

MODELING OF A MACROSEISMIC IMPACT FIELD FOR BULGARIA

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Abstract

Bulgaria, situated in the eastern part of the Balkan Peninsula, is located within the Alpine–Himalayan seismic belt, characterized by high seismic activity. Earthquake activity in Bulgaria and the adjacent region reflects the ongoing geodynamic processes affecting the Balkan Peninsula, where seismicity exhibits significant spatial and temporal variability. In this study, a macroseismic dataset for shallow earthquakes that occurred in and near Bulgaria since the beginning of the 20th century was analyzed. The dataset includes events with moment magnitudes (M_W) ranging from 5.2 to 7.6 and observed intensities from VII to X according to the European Macroseismic Scale (EMS-98). The spatial attenuation of macroseismic intensity was modelled using an elliptical approach, taking into account the regional characteristics of earthquake sources. The results demonstrate a strong correlation between observed and modelled intensities, with correlation coefficients of $r > 0.9$ and $R^2 > 0.8$, confirming the reliability of the proposed attenuation model. The proposed model provides a consistent representation of macroseismic effects and their spatial distribution for strong earthquakes in the region. The proposed approach is applicable to seismic hazard and risk assessment in major urban areas of Bulgaria, particularly Sofia and Plovdiv. The results provide valuable input for

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seismic risk mitigation, urban planning, infrastructure assessment, and engineering decision-making.

Key words: earthquakes, seismogenic zones, macroseismic intensity, EMS-98, Bulgaria

Introduction. Earthquakes are among the most destructive natural hazards, causing severe impacts on human societies and the built environment throughout history. Major destructive earthquakes have repeatedly influenced the development of human settlements and remain a major challenge for disaster risk reduction.

The Balkan region is characterized by high seismic activity and the occurrence of destructive earthquakes. Bulgaria represents a typical example of a seismically active area located in the eastern part of the Balkan Peninsula, which, from a plate-tectonic perspective, forms part of the continental margin of Eurasia. Throughout its history, Bulgaria has experienced numerous destructive earthquakes. The earliest well-documented earthquake affecting the territory of present-day Bulgaria occurred in the 1st century BC in the Black Sea region near Kavarna. Among the most significant historical events, the 1858 Sofia earthquake ($M_W = 6.3$, $I_0 = IX$ MSK) caused severe damage in the city and was associated with the appearance of thermal springs in its western part.

Several of the strongest earthquakes in Europe in the 20th century occurred in Bulgaria between 1901 and 1928, with moment magnitudes (M_W) equal to or exceeding 6.5. Between 1904 and 1906, the south-western part of Bulgaria was affected by significant seismic activity, which began with two devastating earthquakes on 4 April 1904, occurring within 23 minutes of one another. In 1928, a destructive earthquake sequence occurred along the Maritsa River valley in southern Bulgaria, including two major events with magnitudes $M_W = 6.5$ and $M_W = 7.1$. Since 1928, no earthquakes of comparable magnitude have occurred in the country. The strongest instrumental earthquakes recorded after this period include the 1986 Strazhitsa events ($M_W = 5.4$ on 21 February and $M_W = 5.6$ on 7 December) in central northern Bulgaria and the 2012 Sofia earthquake ($M_W = 5.6$ on 22 May) in southwestern Bulgaria.

Macroseismic intensity has been used as an empirical measure of earthquake ground shaking and damage effects for several centuries. Initially introduced as a classification system of earthquake effects in the early 17th century [1], intensity scales have progressively evolved and have become an important tool for the assessment of historical and instrumental earthquakes. The attenuation of macroseismic effects produced by shallow earthquakes has been investigated extensively since the middle of the 20th century (e.g., [2–5]).

In this study, macroseismic intensity is considered a measure of the severity of earthquake shaking based on the three fundamental criteria defined in the European Macroseismic Scale EMS-98 [6]: effects on people, effects on objects

and the natural environment, and damage to buildings.

The aim of this study is to analyze macroseismic intensity data available for Bulgaria and adjacent regions. Using macroseismic intensity observations from 17 shallow earthquakes, new attenuation relationships and magnitude estimation models are developed. Furthermore, empirical relationships between macroseismic intensity and earthquake size, expressed by moment magnitude (M_W), are proposed.

Spatial distribution of seismicity in Bulgaria. The spatial pattern of seismicity in Bulgaria and adjacent areas is presented in Fig. 1. It shows the distribution of historical and instrumental earthquake epicentres ($M_W \geq 4.0$) together with the major active faults in Bulgaria and adjacent regions. The geological and seismotectonic framework is modified according to SOLAKOV et al. [8]. The epicentral distribution indicates that seismicity is not uniformly distributed across the region. Based on tectonic and seismological evidence, the seismicity of Bulgaria is represented by several seismogenic zones, as described in [7] and [8]. Each zone is characterized by its own tectonic, seismic, and geological features. The zones are delimited by the spatial clustering of seismic activity and associated fault systems, as indicated by the epicentral distribution in Fig. 1.

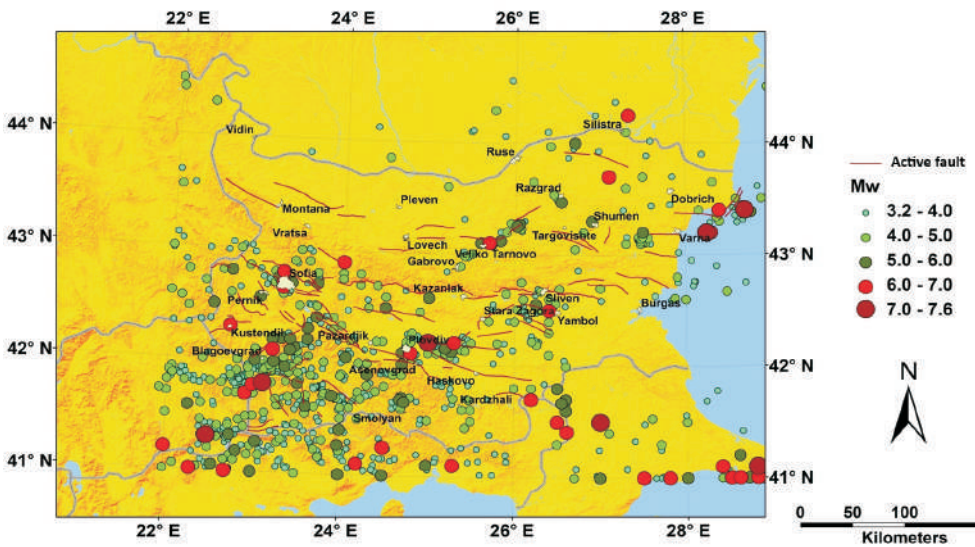


Fig. 1. Seismicity (historical and instrumental) and active faults in Bulgaria and surroundings (modified according to [8])

The main seismogenic zones outlined on the territory of Bulgaria are: Shabla, Gorna Oryahovitsa, Sofia, Maritsa, and Kresna. At the beginning of the 20th century strong earthquakes with macroseismic impact up to intensity X (EMS-98) were realized in the identified seismogenic zones.

Shabla seismogenic zone is located along the eastern margin of the Moe-

sian Platform. This area is characterized by a system of NNE–SSW-oriented faults that separates the platform from the deep structure of the West Black Sea back-arc marginal basin. The most significant earthquakes in this zone are associated with the Kaliakra fault system, a major offshore strike-slip structure identified through seismic profiling investigations in the Black Sea region. Varna is the largest urban centre located within the Shabla seismogenic zone. The strongest documented earthquake affecting the city occurred on 31 March 1901 ($M_W = 7.2$) in the Black Sea region along the Kaliakra fault system [8]. The effects of this earthquake in Varna were described by WATZOF [9]: *“the concussion lasted a few seconds; during this time, we heard a noise, as if from an approaching car; the chandeliers and lamps swayed loudly, the bells began to ring, the city clock stopped, walls and ceilings cracked, many chimneys fell down...”*

Gorna Oryahovitsa seismogenic zone is located in central northern Bulgaria, within the transitional area between the Balkan fold belt and the stable Moesian Platform. The zone is characterized by moderate deformation associated with the tectonic interaction between these two major structural units. The boundary between the Moesian Platform and the Balkan orogen represents a complex tectonic zone where the outermost folds of the Central Balkan–Fore-Balkan region are displaced over the platform along thrust structures [8]. The strongest documented earthquake in this zone occurred on 14 June 1913, with $M_W = 6.8$. The event caused severe damage in several settlements, including Gorna Oryahovitsa (up to 95% damage), Veliko Tarnovo, and Dolna Oryahovitsa (up to 80% damage) [10]. The earthquake produced the strongest documented macroseismic effects in Veliko Tarnovo, the largest city within the zone. The consequences of the earthquake were described in [10]: *“Suddenly we were startled by a terrible roar from Sveta Gora (Holy Mountain), when everything around was cracking with an infernal noise, the picture was scary. The crash was indescribable, everywhere on the pavement and sidewalks, the cornices of the massive buildings, the iron and stone balconies were collapsing with an ugly noise, and the tiles were falling from the roofs.”*

Sofia seismogenic zone is located in southwestern Bulgaria, an area characterized by pronounced tectonic activity. The seismicity of this zone is mainly associated with active faults bounding the Sofia graben, which represents a tectonically active intermontane basin. Earthquake hypocentres are mainly concentrated within the upper 20 km of the crust. Sofia, the capital and largest city of Bulgaria, is located within this seismogenic zone. Due to its population, economic importance, and infrastructure concentration, the city represents one of the areas with the highest seismic risk in the country. Historical records indicate several destructive earthquakes affecting Sofia. The largest documented earthquake associated with this zone occurred in 1858, with an estimated magnitude of $M_W \approx 6.3$ – 6.5 [8]. The earthquake caused extensive damage throughout the city. Historical reports indicate severe effects on religious and public buildings, including damage

to mosques and churches. Changes in the activity of thermal springs were also reported: the flow rate decreased before the earthquake and stopped completely for approximately 24 hours afterward, while new springs appeared near Sofia, Boyana, and Gorna Banya [11]. In the 20th century, the strongest earthquake affecting the Sofia zone occurred in 1917 ($M_W = 5.2$, $I_0 = \text{VII–VIII EMS-98}$). On 22 May 2012, an earthquake occurred near Sofia with $M_W = 5.6$ and maximum observed intensity $I_0 = \text{VII–VIII EMS-98}$.

Maritsa seismogenic zone. The seismicity of Maritsa seismogenic zone is closely related to the WNW–ESE-trending Maritsa fault system and associated secondary structures. These faults represent long-lived tectonic features that have remained active throughout the neotectonic period. Earthquake hypocentres are mainly located within the upper 20 km of the crust, with occasional deeper events reaching approximately 45 km [8]. The seismic history of Plovdiv includes the destructive earthquake sequence of 1928. It consisted of a $M_W = 6.5$ foreshock on 14 April 1928 and a $M_W = 7.1$ main shock on 18 April 1928. These earthquakes produced the strongest documented seismic effects in Plovdiv and the surrounding region. The earthquake sequence caused severe destruction and extensive damage to approximately 74 000 buildings in Plovdiv, Chirpan, and Parvomay [12]. Two surface coseismic ruptures were documented, each extending over several tens of kilometers. The 1928 earthquake sequence represents one of the rare cases where detailed geodetic observations were conducted before and after a major earthquake, providing valuable information on earthquake-related ground deformation [12, 13].

Kresna seismogenic zone is associated with the NW–SE-oriented Struma fault system, which is intersected by numerous neotectonic faults and represents one of the most important active geological structures in southwestern Bulgaria [8]. The zone includes some of the deepest earthquakes recorded in Bulgaria, consistent with the increased crustal thickness beneath the western part of the Rhodope massif, where it reaches approximately 45–50 km. Earthquake hypocentres are mainly distributed within the upper 30 km of the crust, with the highest concentration of seismic foci between 5 and 20 km depth [8]. The high seismic activity of the Kresna zone is related to the Struma fault system. On 4 April 1904, two catastrophic earthquakes occurred within a 23-minute interval. The sequence started with a foreshock at 10:05 UTC with $M_W = 6.8$, followed by the main shock at 10:26 UTC with $M_W = 7.6$. The main shock was felt over a very large area, including Budapest, Hungary, and surface waves were reportedly observed by eyewitnesses in Sofia [14]. Surface ruptures associated with the 1904 earthquake sequence are still visible in the Kresna Gorge. The earthquakes caused severe damage in Blagoevgrad, the largest urban centre within the zone, as well as in Bansko and Razlog [14]. Historical descriptions of the damage in Djumaya (present-day Blagoevgrad) are provided in [15]: “*At Djumaya damage was widespread and in places serious, practically in the lower part of the town,*

where about 100 houses damaged by the first shock were ruined, including one mosque... and the military hospital.”

Method. In this study, the macroseismic intensity field was estimated using the generalized macroseismic model developed for the seismicity of Bulgaria and presented in [4,5]. The attenuation of macroseismic intensity was described by an elliptical isoseismal model, in which the semi-major and semi-minor axes of the isoseismal areas were defined as:

$$(1) \quad \log(a) = c_1(I) * M_W + d_1(I)$$

$$(2) \quad \log(b) = c_2(I) * M_W + d_2(I),$$

where M_W is the earthquake moment magnitude, I is the macroseismic intensity according to EMS-98, a and b represent the semi-major and semi-minor axes of the isoseismal ellipse for a given intensity level, and $c_1(I)$, $d_1(I)$, $c_2(I)$, $d_2(I)$ are empirical coefficients.

The empirical coefficients in Eqs (1) and (2) were determined using regression analysis based on the least-squares method applied to historical and instrumental earthquake data from Bulgaria and adjacent regions. The performance of the obtained relationships is evaluated using the correlation coefficient (r) and the coefficient of determination (R^2). The obtained values indicate the strength of the relationship between earthquake magnitude and the dimensions of the isoseismal areas [16].

The length of the semi-axes a and b (at a fixed intensity I) are estimated based on the available macroseismic data presented in [17,18].

Data. The database created for the purpose of the present research allows a detailed study of the macroseismic field of 17 earthquakes (presented in Table 1). The earthquake parameters are from the catalogues [19,20]. The macroseismic data used in this study (from [17–19]) cover shallow earthquakes that occurred in and near Bulgaria since the beginning of the 20th century.

In Table 1, the earthquake size is expressed by a seismic moment magnitude M_W . The intensity observations are expressed in the European Macroseismic Scale (EMS-98). The magnitude range of the considered earthquakes is between 5.1 and 7.6 and the maximum intensity varies between VIII and X.

Results. Figure 2 presents the variation of the semi-axes of the ellipse (a and b) versus seismic moment magnitude M_W at constant intensities $I = VII$.

The relations that express best-fitting relationships for intensities $I = VII$, VIII and IX are presented below:

$$(3) \quad \log(a_7) = 0.5M_W - 1.57 \pm 0.158$$

$$r = 0.93, r^2 = 0.86, n = 17 \text{ (number of input data)}$$

$$(4) \quad \log(b_7) = 0.42M_W - 1.3 \pm 0.167$$

T a b l e 1

Earthquakes parameters, instrumental and macroseismic data

Year	M	D	H	M _m	M _W	I ₀	b ₉	a ₉	b ₈	a ₈	b ₇	a ₇
1901	3	31	7	10	7.1	IX-X	24	38	44	63	40.5	135
1903	11	25	23	16	5.5	VIII	–	–	3.2	3.2	7	15
1904	4	4	10	2	6.8	IX	13.5	18	32	50	57	76
1904	4	4	10	25	7.6	X	31.5	47.5	40.5	68	78	114
1909	2	15	9	34	5.7	VIII	–	–	2.55	5	7.5	12.5
1913	6	14	9	33	6.8	IX	9	14.5	13.5	32	30	72
1917	10	18	18	58	5.2	VII-VIII	–	–	–	–	6	9.5
1928	4	14	9	0	6.5	IX	9	11	10	57	45	49.5
1928	4	18	19	22	7.1	IX-X	13.5	31.5	18	31.5	45	81
1928	4	25	9	25	5.8	VIII	–	–	9	18	23	32
1931	3	7	0	16	6.2	VIII	–	–	10	14	22.5	31.5
1931	3	8	1	50	6.7	X	9	18	18	31.5	26.5	49
1941	9	1	14	18	5.2	VII-VIII	–	–	–	–	7.5	15.5
1942	8	23	15	41	5.1	VII	–	–	–	–	10	12.5
1986	2	21	5	39	5.4	VII-VIII	–	–	–	–	5.5	8.0
1986	12	7	14	17	5.6	VIII	–	–	4	5	13	18
2012	5	22	0	0	5.6	VII-VIII	–	–	–	–	17.5	27

Abbreviations: M – month; D – day; H – hour; M_m – minute; M_W – seismic moment magnitude; I₀ – macroseismic intensity (EMS-98); a_i, b_i – semi-axes of an ellipse at a fixed intensity I (I = 9,8,7); (a – semi-major axis, b – semi-minor axis); dashes (–) denote non-existent values.

$r = 0.90$, $r^2 = 0.81$, $n = 17$ (number of input data)

$$(5) \quad \log(a_8) = 0.64M_W - 2.83 \pm 0.13$$

$r = 0.96$, $r^2 = 0.92$, $n = 12$ (number of input data)

$$(6) \quad \log(b_8) = 0.57M_W - 2.56 \pm 0.16$$

$r = 0.93$, $r^2 = 0.86$, $n = 12$ (number of input data)

$$(7) \quad \log(a_9) = 0.55M_W - 2.43 \pm 0.092$$

$r = 0.92$, $r^2 = 0.85$, $n = 7$ (number of input data)

$$(8) \quad \log(b_9) = 0.57M_W - 2.84 \pm 0.093$$

$r = 0.93$, $r^2 = 0.86$, $n = 7$ (number of input data).

The obtained regression relationships demonstrate a strong linear relationship between the dimensions of the isoseismal ellipses and earthquake magnitude for fixed macroseismic intensity levels (I = VII, VIII, and IX EMS-98). The coefficient of determination values ($R^2 = 0.81-0.92$) indicate that the proposed log-linear

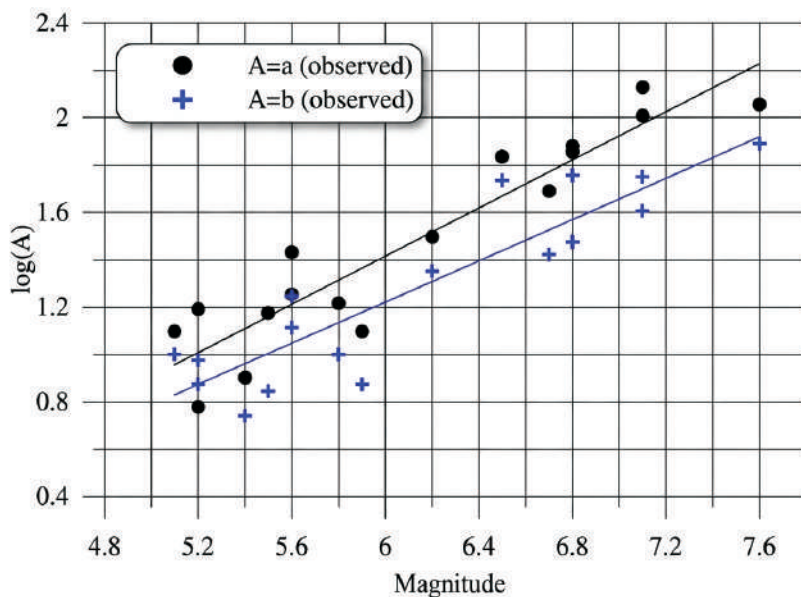


Fig. 2. Relations between semi-axes of the ellipse (a and b) and seismic moment magnitude at constant intensities $I = VII$

relationships explain a significant proportion of the variability in the observed macroseismic data.

Figure 3 presents the modelled macroseismic intensity fields with $I \geq VII$ EMS-98 for hypothetical earthquakes with $M_W = 7.0$ located in Sofia and Maritsa seismogenic zones. These two zones were selected as representative examples because they include major urban areas with different tectonic settings and significant seismic risk.

The modelled intensity fields show elliptical distributions, with the orientation of the major axes corresponding to the dominant geological structures within each seismogenic zone. Fig. 3a and b present the predicted isoseismal ellipses for the mean model and the upper uncertainty level (mean + σ). The $\pm\sigma$ values represent the standard deviation of the regression model and characterize the uncertainty associated with the estimated dimensions of the intensity fields.

Conclusion. The main objective of this study was to develop an empirical approach for estimating the macroseismic impact of strong shallow earthquakes affecting urban areas in Bulgaria and adjacent regions. The proposed elliptical attenuation model provides a quantitative relationship between earthquake magnitude and the dimensions of isoseismal areas. The obtained coefficients of determination ($R^2 > 0.8$) indicate a strong correlation between the semi-axes (a and b) of the isoseismal ellipse and the earthquake moment magnitude (M_W) for a fixed macroseismic intensity level.

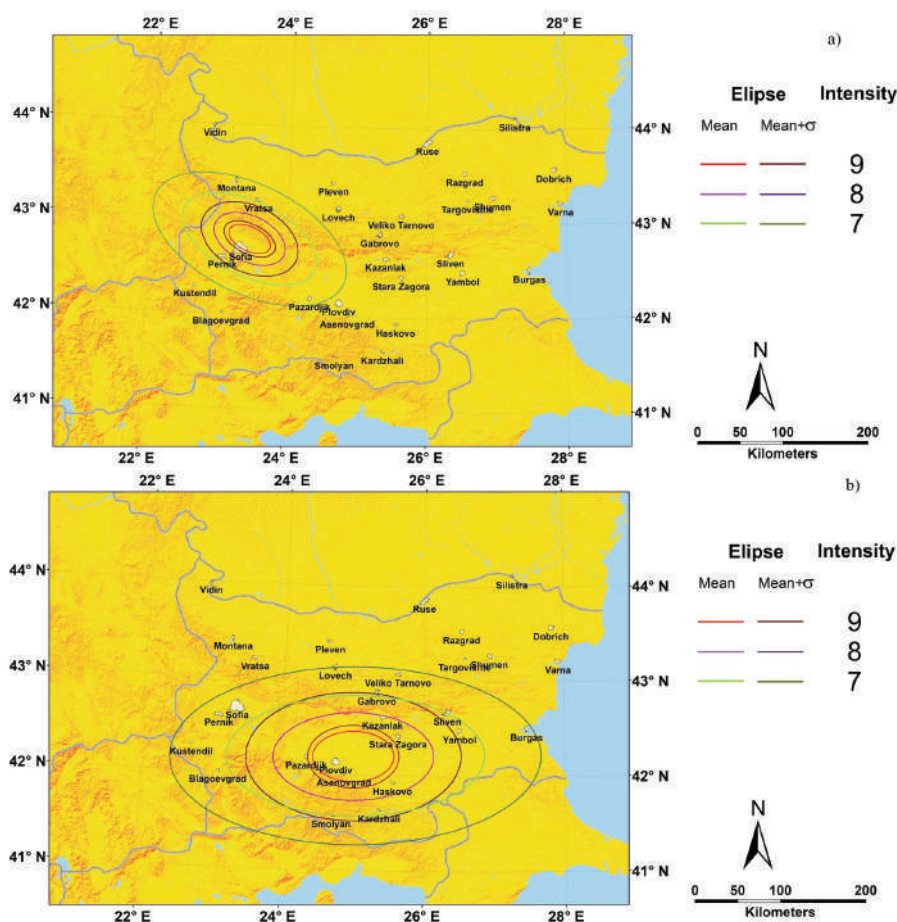


Fig. 3. Macroseismic impact field model for earthquake with $M_W = 7.0$ generated in the seismogenic zones: a) Sofia – $M_W = 7.0$ earthquake in Sofia seismogenic zone; b) Maritsa – $M_W = 7.0$ earthquake in Maritsa seismogenic zone

The developed relationships provide a practical tool for estimating expected macroseismic effects and can support the development of earthquake loss scenarios, and decisions in urban planning and infrastructure management. The proposed approach can also contribute to improved evaluation of potential earthquake consequences for insurance and risk mitigation purposes. Reliable estimation of the possible effects of strong earthquakes is essential for developing effective preventive measures and improving preparedness for future seismic events.

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