COMPARISON OF FOUR EARTHQUAKE DECLUSTERING METHODS APPLIED TO THE HOMOGENEOUS EARTHQUAKE CATALOG FOR BULGARIAN AND ADJACENT REGIONS (1981-2019)

E. Oynakov, I. Aleksandrova, M. Popova

National Institute of Geophysics, Geodesy and Geography-Bulgarian Academy of Sciences, str. Acad. G. Bonchev, bl. 3, Sofia 1113
e-mail:emil.ilievmg@gmail.com

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Abstract. Composite Abstract: The spatial-temporal distribution of seismic activity in Bulgaria and adjacent regions was studied using a homogeneous earthquake catalog from 1981 to 2019. The catalog comprised 1024 earthquakes with Mw≥3.2, collected from the Bulgarian Seismological Network. To isolate primary and secondary shocks and background events, four declustering methods were employed: Gardner-Knopoff (1974), Gruenthal (pers. Comm.), Reasenberg (1985), and Urhammer (1986). The catalog consists of earthquakes in Bulgaria and the surrounding areas (41° – 44°.6N, 22° – 30° E; 1024 events), with a completeness magnitude Mc = 3.2. After declustering, the number of events in the final catalogs varied for each method. The cumulative distribution was analyzed, and mainshocks, foreshocks, and aftershocks were identified for specific events. The study emphasized the importance of declustering in seismic analysis but recognized limitations in data completeness, quality, and algorithmic constraints. The results provided valuable insights for seismologists and specialists studying seismic phenomena and seismic risk assessment.The methods were applied using the ZMAP software

Keywords: Catalog, declustering, completeness

Introduction

The spatial-temporal distribution of seismic activity and tectonics in Bulgaria, as well as in various parts of the world, have been statistically and physically studied by many authors, and some significant results have been obtained (e.g. Solakov, Simeonova, 1993, Boncev et al., 1982, Utsu 1971, Habermann 1983, Frohlich and Davis 1993, Wiemer and Wyss 2000, Ambraseys 2002, Kutoglu and Akcin 2006, Kutoglu et al., 2008,). Bulgaria has a well-defined fault network and established seismicity history. The territory of the country is a high seismic risk zone (I. Aleksandrova, et al., 2018). Over the centuries, Bulgaria has experienced strong earthquakes (Watzof, 1902, Shebalin et al, 1974 and other). In the early 20th century (from 1901 to 1928), five earthquakes with a magnitude greater than or equal to $M_S \geq 7.0$ occurred in Bulgaria (Solakov D., et al., 2011). However, after 1928, no damaging events occurred in Bulgaria, which may cause non-professionals to underestimate the risk of earthquakes. The earthquake in 1986 with a magnitude of Mw = 5.6, which occurred in central northern Bulgaria (near the town of Strazhitsa, studied in Oncescu et al., 1990), is the strongest event of the 20th century after 1928. In 2012, a moderate earthquake with a magnitude of Mw = 5.6 and an epicenter between the towns of Pernik and Radomir caused moderate to severe damage in the epicentral zone. In addition to seismic activity in the Balkans, earthquakes in Greece and Turkey have an impact on the region. Declustering the earthquake catalog is an essential step in analyzing seismic activity as it allows for the separate identification of mainshocks, foreshocks, and aftershocks. This is achieved by removing dependent and repeating events that are characteristic of seismic regimes. Mainshocks are events with higher magnitude and serve as a starting point for analyzing seismic activity in the region. Identifying them is crucial as they provide information about the primary seismic events that can lead to significant destruction and risks to the population and infrastructure.

Data

The database used in this study is taken from the presented homogeneous earthquake catalog for Bulgaria and adjacent regions, covering the period from 1981-2019 (Solakov D., Simeonova S., Raykova Pl., Aleksandrova I., 2020; D. Solakov et al., 2020). The catalog includes instrumental seismicity (Solakov et al. (1993) and Botev et al. (2010)), covering the time interval from 1981-2000, which was updated for the period 2001-2019 using instrumental earthquake parameters. The earthquake data in the catalog is from the Bulgarian Seismological Network (NOTSSI). Currently, the Bulgarian Seismological Network provides reliable registration and high-quality information on earthquakes in Bulgaria and its surroundings (Christoskov et al. (2019). The catalog has been processed by removing duplicate events and quarry blasts. The comprehensive assessment of the catalog's completeness shows that no earthquake with a seismic moment magnitude of Mw 3.2 or higher has been missed during the entire instrumental period (1981-2019) (Solakov D. et al., 2020). The catalog includes 1024 earthquakes with a magnitude of $Mw \geq 3.2$ that occurred in Bulgaria between 1981 and 2019 (Figure 1).

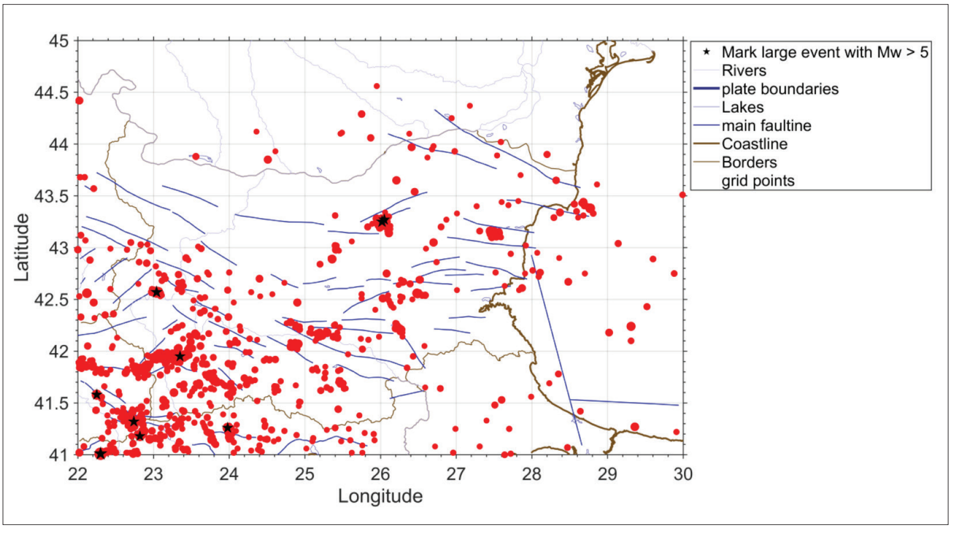

Figure 1. Map of the spatial distribution of earthquake epicenters from the catalog of Bulgaria (1981-2019).

The applied seismic moment magnitude (Mw) contributes to more reliable results and does not require the calculation of new empirical values of a different magnitude type.

Used methods

There are four main methods, Gardner-Knopoff (1974), Gruenthal (pers. Comm.), Reasenberg (1985), and Urhamer (1986), for removing dependent events from the catalog. Each takes into account a different range of distance and time.

Gardner-Knopoff (1974) Method:

This method is based on the concept that aftershocks tend to cluster around the mainshock in both time and space. It uses two separate windows to determine whether an event is an aftershock or part of the background seismicity. The first window is a time window that measures the interval between an earthquake and its potential mainshock, while the second window is a spatial window that measures the distance between the event and the mainshock. If an event falls within these windows, it is considered an aftershock and is removed from the catalog as a dependent event.

Gruenthal (pers. Comm.) Method:

The Gruenthal method is based on the concept of earthquake clustering and uses a probabilistic approach to identify aftershocks. It considers both time and distance parameters but uses a different formulation compared to Gardner-Knopoff. The Gruenthal method defines specific mathematical expressions for time and distance windows, which depend on the magnitude of the mainshock. Similar to the Gardner-Knopoff method, events falling within these windows are classified as aftershocks and excluded from the catalog.

Reasenberg (1985) Method:

The Reasenberg method is another widely used declustering algorithm. It uses a probabilistic approach and defines specific parameters such as minimum and maximum future time for cluster creation, confidence level, effective minimum magnitude limit, and iteration radius factor. The algorithm calculates a future time window based on these parameters and identifies events that fall within this window as aftershocks. The Reasenberg method is considered more robust and flexible, as it allows for adjustments of various parameters to tailor the declustering process to different seismic regions.

Urhamer (1986) Method:

The Urhamer method is based on the concept of using statistical laws to separate aftershocks from background seismicity. It employs exponential decay curves to model aftershock sequences and defines specific distance and time parameters for the declustering process. Similar to the other methods, events that fit the aftershock model are removed from the catalog.

The standard input parameters for the Reasenberg (1985) declustering algorithm are given in Table 1, are as follow:

- τ_{min} is the minimum future time for cluster creation when the first event is not clustered;
- τ_{max} is the maximum future time for cluster creation;
- 'Confidence Level' is the probability of detecting the next clustered event, used to calculate the future time – τ;
- 'hk factor' is the increase in the lowest magnitude limit during clustering: xmeff = xmeff + xkM, where M is the magnitude of the largest event in the cluster; xmeff (Effective min mag cutoff) is the effective minimum magnitude limit for the catalog;
- 'Iteration radius factor' is the number of crack radii around each earthquake considered part of the cluster;
- 'Epicenter error' is the error in determining the coordinates of the earthquake epicenters in km;
- 'Depth error' is the error in determining the depths of earthquake hypocenters in km.

Table 1. Standard and limiting parameters for Reasenberg (1985) - declustering algorithm.

Parameter	Standard value	Modeling scope	
		minimum	maximum
τ_{min} [days]	1	0.5	2.5
τ_{max} [days]	10	3	15
Confidence Level	0.95	0.9	0.99
Effective min mag cutoff	4.0	0	10
xк factor	0.5	0.1	1.8
Iteration radius factor	10	5	20
Epicenter error	1,5	-	-
Depth error	2	-	-

Table 2 presents the approximate sizes of the windows, which are determined by Gardner and Knopoff (1974), Gruenthal (pers.comm.), and Uhrhammer (1986).

Table 2. Approximate sizes of windows according to Gardner and Knopoff (1974), Gruenthal (pers.comm.) and Uhrhammer (1986).

Method	Distance (km)	Time (days)
Gardner and Knopoff (1974)	$10^{0.1238M+0.983}$	$10^{0.32M+2.7389}. \, if\, M \geq 6.5$ $10^{0.5409M-0.547}.else$
Gruenthal (pers.comm.)	$10^{1.77+(0.037+1.02M)^2}$	$\left\|e^{-3.95+(0.62+17.32M)^2}\right\|, if\; M \geq 6.5$ $10^{2.8+0.024M}.else$
Uhrhammer (1986)	$e^{-1.024+0.804M}$	$e^{-2.87+1.235M}$

After declustering with these four methods, the maximum and minimum number of events are those of Reasenberg and Gruenthal methods, respectively. In this article, these basic methods are used to decluster the catalog, and the results of these methods are compared.

Results

After declustering using the methods of Gruenthal, Reasenberg (using standard input parameters), Gardner and Knopoff, and Uhrhammer, the catalog contains 730, 899, 790, and 863 events, respectively (Table 3).

Table 3. Number of events by different methods implemented in ZMAP Software.

Method	Number of events	Number of clusters	Number of foreshocks	Number of aftershocks	Events remaining in the catalog
Reasenberg (1985)	1024	22	20	105	899
Gardner and Knopoff (1974)		43	38	196	790
Gruenthal (pers.comm.)		60	76	218	730
Uhrhammer (1986)		23	20	141	863

One commonly used parameter for characterizing the recording capability of the seismic network is the magnitude completeness (Mc), which is understood as the magnitude above which earthquakes are recorded with a probability close to 1. Having detailed knowledge of the spatial and temporal variations of Mc is critical for many earthquake hazard studies as they assess the statistical properties of microseismicity. Such estimates can only be meaningful if the sampled earthquake catalogs contain complete records of microseismicity events. For example, studies on earthquake distribution or seismicity rates heavily depend on knowledge of Mc (e.g., Wiemer & Wyss 2002; Schorlemmer et al. 2005). The magnitude-frequency distribution of each algorithm is presented in Figure 2.

The cumulative distribution after each algorithm is presented in Figure 3. There is no significant change in the graph and cumulative functions (Fig. 3) until December 7, 1986, when an earthquake with hypocentral parameters 43.230 N/26.020 E; h=14 km Mw=5.6 occurred near the town of Strazhitsa (northern Bulgaria). The earthquake was accompanied by foreshocks and aftershocks series, which appeared as a jump on the cumulative curve graph of the non-declustered catalog (purple line) appeared as a jump. The next jump in the cumulative curve of the catalog is in May 2009 due to the foreshocks and aftershocks accompanying the earthquake of May 24, 2009, with Mw=5.3 near Lake Doiran, Republic of North Macedonia (22.740/41.320E; h=5 km).

The resulting number of events after declustering the catalog (Table 3) shows that the Reasenberg method have a maximum number of events, while the Gruenthal method have a minimum number of events.The map of mainshocks identified by the different methods is shown in Fig. 4. The events identified as mainshocks by all the methods used are 5 (Table 4) and (Fig. 4), while seven events are identified as mainshocks by three of the methods (Gruenthal, Reasenberg, Knopoff). The Knopoff and Gruenthal methods identify 29 common events, the Gruenthal method compared to Reasenberg identifies 10 common events, and Knopoff compared to Reasenberg identifies 9 common main events. Six are foreshocks identified by all four methods, 9 foreshocks are identified simultaneously by all methods; 105 for the methods of Knopoff, Gruenthal, Urhammer; 169 are common to the methods of Knopoff and Gruenthal (fig. 6).

Table 4. Earthquakes identified as mainshock by the four methods.

Longitude	Latitude	Year	Monht	Day	Magnitude	Depth	Hour	Minute
25,41	42,98	2000	8	28	4,2	10	5	16
22,11	41,85	2009	5	5	4,1	7	17	39
23,28	41,96	2013	7	27	4	2	1	48
26,24	42,23	2015	4	2	3,5	11	2	27
22,82	41,18	2018	1	2	5,1	9	4	24

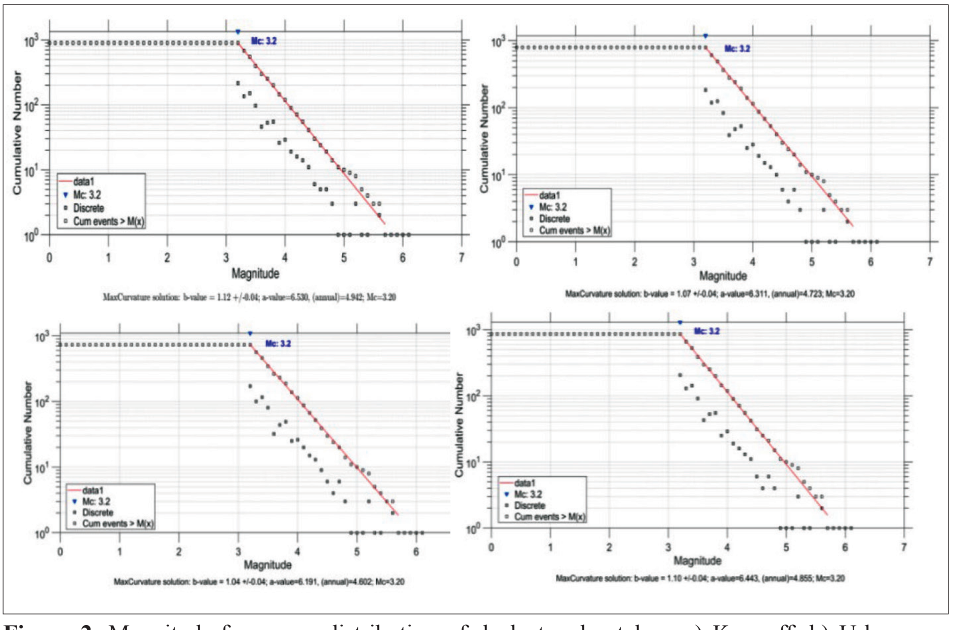

Figure 2. Magnitude-frequency distribution of declustered catalogs a) Knopoff, b) Urhammer, c) Reasenberg, and d) Gruenthal

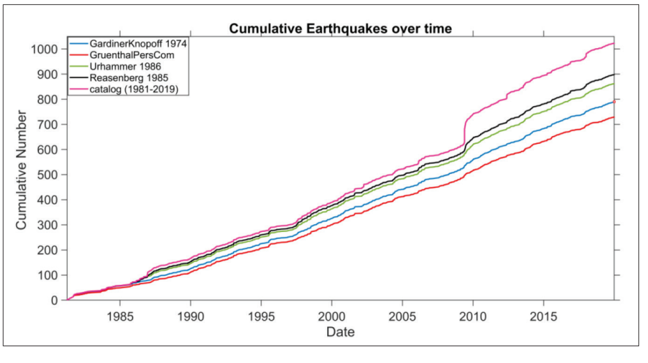

Figure 3. The cumulative distribution of earthquakes after each algorithm applied over the catalog (1981-2019).

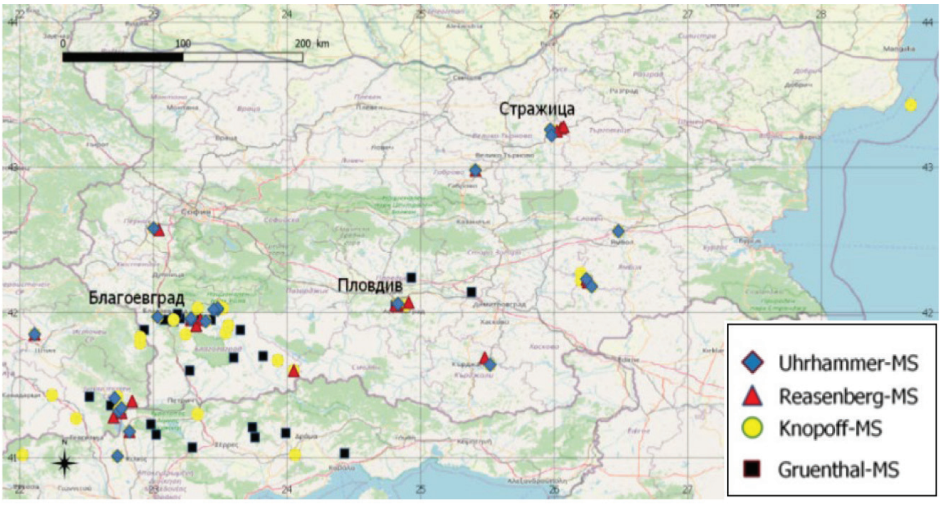

Figure 4. Map of the distribution of earthquake epicenters determined as mainshocks (MS) by each of the methods.

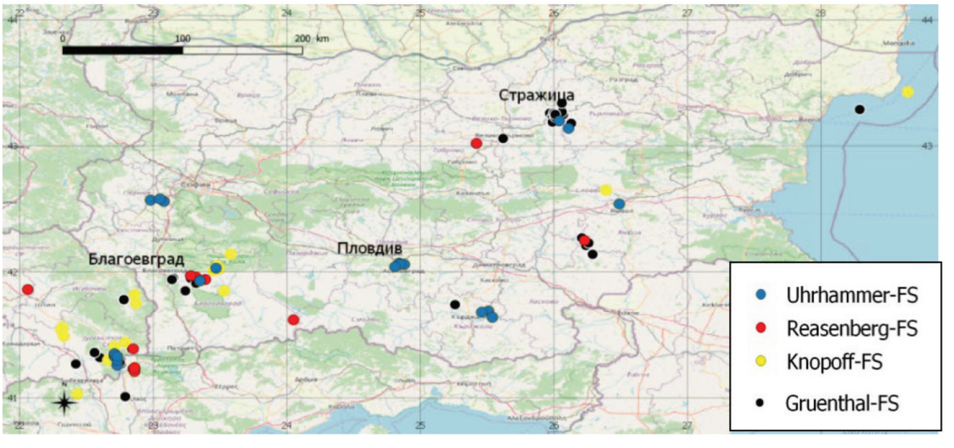

Figure 5. Map of the distribution of the epicenters of earthquakes determined as foreshocks (FS) according to each of the methods.

The number of earthquakes with different magnitudes, after declustering with the methods, is shown in Fig. 7. In this region, there are no events with a magnitude greater than 5.6 for the studied period (1981-2019).Two strongest and well-studied events are particularly important for the assessment of the methods, as indicated in the introduction, namely: near Strazhitsa in July 12, 1986; 14:17; h=14 km; Mw=5.6 and near Pernik in May 22, 2012; 14:00; h=14km; Mw=5.6.

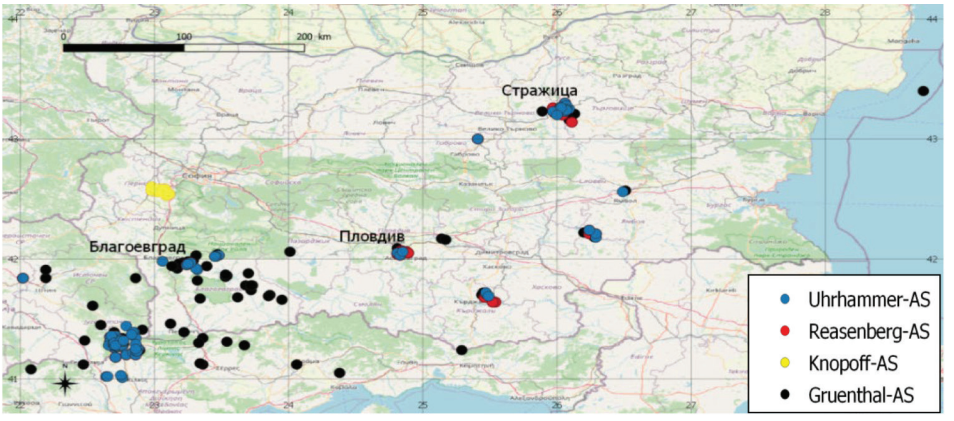

Figure 6. Map of the distribution of earthquake epicenters determined as aftershocks (AS) according to each of the methods.

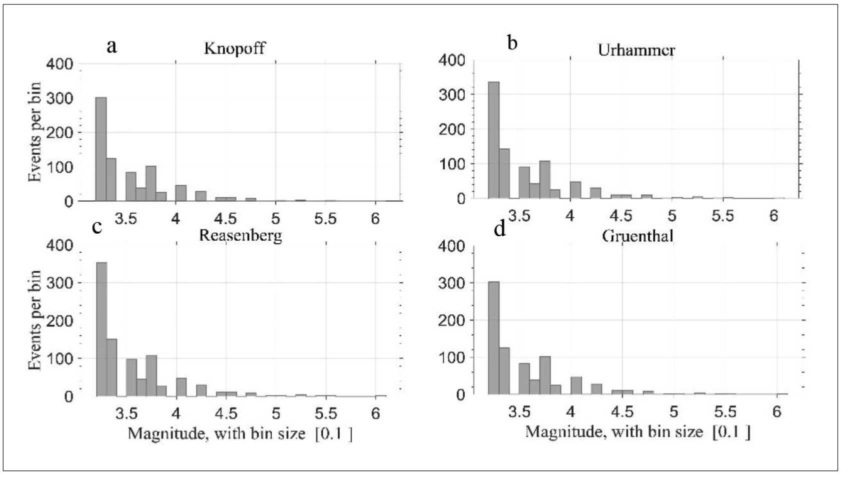

Figure 7. Distribution of earthquakes by magnitude after declustering using the methods of a) Knopoff, b) Urhammer, c) Reasenberg, and d) Gruenthal.

Figure 8 shows a map of the epicenters of earthquakes determined as foreshocks, mainshocks, and aftershocks by the four methods for the earthquake of July 12, 1986; h=14km; Mw=5.6. The review of the results shows that for the period from February 1, 1986 to December 30, 1986, the Gruenthal algorithm detects 2 mainshocks, Knopoff-1, Reasenberg-3, and Urhammer-1, with the Urhammer algorithm not identifying the earthquake of July 12, 1986; 14:17 hours; h=14 km; Mw = 5.6 as a mainshock. The Gruenthal and Urhammer algorithms identify 14 and 2 events, respectively, as foreshocks. As aftershocks, the methods identify 16 for Gruenthal, 16 for Knopoff, 12 for Reasenberg, and 13 for Urhammer. The results are shown both on the map (Figure 8) and in tabular form in Table 5.

Table 5. Results of earthquake declustering in the area of Strazhitsa for the period from February 1, 1986, to December 30, 1986.

Longitude	Latitude	Year	Monht	Day	Magnitude	Depth	Hour	Minute	Gr.	Kn.	Re.	Ur.
26,05	43,27	1986	2	21	5,4	11	5	39			mainshock	
25,97	43,26	1986	2	21	4,4	16	6	18	foreshock	mainshock	aftershock	mainshock
25,99	43,23	1986	2	21	3,5	18	6	20	foreshock		aftershock	
26,02	43,26	1986	2	21	3,8	15	8	36	foreshock		aftershock	
25,62	43,06	1986	3	23	3,2	12	20	50	foreshock			
26,13	43,18	1986	4	10	3,2	0	4	43	foreshock			
26,01	43,21	1986	5	25	3,3	14	16	57	foreshock			
26,03	43,24	1986	5	26	3,2	13	15	46	foreshock			
26,07	43,25	1986	6	20	3,4	10	12	26	foreshock			
26,06	43,27	1986	8	1	3,4	11	14	34	foreshock			
25,99	43,19	1986	8	19	4	13	4	5	foreshock			
26,06	43,34	1986	8	29	3,2	11	19	30	foreshock			
26,01	43,23	1986	9	7	3,3	13	10	47	foreshock			
26	43,26	1986	9	7	3,3	12	10	54	foreshock			
26,01	43,25	1986	11	23	3,4	9	4	34	foreshock			
26,02	43,25	1986	12	7	5,6	14	14	17	mainshock	mainshock	mainshock	
26,11	43,14	1986	12	7	4,4	20	14	53	aftershock	aftershock	aftershock	foreshock
26,04	43,2	1986	12	7	3,3	2	15	20	aftershock	aftershock	aftershock	foreshock
25,98	43,22	1986	12	7	4,8	14	17	26	aftershock	aftershock	aftershock	mainshock
25,98	43,22	1986	12	7	3,2	13	17	39	aftershock	aftershock	aftershock	aftershock
26,06	43,3	1986	12	8	3,3	13	9	31	aftershock	aftershock	aftershock	aftershock
26,03	43,26	1986	12	8	4,5	20	14	44	aftershock	aftershock	aftershock	aftershock
26,04	43,24	1986	12	11	3,4	15	3	52	aftershock	aftershock		aftershock
26,09	43,25	1986	12	12	3,6	10	1	28	aftershock	aftershock		aftershock
26,05	43,27	1986	12	12	4,6	12	19	29	aftershock	aftershock		aftershock
26,02	43,24	1986	12	14	3,2	10	10	29	aftershock	aftershock		aftershock
26,03	43,27	1986	12	15	3,4	6	0	58	aftershock	aftershock		aftershock
26,07	43,28	1986	12	17	4,8	14	22	1	aftershock	aftershock	mainshock	aftershock
26,06	43,23	1986	12	18	4,4	14	7	16	aftershock	aftershock	aftershock	aftershock
26,07	43,25	1986	12	18	4,5	18	17	16	aftershock	aftershock	aftershock	aftershock
26,07	43,25	1986	12	18	3,6	11	23	39	aftershock	aftershock	aftershock	aftershock
26,07	43,24	1986	12	23	3,2	6	17	46	aftershock	aftershock		aftershock

(yellow) - foreshock (red) - mainshock (blue) - aftershock

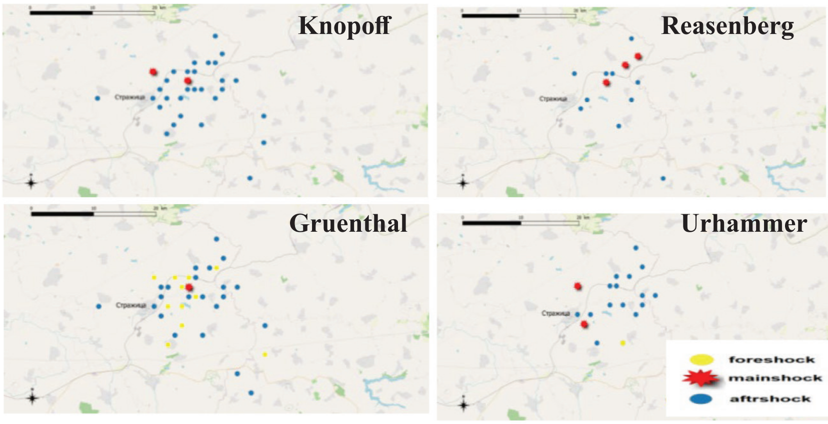

Figure 8. Maps of the epicenters of the events defined as foreshocks, mainshocks, and aftershocks for the region of Strazhitsa for the period from February 1, 1986, to December 30, 1986.

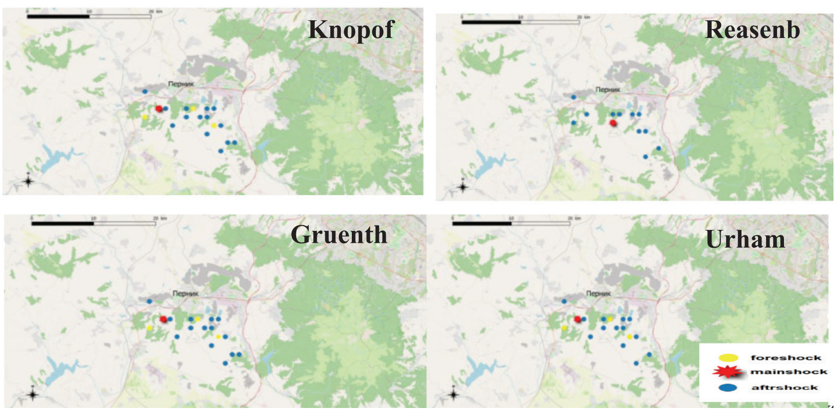

Figure 9. Maps of the epicenters of the events defined as foreshocks, mainshocks, and aftershocks in the Pernik region for the period from 22.05.2012 to 03.09.2012.

The results of the different methods for the earthquake in the vicinity of Pernik on May 22, 2012 at 14:00 with a depth of 14 km and Mw=5.6 are shown on the maps in Fig. 9 and presented in tabular form in Table 6

The results show that for the period from 22.05.2012 to 03.09.2012, the Gruenthal algorithm detects 1 mainshock, Knopoff detects 1, and Urhammer detects 1, and all three do not identify the earthquake on 22.05.2012 at 00:00 hours; h=14 km; Mw=5.6 as a mainshock. The Gruenthal, Knopoff, and Urhammer algorithms identify 3 events as foreshocks. As for aftershocks, the methods determine as follow: Gruenthal - 16, Knopoff - 15, Reasenberg - 12, and Urhammer - 13.

Table 6. Results of declustering for the earthquake in the area of Pernik for the period from 22.05.2012 to 03.09.2012.

Longitude	Latitude	Year	Monht	Day	Magnitude	Depth	Hour	Minute	Gr.	Kn.	Re.	Ur.
23,04	42,57	2012	5	22	5,6	14	0	0				
22,98	42,57	2012	5	22	4,3	4	0	4				
23,08	42,56	2012	5	22	3,2	17	0	16				
23,05	42,58	2012	5	22	3,6	10	0	43				
23	42,58	2012	5	22	4,8	13	1	30				
23,09	42,53	2012	5	22	3,2	10	1	34				
22,98	42,6	2012	5	22	3,4	11	2	11				
23,07	42,58	2012	5	22	4,3	12	2	13				
23,04	42,57	2012	5	22	3,4	2	4	9				
23,08	42,58	2012	5	22	3,3	15	4	29				
23,04	42,58	2012	5	22	3,5	17	17	7				
23,11	42,54	2012	5	23	3,2	11	10	57				
23,02	42,56	2012	5	23	3,3	2	11	41				
23,09	42,56	2012	5	23	3,9	14	21	59				
23,01	42,58	2012	5	29	3,9	8	7	23				
23,07	42,55	2012	5	30	3,6	9	5	36				
23,07	42,57	2012	6	16	3,2	10	4	51				
23,06	42,57	2012	7	14	4,4	8	12	52				
23,1	42,54	2012	7	31	3,4	7	0	10				
23,06	42,57	2012	8	16	3,3	10	2	11				
22,91	41,41	2012	9	3	3,2	4	16	54				

- foreshock **- mainshock** **- aftershock**

Conclusion

For comparison of the declustering algorithms of Gardner-Knopoff (1974), Gruenthal (pers. Comm.), Reasenberg (1985), and Urhammer (1986), the homogenized catalog 1981-2019 of the earthquakes occurred in the region of Bulgaria and adjacent areas are used. The this catalog is a summary of the time of occurrence of the earthquake, geographic coordinates, magnitude, and depth for each presented event. The Wiemer ZMAП (2001) package including the algorithms is used to remove duplicate events, aftershocks. Before declustering, the catalog has 1024 events. After declustering with the algorithms of Gardner-Knopoff, Gruenthal, Reasenberg, and Urhammer, the final catalogs include respectively 790, 730, 899, and 863 main events from 1981 to 2019.

The sequences of fore- and aftershocks reflect local anomalies of the seismic regime and significantly differ in their characteristics from the background regime. The dependence on the degree of declustering of the catalog is given by estimates of the parameters of the seismic process. To isolate fore- and aftershocks from all background events, the algorithms of Gardner-Knopoff (1974), Gruenthal (pers. Comm.), Reasenberg (1985), and Urhammer (1986) are used, which are based on comparing the functions of time and spatial distribution. The procedure for identifying primary and secondary shocks is reduced to constructing a discriminant function that allows each earthquake to be classified into one of three classes: primary and secondary shock or background event. From a physical point of view, the difference between primary, secondary shock, and background event is not obvious; all procedures for identifying accompanying events are based on statistical laws, i.e., on the spatial-temporal localization of aftershocks in the vicinity of the main event.

When identifying primary and secondary shocks, three types of errors are possible: assigning a primary or secondary shock to a group of background or main events, identifying a background event as a primary or secondary shock, and identifying a main event as a primary or secondary shock.

Research based on the data used for seismic events may encounter limitations regarding the completeness, accuracy, and reliability of the obtained results. Here are some of these limitations:

<u>Data Completeness</u>: The used data may not include all seismic events, particularly those that were weak or unreported. The presence of data gaps can restrict the analysis and lead to incomplete or distorted results.

<u>Data Quality</u>: Data on seismic events can be subject to various sources of error, such as sensor issues or data transmission disruptions. This can affect the accuracy and reliability of the obtained results.

<u>Geographical Coverage</u>: The coverage of seismic monitoring in different regions can vary. Some areas may have limited data or be poorly represented in the catalog. This can hinder comprehensive analyses and generalizations about global seismic activities.

<u>Algorithmic Limitations</u>: The computational procedures and software algorithms used for data analysis may have their own limitations. They may be perceived as model-based or approximate methods that do not always reflect a complete and precise representation of seismic activity.

<u>Human Interpretation</u>: Data processing and analysis can involve human interpretation and subjective decisions. This can lead to variations and inconsistencies in the results, particularly in complex cases or ambiguous events.

It is important to bear these limitations in mind.

The fact that the catalog is compiled using statistical data and computational procedures with specialized software for seismic event analysis, such as ZMAP, is highly important information. This means that the catalog has been created through the processing of a large amount of data collected from various seismic sources and sensors.

The use of statistical data and computational procedures is a valuable approach for analyzing seismic data, as it can help identify patterns and trends in seismic activity. The utilization of specialized software like ZMAP further enhances the capabilities for processing and analyzing this data.

Such a catalog can be extremely beneficial for seismologists, geologists, and other specialists studying seismic phenomena. They can utilize this catalog for analyzing seismic events, investigating the geographical distribution of earthquakes, assessing the risk of seismic activities, and other related activities.

This is a good practice that contributes to a better understanding of seismic phenomena and improves our ability to forecast and respond to potential hazards associated with them.

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Сравнение на резултататите, получени по четири метода за деклъстеризиране на земетресения, приложени върху хомогенния каталог на земетресенията за българия и съседните райони (1981-2019)

Е.Ойнаков, И. Александрова, М. Попова

Резюме. Съществуват различни методи за деклъстеризация на каталози от земетресения и тяхното хомогенизиране. Reasenberg (1985) и Gruenthal са известни като методи, които генерират каталог с максимален и минимален брой събития, съответно. В това проучване са приложени четири основни метода за деклъстреризиране (Gardner-Knopoff (1974), Gruenthal (pers. Comm.), Reasenberg (1985) и Urhamer (1986)) върху каталога на земетресенията за периода 1981-2019 г., (Solakov D., et al, 2020). Каталогът се състои от земетресения в България и околностите (41° – 44°, 6 N, 22° – 30°E; 1024 събития), с магнитуд на пълнота Mc=3.2. Методите са приложени с помощта на софтуера ZMAP.