GeoStudies

GeoStudies 1: 75–87 (2024)
DOI: 10.3897/geostudies.1.e133185

Research Article

Seismicity of the Territory of Bulgaria and Adjacent Lands Based on NOTSSI Data for 2023

Emil Oynakov[1], Mariya Popova[1]

1 *National Institute of Geophysics, Geodesy and Geography – Bulgarian Academy of Sciences, Sofia, Bulgaria*
Corresponding author: Mariya Popova (m.popova022@gmail.com)

Abstract

The present study comprehensively analyzes seismic events recorded by the National Operative Telemetric System for Seismological Information (NOTSSI) in 2023. Seismic data are collected in real-time by 26 Bulgarian stations, supplemented by numerous stations from neighboring countries, enhancing the precision of hypocentral location determinations.

The main kinematic parameters and the magnitude of the earthquakes are estimated utilizing an adaptation of the product HYPO'71. In the practice of NOTSSI, two types of magnitude estimates are used. Magnitude M_P is determined by measuring the maximum amplitude of the P wave. The seismic moment magnitude M_W is estimated from the seismic moment M_0 - a quantity that combines the rupture area and the residual displacement along the fault with the strength properties of the medium (shear modulus μ). The present study transforms M_P, into the more reliable and widely used magnitude scale M_W.

M_W allows for homogenizing the magnitude estimates in the available seismological information and creating a homogenized catalog. The energetically homogenized catalog ensures compatibility of the input seismological information and a reliable assessment of the energetic distribution of earthquakes.

The year 2023 was remarkable for the two devastating earthquakes, magnitudes M7.8 and M7.5, that occurred in Eastern Turkey on February 6th, followed by more than 40 000 aftershocks. They caused human losses and enormous material damage. Although they were more than 1500 km from the territory of Bulgaria, the main shocks were partially felt on the high floors of some buildings.

The earthquakes analyzed in Bulgaria and its surroundings in 2023 were primarily low-magnitude events with uneven spatiotemporal distribution. The hypocenters' depth distribution was in the upper levels of the earth's crust. The largest number of events were registered in the Rilo-Rhodope seismic area, which covers the Struma and Rhodope seismic zones. The highest concentration of seismic events is observed again in the Struma seismic zone. In the Srednogorie region, along the Maritsa River valley, on June 7, 2023, occurred the strongest earthquake for 2023. It had a magnitude of 4.8 and an intensity of 6.5 in the epicentral area.

Looking at the overall picture of earthquakes in Bulgaria in 2023, we should also note the weak seismic events in the Burgas and Strandzha regions in Southeastern Bulgaria and the region of Northwestern Bulgaria.

For the last five years, 2023 has been characterized by the highest seismicity, as measured by the number of registered events (68 with M_W>3) and the highest magnitude (M_W4.8).

Key words: Balkan Peninsula, Bulgaria, earthquakes, seismicity, 2023

OPEN ACCESS

Academic editor: Petya Trifonova
Received: 26 July 2024
Accepted: 8 November 2024
Published: 28 November 2024

Citation: Oynakov E, Popova M (2024) Seismicity of the Territory of Bulgaria and Adjacent Lands Based on NOTSSI Data for 2023. GeoStudies 1: 75–87. https://doi.org/10.3897/geostudies.1.e133185

Introduction

The Balkan Peninsula is a prominent region within the Alpine-Himalayan seismic belt, characterized by significant tectonic activity. This high seismicity is particularly notable in Western Turkey, Greece, the Vrancea region of Romania, Bulgaria, Northern Macedonia, Albania, and Serbia. The seismic events in this region show distinct depth distribution characteristics, with two main zones of heightened activity at depths of 20-40 km and 90-110 km, and a less active zone at 50-70 km.

The territory of Bulgaria is prone to earthquakes and has experienced numerous significant seismic events over the centuries. During the 20th century, some of the most powerful earthquakes in Europe occurred in Bulgaria. Between 1901 and 1928, five major earthquakes with magnitudes equal to or exceeding 7.0 were recorded in its territory (Grigorova E et al. 1978): The Shabla earthquake on March 30, 1901 (*Ms* = 7.2) - the earthquake was destructive with an epicenter in the sea about 10 km from the coast; the Kresna earthquakes on April 4, 1904 (*Ms* = 7.1 and 7.8) – the second event was one of the strongest earthquakes in Europe and the strongest in Bulgaria, with an epicenter in the Kresna Gorge (Krupnik). This earthquake damaged many neighboring villages and claimed lives. One of the most destructive earthquakes in Bulgaria occurred on June 14, 1913 (Ms = 7.0) near the town of Gorna Oryahovitsa. The depth of its focus was estimated at 10 km. Two major earthquakes occurred near Plovdiv on April 14, 1928 (M_S = 6.8) and April 18, 1928 (M_S = 7.0). They caused a lot of damage, but the fear from the first event saved lives during the greater shock of the second. (Grigorova E et al., 1979)

After the series of earthquakes in Bulgaria up to 1928, there have been no strong events with M≥ 6, and this silence continues today (Hristoskov L, Solakov D 2009).

In 1986, two earthquakes occurred in the eastern part of the Gorna Oryahovitsa seismic zone—on February 2-nd and December 7-th in the area of the city of Strazhitsa. The event, with a magnitude of M_S=5.7, caused great material damage.

The Pernik (Radomir) seismic region should be noted in the seismic region of Central Western Bulgaria. In 1965, an earthquake with a magnitude of 4.5 and a focus depth of about 12 km occurred there. The most recent significant event, with a magnitude of Mw=5.6, occurred in the same region on May 22, 2012.

Northern Bulgaria is influenced by earthquakes in the Carpathian seismogenic zone, specifically in the Vrancha mountain area. These earthquakes have some of the deepest foci in Europe, reaching up to 200 km. As a result, their impact zone can cover a large area, especially in the case of moderate to high magnitudes.

Notable events include the 1944 earthquake, which had a magnitude of *M=7.7*, and the 1977 earthquake, which had a magnitude of *M=7.4*. The latter caused extensive casualties and destruction.

Methodology

The main kinematic parameters and the magnitude of the earthquakes are estimated by means of an adaptation of the widespread product HYPO’71 (Solakov D 1993). Currently, the magnitude Mp is determined by the formula (Christoskov et al. 2011a, b):

$$M_p = \log\left(\frac{A}{T}\right)_{max} + \sigma_{BB}(\Delta) + s_j \quad (1)$$

where A is the amplitude in μm, T is the period in second (s), and

$$\left(\frac{A}{T}\right)_{max} = \frac{V_{max}}{2\pi} \quad (2)$$

V_{max} is the maximum *P-phase* velocity recorded on the vertical component of the broadband seismograph at epicentral distances less than 10°, $\sigma_{BB}(\Delta)$ is a calibration function; and s_j is the j station magnitude correction.

In the present study, M_P is transformed into the more reliable and widely used magnitude scale M_W, which would allow the creation of a unified and homogenized earthquake catalog, essential for a reliable assessment of seismic hazards in the country and its surroundings. The magnitude M_P is transformed into M_W using the formula (Solakov D et al., 2018):

$$M_w = 0.93M_p + 0.31 \quad (3)$$

The National Data Centre of NOTSSI, has been upgraded with the SeisComPro software for automated data processing, widely utilized within the seismological community and data centers. Developed by the German company Gempa (https://gempa.de), SeisComPro is an extension of the SeisComP3 community package distributed by GFZ Potsdam. Key features of the SeisComP3 package include data acquisition, quality control and recording, real-time data processing and exchange, network status monitoring, automatic and interactive event detection and location, event parameter archiving, and easy access to relevant information about stations, waveforms, and recent earthquakes.

To carry out continuous monitoring of seismicity on a regional scale, the following procedures are carried out daily in NOTSSI: 1) Recognition; 2) Information, determination, and classification of the type and quality of recorded events (weak, local, regional, distant); 3) Identification of the type of events - earthquake (Z), explosion (E) and unrecognized event (U); 4) Recognition and description of different phases (mainly P and S); 5) Determination of the parameters (geographical coordinates **φ** and **λ** in degrees [°], hypocentral depth *H* in km; time in the focus T_0 in GMT and magnitude *M*) of seismic events. These procedures are carried out with the computer program DHYPO and SeisCompPro.

Spatial-Temporal Distribution of Earthquakes

The NOTSSI system recorded 2,438 events with resolved parameters (coordinates, focal time, hypocenter depth, and magnitude) which occurred from January 1 to December 31, 2023. Of these, 1,979 were earthquakes (Fig. 1), while 440 were classified as explosions and unidentified events.

Earthquake activity in neighboring Romania in 2023 is represented by two seismic source zones (Vrancea and Southwest Romania) with weak to moderately strong events, some of which were felt on Bulgaria's territory. A significant number of moderately strong (5.0 < MW ≤ 6.0) events are also observed in the region of western Turkey and Greece (Thessaloniki, Khalkidhiki Peninsula) to be XI.

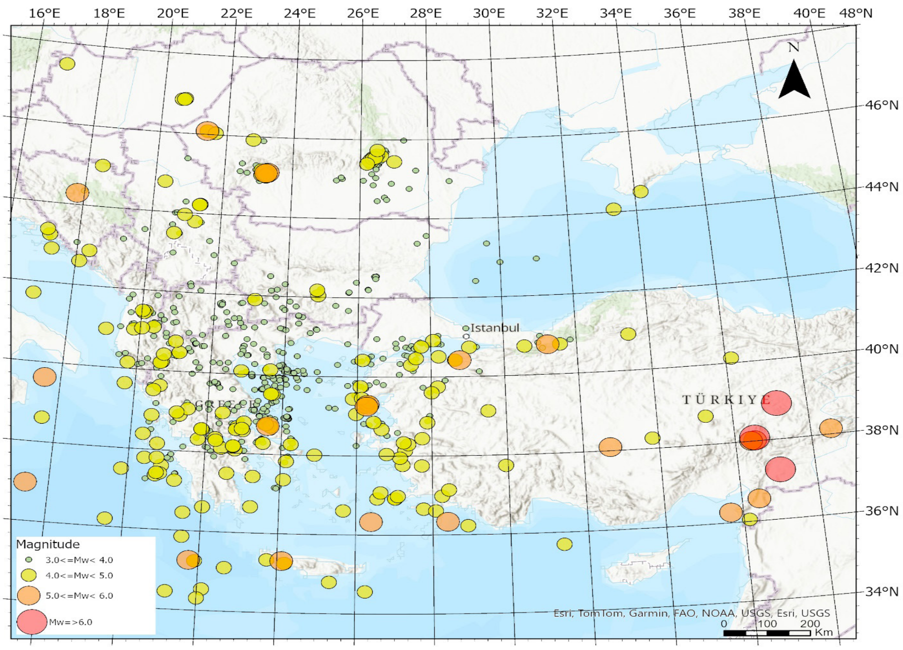

Figure 1. Map of the epicenter's spatial distribution of the 1,979 earthquakes recorded in 2023 by NOTSSI in an expanded geographical area around Bulgaria

On February 6, 2023, two destructive earthquakes struck southern Turkey on the same day (T_0=01:17:36; 37.170°N, 37.080°E, h=20 km, Mw=7.8 and T_0=10:24:49; 28 38.110°N, 37.340°E, h=10 km, Mw=7.5), causing significant loss of life and material damage in 11 cities on the territory of Turkey and Syria. The worst affected area was the province of Kahramanmaraş, located in the Eastern Anatolian Fault Zone (EAFZ). Over 50,000 people in Turkey and about 5,000 people in Syria lost their lives. More than 230,000 buildings were destroyed or so severely damaged that they were uninhabitable (Büyüksaraç et al. 2024). At the focal centers, the intensities of both earthquakes were calculated using the Shebalin relation (Shebalin N V 1978) and were found.

Further analysis is conducted regarding the earthquakes that occurred in 2023 in Bulgaria and the surrounding area within a fixed spatial window of 41° – 44.5° N and 22° – 29° E. The complete list includes 1,022 events, with magnitudes ranging from 1.1 ≤ M_W ≤ 4.8. Calculated hypocenter depths range from 1 ≤ h ≤ 40 km.

One of the essential parameters of the earthquake catalog is the magnitude of completeness (Mc). Mc is a threshold magnitude and indicates that earthquakes with a magnitude greater than Mc have been recorded in a studied area. It is determined using the cumulative frequency-magnitude law of Gutenberg-Richter (1944). Another useful parameter derived from this equation is the *b*-value (slope of the recurrence plot). The value of *b*- is about 1 which is typical for tectonically active zones. The Maximum Curvature Method (Wiemer S 2001) was used to study the spatial and temporal variation of Mc over the instrumental period. Figure 2 presents the frequency-magnitude distribution of the entire catalog in a cumulative form, as the magnitude of completeness of the declustered catalog is estimated as Mc=2.4.

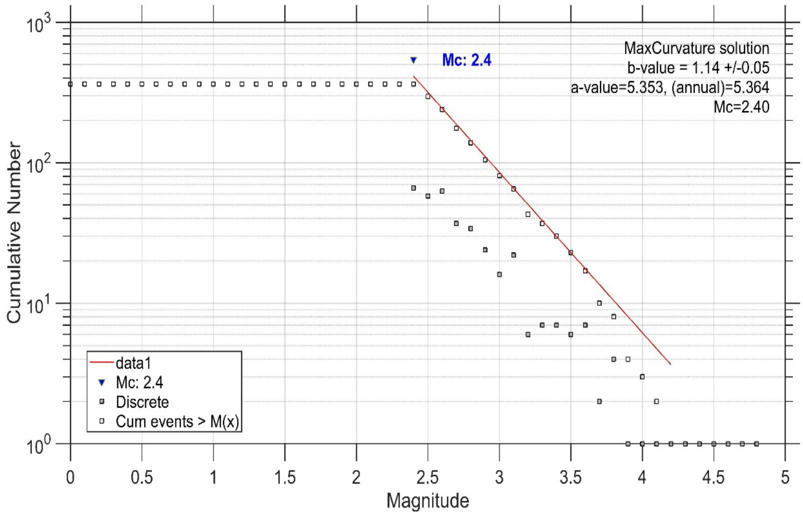

Figure 2. Magnitude-frequency dependence

Figure 2 also demonstrates that the data fits well with theoretical expectations, indicating that the network detected all incoming earthquakes with a magnitude MW ≥ 2.4. For this reason, we accept the value of Mw2.4 as a lower limit of the sample list/catalog. It includes 1,022 events, with magnitudes ranging from 2.4 ≤ MW ≤ 4.8. Calculated hypocenter depths range from 1 ≤ h ≤ 40 km.

Figure 3 shows the spatial distribution of the epicenters of the 2023 earthquakes in Bulgaria and the surrounding area within a fixed spatial window of 41°—44.5° N and 22°—29° E.

The map clearly shows that the highest activity (number of events and released seismic energy) is characterized by the Rila-Rhodope region covering Southwestern Bulgaria. A significant number of weak events characterize the North-Eastern region covering North-Eastern Bulgaria and the northern coast

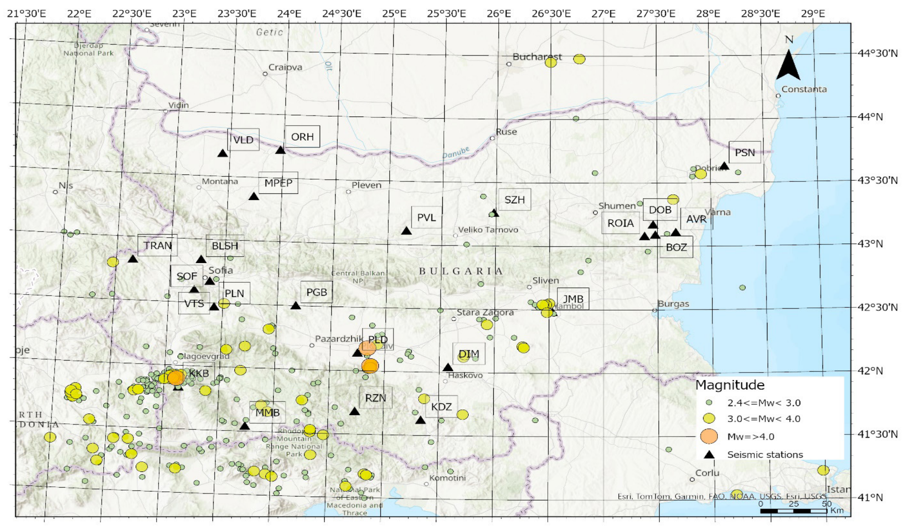

Figure 3. Epicentral map of the earthquakes within the territory of Bulgaria and adjacent areas in 2023. Seismic stations of NOTSSI are marked with black triangles and station codes.

of the Black Sea. Activity is also observed in the Maritsa seismic zone near the city of Plovdiv.

The increased concentration of earthquakes in the southwestern region is consistent with previous years and studies (e.g., Dragomirov D et al. 2018, Buchakchiev V et al. 2017).

To investigate the spatial distribution, the number of earthquakes is calculated in a grid with a cell size of 0.1° x 0.1° (Fig. 4). Confirming the above observation, the highest number of events is obtained around the settlements of Krupnik and Musomishte.

Northern Bulgaria is a relatively quiet area, with most seismic activity concentrated in the eastern part of the region.

The number of events in the magnitude range 2.0 < M_W ≤ 3.0 is 599, in 3.0 < M_W ≤ 4.0 is 66, and there are two stronger earthquakes with magnitudes M_W = 4.1 and M_W = 4.8 respectively. The magnitude distribution is well observed in Figure 5.

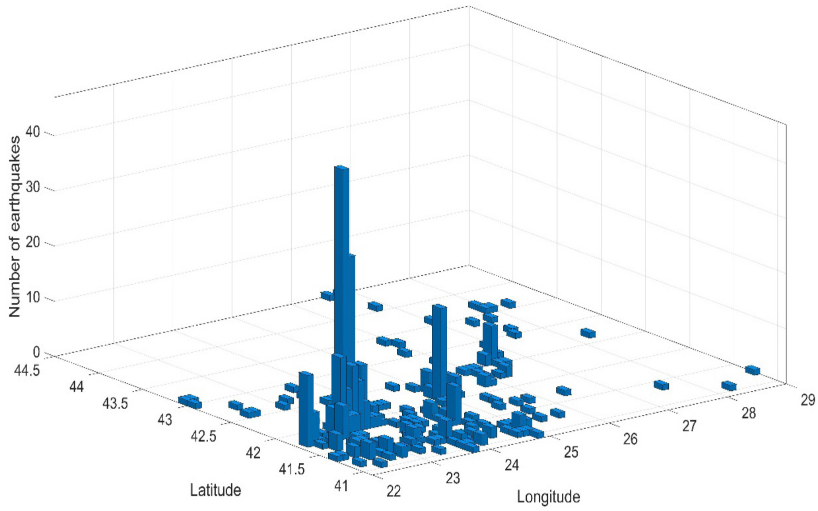

Figure 4. 3-D visualization of the number of earthquakes and the spatial distribution of epicenters in a [0.1° x 0.1°] grid.

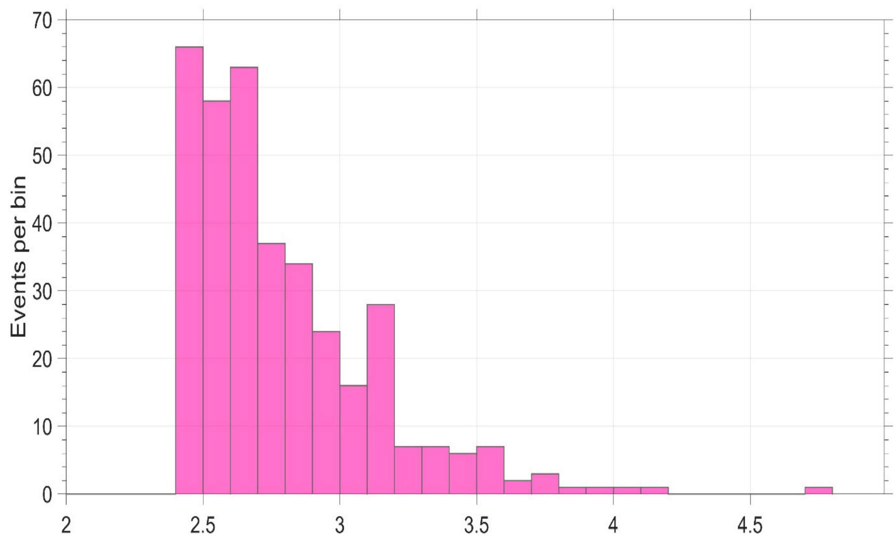

Figure 5. The magnitude distribution of seismic events.

When discussing earthquake parameters, it is important to determine the depth of its focus. Seismic hypocenters occur up to a maximum depth of about 700 km. This depth is usually divided into three zones. Shallow, intermediate, and deep foci are distinguished based on these zones. Shallow earthquakes have foci in the earth's crust up to the border of Mohorovičić, about 30-40 km deep. Intermediate and deep-focus earthquakes originate at depths between 40 and 300 km and between 300 and 700 km, respectively. In practice, the term "deep earthquake" is most often used for foci that occur deeper than 40 km, i.e. in both intermediate and deep zones. The most numerous (9/10 of all seismic foci) are the shallow ones. They also have the most destructive effect, especially when they are strong enough. In shallow earthquakes, the effect on the Earth's surface is limited to a narrow area around the epicenter, and the intensity very quickly decreases with distance from it.

The depth distribution plots in Fig. 6 show that most events for the examined period occur within the depth range of 3-20 km. The number of events decreases gradually beyond 21 km as depth increases. At the same time, the highest number of events (over 80) are observed at depths of 3, 14, and 16 km. Most seismic events with a magnitude $M_W \geq 3$ have depths ranging from 10 to 20 km. All the foci are located in the Earth's crust.

Figure 7 illustrates the temporal distribution of seismicity according to the number of events per month. The number of earthquakes increases during certain months: March (92), June (118), and September (182). The lowest number of earthquakes occurred in August, with only 57 events of magnitude greater than 1.1. Figure 8 demonstrates that there is no definite monthly pattern in the distribution of earthquakes.

Figure 8 shows the daily distribution of the number of earthquakes. The distribution is uneven, with some days experiencing more than 10 earthquakes (e.g., 07.06.2023, 04.09.2023, 09.09.2023, 07.12.2023). There are periods, such as in January, May, July, and September, where there are 1 or 0 events over spans of 3-5 days within Bulgaria. The increased number of events on

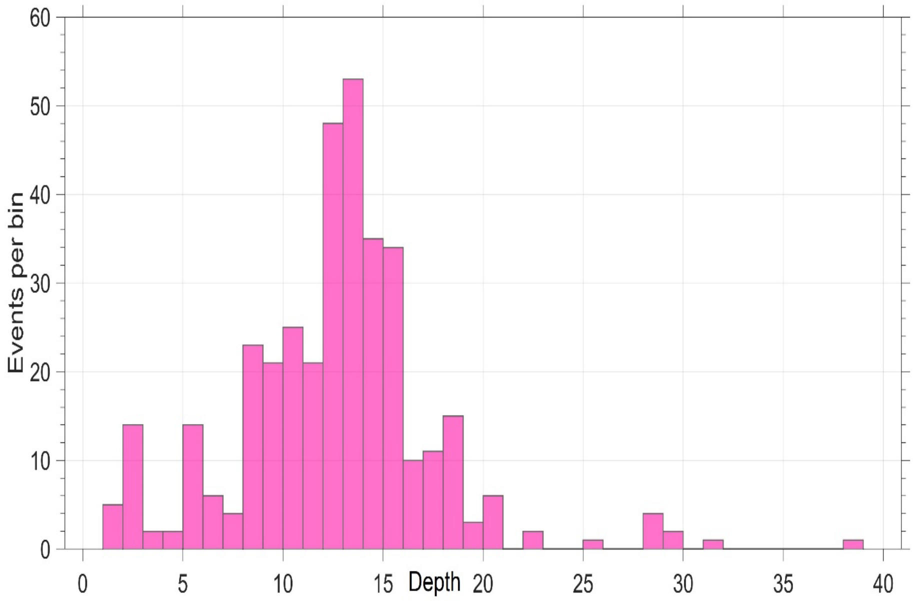

Figure 6. Distribution of the number of events according to depth in kilometers.

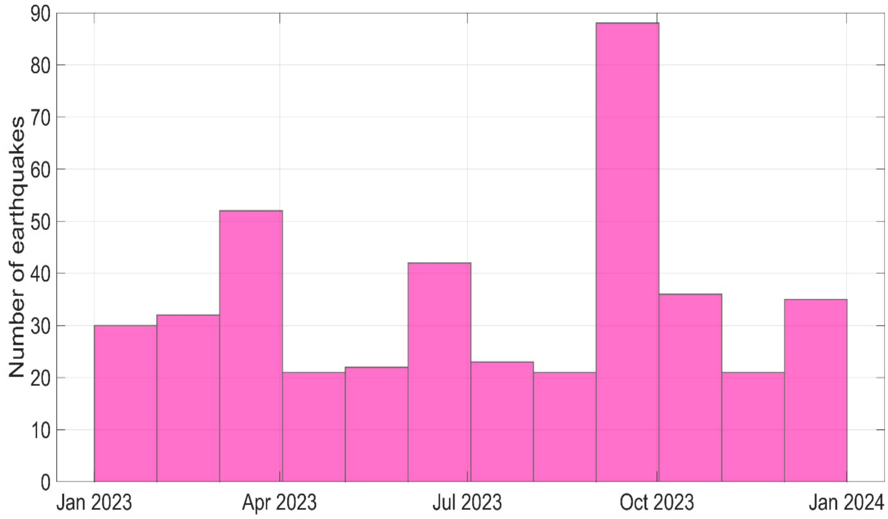

Figure 7. The distribution of the number of events per month.

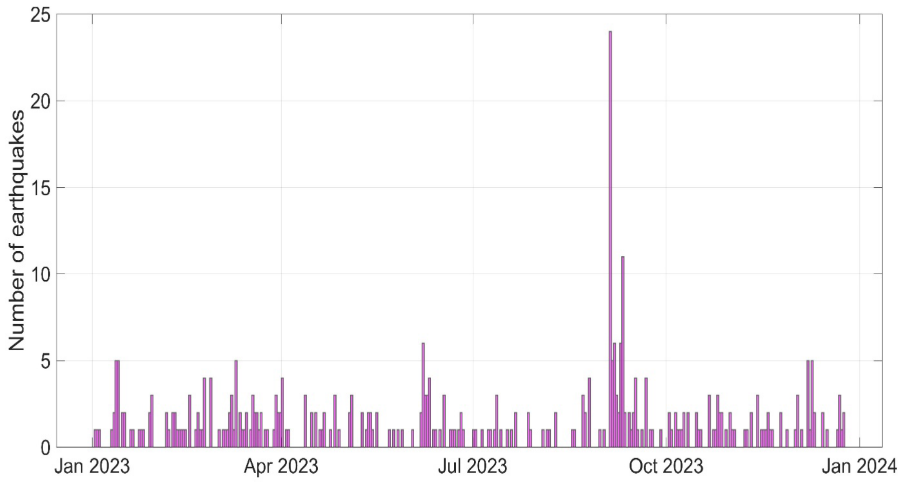

Figure 8. Distribution of the number of events per day.

the aforementioned days is attributed to the aftershock series following the events on 07.06.2023 at 12:26:37 (42.04°N/24.87°E; M_w=4.8), 04.09.2023 at 07:31:52 (41.9°N/23.11°E; M_w=4), 09.09.2023 at 05:25:05 (41.91°N/23.08°E), and 07.12.2023 at 01:30:24 (41.09°N/23.08°E; M_w=3.5).

The spatial-temporal distribution of earthquakes in Bulgaria and its surroundings is uneven. The calculated epicenter density function for 2023 is presented in Fig. 9. Kernel Density Estimation (KDE) is a statistical method used to estimate the probability density of a random variable. It estimates the independent probability density function based on a data sample. Unlike parametric methods, KDE is non-parametric, as it does not make any assumptions about the shape of the distribution.

The figure confirms that the northern part of Bulgaria is relatively quiet. This is because the Moesian platform is assumed to be an element of a stable Paleo-European plate and retained its specific dynamics after the Triassic period, during the last 100-150 million years (Dachev et al. 1995).

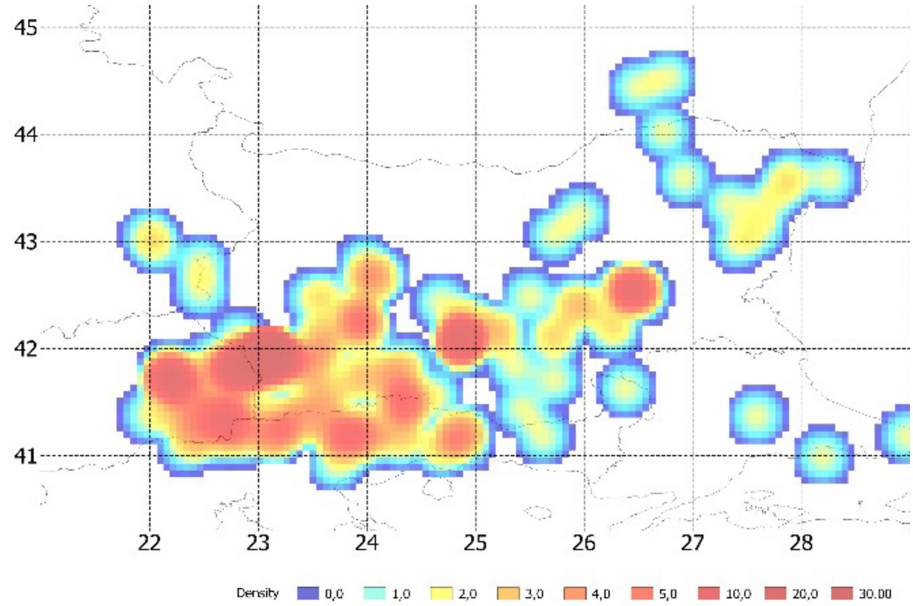

Figure 9. Epicenter density function for the year 2023 calculated on a 0.3^0x0.3^0 decimal degree grid using KDS

An essential area of reactivation of the Fore-Balkan fault is near the town of Gorna Oryahovitsa. The fault was reactivated during the Pliocene-Quaternary period and is still active. This tectonic activity resulted in forming the so-called Resen Trough, which is positioned along that fault in a west-east direction. The 1913 Gorna Oryahovitsa earthquake with a magnitude of 7.0 and the 1986 Strazhitsa earthquakes with magnitudes of 5.5 and 5.7 occurred in the eastern part of the Resen Trough. Small earthquakes (with magnitudes less than 4.0) are still observed in this area.

The Sofia graben is located in the northwestern part of the Srednogorie unit, at the junction between the Sub-Balkan and Maritsa graben complexes (Zagorcev 1992). SE-NW fault zones border it with significant neotectonic activity to the south and north.

The upper Thracian Depression is formed between the Rhodope massif and Srednogorie zones due to negative tectonic processes. The Maritsa fault zone is situated in its central parts. The thickness of the Neogene sediments in this region reaches up to 500 m, and the Quaternary - up to 100 m (near the town of Plovdiv). The depression margins border on re-activated faults, which are most expressed in the southern margin. (Dachev et al. 1995). The recent seismic and tectonic activity in the Upper Thracian Depressions is closely associated with the well-known Maritsa fault system. The Maritsa fault zone's largest quake is the 1928 earthquake with M=7.0. In 2023, the strongest earthquake with magnitude Mw4.8 occurred in this zone.

The southwest territory of Bulgaria is well distinguished on the epicenter density function's map in Fig. 9. During the neo-tectonic stage, this area was marked by uplifting the high-mountainous relief of the Western Rhodopes, Rila, Pirin. Faults in the west and north marginal parts of Rila and the north margin of Pirin are with well-expressed neotectonic activity. Zagorcev (1992) considers that the intense uplift of the western part of the Rhodope massif causes differential neotectonic movement along the pre-existing bordering fault zones, such as Middle-Mesta, Struma, and Maritsa fault zones. Some of Europe's strongest earthquakes in the 20th century occurred in the Kresna-Simitly area - the Kresna earthquakes of April 4, 1904 (MS=7.2 and 7.8). This area is related to the Struma fault zone, which involves a sub-longitudinal Struma fault intersected in a transverse direction by numerous neotectonic faults. Analysis of the last five years shows that this area constantly exhibits the highest level of seismic activity in Bulgaria.

On June 7, 2023, the strongest earthquake recorded in Bulgaria occurred and was felt throughout the country (Fig. 10) (Chamati M, Popova M 2024, Solakov D et al. 2023). The earthquake had a magnitude of MW=4.8, a focal depth of 12 km, and reached maximum intensity in the epicentral area with Imax=6.5 on the Medvedev-Sponheuer-Karnik scale (MSK - 64).

The most significant impact from external seismic sources on the territory of the country was from the earthquake on February 14, 2023 (T0=13:16:50.8; 45.11°N, 23.27°E; depth h=16 km; Mp=5.9). It was felt with a maximum intensity of 4.5 degrees in the city of Vidin (distance Δ=128 km), the village of Gradets, Vidin Province (Δ=127 km), the village of Deleyna, Vidin Province (Δ=128 km), the village of Antimovo, Vidin Province (Δ=124 km), and the village of Bozhuritsa, Pleven Province (Δ=205 km, Δ - epicentral distance in km).

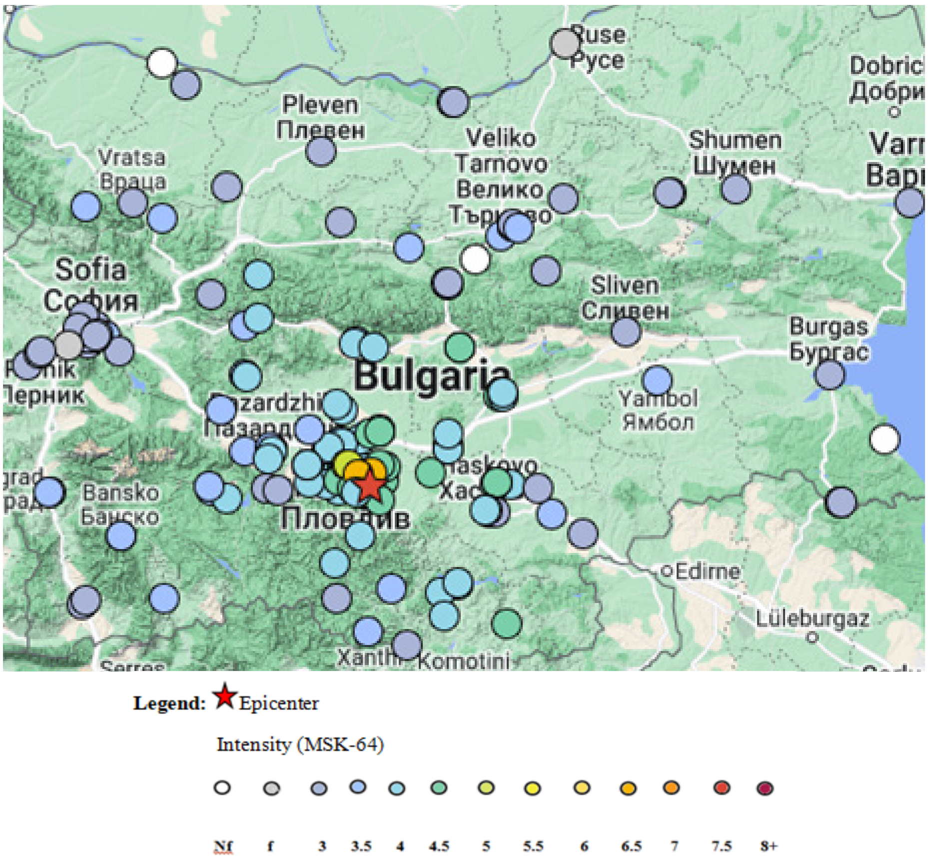

Figure 10. Seismic impacts of the strongest earthquake in 2023 (MW 4.8, 42.04°N/24.87°E; depth=12 km), which occurred on June 7, 2023, with an epicenter near the city of Asenovgrad.

Conclusions

The territory of Bulgaria represents a typical example of a region characterized by high seismic hazards. Over the centuries, the country has experienced strong earthquakes, with one notable event being the most powerful shallow earthquake in continental Europe during the 20^{th} century.

Based on the analysis of 1,022 earthquakes with magnitudes $M_w \geq 2.4$ occurring in Bulgaria and its surroundings in 2023, the following conclusions can be drawn:

1. The year 2023 is generally characterized by low seismicity, in and near Bulgaria compared to the more active southern region of the Balkan peninsula. It is dominated by events with magnitudes below 3.0. There were 25 earthquakes with magnitudes above 3.5, with the strongest two having magnitudes of M_w=4.0 (September 4, 2023; 41.9°N/23.11°E; depth=16 km), M_w=4.1 (October 23, 2023; 42.18°N/24.84°E; depth=13 km), and M_w=4.8 (June 7, 2023; 42.04°N/24.87°E; depth=12 km).
2. The spatial-temporal distribution of earthquakes in Bulgaria confirms the relatively quiet seismic regime in the northern part of the country with values of 2 events per 10 km^2 in the east Dobrogea region. The southwest territory of Bulgaria is well distinguished on the epicenter density function's map values of 20-30 events per 10 km^2.
3. The hypocenters of earthquakes are primarily located in the upper crust (up to 20 km). Most earthquakes are registered in the depth layer between 3 and 19 km.
4. The use of SeisComp 3 software enables the detection of events with small magnitudes (starting from Mw1.1), which allows the analysis of micro-earthquakes.

Acknowledgments

The authors express their gratitude to E. Botev, Bl. Babachkova, T. Iliev, R. Valkov, P. Kirilov, V. Kamenov, D. Lazarov, who worked at NOTSSI in 2023.

The maps were created using ArcGIS Pro. The authors would like to express their gratitude to ESRI Bulgaria for providing preferential licenses under the ESRI Academic Education Program and to Dilyana Hristova for preparing the maps.

The research leading to these results received funding from the Ministry of Education and Science of Bulgaria under Grant Agreement No D01-321/30.11.2023

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Funding

This work was supported by the project "National Geoinformation Center (NGIC)" funded by the National Roadmap for Scientific Infrastructure 2020-2027 by Contract No D01-321/30.11.2023with the Ministry of Education and Science of Bulgaria

Author contributions

Both authors contributed to the study's conception and design. Emil Oynakov and Mariya Popova prepared the materials, collected the data, and analyzed them. They wrote the first draft of the manuscript and edited it according to the reviewer's comments. Both authors read and approved the final manuscript.

Author ORCIDs

Emil Oynakov https://orcid.org/0000-0002-8992-5581
Mariya Popova https://orcid.org/0009-0008-4221-971X

Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

References

Buchakchiev V, Oynakov E, Dragomirov D, Milkov Y (2019) Seismicity on the territory of Bulgaria and the adjacent lands recorded by Notssi In 2017 Bulg. Geophys. J., 2019, Vol. 42, pp. 94-104. https://doi.org/10.34975/bgj-2019.42.9

Büyüksaraç A, Işık E, Bektaş Ö, Avcil F (2024) Achieving intensity distributions of 6 February 2023 Kahramanmaraş (Türkiye) earthquakes from Peak Ground Acceleration records. Sustainability 16(2):599. https://doi.org/10.3390/su16020599

Chamati M, Popova M (2024) Environmental impact of the 7 June 2023 moderate earthquake in Plovdiv and Asenovgrad area, Bulgaria. Lecture Notes in Networks and Systems, 883, Springer, 2024, ISSN:2367-3389. https://doi.org/10.1007/978-3-031-74707-6_6

Christoskov L, Dimitrova L, Solakov D 2011a. Magnitude determinations of P wave by digital broadband seismometers of NOTSSI network for local and regional events. Compres rendus de l'Academie bulgare des Sciences, Vol 65, No 5, pp. 653-660

Christoskov L, Dimitrova L, Solakov D 2011b. Digital broadband seismometers of NOTSSI for practical magnitude determinations of P waves. Bulg. Geophys. J., v.XXXVIII, N1-4/2011, ISSN 1311- 753X, 62-72

Christoskov L, Solakov D, The earthquakes- danger and counteraction. Prof. Marin Drinov academic publishing house, Sofia, 2009, 177 pages

Dachev H, Vaptzarov I, Filipov L, Solakov D, Simeonova S, Nikolova S, Sokolova P, Botev E, Georgiev Tz (1995) Seismology, geology, neotectonics, seismotectonics and seismic hazard assessment for the PNPP Belene site. Report of Project: Investigations and activities for increasing of the seismic safety of the PNPP Belene site, Geophys. Inst., Bulg. Acad. Sci., S, I, pp. 250

Dragomirov D, Oynakov E, Buchakchiev V, Milkov Y (2019) Seismicity on the territory of Bulgaria and the adjacent lands recorded by Notssi In 2018 Bulg. Geophys. J., 2019, Vol. 42, pp. 105-118. https://doi.org/10.34975/bgj-2019.42.10

Grigorova E, Christoskov L, Sokerova D, Rizhikova S, Roglinov A (1978) Catalogue ofearthquakes in Bulgaria and the nearby territories during the period 1st cent. BC - 1977.

Archives of the Geophysical Institute, Bulg. Acad. Sci., Sofia, 1978

Grigorova E, Sokerova D, Christoskov L, Rijikova S (1979) Catalogue of the earthquakes in Bulgaria for the period 1900–1977, Archives of the Geophysical Institute, Bulg. Acad. Sci., Sofia, 1979 (in Bulgarian)

Gutenberg B, Richter CF (1944) Frequency of earthquakes in California. Bulletin of the Seismological society of America, 34(4), 185-188. https://doi.org/10.1785/BSSA0340040185

Shebalin NV Seismic Scale and Methods of Measuring Earthquake Intensity. In Foci of Strong Earthquakes in the USSR; IPE AS USSR Publ.: Moscow, Russia, 1978, pp. 87–109 (In Russian)

Solakov D 1993 An algorithm for hypocenter determination of near earthquakes. Bulg. Geophys. J. 19 (1), 56-69

Solakov D, Simeonova S, Raykova P, Aleksandrova I (2018) Empirical relations converting Md and Mp magnitudes applied in Bulgarian seismological routine practice to moment and magnitude. Comptes rendus de l'Acad´emie bulgare des Sciences, 71, 8, 1076-1085. https://doi.org/10.7546/ crabs.2018.08.09

Solakov D, Simeonova S, Trifonova P, Metodiev M, Raykova P (2023) Earthquake scenarios and population exposure for the city of Plovdiv. Natural Hazards, volume 118, issue 3, pages 2153- 2171, ISSN 0921030X, DOI 10.1007/s11069-023-06087-7. https://doi.org/10.1007/s11069-023-06087-7

Wiemer S (2001) A Software Package to Analyze Seismicity: ZMAP Seismological Research Letters, 2001, 72 (3), 373-382. https://doi.org/10.1785/gssrl.72.3.373

Zagorcev IS (1992) Neotectonic development of the Struma, (Kraishtid) Lineament, Southwest Bulgaria and Northern Greece, Geological Magazine 129 (2), 197–222. https://doi.org/10.1017/S0016756800008281