

CARTOGRAPHIC REPRESENTATION ANALYSIS OF EARTHQUAKE HAZARD AND RISK MAPS FOR THE SOFIA REGION

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Abstract

The concentration of population and socio-economic and cultural activities in the capital city of Sofia leads to an increase in seismic risk with possible long-term consequences. This paper examines some aspects of seismotectonic model inputs, seismic source assumptions, and seismic activity modeling that are particularly important in seismic hazard and risk mapping. Several thematic maps published in the last two decades as a final product of the seismic hazard assessment (SHA) for Sofia are analyzed. The cartographic evaluation of these thematic maps is performed regarding hazard map content, depicted content, visualization methods, and cartographic layout. Comparisons are made with seismic hazard maps of other countries, and the advantages and disadvantages of specific criteria followed in the preparation of the map products are analyzed. Available national and European web-based GIS platforms providing access to up-to-date versions of seismic hazard and risk maps with different spatial resolutions for the Sofia region are discussed.

Keywords: seismic hazard and risk, thematic maps, cartographic methods, Sofia region

INTRODUCTION

Seismic hazard and risk analysis and mapping are carried out at different levels – from global to regional, settlement to individual sites of national importance as a part of the critical infrastructure. For example, Frolova et al. (2017) addressed seismic hazard analysis and mapping at national, regional, and urban levels and paid attention to the information and web technologies used for data verification on built environment inventory and vulnerability. Thematic

maps of individual seismic parameters are prepared at different scales with different scopes and cartographic quality depending on the available data, methods and techniques. The seismic hazard in a given geographic area is often represented on a map by various ground motion parameters (e.g., peak ground acceleration (PGA) or qualitative indicators related to economic and social losses using a color scale and/or isolines. These parameters are determined through probabilistic and deterministic approaches. A significant part of seismic risk research is aimed at assessing the damage of buildings in percentages related to the direct economic losses for their repair, partial or complete destruction. According to national census statistics, some studies estimate the number of victims in collapsed buildings.

In recent years, catastrophic earthquakes worldwide and their associated damage have highlighted the need to assess seismic hazard and risk at the level of an administrative unit – a settlement. The number of studies on settlements that are most vulnerable to earthquakes and scientific publications devoted to the development of methodologies for the assessment of seismic risk at the urban scale by applying different approaches to assess their vulnerability and for spatial planning is growing worldwide (e.g., Moschetti et al., 2018; De Risi et al., 2019; Baldassarre et al., 2024). Data collection and analysis is increasingly done through the Geographical Information System (GIS) (Solakov et al., 2019; Trifonova et al., 2019; Jena et al., 2020). After the adoption in 2018 of the National Methodology for Analysis, Assessment and Mapping of the Seismic Risk of Bulgaria (<https://shorturl.at/abPW7>), which laid the foundation for the preparation of thematic maps for all settlements in the country, GIS has become a standard for preparing the specialized thematic maps for seismic hazard and risk.

Recently, the tendency towards the concentration of the population and the socio-economic and cultural activities in Sofia has been clearly expressed, which leads to an increase in seismic risk with possible long-term consequences. Sofia is located in a young graben and has experienced several strong earthquakes, such as the 1818 M6.0 earthquake (VIII–IX MSK-64) and the 1858 M6.5 earthquake (IX–X MSK-64). In the XXth century, the strongest earthquakes were the 1904 Ms5.0 (VI–VII MSK-64) event and the 1917 Ms5.3 event (VII–VIII MSK-64; Bonchev et al., 1982; Solakov et al., 2001). After about 95 years, a new moderately strong earthquake (ML=5.8; Mw=5.6, VII–VIII MSK-64) was realized in the Sofia seismic zone on May 22, 2012 (Solakov et al., 2019). The instrumental seismicity is distributed to a depth of 32 km, with a higher density at depths between 2 and 10 km. Of interest is an 'inactive layer' between 10 and 20 km, beneath the Vitosha fault, and a deep concentration of loci between 20 and 32 km (Stanishkova and Slejko, 1991).

Seismic hazard assessment (SHA) for the Sofia region was the subject of numerous scientific studies using the two generally accepted approaches – deterministic seismic hazard assessment (DSHA) and probabilistic seismic hazard assessment (PSHA). In contrast, scientific publications on seismic risk assessment are limited. The present work aims to review and critically analyze the thematic maps prepared over the years for the territory of Sofia. We discuss some aspects of seismotectonic model inputs, seismic source assumptions, and seismic activity modeling that are crucial in hazard and risk mapping. Several thematic maps published in the last two decades as the final product of the SHA for Sofia are included in the present analysis. The cartographic evaluation of these thematic maps was carried out regarding hazard map design, depicted content, visualization methods, and layout for using and reading information about the capital territory. Publicly available national and European web-based GIS platforms providing access to up-to-date versions of seismic hazard and risk maps at different spatial resolutions for the metropolitan area are also briefly reviewed.

SEISMIC HAZARD AND RISK ASSESSMENT

Since the 1990s, a seismic hazard assessment (SHA) and its mapping have been carried out on the national level (Bonchev et al., 1982; Orozova-Stanishkova & Slejko, 1994; vanEck and Stoyanov, 1996) and on city level (Solakov et al., 2001; Paskaleva et al., 2004; Solakov & Simeonova, 2006; Yosifov et al., 2018). The SHA was improved by supplementing the database of past events over the Bulgarian territory, improving the quality of seismic catalogs, and advancing the methods and technologies for data processing, analysis, and interpretation (e.g., Solakov et al., 2019), a more reliable assessment of the seismic hazard at the regional and local level for seismic risk management can be achieved (e.g., Kaneva, 2020). The reliability of the regional seismic hazard and risk assessment depends on the quality and quantity of data on historical and instrumental earthquakes. The National Seismic Network (NOTSSI) provides reliable registration and quality information about M>3.0 earthquakes. The accuracies of the determined earthquake parameters are, respectively: time or origin 0.1–1 s, coordinates 0.02–0.2 degrees, depth 1–10 km, maximum intensity 0.5 MSK-64, magnitude 0.1–0.30 of the magnitude unit (Solakov et al., 2019). In scientific research, the DSHA and PSHA approaches are commonly used, and in the modern application of the latter, aleatory (random) and epistemic (model) uncertainties are considered to improve probabilistic estimation (Glazer, 2016; Zanetti et al., 2023).

STUDIES OF THE SOFIA REGION

In the past three decades, seismic hazard analysis for the Sofia region has been the subject of numerous scientific studies and publications, while the scientific literature on seismic risk assessment at the urban level is limited. Sofia is in a thick sedimentary basin that fills a graben, approximately 80 km long and over 20 km wide. The faults in the Sofia

graben remain barely identified (Raudlov et al., 2023). Fig.1 shows the geological units, faults bounding the graben, and earthquakes with magnitude $M > 3.0$.

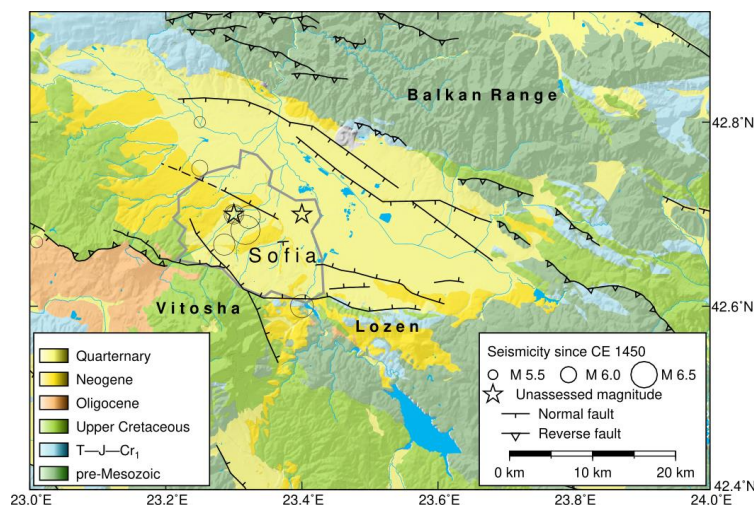


Figure 1. Geological map of Sofia area, main faults and seismicity since CE 1450

For a site-specific SHA, it is necessary to define the regions where future earthquakes will likely occur and the corresponding occurrence rates. Based on geology and historical seismicity, seismic zones can be defined. Three major seismic zones were defined for the Bulgarian territory: Moesia, Srednogorie and Rila-Rhodope zones (Bonchev et al., 1982; Orozova-Stanishkova & Slejko (1994). The Sofia region belongs to the Srednogorie zone. The SHAs for Sofia have been depicted on thematic maps at different scales. Below are systematized inferences after reviewing the seismic hazard and risk maps for the capital territory and nearby surroundings. Some of the comparative study results are not presented here due to volume limitations.

The seismotectonic model of Orozova-Stanishkova & Slejko (1994) contains two area seismic sources in the Sofia region: the Sofia zone located in the west and the Etropole zone in the east. According to Todorovska et al. (1995), the earthquakes in the Sofia zone follow the Gutenberg–Richter type magnitude–frequency distribution with a coefficient of 1.921 and b -value of 0.61, for the magnitude range between $M_{min}=2.75$ and $M_{max}=7.0$ and a depth distribution between $h_{min}=5$ and $h_{max}=40$ km.

The seismic risk for several European cities has been assessed within the European project RISK-UE framework, launched in 1999. The results of the detailed seismic hazard and risk studies were published in the book “Earthquake Risk Assessment and Management - Geo-scientific and Engineering Knowledge for Earthquake Risk Mitigation: developments, tools, techniques” by Oliveira et al. (2008). Only the Triaditsa district was covered for Sofia due to a lack of data. The detailed study of SHA and risk estimation was carried out by the former Central Laboratory of Seismic Mechanics and Earthquake Engineering at the Bulgarian Academy of Sciences (see, e.g., Kaneva, 2020).

The first PSHA for the Sofia area using the Cornell-McGuiri approach and EQRISK machine code was presented by Solakov et al. (2001). The authors used data from Bonchev et al. (1982), newly compiled seismicity catalogs, and updated parameters of the seismic sources to calculate the PGA. The adopted seismic source zone was modeled with a Gutenberg–Richter magnitude–frequency distribution with $a=1.97 \pm 0.18$, $b=0.69 \pm 0.035$, $M_{min}=4.0$, $M_{max}=7.0$. Fig. 2 shows maps of the seismic hazard, expressed as PGA values for the Sofia area under different scenarios, which were compiled by different authors (Solakov et al., 2001; 2009; Foteva et al., 2006; Kostov et al., 2007).

A more detailed map of surface zoning in the Sofia region, according to the engineering geological structures and considering seismic activity, was published by Ivanov (2002). The map represents different types of geological soils with great diversity and variability in lithological species' engineering seismic-geological conditions filling the Sofia kettle. The map is used by Paskaleva et al. (2004) to carry out a deterministic microzonation of Sofia city. The authors studied the site effects in a part of metropolitan Sofia based on modeling seismic ground motion along three cross-sections. They determined synthetic strong motion waveforms computed for an $M7.0$ scenario earthquake by applying a hybrid modeling method based on the modal summation technique and finite differences scheme. Paskaleva et al. (2004) calculated the response spectra ratio determining site amplification. A set of time histories and quantities of earthquake engineering interest were supplied, which allowed the definition of six zones characterized by specific response spectra. The obtained results can serve as an initial "database" that describes the ground motion in the central urban area of the capital.

In a recent model of seismic sources used for the SHA performed within the framework of the project “Seismic risk management of buildings,” purpose-funded by the Bulgarian government and implemented by NIGGG-BAS, the region around Sofia was divided into two seismic source zones named S1 and S2 (Solakov et al., 2019). Several faults with different dip directions are located in the Seismic Zone S1 (Sofia) and have a length of up to 43 km. The magnitude-frequency for S1 was modeled with $a=2.27$ and $b=0.8$ for $M_{\min}=3.2$. The maximum observed magnitude was 6.1 and the maximum assumed magnitude was 7.0. The S1 area source was delineated in the western periphery of the Srednogorie seismic region. The S1 area source contains two fault sources dipping to the north with diffuse earthquakes of M6.5. For the second zone S2 (Etropole) source zone, the parameters in the magnitude–frequency were respectively $a=2.39$, $b=0.8$, for $M_{\min}=3.2$, $M_{\max}^{\text{obs}}=6.5$ and $M_{\max}=7.0$. The S2 seismic zone was located in the Srednogorie seismic region and east of the Sofia seismic zone S1. Four faults are located in the S2 zone, striking in a direction NW-SE and having a length of up to 57 km. The maximum magnitude of the diffuse seismicity on these fault sources was assumed to be 6.0. The zones S1 and S2 in Solakov et al. (2019) almost coincide with the zones of Orozova-Stanishkova & Slejko (1994), but their magnitude–frequency distributions are different.

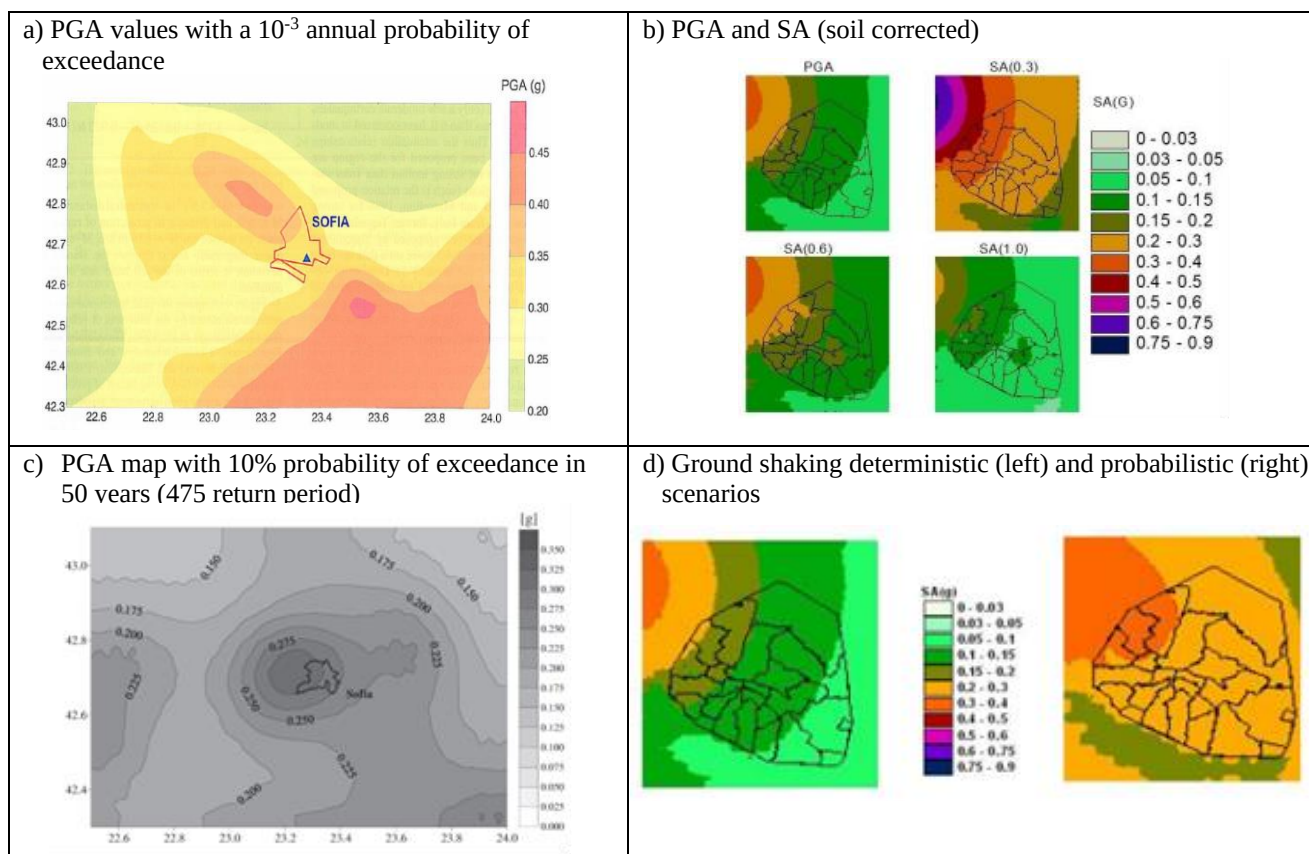


Figure 2. Seismic hazard maps expressed as horizontal PGA values for the Sofia area under different scenarios: a) Solakov et al. (2001); b) Solakov et al. (2009); c) Foteva et al. (2006); d) Kostov et al. (2007)

Alexandrova (2013) evaluated the macroseismic effects of the 2012 $M_w5.6$ earthquake on about 780 buildings in Sofia using documents and reliable information from the Archives Department of the Metropolitan Municipality. Based on in situ observations and according to the MSK-64 and EMS-98 scales, the buildings were assigned the intensity at which the given degree of damage is most likely to occur. Prevailing impacts are rated at VII-VIII degrees (MSK-64) with a concentration in the central part of the city. Most houses were built at the beginning of the 20th century and have not been renovated or are uninhabitable. A thematic map of the documented damages, assessed as intensities according to the MSK-64 and EMS-98 scales, has not been drawn up. The results from this study have been used in the updated hazard assessment of catastrophic earthquakes and their consequences (Solakov et al., 2021).

For Sofia's seismic microzoning, it is necessary to consider the engineering geological and hydrogeological conditions. The shear-wave velocity at a depth of 30 m, V_{s30} , is an essential parameter for evaluating the dynamic behavior of soil. Several maps for the Sofia region of V_{s30} have been prepared with different spatial resolutions, and classes of soil layers have been mapped. As an example, some published in scientific literature maps of V_{s30} for Sofia are presented in Fig. 3. Classified surface geological conditions determined by Ivanov (2002) were used by Paskaleva et al. (2012) to draw a 30-m deep model of the geotechnical soil classes A, B, C, D and E for the central part of the city (Fig. 2a). Using a diversity of data sources, most with archive origin, a min-max V_{s30} map (Fig. 3b) was compiled by Kisiov et al.

(2020). Another map with three soil classes, shown in Fig. 3c, was prepared by Solakov et al. (2021). For comparison, the USGS Vs30 map (Allen and Wald, 2007) is shown in Fig. 3d. When comparing the maps of Vs30 in Fig.3, it is evident that they differ both in terms of the areal distribution of the soil classes and the values of Vs30.

In 2020, a World Bank report was published on the risk profile of 27 earthquake-prone cities in Central Europe, the Balkans and Central Asia, including Sofia (World Bank, 2020). Seismic risk analysis of multifamily buildings was performed with the open-source software OpenQuake developed by Global Earthquake Model (GEM, 2018) using the PSHA approach under different scenarios and combining hazard, exposure and vulnerability models. Economic and human losses under two scenarios were assessed. The report noted that the estimated losses depend on the reliability of the input data.

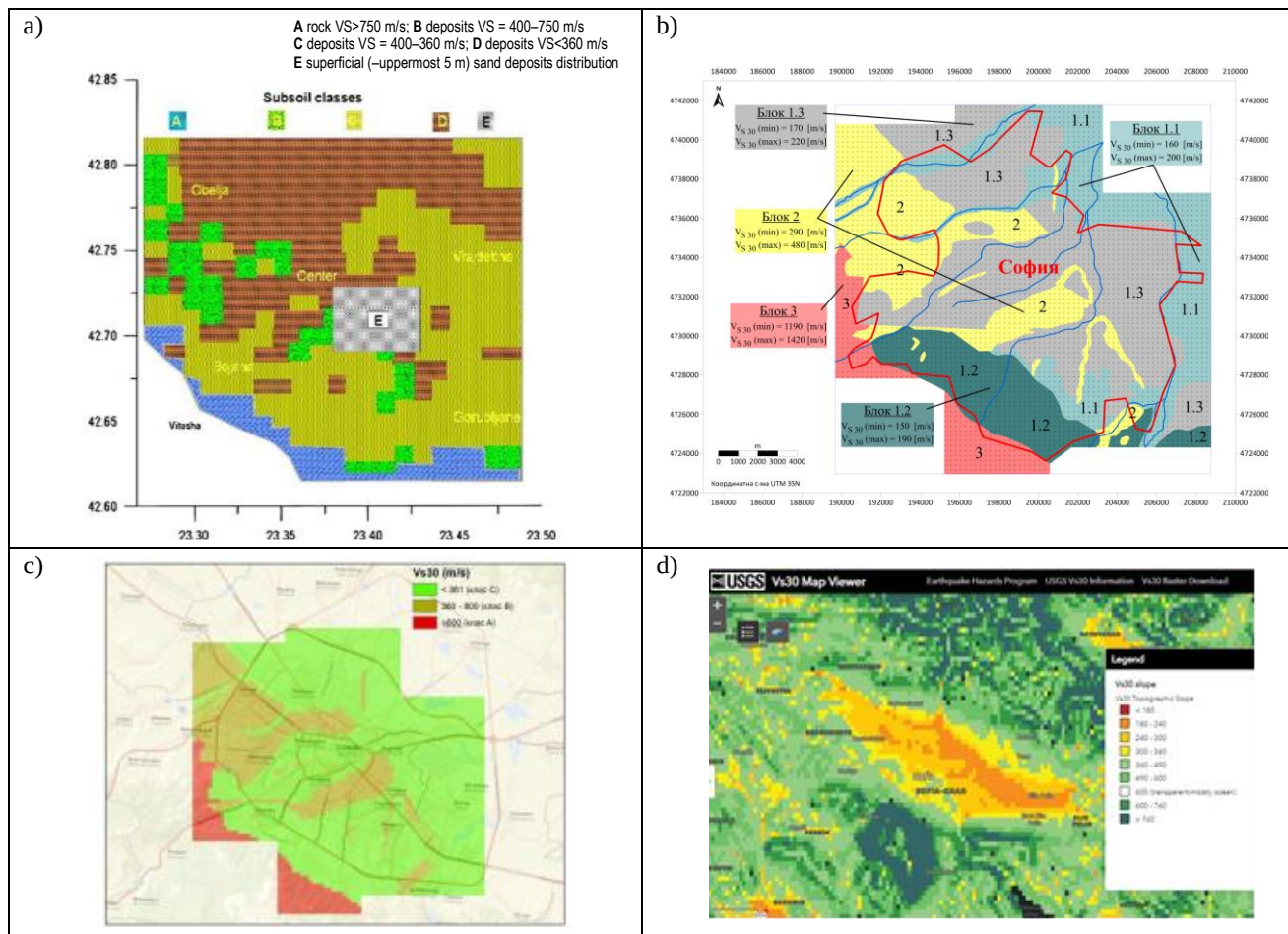


Figure 3. Models for subsoil classes and Vs30: a) Paskaleva et al. (2011); b) min-max Vs30 for blocks with similar shear waves velocities Vs (Kisyov et al., 2020); c) Vs 30 (Solakov et al., 2021); d) UASGS Vs30 (Allen and Wald, 2007)

ON UNDERLYING ISSUES AND CHALLENGES

On the methodological approach in the seismic hazard and risk assessment

The seismic hazard assessment depends on information about past events before the instrumental registration and the data quality of such events in the Bulgarian territory (e.g., Lee et al., 1990). Primary information is often incomplete, inaccurate, missing, or difficult to collect from various sources. Due to the complexity of seismic source parameterization, a good understanding of how seismic data are acquired will help improve the reliability of their interpretation (Glazer, 2016) and assess hazard and risk. The review of the published SHA maps shows that some progress has been made in Sofia's seismic microzoning. Despite adopting the National methodology for analyzing, assessing, and mapping seismic risk in 2018 by the Ministry of Regional Development and Public Works as a normative document, the preparation of thematic maps has been postponed due to financial problems, lack of infrastructure and equipment, poor coordination and leadership at local and state level.

The seismic activity in the Sofia seismic zone cannot be considered separately from the rest of the country and outside seismogenic sources (Lee et al., 1990; Yosifov et al., 2018; Solakov et al., 2019). Another issue is that seismic model simulations are often carried out with input data of various qualities and available information about past seismic

events. Essential components in SHA are source locality, geometry and kinematics, and earthquake rupture forecast, chosen as the magnitude–frequency distribution of the seismic sources. Modeling in both deterministic and probabilistic assessments casts serious doubt on the significance of the estimated seismic hazard, so efforts are being directed toward reducing epistemic uncertainties (rising from limited knowledge; e.g., Zanetti et al., 2023). The published SHAs for Sofia are also subject to general criticism (e.g., Wyss et al., 2012), such as their inputs being mostly historical data.

It should be borne in mind that the period of the described historical and recorded earthquakes is too short. It should be noted that the seismic data constitute a representative set to characterize the seismic regime, which is variable in time and space, and to determine the seismic hazard, these data are insufficient. Historical records of earthquakes in the Sofia region date back to 1450 CE. This short period is a statistically nonrepresentative part of the period in which most faults in the population are supposed to rupture more than twice, considering that the known inter-event periods of the surface-rupturing earthquakes on adjacent faults range from 10^3 to 10^4 years (Vanneste et al., 2006; Meyer et al., 2007; Radulov et al., 2023a). The number of events is too small to perform a statistical analysis and obtain a reliable estimate of the seismic parameters for the Sofia region. The magnitude–frequency distributions, which were used in the PHSA for Sofia (e.g., Solakov et al., 2001; Solakov and Simeonova, 2006; Kostov et al., 2007), therefore, should be considered unreliable from a physical point of view, though statistical manipulations try to suggest representativeness of the sample. Solution for an improved estimate of the magnitude–frequency distributions can be modern approaches based on fault slip rates and accounting for associated background seismicity (Chartier et al., 2019), successfully applied in areas with low strain rates (Gómez-Novell et al., 2020). In this regard, it is good to follow good world and European practices (e.g., Pagani et al., 2018; De Risi et al., 2019; Baldassarre et al., 2024).

It is worth mentioning that limited geological data were used to identify two fault sources in the Sofia basin (Kastelic et al., 2011) that were included in the European (Basili et al., 2013, 2023) and global (Styron and Pagani, 2020) databases of seismogenic faults. Considering global trends in slowly deforming lithospheric boundaries, it was assumed that the fault slip rates in Sofia are about 0.2–0.3 mm/yr. This value is highly conjectural because slip rates vary across zones of distributed deformation, which also applies to Sofia's surroundings (Radulov et al., 2023b). For this reason, the application of modern approaches will not lead to a significant improvement in SHA. Paleoseismological techniques should determine the actual slip rates. In addition, the velocities determined by GNSS measurements on the country's territory over the last two to three decades can be used to specify the strain rates. In this direction, good practices can be followed in updating the seismic hazard model for Europe and the first European seismic risk model (ESRM20), recently available to the scientific community (Dallo et al., 2024). All models are harmonized, and the underlying datasets, workflows, and software used are publicly available, allowing reproducibility of results and opportunity for further research.

A more general geotechnical map has been used in some SHA scenarios for the Sofia municipality area (Solakov et al., 2001; 2009). The macroseismic intensity was directly related to the different types of soils; respectively, a higher intensity $I=VII$ was attributed to soft soils and a lower one, $I=VI$ to rocks. Verification of an earthquake scenario for the city of Sofia was carried out by Alexandrova (2013) with a deterministic earthquake scenario in macroseismic intensity (in MSK-64) generated assuming the realization of a "reference" damaging earthquake of magnitude $M_w5.6$ with a higher probability of occurrence at a distance 25 km from the city center. The modeled seismic effects by Aleksandrova (2013) were compared with the observed distribution of intensity function during the 2012 Pernik earthquake, which could not provide a sufficiently reliable assessment for the capital region. The DSHA and PSHA can be improved by obtaining more accurate attenuation models based on local strong motion records.

Furthermore, in seismic modeling under different scenarios and known fault parameters, different kinematic scenarios should not be modeled arbitrarily, such as assuming that earthquakes of a certain magnitude are distributed with a random source direction. Determining the characteristics of the seismic zone requires integrating geological, geodetic, seismological and geotechnical knowledge at a regional and local scale. In specialized software, there are various options for modeling a seismic source. For example, the open-source software OpenQuake (GEM, 2018) contains five typologies – point and area sources for modeling distributed seismicity, simple fault, complex fault, and characteristic fault for modeling fault-based seismicity. If rupture orientation is considered arbitrary, this behavior can potentially lead to unrealistic seismic scenarios where earthquake ruptures are inconsistent with the region's geometry and the tectonic features through which they are represented. Area-source seismic modeling requires carefully assessing associated activity rates and prevailing fault orientations. For the investigated territory of the Sofia region, the fault surfaces and their respective geometric orientation are well-known: WNW-SE for the northern (North-Sofia) fault and WNW-SE for the southern (Vitosha) fault (Radulov et al., 2023b), but further detailed studies of the fault segments to refine their seismogenic potential.

So far, region-specific scaling equations for strong ground motion spectra are unavailable for Bulgarian territory and specifically for the Sofia seismic zone (Yosifov et al., 2018). In most cases, frequency-dependent attenuation and scaling equations in terms of magnitude developed from simulated strong motion data or regional-specific attenuation in terms of the local intensity of shaking and scaling equations for some other regions have been used for the SHA for the Bulgarian territory (Solakov et al., 2019). It would be best to derive spectral scaling equations for the Sofia region from

analyses of on-ground geophysical measurements. In this regard, a research project (acknowledged below) was recently initiated to microzoning the capital's urbanized area to define the design characteristics of the strong ground motion more accurately. A study has been carried out by an equivalent linear 1-D earthquake site response analysis by considering the soil dynamic characteristics for specific locations with geological boreholes, as presented in (Oynakov et al., 2024). This preliminary study is an initial step in elucidating the inelastic soil deformations that occur after exceeding a certain earthquake intensity.

Cartographic layout of seismic hazard and risk maps

Seismic risk assessment, mitigation, and management are closely related to spatial data compatibility (Pashova et al., 2015). The access, sharing and exchange of geospatial information according to the Directive 2007/2 of the European Commission for establishing an INfrastructure for SPatial Information (INSPIRE; <https://inspire-geoportal.ec.europa.eu/>) support informed decisions and more effective actions in all spheres of public life, including earthquake risk prevention. The application of the INSPIRE Directive related to seismic risk areas is given in Annex III, Topic 12 - Natural risk areas. According to this application, the aim is to define seismic risk zones, which are depicted on maps, based on a methodology that considers the hazard and vulnerability according to the specific local conditions. So far, in Bulgaria, there are still specific difficulties in collecting, analyzing, harmonizing, and visualizing the data and their full use for assessing seismic hazard and risk (Yosifov et al., 2018; Solakov et al., 2019). The major challenge within this effort has been combining the heterogeneous data necessary for further estimating the earthquake disaster indices (e.g., Trifonova et al., 2019). These data have been collected from various sources in different formats, sizes, standards, and precision. Wide-ranging data sets are gathered to be used by risk estimation procedure, relying on a holistic indices-based approach for express expert seismic risk assessment.

GIS is effectively used in the overall process of seismic hazard and risk assessment – from the initial collection and harmonization of relevant data sets (seismic catalogs, active faults, geodetic measurements, strong ground motions, etc.) in compiling seismic source models to predict future seismicity and its effects (synthesizing realistic ground motions time series; see, e.g., Lee and Trifunac, 1985), to the preparation of official national hazard maps, development of necessary building codes and determination of earthquake probability levels (Jena et al., 2020). Maps are essential sources of information about hazards, vulnerabilities and risks in a given area and provide helpful information that can support a range of risk reduction strategies and relevant priorities (Pashova et al., 2016). For the spatial planning of urbanized areas and assessment of critical facilities or for performing risk assessment, it is crucial to have high-quality data with good temporal and spatial resolution (Pashova et al., 2015; Zanetti et al., 2023). GIS modules/platforms for seismic hazard and risk assessment are increasingly popular and widely used in research practice. Once created, the database can be supplemented, updated and reused, allowing the creation of digital products such as thematic layers, the paper printing of specialized thematic maps, or their visualization through web portals.

Over the last few years, the preparation of thematic maps of the seismic hazard for the Bulgarian territory and individual cities has been mainly carried out in a GIS environment (Solakov et al., 2019; 2021; Trifonova et al., 2019). A separate matter is the specific content that is depicted on these maps. Some aspects regarding the quality content of the maps were discussed earlier in the text. Given the European practice for open access to all data, procedures and results of the preparation of the seismic hazard and risk maps within the European continent (Dallo et al., 2024), the same cannot be said for the practice in Bulgaria when assessing the seismic hazard and risk. The prepared thematic maps of the seismic hazard presented as PGA with three return periods are accessible through the geoportal of the MRDPW (<http://gis.mrrb.government.bg/>) in graphic raster format.

Modern cartographic methods enable the specialized content displayed on the thematic maps to be oriented to the users (Pashova, 2015; Dallo et al., 2024). When preparing cartographic products, it is necessary to use basic cartographic rules, logical systems of map legends and symbols, and cartographic generalization methods. When making maps, five basic principles (legibility, visual contrast, figure-ground, hierarchical organization and balance) are followed, which ensure correct perception and understanding of the map content. While studying the examples of various parameters of the seismic hazard presented in raster or vector format shown above, it becomes clear that a significant part of them do not have the necessary qualities of a cartographic product. In some of them, especially in the initial stage of making such specialized maps at the local level for the territory of Sofia, geographical coordinates and scale, conventional signs and legends are missing, which makes it difficult to read them. Others lack inscriptions, primary cartographic content, legend, and designations of symbol systems, which further complicates perception and complex orientation for the spatial arrangement of the natural earth surface depicted on the map and the specific thematic content. After the initial development of thematic maps for SHA in a GIS environment (Simeonova et al., 2006; Solakov et al., 2009), it is now one of the main tools in scientific research in processing large volumes of data, standardizing them, creating thematic layers, combining and interactive visualization (Solakov et al., 2019; 2021).

Modern cartographic methods and computer technologies allow specialized map content to be displayed in 2D, 3D and 4D, and interactive web environments. In cartographic practice, there are proposals for standards for symbol systems for representing natural hazards and risk processes, but only for 2D maps. Most systems are perceived as national standards, developed in a particular scientific field, and are often tricky for non-professional users to understand. Recently, Internet technologies, platforms, and interactive means have increasingly been used to visualize specialized thematic content, which different users can more easily perceive. Such examples for Europe are the hazards. EFEHR web platform (<http://hazard.efehr.org/>), which provides access to interactive tools such as seismic hazard models, products and information, and <https://maps.eu-risk.eucentre.it/>, which is a service of the European Facilities for Earthquake Hazards and Risk (EFEHR), providing exposure, vulnerability and risk data and results. Another helpful web platform is <https://maps.openquake.org/>, through which the GEM Foundation provides globally available seismic hazard and risk models and datasets (GEM, 2018).

CONCLUSIONS

Based on the studied cartographic materials and the sequence of processes in assessing the seismic hazard and risk for the territory of Sofia, the following conclusions can be drawn:

- The prepared cartographic products - specialized thematic maps for seismic hazard and risk assessments should present general geographic and thematic content following the best world and European practices in this field.
- The seismotectonic model for Sofia should be based on new geological and strain rates determined by joint analysis and interpretation with geodetic data. Due to the incompleteness of the seismic catalog, a statistically reliable analysis to estimate seismic parameters used in the PSHA approach is challenging. In order to improve this model for the Sofia region, paleoseismological studies and joint analyses with geodetic data must be carried out.
- More realistic estimates of the maximum expected PGA (velocities, displacements, etc.) under different seismic scenarios can be obtained if more detailed geophysical measurements are performed in the Sofia area. A factor that can improve the assessment is a thickening of the network of GNSS points for detailed determination of strain rate from geodetic data, as is the practice in the SHA in other countries, the so-called GNSS-seismology.
- Additional complex measurements and studies are required to determine local slow tectonic movements and deformations along active fault structures in detail. Further studies through paleoseismic trenches on selected segments of the faults bounding the Sofia Basin to the south and north would clarify the geological history of fault activity and their realistic representation in the seismotectonic model used in the SHA.
- As evident from published reviews of regional and local seismicity, the lack of instrumental records of strong motions requires an appropriate scenario-based approach to seismic risk assessment and advanced ground motion modeling procedures to define seismic input to model studies. Given a specific earthquake scenario and a suitable structural model based on detailed geological, geophysical and geotechnical data, it is possible to realistically estimate the local amplification in the frequency range of interest for civil engineering and obtain valuable parameters for the realistic microzoning of the Sofia area.
- The secondary effects triggered by earthquake events, such as landslides, floods, etc., should also be considered as the next step in SHA (e.g., Pashova et al., 2016). So far, such a multi-hazard assessment has not been done with a view to the prevention of the densely populated capital Sofia.
- In terms of software provision, accessible open-source programs should be used, and modern methods for processing the ever-increasing volume of seismic and other types of data and information, such as machine and deep learning, can be applied.
- It becomes more necessary to improve information sharing and realize the need for collaborative, multidisciplinary efforts to assess the available databases and their harmonization by national and European legislation.

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