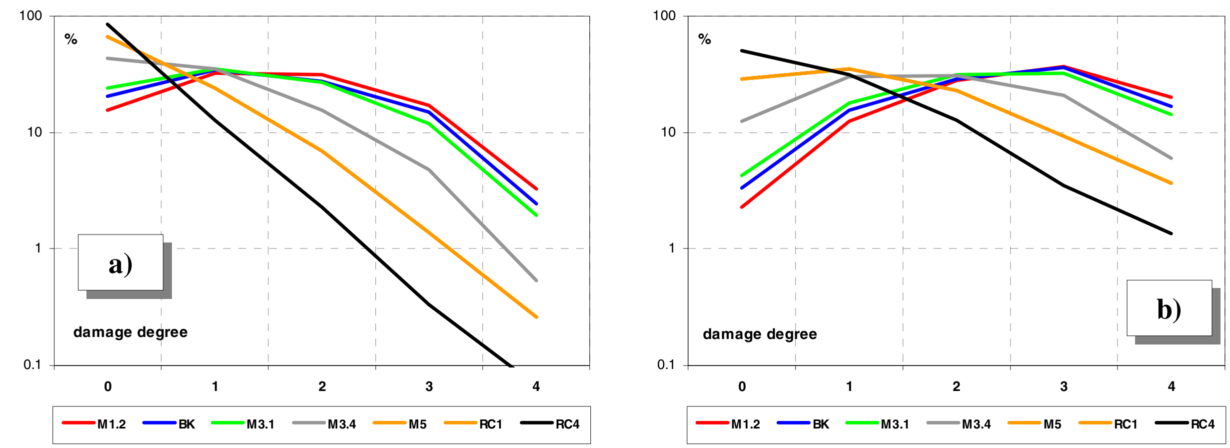


Fig. 4. Expected damages for scenarios: a) S475-84 and b) S475-50

Due to the fact that the traditional buildings are dominant type of buildings in Bitola (> 60% of the total number of buildings) the buildings vulnerability is estimated as extensive.

For scenarios with 84% probability of occurrence the centers of gravity of the damage histograms are located at the maximum level - damage degree 3 for buildings type M1.2 and damage degree 2 for the rest of the building types. Hence, it is considered that the estimated vulnerability of buildings in the Bitola urban region implies to significant economical losses from future earthquakes with negligible level of morbidity and mortality of the population.

The most unfavorable seismic performance is expected to traditional buildings in the Bitola urban region. For scenario S475-84, 12-17% they would experience unacceptable seismic performance, i.e. there is 84% probability that for 83-88% of the traditional buildings the seismic risk level would be acceptable. For scenario S475-50 the unacceptable seismic performance is estimated to 20-36% of the traditional buildings.

CONCLUSIONS

The probabilistic earthquake scenarios are the latest generation of scenarios and its is considered that they give more reliable seismic risk estimation if compared to deterministic and hybrid ones.

A GIS-oriented method for elaboration of probabilistic earthquake scenarios (PES-RDM method) is recently developed. It is based on: 1) determination of hazard-consistent earthquake; 2) buildings typological inventarization; and, 3) buildings fragility analysis. The proposed concept for the hazard-consistent earthquake provides: 1) analytical determination of an event-earthquake; 2) accomplishing a theoretical link between probabilistic and deterministic seismic hazard analysis; and, 3) seismic hazard parameters distribution with a uniform risk index. An original concept for fragility analysis with a two-levels estimation, is included in PES-RDM. The fragility estimation level to be used, depends on the characteristics of the available data and the type and purpose of the study. Level 1 fragility is suitable for damage estimation at regional level, i.e. estimation by building types. Level 2 fragility is suitable for damage estimation at regional level as well as individual buildings.

The probabilistic earthquake scenarios elaborated with the PES-RDM method determine: 1) the damage amounts and distribution; 2) buildings performance by application of predefined performance targets; 3) probability of occurrence of certain damage/performance state; and, 4) the global uncertainty in the damage/performance estimation (coefficient of variation in cumulative lognormal damage distribution).

Due to the fact that the traditional buildings dominate in the City of Bitola (> 60% of the total number of buildings) the buildings vulnerability is estimated as extensive with more then 65% of damaged traditional buildings for the worst-case scenario. This implies to significant economical losses from future earthquakes, with negligible level of morbidity and mortality of the population. The most unfavorable seismic performance is expected to traditional buildings in the Bitola urban region. The estimated performance coefficients revealed the fact that the modern RC buildings experience low level of unacceptable seismic performance due to the application of the aseismic design codes in their design. General buildings seismic performance assessment for the Bitola urban region should be provided on the basis of decided economic criteria for the level of acceptable/unacceptable seismic risk.

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