PROCEEDINGS OF SCIENCE

Probability seismic hazard analysis (PSHA) for East Macedonian Seismic zone

Ljubcho Jovanov[a,*], **Katerina Drogreshka**[a] **and Jasmina Najdovska**[a]

[a] *Seismological Observatory at Faculty of Natural Sciences and mathematics, Ss. Cyril and Methodius University,*
blvd. Goce Delcev 9, Skopje, Republic of North Macedonia

E-mail: ljovanov@pmf.ukim.mk

The aim of this research was to analyze the earthquake hazard of the East Macedonian seismic zone by determining the *a* and *b* values in Gutenberg-Richter law. For this purpose, the previously known division of the zone to six epicentral areas was used. The *b* and *a* values were calculated for the epicentral areas where the seismic data permits, using the least square method. Using these values, the mean return period, the most probable maximum magnitude in *t* year time period and the probability for an earthquake occurrence with magnitude $\geq M$ within time span of *t* years were estimated. Furthermore, maps with spatial variations of the parameters will be provided.

Keywords: earthquake hazard, *b* value, East Macedonian seismic zone, probability

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*Speaker

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1. Tectonic of the East Macedonian Seismic zone

The Earth's crust on the Balkan Peninsula is highly heterogeneous due to former plate motions and continental collisions. Subduction of the African plate under the Eurasian plate is now located in the Hellenic subduction zone, and neotectonic movements are dominating, triggering high seismic activity [**1**].

The territory of North Macedonia in the southern part of the Balkan Peninsula, represents an area with high seismic activity, exposed to strong earthquakes authored by autochthonous sources and sources in the bordering parts. Most of these earthquakes are destructive and with catastrophic consequences.

The intensive seismic activity manifested in three seismic zones: West-Macedonian seismic zone, Vardar seismic zone and East-Macedonian seismic zone, is characterized by extensive neotectonic and recent destructive processes.

The East-Macedonian seismic zone is regarded as zone with the highest seismic hazard in N. Macedonia with the strongest earthquake (1904,M_L7.8) ever recorded on the continental part of the Balkan Peninsula. It has been defined as a zone with an intersection of several fault structures stretching in different directions [**2**].

The clustering of epicenters on the territory of the East Macedonian seismic zone shows six epicentral areas (figure 1) whose spatial distribution indicates complex seismogene characteristics of the terrain [**3**].

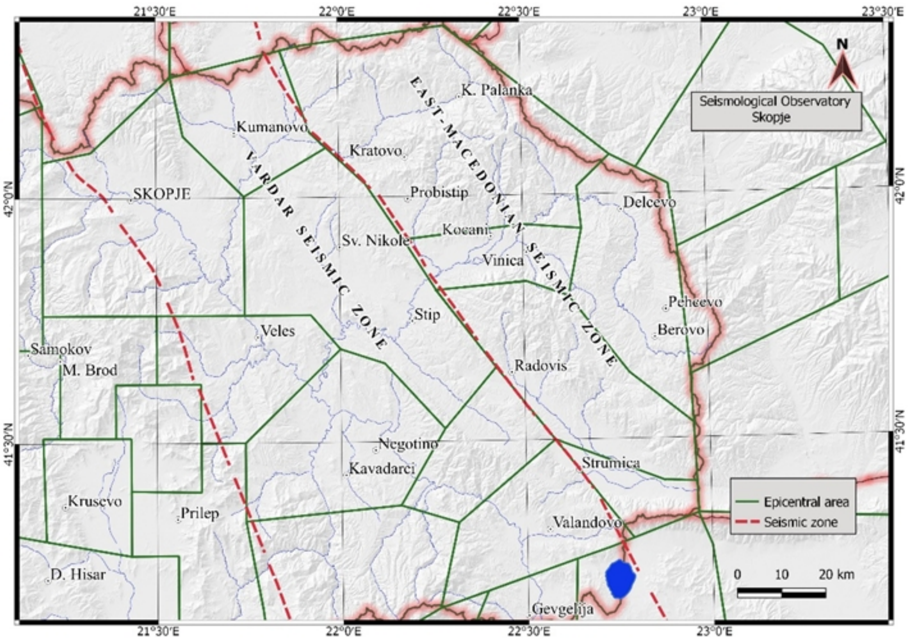

Figure 1 Spatial distribution of the epicentral areas in the East Macedonian seismic zone

2.Data

The Seismological Observatory of the Republic of North Macedonia (SORM) has been keeping a database of all earthquakes from 1901 onward. The catalog includes different methods of determining the epicenters and magnitudes of the earthquakes, resulting with different magnitude scales included (M_b – body wave magnitude, M_s – surface wave magnitude, M_L– local magnitude and the newest one M_w– moment magnitude). From the beginning of the twentieth century as far as 1957, when the observatory started to operate, the main characteristics of the earthquakes were determined using macroseismic data. From 1957 onward, the characteristics of the earthquakes are determined according to data collected by an instrument in one of the national seismological stations. In this time three generations of instruments each of them with a different level of sensitivity, were installed – the first generation has the lowest, and the third has the highest sensitivity. Knowing this, and bearing in mind that the seismological network in North Macedonia contains only one seismological station placed in the Eastern seismic zone, data from 1980 to 2018 [4], [5], [6], [7] was used for the calculations. The data from last two years is not included due to unfinished relocation process of the epicenters.

By choosing this timeframe, the main requirement for the seismic hazard calculations is implemented – homogenization of the catalogue. During this period, a uniform magnitude scale is used – local Richter magnitude scale. The official earthquake catalog includes 4297 events.

In order to evaluate the earthquake hazard of a zone, foreshocks and aftershocks should be extracted from the catalogue. This means that a declasterization process is necessary. For this purpose, the Gardner and Knopoff method (1974) was used in ZMAP software [13]. As a result, 1620 events were eliminated and 2687 events were left for further calculations.

3.Methods

The empirical relationship between the frequency of earthquake occurrence and magnitudes, known as Gutenberg-Richter law, can be expressed as (1)

$$logN = a - bM \tag{1}$$

where N is the cumulative number of events with a magnitude greater or equal to M, and a and b are seismic parameters (defined by [8]) that need to be determined. The b parameter represents the proportion of large and small earthquakes, but is also connected with the spatial distribution of stress and strain in a given region. The average value of this parameter is determined to be around 1.00, but not exactly 1, with a deviation between 0.5 and 1.5 depending on the geology, tectonics, seismogenic regimes etc [9]. Besides this, the a parameter is dependent on the level of seismicity in the region of interest, as well as the length of the observed period and the number of registered earthquakes. Spatial distributions of a and b can have significant deviations even between two neighboring points.

The values of these parameters were estimated by the software ZMAP. Using the software, maps of spatial variations (grid of 25 km^2) for both of them were created.

The most significant issue that may affect the values of a and b was detected to be the magnitude of completeness (M_c), due to an insufficient number of stations in the selected area [10]. M_c was determined using the maximum value of the first derivative of the frequency-magnitude curve and a value of 2.7 was assigned. In this case, the number of events for further calculations was reduced to only 128 earthquakes spatially distributed through the whole zone.

Finally, the main seismic hazard parameters can be obtained. Even though ZMAP automatically calculates the values of a, b, the annual value of a – expressed as a_1 and the standard deviation of b, the calculations were also done manually. For this purpose, equations (2), (3) and (4) [11] were used

$$b=\frac{\log e}{\overline{M}-M_{min}}=\frac{0.4343}{\overline{M}-M_{min}} \tag{2}$$

$$a_1=a-logt \tag{3}$$

$$\sigma_b=\frac{b}{\sqrt{N}} \tag{4}$$

where $\overline{M}$ is mean magnitude of the catalogue, M_{min} is minimal magnitude, t is time period covered by the catalogue and N is the number of events. The results derived with both methods were nearly identical.

Furthermore, the expected time period of occurrence of an earthquake with a magnitude $\geq M$, known as mean return period (5);

$$T_m=\frac{10^{bM}}{10^{a_1}} \tag{5}$$

the most probable maximum magnitude for a time period of t years (6)

$$M_t=\frac{a_1+logt}{b} \tag{6}$$

and the probability for an earthquake occurrence with magnitude $\geq M$ within time span of t years (7) were calculated [11].

$$P_t=1-e^{-10^{a_1-bM}t} \tag{7}$$

For all of the relations mentioned above, local magnitude scale (M_L) was used.

4.Results and discussion

In this study, an effort to evaluate the seismic hazard parameters for the Easte Macedonian seismogenic zone was made. Firstly, an attempt to calculate the parameters for all of the six smaller units – epicentral areas, contained in the zone was performed.

As a result of an insufficient number of stations (only one), two of the epicentral areas had not registered any events, and one had less than ten earthquakes registered for the considered period. As a consequence, the division of the zone was excluded in order to determine the parameters for the zone as a whole.

The seismicity parameters *a* and *b* were estimated using the Gutenberg-Richter law automatically using the software ZMAP and confirmed manually using the least square method. The values for the parameters are given in table 1.

a	*b*
4.54	0.91 ± 0.07

Table 1 Values of the parameters a and b

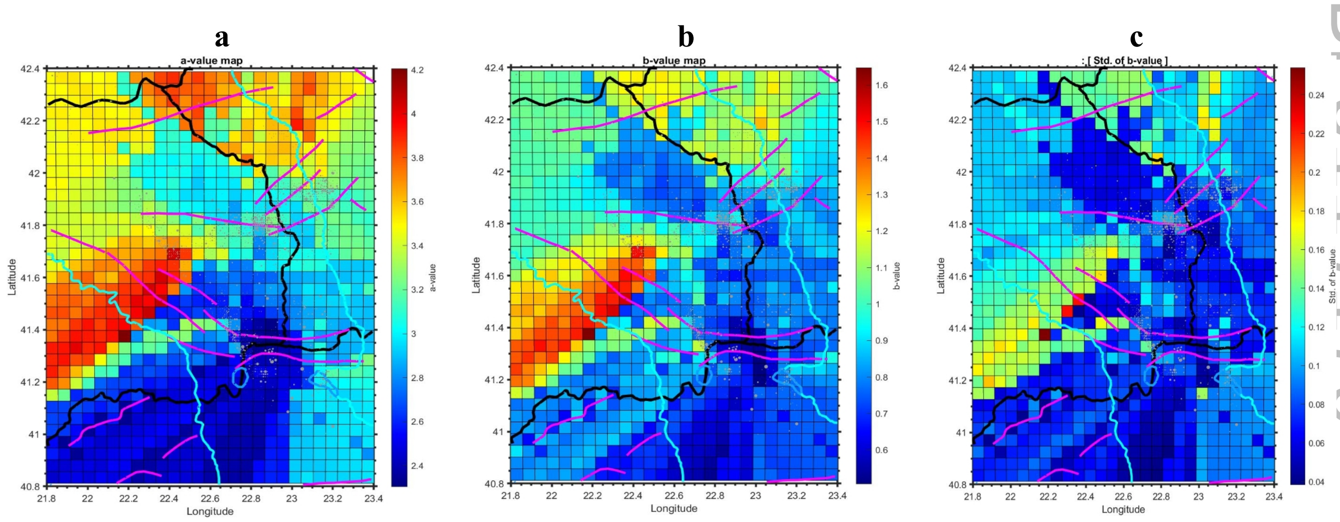

Figure 2 Maps of spatial variations of: a) parameter a; b) parameter b and c) standard deviation of parameter b

As the map of spatial variation of *a* (fig. 2a) shows, the biggest seismic activity is noticed around the town of Radovis and Stip, continuing to the Vardar seismogenic zone. Anew, the map of the spatial variation of *b* (fig. 2b) confirms the seismic activity of the region as a consequence of widespread strain and stress in the region of Stip and Radovis, far bigger (1.3-1.5) than the normal value of *b* (around 1.0). Nowadays, the monitoring of the seismicity of the zone with registering more than ten (10) micro ($M_L \leq 1.0$) to minor ($M_L \leq 3.0$) earthquakes every day, provides another confirmation of the correctness of the seismicity parameters.

Referring to the European Macroseismic Scale (EMS-1998), and the relation between the intensity and magnitude of earthquakes [12], significant impact on the environment (buildings, people, animals, Earth's crust) in the Eastern zone, have earthquakes with magnitude bigger than 5.0. According to this, calculations for the mean return period and the probability of exceedance were made for earthquakes with magnitude bigger than 5, starting with magnitude 5.5 and ending with magnitude near the magnitude of the strongest earthquake ever registered not in the Easte Macedonian zone, but on the Balkan Peninsula as a whole, M_L=7.8.

M	5.5	6.0	6.5	7.0	7.5	8.0
$T_m(years)$	133.4	380.2	1083.9	3090.3	8810.5	25 119.1
$T_m(years)$	133	380	1084	3090	8811	25 119

Table 2 Mean return period for given magnitude

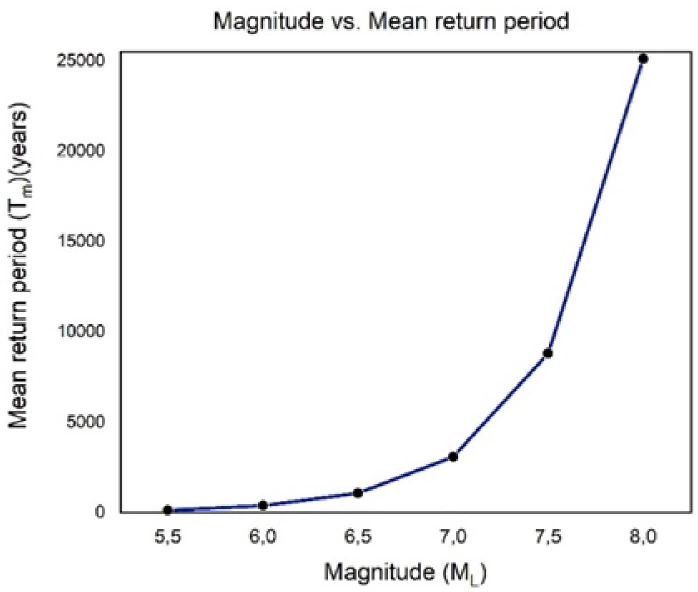

Figure 3 The return period graph

As the results on table 3 and figure 4 show, in the next three to five decades, an earthquake with magnitude bigger than 5.0 should not be expected. As the data in the catalogue shows, the biggest registered event in the past 38 years had a magnitude of M_L4.8 The expected return period for 5.5 magnitude earthquake (table 2 and figure 3) is nearly 133 years, and for an earthquake equal to the strongest ever recorded in North Macedonia is ~25 000 years.

$t(years)$	1	2	5	10	25	50	100	200	500
M_t	3.2	3.5	3.9	4.3	4.7	5.0	5.4	5.7	6.1

Table 3 The most probable magnitude in given time span

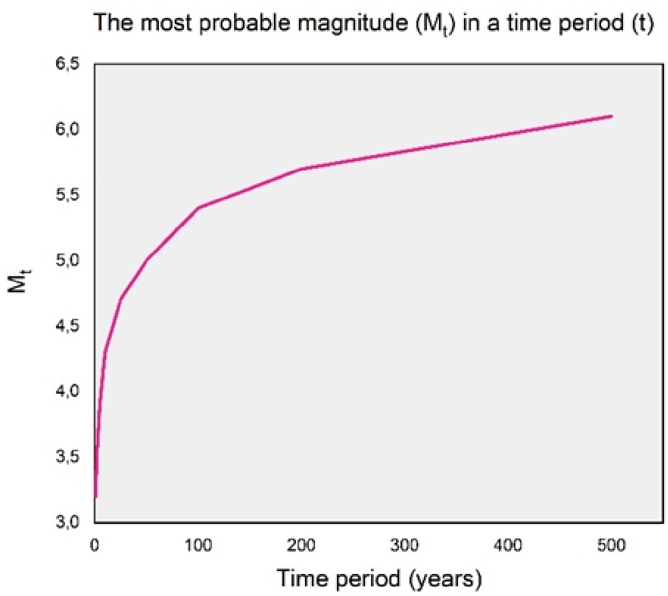

Figure 4 The most probable magnitude graph

	25 years	50 years	100 years
M	P_{25}	P_{50}	P_{100}
5.5	0.171	0.313	0.528
6.0	0.064	0.123	0.231
6.5	0.023	0.045	0.088
7.0	0.008	0.016	0.032
7.5	0.003	0.006	0.011
8.0	/	0.002	0.004

Table 4 The probability that earthquake with magnitude M will be exceeded in time period of 25, 50 and 100 years

Finally, table 4 and figure 5 show that the probability of exceedance for earthquakes with magnitude bigger than 5.5 for next 25 years is smaller than 20%, while for a time span of 100 years, the probability of exceedance is bigger than 50%.

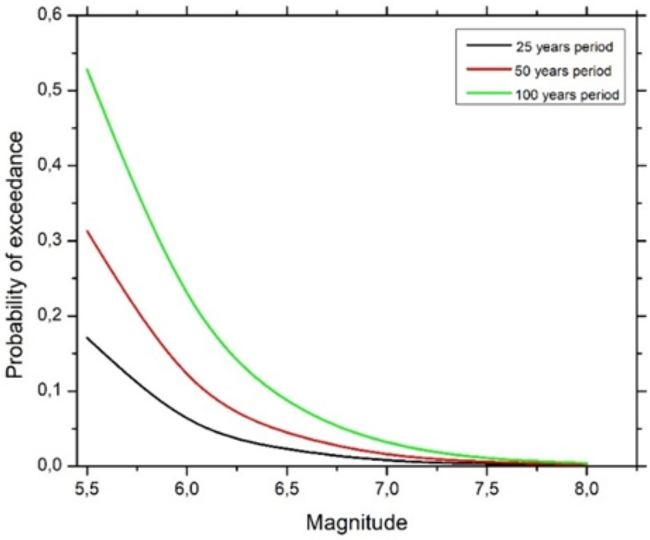

Figure 5 The probability of exceedance of earthquakes graph

5.Conclusion

All the mentioned above shows that the probabilistic seismic hazard analysis can give us reliable results about the expected seismicity of a given region. However, the results are depended on many factors such as: the geology of the terrain, the number of running stations, the sensitivity of the instruments, a homogenized catalogue of earthquakes etc. The most important factors that dictate the movements of the Earth's crust are complex regional tectonic regimes. At the moment the terrain of the Balkan Peninsula is influenced by double subduction processes – subduction of part of the Adriatic plate under Albania and N. Macedonia and subduction of the African plate under the Hellenic belt. These movements generate a bigger amount of stress and strain dissipated on the territory of N. Macedonia, especially the Eastern zone, which results with unexpected activation of non-active faults. As the name of the applied method says "probabilistic", all of the results presented above are theoretically correct within an interval of confidence, but are not final. Global changes of the tectonic regime highly influence the final results.

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