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Seismic hazard assessment for the Sofia area

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Abstract
The capital of Bulgaria, Sofia, is situated in the center of the so-called Sofia area. This is the most populated industrial and cultural region of Bulgaria that faces considerable earthquake risk. We apply a version of machine code EQRISK for hazard assessment of the Sofia area according to the Cornell-McGuire approach. The probabilistic seismic hazard analysis is based on a simplified seismogenic model, which is derived from seismic zoning of Bulgaria. We show, using a Monte Carlo approach, that uncertainties in seismic input have a relatively small effect on the PSHA output, especially when compared with uncertainties associated with the attenuation relationship. Our PSHA map shows that a 10^{-3} annual probability of the PGA exceeds 0.3 *g* in much of the Sofia area.

Key words *seismic hazard assessment – Central-Balkan neotectonic region – seismicity – attenuation relationships – treatment of uncertainty*

1. Introduction

The Sofia area is the most populated (the population exceeds 1.2 millions inhabitants), industrial and cultural region of Bulgaria that faces considerable earthquake risk. The city of Sofia, situated in the center of the area, is the capital of Bulgaria. Over the past centuries, the town of Sofia has experienced strong earthquakes: the 1818 earthquake with epicentral intensity VIII-IX MSK and the 1858 earthquake with I_0 = IX MSK (Watzof, 1902). After a quiescence of about 50 years, a strong event with M = 6.5 occurred in 1905 near the western marginal part of the Sofia area. However, no such large earthquakes have occurred in the Sofia area since 1905 (Christoskov *et al.*, 1995), which may induce non-professionals to underestimate the earthquake risk. A strong earthquake in the Sofia area can have disastrous consequences in a large region. In this paper, we present a Probabilistic Seismic Hazard Analysis (PSHA) and sensitivity analysis for the Sofia area.

The seismic hazard analysis is the computation of probabilities of occurrence per unit time of certain levels of ground shaking caused by earthquakes. A PSHA requires a model consisting of three main elements: the model of sources of potential future earthquakes, that is a configuration of seismically active zones and/or faults, a statistical description of seismicity in these zones, and an attenuation function relevant to the hazard parameter considered (McGuire, 1993). The PSHA output is defined as the probability that a ground motion parameter will be exceeded within a given time period. We have chosen the Peak Ground Acceleration (PGA) as an output parameter.

Several papers have been published on the seismic hazard in Bulgaria, among others, Boncev *et al.* (1982), Orozova-Stanishkova and Slejko (1994), and van Eck and Stoyanov (1996). Boncev *et al.* (1982) proposed the seismic zoning of Bulgaria based on an analysis incorporating most of the seismicity, geological and geophysi-

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cal data available to date. The study presents seismic hazard maps for Bulgaria in terms of MSK-64 intensities for a 100, a 1000 and a 10000 year return period (or for 10^{-2}, 10^{-3} and 10^{-4} annual probabilities of exceedance). Orozova-Stanishkova and Slejko (1994), considering different probabilistic approaches, provide seismic hazard estimates for both intensity and horizontal PGA for Bulgaria in a 100-year return period. Seismicity data (concerning the strong events) from the NOAA (1988) earthquake catalogue and a seismotectonic model proposed by Orozova-Stanishkova and Slejko (1994) were used for the PSHA of Bulgaria. Van Eck and Stoyanov (1996) performed a PSHA for Southern Bulgaria. For this purpose they compiled and interpreted a regional seismicity catalogue based on the Bulgarian and Greek earthquake catalogues and proposed a zonation model based on the hypothesis that Southern Bulgaria and Northern Greece can be considered as one seismotectonic unit related to that of the Aegean Sea.

Our paper uses some data presented in Boncev *et al.* (1982) such as configuration of the seismic source zones within the 200 km region surrounding the Sofia area and the maximum expected magnitude for each zone. Otherwise our paper differs in many aspects. We consider a newly compiled regional and near regional seismicity catalogue, we use different seismic characterization of the seismic sources and finally we specify seismic hazard in terms of PGA instead of intensities.

In our paper, we first review the seismotectonics and seismicity of the region surrounding the Sofia area (within a radius of about 200 km). We compile and interpret a regional seismicity catalogue. Next, we present a seismicity model for the considered region. We continue with PSHA and a sensitivity analysis, involving the attenuation models and seismicity statistics of the seismogenic sources. Finally, the results are discussed and conclusions drawn.

2. Geological outline

The eastern part of the Balkan Peninsula is an element of the continental margin of Eurasia from a plate-tectonic point of view. This margin is located between the stable part of the European continent (the Moesian platform) to the north and ophiolitic sutures (Vardar and Izmir-Ankara) to the south. South of the suture, fragments of the passive continental margin of Africa crop out (Boyanov *et al.*, 1989). The neotectonic movements on the Balkan Peninsula were controlled by extensional collapse of the late Alpin orogen, and were influenced by extension behind the Aegean arc and by the complicated vertical and horizontal movements in the Pannonian region (Zagorcev, 1992a).

The sketch map of the main tectonic units in the region surrounding the Sofia area (within a radius of about 200 km) is presented in fig. 1. (from Dachev *et al.*, 1995). The considered region covers the southern part of the Moesian platform and the northern part of the Central-Balkan neotectonic region (as defined by Zagorcev, 1992a).

The Moesian platform (plotted as MP in fig. 1) covers most of Northern Bulgaria and is assumed (Dachev *et al.*, 1995) to be an element of the stable Paleo-Europe plate and retains its specific dynamics during the neotectonic cycle.

The Central-Balkan neotectonic region, as defined by Zagorcev (1992a), is situated between the Stara-planina and Dinarian-Hellenic linear morphostructures. The region is characterized by a complicated block structure (horst-and-graben pattern) dominated by bordering fault zones, such as the NNW-SSE Struma and Vardar, the WNW-ESE Marica and the Middle-Mesta. Transverse fault zones striking SW-NE are most important for the development of the Vardar and Struma zones and the whole Central-Balkan neotectonic region. The principal fault zones acted mostly as normal faults during the neotectonic stage.

The Stara-planina linear morphostructure almost coincides with the Stara-planina (SP in fig. 1) and Fore-Balkan (FB in fig. 1) zones of the Balkanides (Zagorcev, 1992a). The Fore-Balkan is a negative tectonic unit, which is characterized by fold-block structures represented by narrow anticlinales and wide synclines. The Stara Planina is a young Alpine mountain chain, which was uplifted as linear neotectonic morphostructure externally rimmed by the Pannonian and Precarpathian basins (Zagorcev, 1992a),

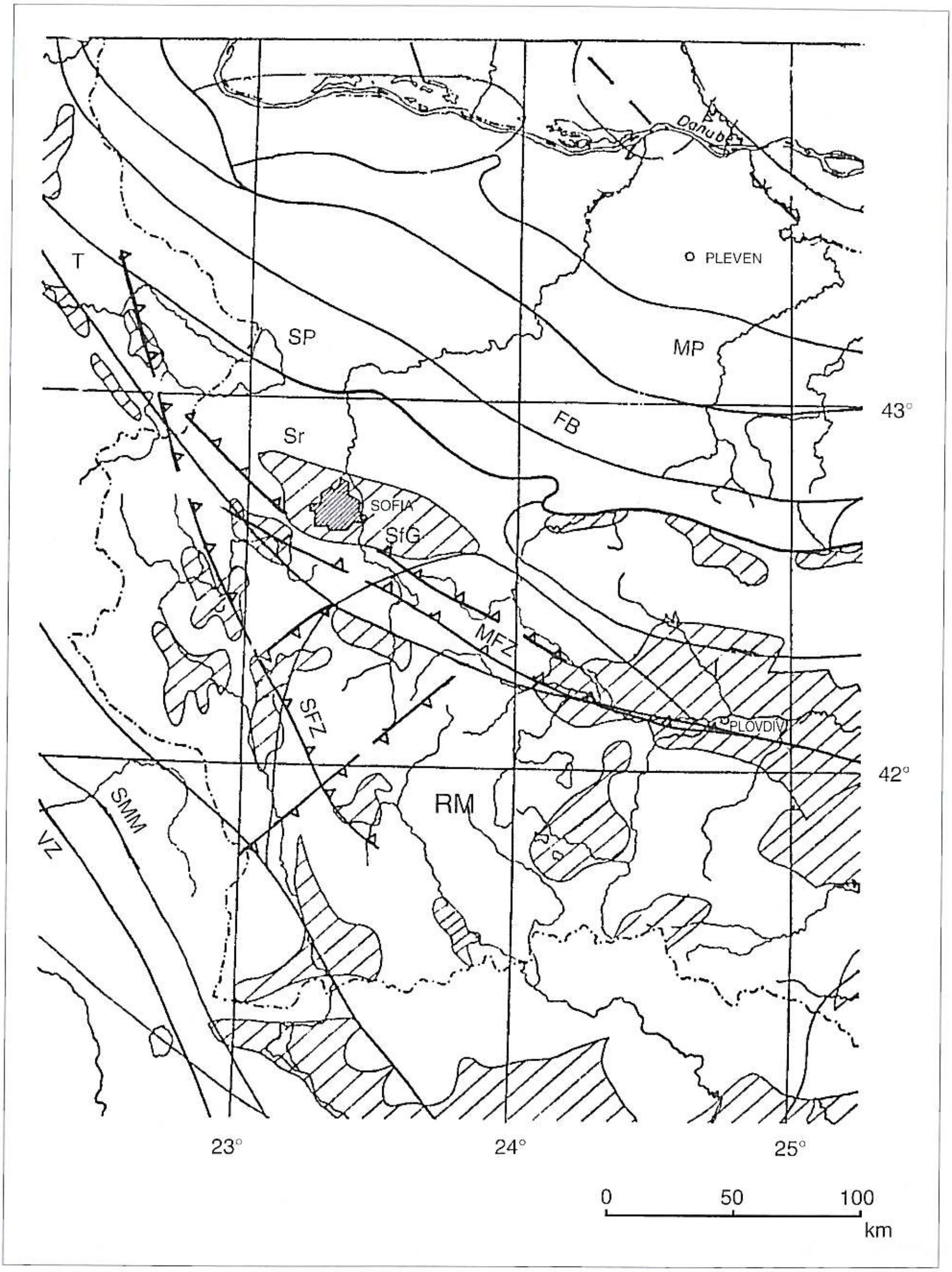


Fig. 1. Sketch of the neotectonics of the central parts of the Balkan Peninsula (modified from Dachev *et al.*, 1995). Our area of investigation essentially comprises the Moesian platform (MP), the Stara-planina (SP), the Fore-Balkan zone (FB), the Srednogorie (Sr), the Rhodope massif (RM), the Sofia graben (SfG), the Marica fault zone (MFZ) and the Struma fault zone (SFZ). Other important tectonic structures indicated are: Serbian-Macedonian massif (SMM), Tymok tectonic unit (T) and Vardar zone (VZ).

and limited to the south of the Sub-Balkan neotectonic fault zone.

Srednogorie (Sr in fig. 1) and Tymok (T in fig. 1) units composed a belt with widely occurring phenomena of volcanic and plutonic magmatism of an island-arc type in the Upper Cretaceous. Well-defined block and horst structures divided by deep graben depressions infield with Neogene-Quaternary sediments were formed within this region (Dachev *et al.*, 1995). The south boundary of the Srednogorie zone is represented by the Marica fault zone (MFZ in fig. 1), which is the most prominent neotectonic structure and divides Srednogorie from the Rhodope massif (RM in fig. 1).

The contemporary structure of the Rhodope massif is assumed (Dachev *et al.*, 1995) to be a result of polyphase Alpine tectonogenesis. During the neotectonic phase, the Rhodope experienced predominantly positive dome, dome-block and horst vertical movements. Zagorcev (1992b) considers that the most thickened crustal lens of the Rhodope massif (40-55 km) coincide with a pronounced isostatic anomaly and the most intense (up to 0.5 mm/yr) recent vertical uplift. Moreover, he proposes that intense uplift of the western part of the Rhodope massif caused differential neotectonic movements along the preexisting bordering fault zone, such as the Marica, Middle-Mesta and Struma fault zones (SFZ in fig. 1).

The Serbian-Macedonian massif (SMM in fig. 1) is located closer to the suture of the Vardar zone (VZ in fig. 1). That is the reason for its more intensive segmentation by epi-Kimmerian collision and abduction processes, as well as by post-collision graben-forming processes and phenomena of profuse Paleogene-Neogene sedimentation and magmatism (Dachev *et al.*, 1995).

The area of Sofia is situated in the most northern part of the Central-Balkan neotectonic region. The contemporary tectonic activity of the Sofia area is associated predominantly with marginal faults of the Sofia graben (SfG), which is developed at the junction between the Sub-Balkan and Marica graben complexes (Zagorcev, 1992a). The south and north boundaries of the Sofia graben are represented by SE-NW fault zones with expressive neotectonic activity.

In our subsequent PSHA we follow the seismic zoning of Bulgaria proposed by Boncev *et al.* (1982) which is supported basically by the most recent tectonic model for the considered region here presented.

3. Seismicity

The seismicity of the Sofia area and its surroundings (within a radius of 200 km) is mainly compiled from the following catalogues: *Catalogue of Earthquakes, Part I and Part II* (Shebalin *et al.*, 1974); *New Catalogue of Earthquakes in Bulgaria for the Period V Century B.C.-XIX Century* (Christoskov *et al.*, 1979); *Catalogue of Earthquakes in Bulgaria and Adjacent Areas for the Period 1900-1977* (Grigorova *et al.*, 1979); and *Bulgaria Catalogue of Earthquakes 1981-1990* (Solakov and Simeonova, 1993). The data have been checked and complemented with data about historical events prior to 1900 (from Sokerova *et al.*, 1992 and Christoskov *et al.*, 1995), data from NOAA catalogue and from Seismological Reports of the Bulgarian National Operative Telemetric System for Seismological Information (NOTSSI).

Seismicity data can be divided into three time-period categories with a different determination accuracy of earthquake parameters (Ho, φ, λ, h, M):

1) Pre-1900, pre-instrumental, historical era; data sources are historical and macroseismic only (low accuracy of earthquake parameters).

2) 1900-1970, early instrumental data; principal information is non-instrumental.

3) 1970-1995, modern instrumental data are available (the best determined quakes).

The size of the quakes is given in terms of surface-wave magnitude M_s. The earthquake catalogue thus obtained for the territory of the considered region consists of 516 events with magnitude $M_s \geq 4.0$ which were used for all the following analyses of the regional seismicity. Using a space-time magnitude dependent window as proposed by Christoskov and Lazarov (1981) for the Balkan region we identified the aftershocks. The Stepp (1971) test indicates that the catalogue can be considered complete in the last 350 years for magnitudes larger than 6.0,

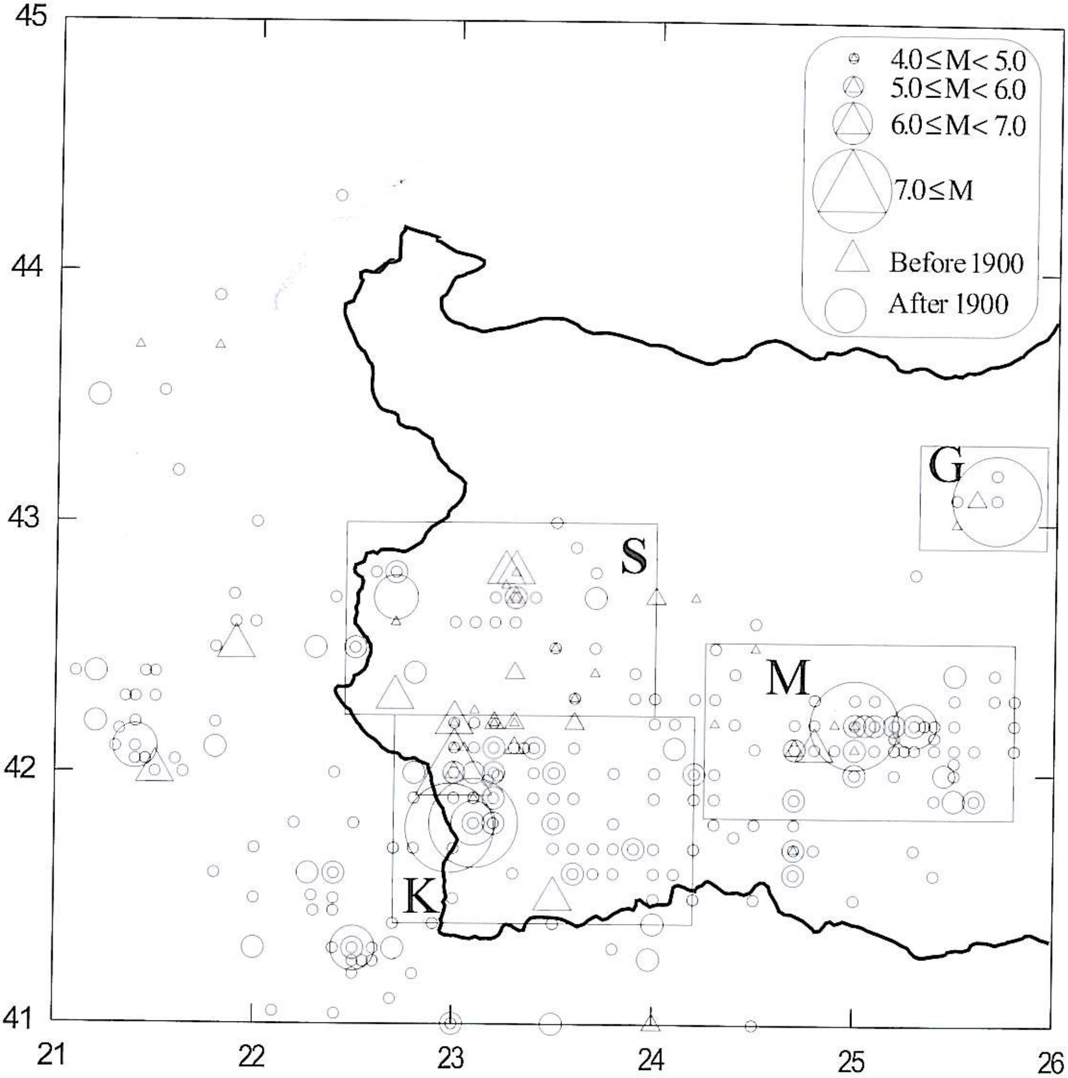


Fig. 2. Seismicity ($M_s \geq 4.0$) of the study area. The magnitude key is shown in the upper right corner.

and after 1900 for $M_s > 4.0$ (Sokerova *et al.*, 1992).

The spatial pattern of seismicity for the Sofia and adjacent areas (within a radius of 200 km) is shown in fig. 2. This figure represents the epicentral map of the earthquakes with $M \geq 4.0$ that occurred in the considered region. The region involves Western Bulgaria, parts of Central and Northeastern Bulgaria, the eastern part of former Yugoslavia and the most northern part of Greece.

From the analysis of the depth distribution (Sokerova *et al.*, 1992), it was recognized that the earthquakes in the region occurred in the Earth's crust up to 45 km. The hypocenters are mainly located in the upper crust, and only a few events are related to the lower crust. The maximum density of seismicity involves the layer between 5 and 25 km.

3.1. *Regional seismicity*

The epicentral map (fig. 2) shows that seismicity in the region is not uniformly distributed. The seismicity of Bulgaria can be related to seismic zones defined by Sokerova *et al.* (1992) on the basis of spatial distribution of seismicity and the expected source zones as suggested by Boncev *et al.* (1982). The region we considered involves the following seismic zones, within the territory of Bulgaria: Marica, Kresna and Gorna Orjahovica. Its own specific tectonic, seismic, and geological particulars characterize each zone.

Marica seismic zone – marked by symbol M in fig. 2. Seismicity in the Marica zone is predominantly associated with the WNW-ESE oriented Marica fault zone. The Marica fault with its satellites belongs to structures with a long-lasting development, which continues in the neotectonic period. The largest of its segments, which is with well-expressed Neogene-Quaternary activity, reaches a length of about 70 km (Dachev *et al.*, 1995). The strongest earthquakes which affected the zone are those in 1928 (the Chirpan earthquake of April 14, 1928 with $M_s = 6.8$ and the Plovdiv earthquake of April 18, 1928 with $M_s = 7.0$). The hypocenter distribution involves the surficial 20 km, with sporadic events down to 45 km. The highest density of foci is observed at 5-10 km depth (Sokerova *et al.*, 1992).

Kresna seismic zone – marked by symbol K in fig. 2. The deep NW-SE oriented Struma fault, which is intersected, in a transverse direction, by numerous neotectonic faults is the most important structure in this area. The high seismic activity of the zone is related to the Struma fault zone. Some of Europe's strongest earthquakes 20th century occurred in the Kresna seismic zone – the Kresna earthquakes of April 4, 1904 (M_s = 7.2 and 7.8). The deepest earthquakes in Bulgaria occurred in the Kresna zone, where the crustal thickness is also large (under the west part of the Rhodope massif it reaches 45-50 km). The hypocenters of the earthquakes are distributed mainly in the surficial 30 km with the highest concentration of foci between 5 and 20 km. The hypocenters have maximum focal depth down to 50 km (Sokerova *et al.*, 1992).

Gorna Orjahovitza seismic zone – marked by symbol G in fig. 2. This zone is situated at the border of the considered 200 km region surrounding the Sofia area. The main tectonic structure in this area is the E-W extended Resenski trough, which formed during the Quaternary period. Two sublatitudinal faults, which are reactivated segments of the Fore Balkan fault, and an oblique fault in NE-SW direction marks the boundaries of the Resenski trough (Dachev *et al.*, 1995). The strongest event here occurred in 1913 ($M_s = 7.0$), followed by seismic quiescence until 1986 when the two moderate Strazhitza earthquakes occurred ($M_s = 5.3$ on February 21 and $M_s = 5.7$ on December 7). The seismicity in the zone is shallow, concentrated mainly in the surficial 15 km, with rare events down to 25-30 km depth (Sokerova *et al.*, 1992).

The zones outside Bulgaria (such as the eastern part of former Yugoslavia and the most northern part of Greece) are here schematized in a very general way. The differences within each of these zones are not considered.

3.2. *Seismicity of the Sofia area*

The Sofia area coincides with the Sofia seismic zone as defined by Sokerova *et al.* (1992), which is marked by symbol S in fig. 2. Seismicity in the zone is related mainly to the marginal neotectonic faults of Sofia graben. The available historical documents prove the occurrence of destructive earthquakes during the 15th-18th centuries in the Sofia zone (Watzof, 1902). However, the information on the ancient events is very incomplete and uncertain and only an approximate estimation of their location is possible. The first well-documented strong earthquake of magnitude $M_s = 6.0$ occurred in 1818 near the town of Sofia (Christoskov *et al.*, 1979). The largest earthquakes which affected the zone are those in 1858 (near the town of Sofia) and in 1905 (near the town of Trun in the western marginal part of the zone). Both had a magnitude $M_s = 6.5$ (Grigorova *et al.*, 1979; Christoskov *et al.*, 1995). The 1858 earthquake caused heavy destruction to the town of Sofia and the appearance of thermal springs in the western part of the town. During the present century, the strongest event occurred in the vicinity of the town of Sofia is the 1917 earthquake with $M_S = 5.3$ and $I_0 =$ VII-VIII MSK. The earthquake was felt in an area of 50000 km^2 and followed by aftershocks, which lasted more than a year (Kirov, 1952; Petkov and Christoskov, 1965). No earthquakes with magnitude larger than or equal to 5 have been localized in the Sofia seismic zone since 1917. The strongest event of recent years is the magnitude 4.3 quake in 1980. The seismicity involves the surficial 20 km. A bimodal depth distribution with expressed peaks at 5 and 15 km is observed in the earthquake data (Sokerova *et al.*, 1992).

4. Probabilistic seismic hazard analysis

We performed a PSHA, using the so-called deductive method (McGuire, 1993), which deduces what the causative sources, characteristics, and ground motions for future earthquakes are. This method was first published by Cornell (1968), with many applications since. More specifically, a version of machine code EQRISK (McGuire, 1976) is used in the present study with PGA as a hazard parameter. The main difference from the original code consists in using calculation procedures for a coordinate transformation and distance integration presented in Bender and Perkins (1982). The machine code was implemented to use different attenuation relations for each source zone. The analysis methodology is based on the concept that the seismic hazard at a site is a function of three main components: the space geometry of seismic sources, the characteristics and statistics of their seismicity and the characteristics of seismic wave propagation in the region. The resulting hazard at a specified site is obtained by integrating the effects of ground motion from earthquakes of different size occurring at different locations within different seismic sources, and with different frequencies of occurrence.

4.1. *Seismic sources*

We modeled seismicity in the Sofia area and its surroundings (within a radius of 200 km) by areal sources, each of which is deemed to be uniform in the character of its seismicity. In this particular study, we use a seismic source model that is derived from the seismic zoning of Bulgaria (Boncev *et al.*, 1982) and corresponds to the here presented seismotectonic characteristics of the considered region. The model includes all seismic sources that substantially influence the seismic hazard of the Sofia area. We consider four seismic source zones (two single source zones and two multiple source zones) on the territory of Bulgaria as presented in fig. 3. We assume an equal probability that an earthquake could occur in any place within a single source zone. For seismic zones that include more than one source (such as Sofia and Kresna, see fig. 3) we accept that: 1) earthquakes of magnitude M are uniformly randomly distributed within all sources with $M_{\max}$ larger than or equal to M; 2) an equal b values for each source; 3) the number of earthquakes in a given single source is proportional to its size. 4) different $M_{\max}$ for each source (see fig. 3). We accept that earthquakes with magnitude less than 5.0 (considered as background seismicity) occur all over the Sofia seismic zone as assumed in Boncev *et al.* (1982).

Seismicity in the eastern part of former Yugoslavia (marked in fig. 3 as Macedonia) is here modeled by a hypothetical areal source, which is located at a minimum distance of 100 km from the city of Sofia. We modeled a seismic zone in Northern Greece as a point source at a minimum distance of 240 km (fig. 3).

4.2. *Seismicity parameters*

Cornell (1968) assumes a Poisson process as a time-of-occurrence model for each seismic source zone. Consequently the seismicity statistics are defined by specifying the magnitude-frequency relation with the annual seismic rate parameter, λ, the b-value of the Gutenberg-Richter exponential relation, the minimum magnitude, $M_{\min}$ and the maximum possible magnitude, $M_{\max}$. The rate of occurrence λ is calculated on the basis of the Gutenberg-Richter parameters a and b ($\log N = a - b\,M$). The parameters a and b for a cumulative frequency-magnitude relation were

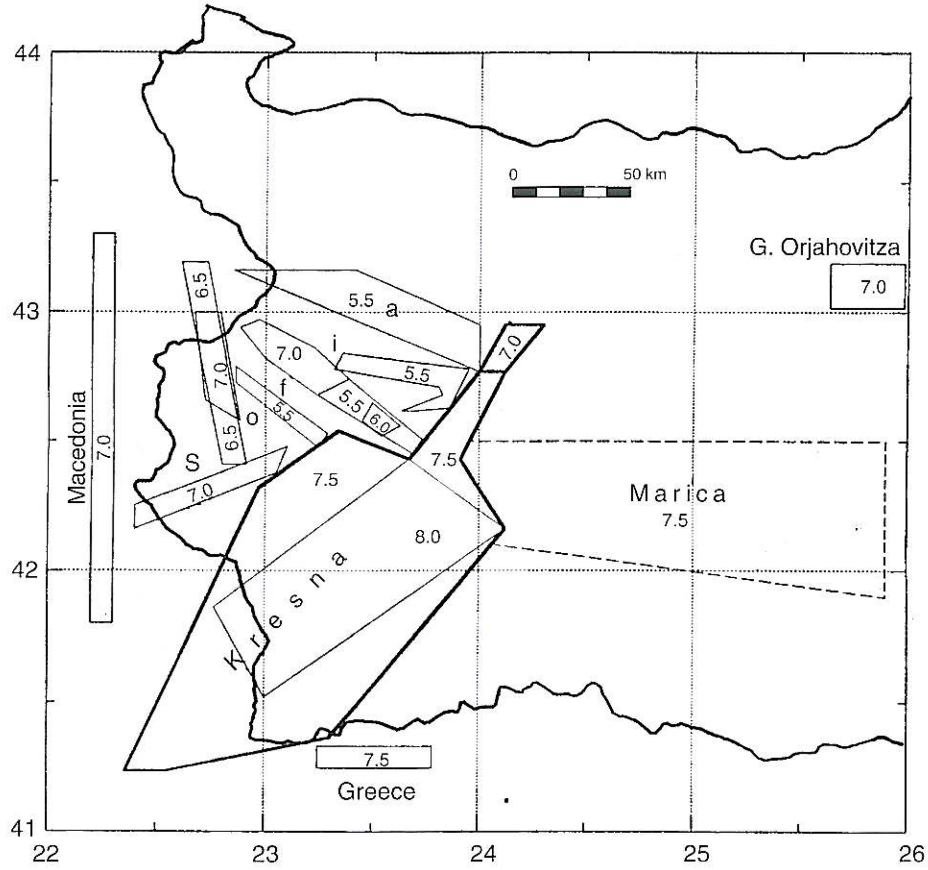


Fig. 3. The seismic source model (modified from seismic zoning of Bulgaria presented in Boncev *et al.*, 1982) used in the study. See table I for details of each zone.

calculated by the least square method, by considering the main events with magnitude larger than, or equal to, 4.0 for each seismic source zone on the territory of Bulgaria. Standard deviations of *a* and *b* values were also calculated. The values of λ and b presented by Orozova-Stanishkova and Slejko (1994) are used in our PSHA for the hypothetical source in the eastern part of former Yugoslavia. We chose the *b*-value obtained by Hatzidimitriou *et al.* (1985) for the seismic source in the northern part of Greece. The λ value for this source is determined from available seismicity data for Northern Greece.

The M_{max} we used in the analysis are the maximum expected magnitudes proposed by Boncev *et al.* (1982) and presented in fig. 3. The values of M_{max} were obtained as an expert judgement based on geological, historical and instrumental evidence for each source. The PSHA model parameters, λ, b, M_{min} and M_{max} are summarized in table I. for each seismic source zone.

The uncertainties regarding the parameters a, b and M_{max} have been considered in the sensitivity analysis.

4.3. *Peak ground acceleration attenuation*

The attenuation of the PGA and its uncertainty is of substantial importance in hazard

Table I. Seismic source zones and characteristic seismicity parameters. Parameters: λ - seismicity rate for magnitude larger than M_{min}; a and b - Gutenberg-Richter parameters; M_{min} - the smallest magnitude considered in the PSHA; M_{max} - maximum expected magnitude as presented by Boncev *et al.* (1982). The parameters a and b for which no error bounds are given are kept fixed in the sensitive analysis.

Seismic zone	λ	a	b	M_{min}	M_{max}
Sofia	0.16	1.97 ± 0.18	0.69 ± 0.035	4.0	7.0
Kresna	0.81	3.31 ± 0.12	0.85 ± 0.02	4.0	8.0
Marica	0.53	3.32 ± 0.24	0.90 ± 0.04	4.0	7.5
G. Orjahovica	0.013	1.76 ± 0.33	0.73 ± 0.06	5.0	7.0
Macedonia	0.67	2.59	0.69	4.0	7.0
Greece	0.17	2.43	0.64	5.0	7.5

analysis. Ground motion attenuation relationships define the values of a ground motion parameter, such as Peak Ground Acceleration (PGA), as a function of earthquake size (magnitude M) and the distance in terms of both the expected values and the dispersion of the expected values. Attenuation relationships are developed usually from the statistical analysis of strong motion data. Unfortunately, only a few strong motion records are currently available for the territory of Bulgaria (Nenov *et al.*, 1990) where most of the earthquake history is pre-instrumental (only a few moderate earthquakes, magnitude less than 6.0, have occurred in modern times). Thus the attenuation relationships which have been proposed for the region are either based on strong motion data from surrounding regions (such is the relation proposed by Petrovski and Marcellini, 1988 for strong motion data from Italy, former Yugoslavia and Greece, and the one proposed by Theodulidis and Papazachos, 1992 based on a data set from earthquakes predominantly in Greece) or obtained by using empirical attenuation relationships derived from local intensity attenuation curves (such is a relation proposed by Orozova-Stanishkova and Slejko, 1994).

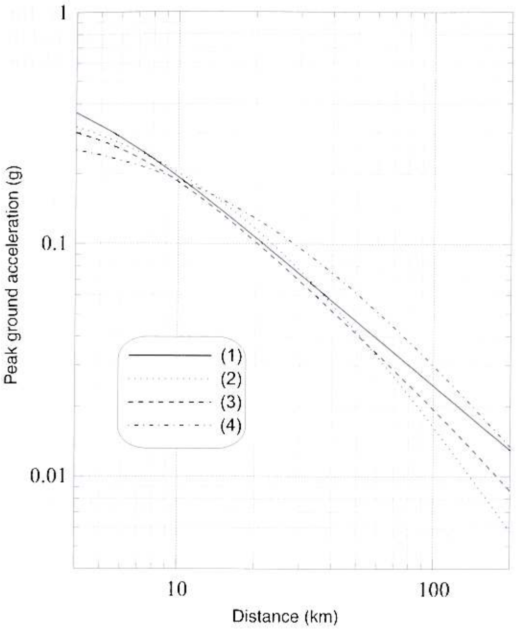
Two approaches for choosing a PGA attenuation relation that compares best with the regional data are possible. The first approach is to estimate PGA by using intensity attenuation relations based on local data. An alternative is to compare well-based empirical PGA attenuation relationships for other regions to the available data. These relationships should incorporate known characteristics of local earthquake motions. The first method has the disadvantage of unacceptable large uncertainties and known differences cannot be incorporated directly. Therefore, in the present study we chose the second method with the PGA attenuation relationship proposed by Ambraseys *et al.* (1996). The relation is based on a large data set from shallow earthquakes in Europe and Midle East (as reported in Douglas, 2001).

The PGA for stiff soil ($360 < V_s \leq 750$ ms^{-1}) is given by the expression

$$\ln a = -3.138 + 0.6125\,M - 0.922\,\ln(r) \qquad (4.1)$$
$$(\sigma_{\ln a} = 0.576),\ (g)$$

where $r = (d^2 + 3.5^2)^{1/2}$ (d - epicentral distance for $M \leq 6.0$, and distance to projection of rupture plane on surface for $M > 6.0$) in km, M - earthquake magnitude and σ denotes the standard deviation in terms of the left-hand side of the equation.

Figure 4 compares the peak horizontal accelerations estimated by the four sets of relationships (Ambraseys *et al.*, 1996; Theodulidis and Papazachos, 1992; Ambraseys and Bommer, 1991, and Petrovski and Marcellini, 1988) for magnitude $M_s = 6.0$. A comparison of predicted PGA shows a very good agreement at source-to-site distances from 5 to 50 km among the relations of Ambraseys *et al.* (1996), Theodulidis and Papazachos (1992) and the one by Ambraseys and Bommer (1991). The relationship by



Ambraseys *et al.* (1996) is more conservative and tends to predict larger PGA both in the near field (distances less than 5 km) and for distances larger than 50 km. The relation by Petrovski and Marcellini (1988) predicts the lowest ground motions at small distances (up to 10 km) and the largest PGA values at large source-to-site distances.

Van Eck and Stoyanov (1996) compared the estimated horizontal PGA using the empirical attenuation curve of Ambraseys and Bommer (1991) based on data from shallow earthquakes in Europe and regionally observed PGA values (Nenov *et al.*, 1990). The results indicate a relatively good coincidence of the mean values, but

Fig. 4. Empirical PGA attenuation curves for $M_S = 6.0$ by (1) Ambraseys *et al.* (1996); (2) Theodulidis and Papazachos (1992); (3) Ambraseys and Bommer (1991), and (4) Petrovski and Marcellini (1988).

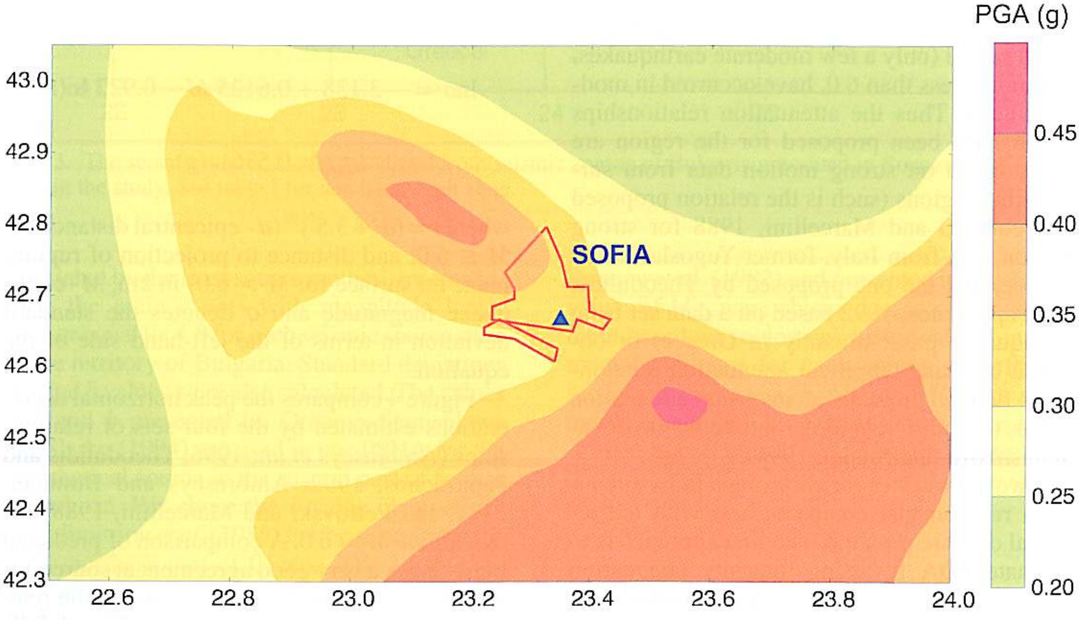


Fig. 5. Horizontal PGA values with a 10^{-3} annual exceedance probability for the Sofia area. The presented results are for the attenuation relationship by Ambraseys *et al.* (1996). The test site is indicated by a triangle.

a large data scatter. It is supposed that the scatter is due to the specific site conditions, which have not been corrected. As detailed site information about these data is presently not available we study the influence of this uncertainty on our PSHA results in the sensitivity analysis.

4.4. *Seismic hazard map*

The seismic hazard map for the Sofia area was obtained using the model of seismic sources presented in fig. 3 and specified in table I. Hazard curves are calculated at a grid interval of 0.05° latitude and 0.06° longitude using the attenuation relations of Ambraseys *et al.* (1996). Figure 5 displays the seismic hazard for annual probability of exceedance 10^{-3} expressed in PGA. Figure 6 presents the seismic hazard for a site situated in the southeastern part of the town of Sofia (shown in fig. 5). The hazard map shows that the southeastern part of the Sofia area has enhanced hazard. The highest contour values are 0.45-0.46 *g*. A qualitative assessment of the significant seismic hazard shows that the PGA of 0.3-0.35 *g* will be exceeded at least once in 1000 years (*i.e.* annual probability of exceedance 10^{-3}) with probability 0.62 in much of the town of Sofia. The estimated PGA for the Sofia area varies between 0.20-0.46 *g* for annual probability of exceedance 10^{-3}. Of the specific site investigated we find a comparatively good coincidence of the PGA values estimated by using different empirical attenuation curves. The maximum difference between PGA predicted by the four considered attenuation relations is about 0.07 *g* for annual probability of exceedance 10^{-3}. This difference is reduced to 0.045 *g* if the relation of Petrovski and Marcellini (1988) (which is the most conservative for distances larger than 20 km and has the largest standard deviation) is excluded (see fig. 7).

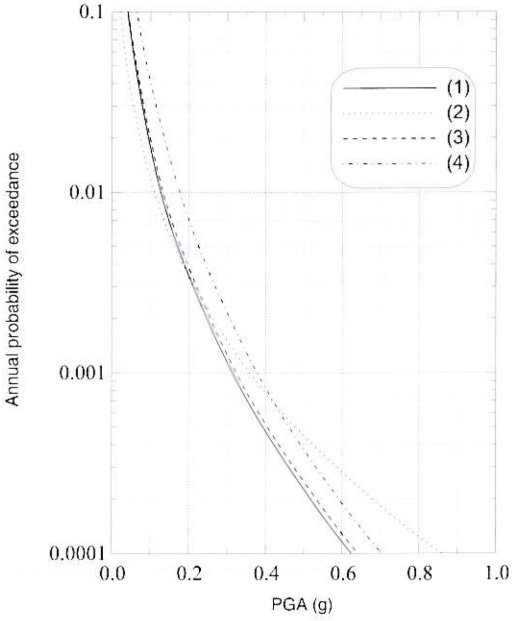


Fig. 6. PSHA for the test site with four alternative attenuation models: (1) Ambraseys *et al.* (1996); (2) Theodulidis and Papazachos (1992); (3) Ambraseys and Bommer (1991), and (4) Petrovski and Marcellini (1988), the same seismic source model and the same seismicity characteristics.

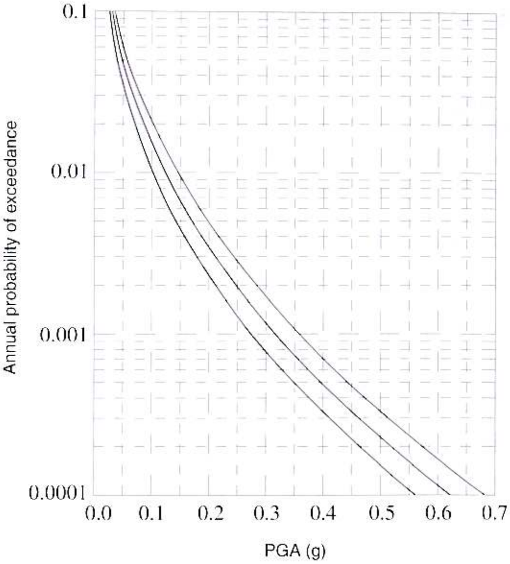


Fig. 7. PSHA for the test site with the same seismic source model and the same attenuation model but with different seismicity characteristics. In the figure, the lower, middle and upper curves indicate the 15% confidence, mean and 85% confidence respectively.

5. Sensitivity analysis

Although the PSHA results were estimated using the currently available practices, the question of its reliability lingers due to the limitation of the available data. Therefore we performed a sensitivity analysis.

Two types of variability are defined in the seismic hazard analysis-aleatory variability (or randomness inherent in the natural phenomena) and epistemic variability (or uncertainty that comes from statistical or modeling variations). Segregating seismic hazard variability into two types is important because the seismic hazard estimates will evolve with time as we learn more about seismicity, tectonics and strong ground motion estimation (McGuire, 1993).

Modern methods of the seismic hazard analysis allow all information on tectonics, seismicity, and earthquake ground motion to be incorporated into the analysis. Alternative interpretations can be accommodated through a quantitative evaluation of uncertainties, expressing uncertainties in seismic hazard as a function of uncertainties in the inputs. Uncertainties can be treated in a sensitivity analysis that considers all plausible models and model parameters to provide insights into the effects of different assumptions (McGuire, 1993).

In our sensitivity analysis, we use a combination of the two widely used methodologies, *i.e.* the logic tree approach (Coppersmith and Youngs, 1986) and the Monte Carlo analysis (Bungum *et al.*, 1986). The logic tree formulation for seismic hazard analysis involves specifying discrete alternatives for states of nature or parameter values and specifying the relative likelihood that each discrete alternative is a correct value of the input parameter. Monte Carlo analysis is used to estimate the impact in hazard assessment of parameters whose values could, in concept, be random variables with known distribution. The Monte Carlo approach performs a PSHA on a basis of randomly chosen models and parameters for which we obtained a large number of probability-of-exceedance curves.

Our approach to the sensitivity analysis is to divide it into two parts: characteristics of the seismicity within the seismic sources and the attenuation relationship. Current knowledge of the regional seismicity makes a meaningful sensitivity analysis for different characterizations, *i.e.* for a Monte Carlo approach sensitivity analysis of the seismicity within different seismic sources. For the attenuation relation we compare the influence of a different standard deviation $\sigma_{\ln a\max}$. In our sensitivity analysis we use the attenuation relationship of Ambraseys *et al.* (1996).

The parameters of magnitude-frequency curves were estimated from historical catalogues of earthquakes but with a margin of uncertainty. The maximum magnitude for each source is also uncertain, as no value can be proved to be a boundary limit. We incorporated uncertainties in the basic parameters of the seismicity distribution in our sensitive analysis by considering a range of truncated exponential distributions modeling the magnitude-frequency relation in the specific range of values of a, b and $M_{\max}$. We assume a and b to be normal randomly distributed with means and standard deviations presented in table I. An additional constraint for b value is that $0.5 \leq b \leq 1.2$. The correlation between a and b estimates that results from the least square method is also taken into account in the generation of random values. We consider the estimation errors of parameters a and b in our sensitive analysis.

The uncertainties in the maximum possible magnitude estimates have been included in the sensitive analysis by considering uniform distribution in the range $M_{\max} - 0.2$, $M_{\max} + 0.2$ ($M_{\max}$ for each seismic source is presented in fig. 3).

5.1. *Results*

For the sensitivity analysis on the characterization of the seismicity in the seismic sources we ran a PSHA for 1000 randomly chosen models within the above specified constraints. The results concerning the site in the southeastern part of the town of Sofia are presented in figs. 7 and 8. The lowest curve indicates the 15% confidence, the mean hazard curve is given in the middle and the upper one is the 85% confidence curve. Figure 7 shows that the variability is relatively low, especially when considering the assumed uncertainties. The 15%-85% range in the seismic hazard due to the characteristics of the seismicity within the seismic sources appeared to be about 0.084 *g* for annual probability of exceedance 10^{-3}. Figure 8 presents both the obtained PGA distribution for annual probability of exceedance 10^{-3} and its log-normal model approximation. The figure shows that the PGA distribution is very close to log-normal distribution (maximum difference of 0.025 for 1000 cases).

In order to investigate the influence of the amount of scattering of the observations around the attenuation relation of Ambraseys and Bommer (1991), we considered five different standard deviations $\sigma_{\ln a\mathrm{max}}$, *i.e.* 0.376, 0.476, 0.576, 0.676 and 0.776. $\sigma_{\ln a\mathrm{max}} = 0.576$ corresponds to the one given by Ambraseys *et al.* (1996) based on a data set from shallow earthquakes in Europe and the Middle East. We found the seismicity characteristics constant and used the same seismic source model. It turns out that the standard deviation has considerable influence on the PSHA as illustrated in fig. 9. A rough comparison with the available observational data in Bulgaria (Nenov *et al.*, 1990) shows that a large uncertainty, $\sigma_{\ln a\mathrm{max}} \approx 0.8$ should be considered. Thus, seismic hazard estimates, considering this uncertainty, fall somewhere among the upper three curves in the hazard plot in fig. 9. This may increase the 1000-year period (10^{-3} probability of exceedance) seismic hazard for the site at the most with 0.13 *g*. Consequently, an attenuation relationship based on local data could reduce the uncertainty in the PSHA. Van Eck and Stoyanov (1996) inferred similar results for Southern Bulgaria.

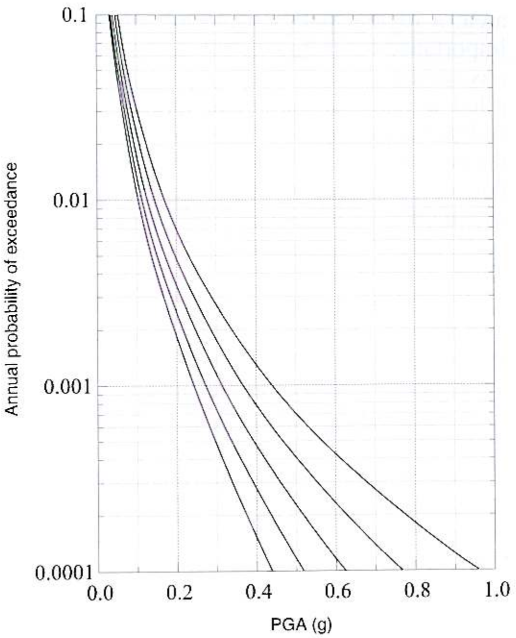


Fig. 9. PSHA for the test site with the same seismic source model and the same seismicity characteristics but with different (0.376, 0.476, 0.576, 0.676, and 0.776) standard deviations in the PGA attenuation model.

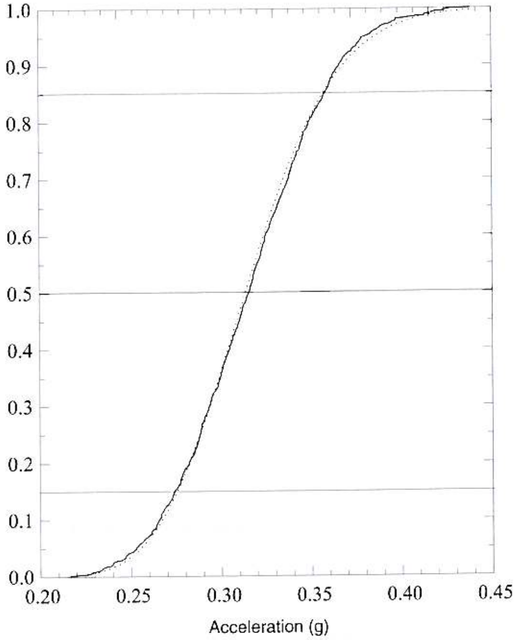


Fig. 8. PGA distribution for 10^{-3} annual probability of exceedance. The solid line corresponds to the observed distribution, the dashed line to the lognormal model distribution.

6. Discussion

Our initial purpose was to perform a Probabilistic Seismic Hazard Analysis for the Sofia area, a region that is of social and economic importance for Bulgaria, but also prone to serious seismic hazard. For this purpose, we compiled a regional catalogue largely based on Bulgarian earthquake catalogues and reviewed the regional seismotectonics. For a test site in the southeastern part of the town of Sofia, we present the seismic hazard and its uncertainties with respect to attenuation and seismicity modeling.

Our seismic source model is based on seismic zoning of Bulgaria (Boncev *et al.*, 1982) that corresponds to the recent interpretations of the regional geology and geophysics (Boyanov *et al.*, 1989; Zagorchev, 1992a,b; Dachev *et al.*, 1995). Although this zonation is probably not the best model for hazard analysis in this tectonically complex region, we believe this to be closer to recent regional tectonic studies than the more detailed zone model and the generalized regional model as proposed by Orozova-Stanishkova and Slejko (1994) and van Eck and Stoyanov (1996) respectively. However a relevant regional seismotectonic model and sensitive analysis with respect to zonation may influence significantly PSHA estimates and should therefore receive serious attention in future work.

In modeling the seismicity characteristics, we met some problems of more general nature. Although the Bulgarian catalogue of earthquakes extends far back in time, it is still too short to identify seismic hazard models other than a Poisson process, *i.e.* independent events and stationary seismicity rates. For the same reason (lack of alternative evidence), we chose the truncated exponential distribution with three parameters to model the magnitude frequency relation.

In our PSHA, aftershocks are excluded from the magnitude frequency distribution modeling. Practically, this implies that our seismic hazard estimates are inappropriate after the occurrence of large earthquakes in close temporal and spatial vicinity.

The PSHA shows that PGA for the Sofia area varies between 0.25-0.45 *g* for 10^{-3} annual probability of exceedance. Results reported by other authors (Boncev *et al.*, 1982; Stanishkova and Slejko, 1991) are confirmed by our PGA estimates for the Sofia area. The seismic hazard map for Bulgaria in terms of MSK-64 intensities for a 1000 year return period proposed by Boncev *et al.* (1982) reveals a maximum intensity equal to or higher than IX (MSK) for much of the Sofia area. (The adopted Bulgarian building construction code is based on this hazard map). Stanishkova and Slejko (1991) predicted for the town of Sofia a maximum intensity up to X (MSK) for a 1000 year return period. We obtained, using a recurrent relation between PGA and intensity (MSK) proposed by Orozova-Stanishkova and Slejko (1994), that the values of 0.27-0.40 *g* PGA with 10^{-3} annual probability of exceedance, correspond to intensity IX-X (MSK).

7. Conclusions

The PSHA for the Sofia area can be seen as a typical regional probabilistic seismic hazard analysis case. The main results from our study can be summarized as follows:

1) The PSHA shows significant seismic hazard in the Sofia area. We find that with 0.37 probability for much of the Sofia area, the PGA of 0.3-0.4 *g* will not be exceeded in 1000 years.

2) We show, using a Monte Carlo approach, that not large uncertainties in seismic characteristics have relatively little effect on the final seismic hazard.

3) We find that the amount of scattering of observations around a standard attenuation curve has a comparatively large influence on PSHA.

4) From our analysis, we conclude that a PSHA for the Sofia area can be improved if we obtain: i) more accurate attenuation models based on regional strong motion records; ii) a precise regional seismotectonic model relating seismicity to the contemporary active tectonic faults; iii) a more reliable estimation of the seismic characteristics.

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