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SPATIALLY-SMOOTHED SEISMICITY MODELLING OF SEISMIC HAZARD IN THE SOFIA AREA

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Галина Фотева, Минка Илиева, Емил Ботев. МОДЕЛИРАНЕ НА СЕИЗМИЧНИЯ ХАЗАРТ ЗА РАЙОНА НА СОФИЯ ПО МЕТОДА НА ПРОСТРАНСТВЕНО ИЗГЛАДЕНАТА СЕИЗМИЧНОСТ

В настоящата работа са представени резултати от предварителна оценка на сеизмичния хазарт в Софийска област на базата на метода на пространствено изгладената сеизмичност, предложен за пръв път от Франкел (1995) и впоследствие претърпял различни модификации. При нашето изследване е използвана модификацията, приложена за оценка на сеизмичния хазарт в Словения (1997). Съставени са карти на максималното хоризонтално земно ускорение за четири модела, като първите три са подобни на първите три модела на Франкел, а четвъртият е подобен на този, използван при оценка на сеизмичния хазарт на територията на Словения и се отнася за цялата реализирана сеизмична енергия. При комбинирането на тези четири модела с различи тегловни каефициенти е получена карта на хоризонталното максималното земно ускорение, отнасяща се за период от 50 години с 10% вероятност за надвишаване. Съставена е също карта и за възможно най-лошия случай, като са взети предвид най-високите стойности за всяка точка от четирите модела.

Galina Foteva, Minka Ilieva, Emil Botev. SPATIALLY-SMOOTHED SEISMICITY MODELLING OF SEISMIC HAZARD IN THE SOFIA AREA

In this work are presented the results of the preliminary assessment of the seismic hazard in the Sofia area on the basis of the method of spatially-smoothed seismicity, proposed for the first time by Frankel (1995) and subsequently undergone various modifications. A modified variant of the method which is applied on the territory of Slovenia (1997) is used in presented work. To characterize the seismic hazard four models are used to derive one probabilistic hazard map. The three of our models are similar to Frankel’s first three models, and the fourth model is associated with the total released seismic energy, which idea is accepted according to Slovenian approach. A final map of horizontal peak ground acceleration with 10% probability for exceedance in 50 years is derived as a result of the combination between 1, 2, 3 and 4 models. A worst-case map is constructed taking into account only the hignest values of the seismic hazard assessments at each location from all the models.

Keywords: earthquake, seismic hazard, spatially smoothed seismicity, PGA maps
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1. INTRODUCTION

Seismic hazard is the assessment of the probability the level of the ground shaking, caused by earthquakes at a given place to exceed a fixed value in a given period of time. The ground motions could be expressed by maximal acceleration, maximal velocity or maximal displacement. Recently the peak ground acceleration (PGA) is the most used ground motions parameter in the seismic hazard assessments (SHA). Several kinds of methods for SHA had been created in the past: observational, deterministic, statistical, probabilistic, time dependent hazard, spectral hazard. At present two probabilistic methods are applied for the calculation of seismic hazard: the historical method and the deductive method [1]. The deductive method (proposed by Cornell [2] in 1968) requires knowledge about: catalogue of earthquakes; geometry of the seismic faults and source zones; earthquake recurrence with different magnitude M; maximal magnitude M of the earthquakes in seismic sources; attenuation law of seismic waves in the region of interest. The seismic hazard maps developed on the basis on delineation of seismic source zones are related to many uncertainties due to a lack of qualitative geological and seismotectonic data. As an attempt to avoid the uncertainties related to the source geometry, Veneziano et all. [3] suggested the historical method in 1984, which requires only a catalogue of the earthquakes and appropriate functions of attenuation of earth movements in the studied region. These methods subsequently were developed further. In 1995 Frankel published the methodology of spatially smoothed seismicity [4] as an improved variant of the historical method. This method does not exclude the possibility for including seismotectonic parameters in the seismic hazard assessment. For parameter, describing the ground motion, is chosen the PGA. This method was applied for preparation of maps for the Central and Eastern States of America, representing the area distribution of PGA with 10 % probability for exceedance for the period of 50 years. Later on this method was developed further by the same author et all [5], [6] and others and is used for making PGA maps of the territory of USA. A modified variant of the method is applied for SHA on the territory of Slovenia [7, 8].

The earthquake danger can be estimated by means of seismic zoning, seismic hazard and risk assessment methods. The prognostic seismic zoning for the territory of Bulgaria is realized through a complex analysis of geological, geophysical and seismological data [9]. The seismic hazard assessment of Bulgaria in the paper of Orozova-Stanishkova & Slejko [10] is carried out by different methods: the Gumbel, the Cornell, and the fault rupture model methods. For the Sofia region some results of the microzoning investigations derived by Petkov & Christoskov [11], Petkov et all. [12] and Demirev et all. [13] are known. Some of the various attempts for seismic hazard assessments are presented in Solakov et all.[14], Slavov et all.[15] and Josifov & Paskaleva [16]. In the first of these assessments the deductive method of Cornel-McGuier is used and deterministic approach is applied in the next two. The method of Cornell-McGuire is used by Van Eck & Stojanov [17] for SHA in South Bulgarian territory.

Seismic hazard assessment for the Sofia area is of specific importance taking into account the high seismic activity of the region and the highest concentration of the residential and industrial buildings and constructions in and around the capital of Bulgaria. In this paper an attempt for SHA of the Sofia region is made on the base of the method of spatially smoothed seismicity of Frankel, using the modified version applied in Slovenia [8].

2. SEISMOLOGICAL DATABASE

The SHA for the area limited by the coordinates 42.3°N–43.1°N, 22.5°E–24.0°E is carried out. The seismicity database for one much larger region (41°N–45°N, 21°E –26° E) is taken into account according to the requirements of the used method. This region comprises West and Central Bulgaria, as well as some parts of Romania, Serbia, Macedonia and Greece. According to this the earthquake data from Bulgarian [18, 19, 20], Greek [21], Turkish [22], Balkans [23] and International Seismological Center [24] earthquake catalogues are used for compilation of our input catalogue [25].

The compiled catalogue for the period contains various kinds of magnitude, such as M_S, M_L, M_d, and m_b. The method of spatially-smoothed seismicity requires all kind of magnitudes to be converted in one and the same kind. In our case the surface wave magnitude M_S was most frequently available. That is why it is decided to use M_S as a uniform measure of earthquake size for all the events. For this purpose the next empirical relations between M_S, M_L, and m_b are derived [25]:

$$M_S = 1.684\ m_b - 3.455,$$
$$M_S = 1.591\ M_L - 2.729.$$

By means of these equations the magnitudes of all 1973 events (with aftershocks) in the studded area are converted in M_S. Aftershoks were removed from the catalogue in order to follow the poissonian probability model. For this separation the earthquake analysis software SEISAN [26] is used. The number of main events with $M \geq 2.9$ is 1267. The compiled earthquake catalogue completeness is assessed for different intervals of time and different magnitudes. Generally it could be accepted that the catalogue is approximately complete for magnitude 3.7 since year 1900 and for magnitude 5.0 since year 1700 [25]. There are 328 events with $M \geq 3.7$ in the subcatalogue 1900–2003 and 71 events with $M \geq 5$ in the subcatalogue 1700–2003. The maximal observed value is 7.8.

The map of epicenters of all main events with magnitude $M \geq 3.7$ (382

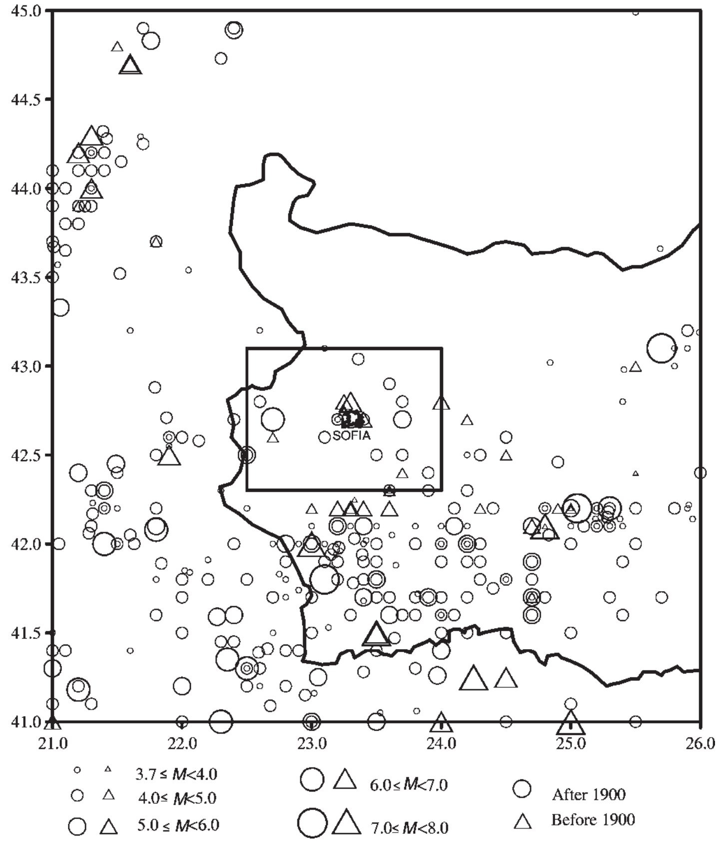

Fig. 1. Epicentral map of the study area for the earthquake with $M \geq 3.7$ during the period 1700–2003

in number) during the period 1700–2003 is presented on Fig.1. According to accuracy of determination of hypocentral parameters [27], the presented earthquakes could be divided into three time-period classes:

- before 1900–historical period, with only macroseismological (non-instrumental) data sources
- 1900–1970–early instrumental and macroseismological data sources
- after 1970–with relatively modern instrumental data .

Additionally it could be asserted that after 1980 the modern Bulgarian and Greece national seismological networks started operation that is a presumption for the highest accuracy of the hypocenter determinations.

3. METHOD

The method of spatially smoothed seismicity of Frankel [4] and its modification applied in Slovenia [8] are used in this paper for SHA. Four models to characterize the seismic hazard are used by Frankel to derive one probabilistic hazard map. These models are based on historical seismicity that has been spatially-smoothed to different length scales.

The authors consider the hazard from earthquakes with moment magnitudes $M \leq 7.0$. He use a minimum magnitude $M = 4.5$ for the hazard calculation, because it is accepted that only events with $M \geq 4.5$ may cause damages in the buildings.

In the first model it is assumed, that the moderate earthquakes will occur generally in areas where there had been significant numbers of small events. It is determined by observations that the moderate earthquakes with magnitude 5–7 took place in regions where considerable number of weak earthquakes (with magnitude $M \geq 3.0$) is observed.

The model is based on the spatially-smoothed a-values derived from the magnitude 3 and larger earthquakes. Here a is the level of the activity according to Gutenberg–Richter relation

$$\log N = a - bM,$$

where N is the number of events with magnitude higher or equal to M. In such a way this model elucidates the most probable areas where moderate earthquakes could happen in the future.

In the second model it is assumed that the events of engineering interest ($M \geq 5.0$) will occur near the sites where they have occurred in the past. The model is based on the spatially-smoothed a-values derived from earthquakes with magnitude 5.0 and above events. This model is intended to account for the possibility of well localized seismogenic structures which repeatedly generate moderate $M \geq 5.0$ earthquakes.

The third model is based on a uniform source zone. It covers the possibility of occurrence of moderate earthquakes in areas that have been quiescent historically. This model smooths the observed seismicity over the entire region.

In the three models the magnitudes are supposed to be distributed by log-linear Gutenberg-Richter equation.

In the last model Frankel considers only the strongest events with moment magnitude $M > 7.0$, taking into account as characteristic earthquakes, generated by individual faults.

Frankel subjectively used the weighting scheme of 0.5, 0.25, 0.25, and 1 for models 1, 2, 3, and 4 respectively. He calculated the combined PGA map for a 475 year return period, corresponding to a 10% probability of exceedance in 50 years. Frankel also presented the worst-case map, showing the highest PGA values from the four models at each location.

In our investigations model 1 assumes, that future earthquakes may occur in areas where they have occurred in the recent past, regardless of their magnitude. For model 4 a new approach to calculating seismic activity rate was used, taking into account the total released seismic energy, which idea is accepted according to [8]. We subjectively used the weighting scheme of 0.4, 0.4, 0.1, and 0.1 for models 1, 2, 3, and 4 respectively.

4. SEISMICITY MODELLING

Theoretical assumptions and calculations of the seismic hazard are similar to these in paper [8]. Following the basic idea of Frankel, the authors derived a four models weighted mean PGA map and worst case map for Slovenia for the same return period. However, they modified the original method and adopted it to local seismic properties. They also made some modifications in order to increase the accuracy of computations.

Models 1 and 2 are based on spatially-smoothed historical seismicity. The spatially-smoothing of seismicity is performed by a circular Gaussian function. In this function the correlation distance c accounts for the estimated error in the epicentral location. The horizontal peak ground acceleration is selected as a ground motion parameter. The attenuation has proven to be a highly influential factor of seismic hazard. In view of that, the choice of ground motion attenuation model is of great importance. In this study the peak ground acceleration attenuation relationship proposed by Ambraseys et all. [28] is used.

In the first model 328 main events with magnitude $M \geq 3.7$ are taken into account for the period from 1900 to 2003. In the second model 71 main events with $M \geq 5.0$ from 1700 to 2003 are used. These particular magnitudes and their specific periods are chosen according to the evaluation for the completeness of the catalogue [25]. The region of interest is divided to a grid with cells 0.05º N and 0.06º E (cells with 5 km long sides). For model 1 a correlation distance c = 10 km is used and for model 2 c = 15 km, which is of accordance to errors in determination of the coordinates of the epicenters between 30 km and 45 km respectively.

In model 3 the same database is used as well as in model 1–all the events with magnitude $M \geq 3.7$ for the period from 1900 to 2003. The hazard is calculated under the assumption of a large area seismic source where the values of coefficients a and b from the Gutenberg-Richter relation are accepted to be equal all over the area. The main calculation is the same, but the summing is taken over the cells in the entire source zone.

The seismic hazard for model 4 is calculated in the same way as in the first two models taking into account all events (main and aftershocks).

Models 2, 3, and 4 are normalized to model 1, so that the total activity rate in a chosen area, called “the influence area”, is the same in all models. The four models differs only the spatial distribution of seismic activity.

To prepare a combine map of the seismic hazard the probabilities of exceedance from all models are added together with different weights. We have chosen a weight 0.4 for model 1 and 2 and a weight of 0.1 for model 3 and 4. A larger weight is given to models 1 and 2, because they are based on more reliable data and presumably, better represent the real seismic activity. Also the sum of these coefficient (respectively 0.4, 0.4, 0.1, and 0.1 for the models) is equal to 1 unit it is obvious that the final model keeps the historical rate of the events with magnitude $M \geq 4.5$.

A worst case map is constructed taking into account only the maximal values of the seismic hazard assessments from all the models at each location.

As it is seen from the explanations presented above the Frankel’ method proposes direct SHA on the base of spatially smoothed seismicity. In such a way some uncertainties associated with the geometry and localization of the seismic source zones (specific for the world spread Cornell approach for SHA) are avoid.

In our case the programmed package OHAZ is used for the SHA.

5. RESULTS

The results obtained are represented as maps for the spatially distribution of horizontal peak ground acceleration with 10% probability of exceedance in 50 years, which corresponds to the return period of 475 years. The values of PGA are presented in parts of g (m/s^2) for stiff soil sites. Contour interval is 0.025 m/s^2. The seismic hazard is calculated for magnitude interval $4.5 \leq M \leq 7.8$.

On the Fig.2 a map of PGA for the seismicity model 1($M \geq 3.7$, 1900–2003) is presented. The highest and the lowest contour values are 0.300 g and 0.150 g respectively. Highest hazard are established in the central part of the studied territory (the Sofia valley) as well as in the south-eastern part.

On the Fig.3 a map of PGA for the seismicity model 2 is presented. The highest and the lowest contour values are 0.400 g and 0.150 g. Similar to the previous model the highest values of the hazard are established in the central part of the studied territory (the Sofia valley). Also high values (0.250 g) are observed to the south.

For the model 3 the observed value of PGA is 0.127 g.

On the Fig. 4 a map of PGA for the seismicity model 4 is presented.

On the Fig. 5 a combined map with specific weight coefficients for all 4 models (respectively 0.4, 0.4, 0.1 and 0.1) is presented. Weights of the models are based on the reliability of the sub catalogues used. The highest and the lowest contour values are 0.275 g and 0.150 g respectively. Highest hazard for the Sofia valley and the central parts to the south is observed.

On the Fig. 6 a worst-case map is presented. This map shows the highest PGA value from the four models at each location.

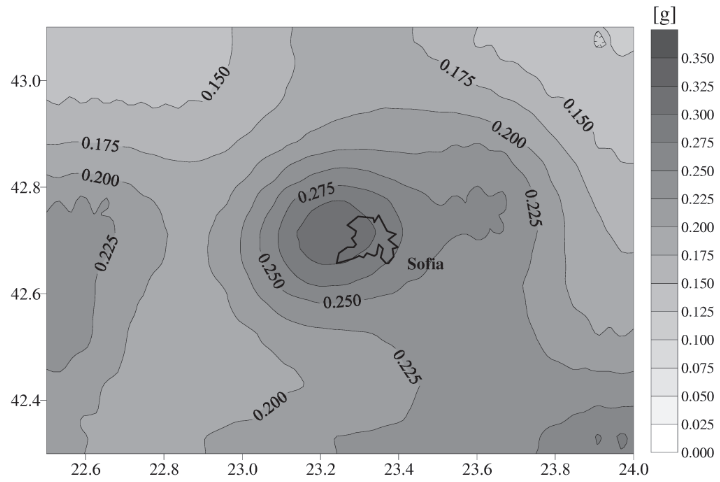

Fig. 2. PGA map for the model 1 with 10% probability of exceedance in 50 years (475 return period)

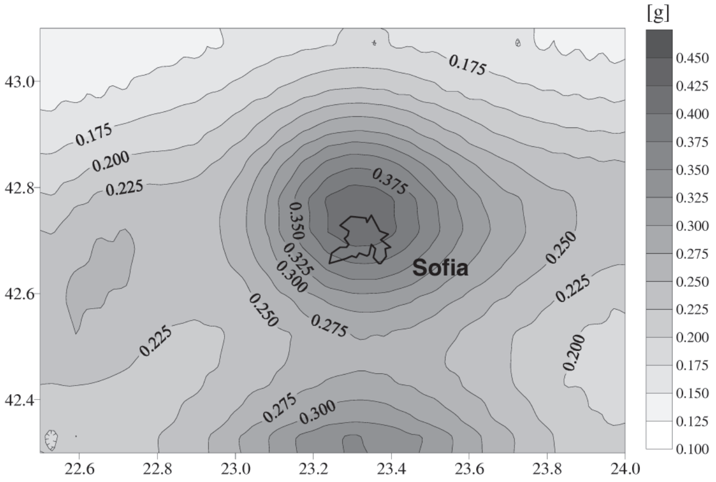

Fig. 3. PGA map for the model 2 with 10% probability of exceedance in 50 years (475 return period)

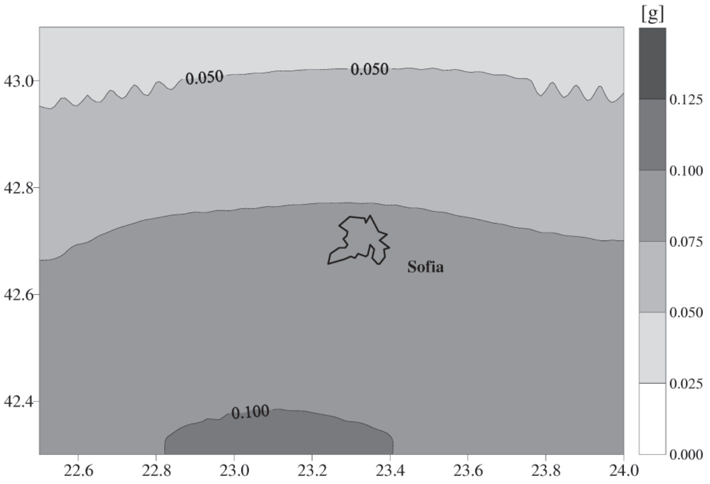

Fig. 4. PGA map for the model 4 with 10% probability of exceedance in 50 years (475 return period)

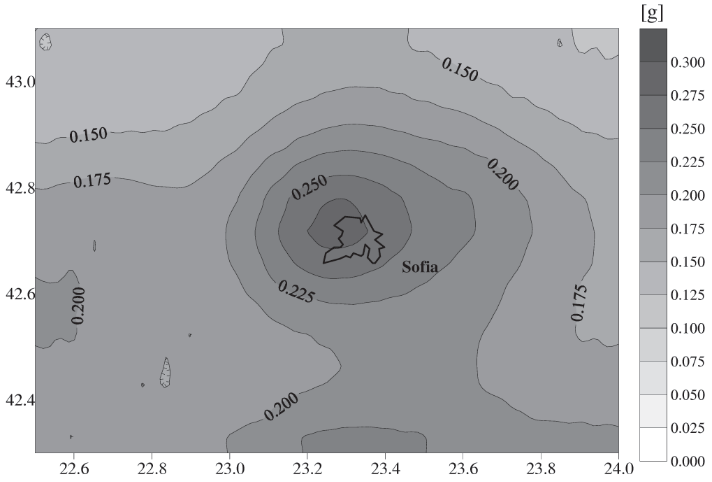

Fig. 5. Combined PGA map, derived from models 1 to 4 (0.4, 04, 01, 01 weight, respectively) with 10% probability of exceedance in 50 years (475 return period)

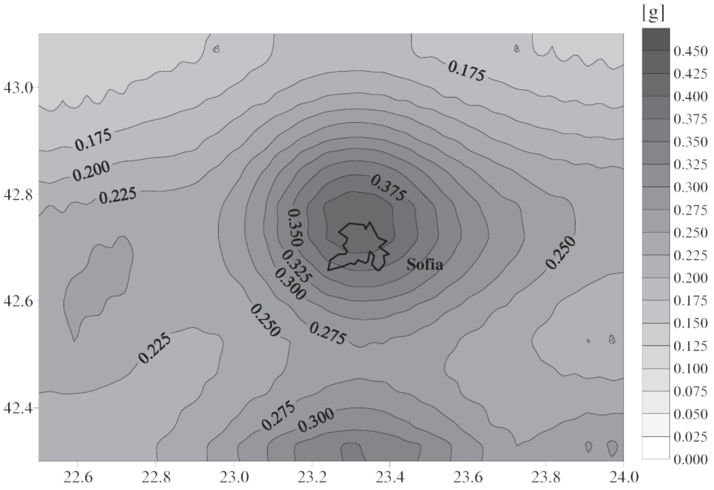

Fig. 6. Worst-case PGA map, derived from four models with 10% probability of exceedance in 50 years (475 return period)

Other authors, using different approaches predicted seismic hazard for a different time periods. Stanishkova and Slejko [10] provided seismic hazard assessment of Bulgaria in a 100 year time period and 37% probability level of nonexceedance. In particular, for the Sofia area, using the Cornell approach, they obtained approximately 81 Gal (cm/s^2) value of the horizontal PGA. Solakov et al. [14] applied the deductive method of Cornell-McGuire and obtained PGA value for the Sofia area between 0.25–0.45 g for 10^{-3} annual probability of exceedance. They find that 37% probability for the much of the Sofia area, the PGA of 0.3–0.4 g will not to be exceeded in 1000 years.

6. CONCLUSIONS

A seismic hazard assessment for the Sofia area by the Frankel' method of spatially-smoothed seismicity is done in presented work. This method produces probabilistic hazard maps, using only the earthquake catalogue, without the use seismic source zones. A combined map for the spatial distribution of horizontal PGA with 10% probability of exceedance in 50 years (475 return period) is derived from 4 models. The highest and the lowest contour values are 0.275 g and 0.150 g respectively. A worst-case map is also computed. The main result of our research study is that in the central part of the region of interest, including Sofia valley and Sofia city, substantial seismic hazard is observed.

The accuracy of the seismic hazard assessment can be improved using a more precise attenuation model, based on regional strong motion records. The next important step could be the including of information about the fault structures and calculations of spectral hazard.

Any kind of comments and critical notes are welcome.

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