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## DETERMINISTIC SEISMIC HAZARD ANALYSIS OF THE CITY OF STRUMICA

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**Abstract:** Seismic risk assessment is defined as the first and most significant step toward reducing potential losses from earthquakes as natural disasters, analyzed on local, urban, national, and continental level. This process includes validation and assessment of seismic hazard, which determines the expected level of ground motion that can be expected at a specific location. It is followed by the development of an exposure model containing a database of assets and people exposed to the hazard, and vulnerability assessment of the exposed elements conducted through the development and application of vulnerability functions that determine the probability of loss depending on the intensity of ground shaking. These three components of seismic risk enable the creation of relevant risk assessment analyses, leading to improved system preparedness before, during, and after emergency or crisis situations and/or disasters.

This study will analyze the first component of risk — seismic hazard. Through a deterministic seismic hazard assessment, the maximum level of ground motion expected within the territory of the city of Strumica will be determined as a pilot study within this research. The assessment will be based on selected, most credible past earthquake scenarios that have affected the city and its surrounding area. Following the history of neotectonics and seismicity in the territory of North Macedonia, the earthquake scenarios Pehcevo - Kresna (1904) with a magnitude of 7.2 and Valandovo - Dojran with a magnitude of 6.7, were selected as the most relevant past earthquake scenarios that had a significant impact on the analyzed area — the city of Strumica.

In order to visualize the obtained results, the two earthquake scenarios are simulated online using the open source software tool — OpenQuake Engine. The simulation is performed on the active fault source model ESHM20, developed as part of the European Database of Active Seismic Faults, with the obtained results appropriately illustrated for relevance analysis.

The process of seismic hazard assessment, as the first and most significant step in defining risk, through modeling past earthquake scenarios with the city of Strumica as a case study, can greatly assist researchers. This approach enables the simulation of potential outcomes, testing of strategies to mitigate earthquake impacts at a specific location, as well as updating existing and creating new emergency and disaster management plans, where the risk factor remains an essential component.

**Keywords:** seismic risk assessment, hazard, exposure model, vulnerability

### 1. INTRODUCTION

Earthquakes, landslides, floods, and fires are among the most common types of natural hazards that cause loss of life, property damage, and property loss (Javad Vaziri, Soleymani, Hasani, Mosavi Nezhad, & Momivand, 2022). These natural disasters have significant medium - and long-term consequences on the built environment, existing infrastructure, and affected populations in impacted regions. In particular, earthquakes as natural disasters can trigger secondary disasters such as fires, landslides, tsunamis, and intense ground shaking, further amplifying their destructive impact. To minimize potential damage, it is essential to identify the underlying causes of these hazards. For this purpose, seismic hazard analyses are conducted for specific locations or groups of locations, enabling the prediction of future ground movements and the implementation of preventive measures.

Seismic hazard assessment analyses are classified into probabilistic and deterministic seismic hazard analysis. Deterministic seismic hazard assessment estimates the maximum ground motion that can occur at a specific location based on selected past earthquake scenarios and precise field observations (Javad Vaziri, Soleymani, Hasani, Mosavi Nezhad, & Momivand, 2022). In contrast, probabilistic seismic hazard analysis assesses the likelihood of exceeding various levels of ground motion at a given site (or across a region), considering all potential earthquakes (Primer, 2001). These two approaches are often regarded as fundamentally different methods for calculating ground motion during an earthquake. However, the choice of an appropriate approach is typically based on the nature of the project and the seismic characteristics of the region under study (Boomer, 2002). Additionally, the quantity and quality of available data for characterizing seismicity play a crucial role in the decision-making process.

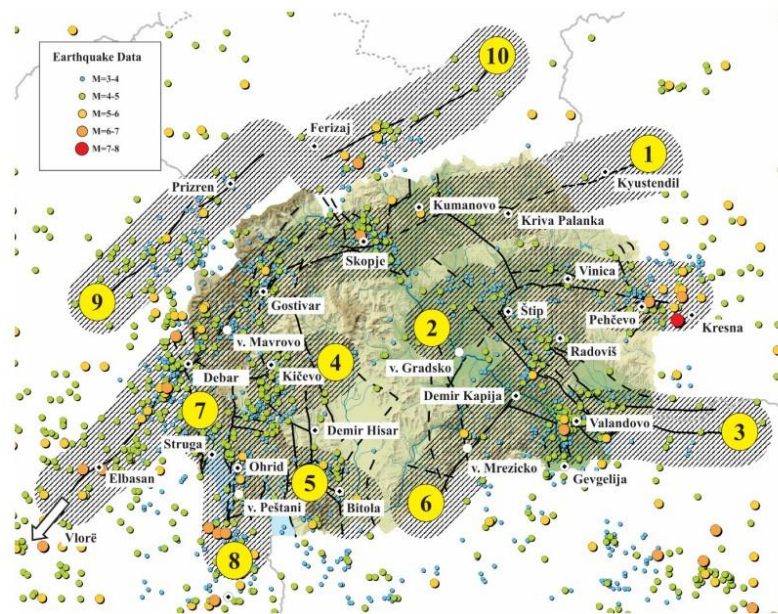
In order to verify the seismic risk assessment methodology, in this study, the seismic hazard is determined through a deterministic seismic hazard assessment (DSHA), whereby two past earthquake scenarios that had a significant impact on the city of Strumica are selected as the most reliable earthquake scenarios as a case study in this research. This include the Pehcevo-Kresna earthquake (1904) with a magnitude of 7.2 and an epicenter in Krupnik, Bulgaria

(Milutinović, et al., 2017) and the Valandovo-Dojran earthquake with a magnitude of 6.7 and an epicenter in the Valandovo region (Milutinović, et al.,2017).

## 2. SEISMOTECTONIC CHARACTERISTICS OF THE TERRITORY OF THE REPUBLIC OF NORTH MACEDONIA

The locations of past earthquakes in the Republic of North Macedonia are closely linked to faults that have been active in this region for the past 10,000 years. These seismic events result from tectonic movements that release accumulated energy, producing weak to moderate earthquakes and, at times, stronger ones. These occur along faults that traverse complex geological formations and tectonic structures (Dumurdjanov, Milutinovic, & Salic, 2020). The regional seismicity of North Macedonia is currently modeled with 10 active seismic zones (Fig.1), each characterized by the presence of one or more faults. These primary faults along with local diagonal and/or parallel faults drive continuous zonal seismic activity, holding the potential to generate future destructive earthquakes.

*Figure 1: Seismic Tectonic Map and Active Seismic Zones of the Republic of North Macedonia (Dumurdjanov, Milutinovic, & Salic, 2020)*



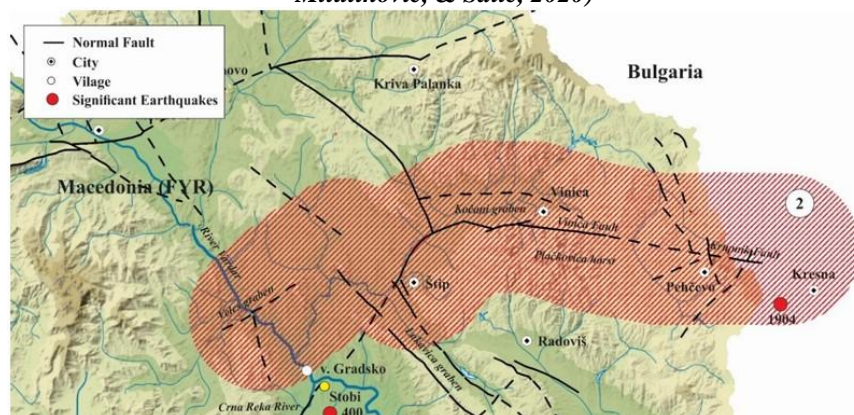
The adopted seismotectonic model of our country illustrated at Fig.1 consists of three complex seismotectonic zones (1,2,3) and seven additional seismotectonic zones (4–10), which encompass only the seismic sources that defines them (Dumurdjanov, Milutinovic, & Salic, 2020).

### Seismic and tectonic characteristics of the city of strumica

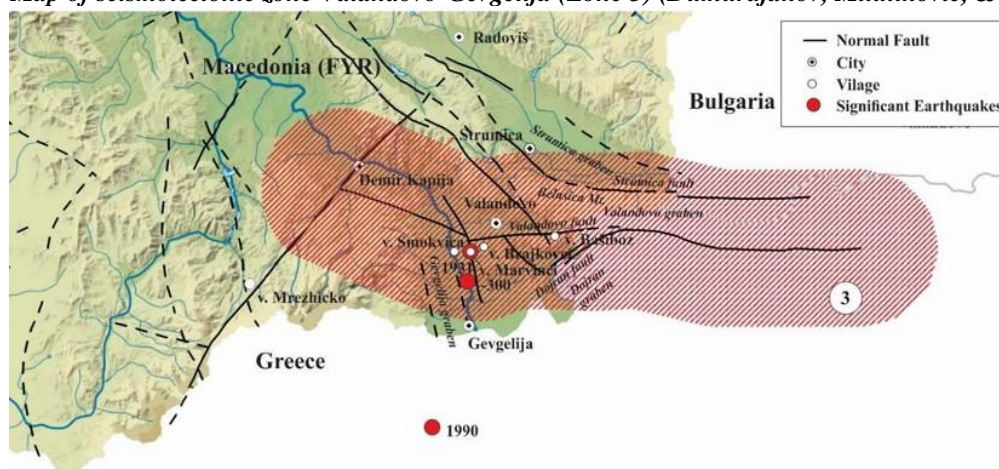
The city of Strumica and the Strumica valley are geographically located within a transition zone between two geotectonic units: the Vardar zone and the Serbian-Macedonian massif. This area extends across two seismic zones, namely: Zone 2: Kresna-Pehčevo-Vinica-Stip Gradsko (Fig. 2) and Zone 3: Valandovo-Gevgelija (Fig. 3) which include several local epicentral areas: Valandovo area as well as strong earthquakes from neighboring epicentral areas, including the **Pehchevo-Kresna earthquake in 1904 (Mw 7.2)**. Additionally, it has experienced seismic activity from earthquakes originating in nearby seismogenic zones outside the country's borders (Popovski, 2017).

The analyzed region has historically been affected by strong local earthquakes, such as the **Valandovo earthquake in 1931 (Mw 6.7)**, as well as significant seismic events from neighboring epicentral areas, including the **Pehchevo-Kresna earthquake in 1904 (Mw 7.2)** (Popovski, 2017). The most seismically active part in Zone 3 (Fig. 3), where the city of Strumica predominantly belongs, is the Valadovo area, which is located about 15 km from the city of Strumica. Chronologically, two stronger earthquakes were registered in the Valandovo area, which occurred on 7<sup>th</sup> of March (Mw.6) and 8<sup>th</sup> of March (Mw.6.7) in 1931. The strongest earthquake to hit the Valandovo area in more recent times was an earthquake registered in 1990 with Mw. 5.5 (Dumurdjanov, Milutinovic, & Salic, 2020).

**Figure 2: Map of seismotectonic zone Kresna-Pehčevo-Vinica-Stip-Gradsko (Zone 2) (Dumurdjanov, Milutinovic, & Salic, 2020)**



**Figure 3: Map of seismotectonic zone Valandovo-Gevgelija (Zone 3) (Dumurdjanov, Milutinovic, & Salic, 2020)**



In addition to the seismicity of our country, Domurdzanov et al. (2005) have conducted detailed research in the domain of tectonics, with a special focus on the Vardar zone, where the Strumica valley predominates (Salic, 2015). Within the European framework, in recent years, numerous efforts have been made, within the framework of a series of scientific research projects in the field of seismic hazard, to re-evaluate the seismogenetic capacity of fault structures and to map them, a process that requires the integration of relevant seismological, geological, geophysical, paleomagnetic, paleoseismological and geodetic data (Salic, 2015).

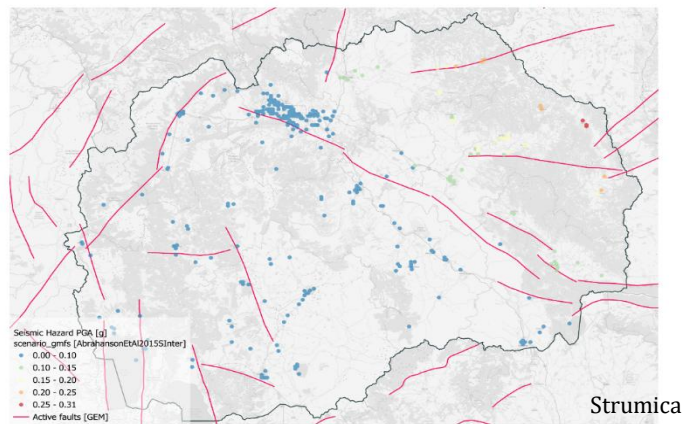
One such globally significant project is SHARE, developed under the **Seventh Framework Programme** of the **European Commission's** cooperation initiative, whose main goal was to provide a seismic hazard model for the Euro-Mediterranean region along with mechanisms for further updating (Giardini, Woessner, & Danciu, 2014). The SHARE project contains the European Database of Active Faults and Seismogenic Sources (EFEHR/Active faults). For the deterministic seismic hazard analyses conducted in this study, a synthesized dataset of active seismic faults from the European Database of Active Faults and Seismogenic Sources (EFEHR/Active faults) (Danciu, et al., 2021) developed within the SHARE project was used. This dataset is fundamentally based on the work of Domurdzanov et al. (2005).

### 3. SEISMIC HAZARD ASSESSMENT OF THE CITY OF STRUMICA

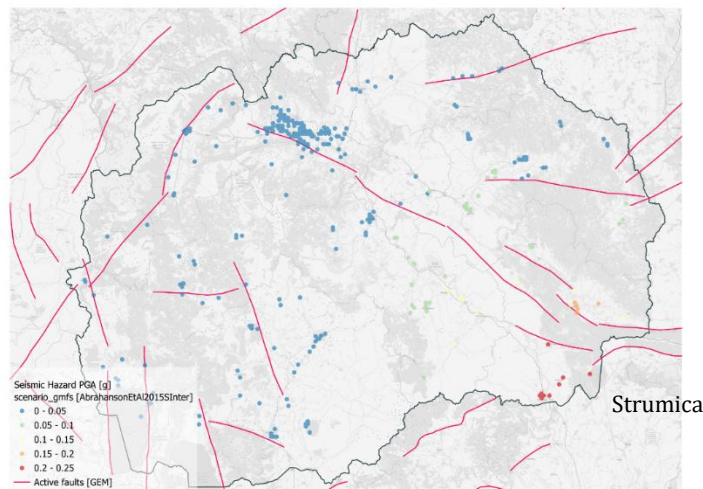
In order to validate the methodology for seismic risk assessment, in this paper, the seismic hazard is determined through deterministic seismic hazard assessment (DSHA). This approach estimates the maximum level of ground motion expected in the city of Strumica, selected as a case study. The assessment is based on two selected historical earthquake scenarios: Pehčevo-Kresna earthquake (1904) with a magnitude of 7.2 and an epicenter in Krupnik, Bulgaria (Milutinović, et al., 2017), and Valandovo-Dojran earthquake with a magnitude of 6.7 and an epicenter in the Valandovo region (Milutinović, et al., 2017).

The two earthquake scenarios are simulated online using the Open Quake Engine software tool (Pagani, et al., 2014). The magnitude, location, and characteristics of active seismic faults for the selected scenarios are retrieved from the European Database of Active Seismic Faults (EFEHR/Active Faults (Basili, et al.) To estimate the ground motion, this study considers the characteristics of active seismic faults, earthquake magnitude, local geological conditions and the distance between the earthquake source and the site of interest. Among the European models available in the Open Quake Engine software platform (Pagani, et al., 2014) the Abrahamson EtAl2015Sinter ground motion model (Abrahamson, Gregor, & Addo, 2016) is selected as a prediction of earthquake attenuation. The necessary parameters for local soil depth are obtained from the European Seismic Hazard Model (ESHM20) database (Danciu, et al., 2021) using site-specific soil condition parameters for the territory of North Macedonia. Taking into account all the abovementioned data, two ground motion fields are generated online using the Open Quake Engine software tool (Pagani, et al., 2014), one for each chosen earthquake scenario, respectively. These expected ground motion fields indicate the intensity of ground motion at the location in question - the city of Strumica, represented as the expected spatial distribution of peak ground acceleration PGA (g). The obtained results (Fig.4-Fig.5) are plotted and visualized using the opensource software tool - Quantum Geographic Information System (QGIS) (Palino & Sparks) on the active fault source model ESHM20 developed as part of the European Database of Active Seismic Faults (Danciu, et al., 2021) for relevance applicable by GEM (GEM, n.d.).

**Figure 4: Map of North Macedonia with PGA values obtained from the analysis of the Pehčevo-Kresna earthquake scenario in the Open Quake Engine software tool using the Active Fault Sources ESHM 20 model applied by GEM for relevance**



**Figure 5: Map of North Macedonia with PGA values obtained from the analysis of the Valandovo-Dojran earthquake scenario in the Open Quake Engine software tool using the Active Fault Sources ESHM 20 model applied by GEM for relevance**



The spatial distribution of the maximum ground acceleration PGA (g) for the Strumica city region, based on the two selected earthquake scenarios (Milutinović, et al., 2017), (Milutinović, et al. 2017) and the chosen GMPE (Abrahamson, Gregor, & Addo, 2016) indicates a significantly higher intensity near the earthquake source. Specifically, for the **Valandovo-Dojran earthquake scenario** (Mw 6.7), the PGA values range between **0.10 g – 0.15 g**, whereas for the **Pehčevo-Kresna earthquake scenario** (Mw 7.2), the values range between **0.15 g – 0.2 g**. Despite the fact that the **Pehčevo-Kresna scenario** has a higher magnitude (7.2) compared to the **Valandovo-Dojran scenario** (6.7), the greater **epicentral distance** of the Pehčevo-Kresna earthquake (Mw 7.2) — **100 km** from the pilot study area (Strumica)—results in lower PGA values in the city. In contrast, the **Valandovo-Dojran earthquake** (Mw 6.7), has a significantly shorter epicentral distance, approximately **15 km** from Strumica, leading to higher PGA values in the region. In both earthquake scenarios, the intensity decreases as the distance from the earthquake source increases.

#### 4. CONCLUSION

The validation of real records and observations of past earthquakes through seismic hazard analysis, as the first component in seismic risk assessment, serves a single purpose—to confirm the reliability of seismic vulnerability assessments for urban areas. In this study, the city of Strumica is used as a case study where the seismic hazard is estimated through a deterministic seismic hazard assessment to determine the maximum level of ground motion expected in analyzed area. The evaluation is based on two historically significant earthquake scenarios: Pehchevo-Kresna earthquake (1904) with a magnitude of 7.2 (Milutinović, et al., 2017) and Valandovo-Dojran earthquake (1931) with a magnitude of 6.7 (Milutinović, et al., 2017). According to the Available **list of the most significant earthquakes affecting the territory of North Macedonia** (Cejkowska, Pekevski, Drogreska, & Najdovska, 2016) these events represent the most relevant past seismic scenarios with a destructive impact on Strumica and its surroundings since 1900. These two earthquake scenarios were simulated online using the Open Quake Engine software tool (Pagani, et al., 2014) with all necessary key parameters sourced from the European database of active seismic faults (EFEHR/Active Faults) (Basili, et al.), for both scenarios, respectively.

The spatial distribution of the maximum ground acceleration PGA (g) for the Strumica city region for the two selected past earthquake scenarios, and in accordance with the available data base and analyzed results from previous geological, tectonic, neotectonic and seismological research and the selected GMPE (Abrahamson, Gregor, & Addo, 2016), shows that the proximity of the earthquake source is a primary factor influencing the increase in the intensity of ground motion at the location in question. Although the Pehchevo-Kresna earthquake scenario has a higher magnitude of 7.2 compared to the Valandovo-Dojran scenario with a magnitude of 6.7, its greater epicentral distance—located in Krupnik, Bulgaria, approximately 100 km from the analyzed pilot region, Strumica—significantly reduces the peak ground acceleration values at the study site. Conversely, the Valandovo-Dojran earthquake scenario has an epicenter in the Valandovo region, only about 15 km from Strumica. This closer proximity substantially increases the peak ground acceleration values within this scenario.

The seismic hazard assessment methodology presented in this paper provides valuable insights into the potential severity of earthquakes, which are essential for establishing design and construction criteria within the existing regulatives. With this objective in mind, the obtained results can be utilized to formulate hazard mitigation strategies for the city of Strumica, taking into account the seismic performance of the area.

#### REFERENCES

- Abrahamson, N., Gregor, N., & Addo, K. (2016). BC Hydro Ground Motion Prediction Equations for Subduction. Sage Journals, 32(1), 36.
- Afsari, N., Abdipour, M. S., & Taghizadeh-Farahmand, F. (2022). Seismic hazard analysis from deterministic method using fuzzy logic in Anzali Port. *Earth Science Informatics*, 15(3), 563–572.
- Basili, R., Kastelic, V., Demircioglu, M. B., Garcia Moreno, D., Nemser, E. S., Petricca, P., & Sboras, S. (n.d.). The European Database of Seismogenic Faults (EDSF) compiled in the framework of the Project SHARE. Retrieved from <https://seismofaults.eu/edsf13>
- Bhatti, N., Naval, S., & Deep, G. (2023). Deterministic seismic hazard analysis for Amritsar, Punjab, India. In A. K. Agnihotri, K. R. Reddy, & H. S. Chore (Eds.), *Proceedings of Indian Geotechnical and Geoenvironmental Engineering Conference (IGGEC) 2021, Vol. 1* (pp. 381–393). Springer.
- Boomer, J. J. (2002). Deterministic vs. Probabalistic Seismic Hazard Assessment: An exaggerated and obstructive dichotomy. *Journal of Earthquake Engineering*, 6, 43-73.
- Cejkowska, V., Pekevski, L., Drogreska, K., & Najdovska, J. (2016). Report per the Project of tStandardization Institute of the Republic of Macedonia entitled National Annexes for Eurocodes. Skopje: Faculty of Natural Sciences and Mathematics, Seismological Observatory.

- Danciu, L., Nandan, S., Reyes, C., Basili, R., Weatherill, G., Beauval, C., Giardini, D. (2021). The 2020 update of the European Seismic Hazard Model. Zurich: EFEHR.
- Dumurdžanov, N., Milutinovic, Z., & Salic, R. (2020). Seismotectonic Model Backing the PSHA and Seismic Zoning of Republic of Macedonia for National Annex to MKS EN 1998-1:2012 Eurocode 8. *Journal of Seismology*, 24, 319-341.
- GEM. (n.d.). Global Earthquake Model Foundation. Retrieved from <https://www.globalquakemodel.org/>
- Giardini, D., Woessner, J., & Danciu, L. (2014). Mapping Europe's Seismic Hazard. *EOS*, 95(29), 261-262.
- Javad Vaziri, S., Soleymani, A., Hasani, H., Mosavi Nezhad, S., & Momivand, K. (2022). Comprehensive Review on Deterministic Seismic Hazard Analysis(DSHA) and Probabilistic Seismic Hazard Analysis (PSHA) Method. 2nd.International 2nd Conference on Architecture, Civil Engineering, Urban Development, and Environment, Tabriz, Iran, 12.
- Milutinović, Z., Cernih-Anastasovska, D., Dumurdžanov, N., Šalić, R., Drogreška, K., Čejkowska, V., Tomić, D. (2017). Razurnuvacki zemjotres vo Valandovo od 1931 godina. Skopje: Porta 3.
- Milutinović, Z., Cernih-Anastasovska, D., Dumurdžanov, N., Šalić, R., Drogreška, K., Čejkowska, V., Tomić, D. (2017). Zemjotresot Pehcevo-Kresna-najsilen na Balkanot. Skopje: Porta 3.
- Pagani, M., Monelli, D., Weatherill, G., Danciu, L., Crowley, H., Silva, V.,Vigano, D. (2014). OpenQuake Engine: An open hazard (and risk) software for the Global Earthquake Model. *Seismological Research Letters*, 85 (3), 692–702.
- Palino, G., & Sparks, E. (n.d.). QGIS: An Introduction to an Open-Source Geographic Information System. Mississippi: Mississippi State University.
- Popovski, R., Panov, Z., Pekevski, L., Doneva, B., & Karanakova Stefanovska, R. (2017). Some Characteristics of the Seismic Activity in the Radovish-Strumica-Valandovo Area (Republic of North Macedonia) (in macedonian). *Tehnologija na podzemna i povrshinska eksploatacija na mineralni surovini (Zbornik na trudovi)*, 168-178.
- Primer, A. (2001). Probabilistic Seismic Hazard Analysis (PSHA).
- Rao, G. N. S. N., & Satyam, D. N. (2022). Deterministic and probabilistic seismic hazard analysis of Tindharia, Darjeeling Sikkim Himalaya, India. *Journal of the Geological Society of India*, 98(6), 1295–1300.
- Salic, R. (2015). Sovremen pristap za opredeluvanje na seizmickiot hazard vo Republika Makedonija (in macedonian). Skopje: IZIS-UKIM.