On the completeness of Bulgarian earthquake data

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Милен Цеков, Емил Ботев, Антония Мокрева, Валентина Протопопова, Върху пълнотата на българските земетръсни данни. В настоящата работа изследваме пълнотата на българските земетръсни данни посредством два метода: (1) метод на максималната кривина и (2) метод на стабилността на b-стойността. Нашите резултати показват, че след 1984 година българските земетръсни данни са пълни най-малко за магнитуд над 2.5. За периода 1981-1984 магнитудът на пълнота е 2.8. За 2013 година магнитудът на пълнота е 2.2, по консервативна оценка, като за определени зони от страната той е дори още по-малък. Земетръсните данни за България преди 1980 година са много по-непълни. Посредством използваните два метода се получават оценки от M=4.4 за магнитуда на пълнота на българските земетръсни данни за периода 1901-1977. Тази оценка се отличава от предишни оценки на други автори (базирани на метода на Степ), според които магнитудът на пълнотата на българските земетръсни данни след 1900 година е 4,0. Ние показваме, че българските земетръсни данни не са пълни над M=4.0 дори и за периода 1941-1977.

Assessing the magnitude of completeness of earthquake catalogs is an important initial step to any kind of statistical analysis of earthquake data. An incorrect estimate of the magnitude of completeness may result in biased estimates of other parameters and wrong conclusions. In this paper we estimate the magnitude of completeness of recent instrumental and historical Bulgarian earthquake data using two alternative techniques: (1) the Maximum Curvature (MAXC) technique (Wyss et al., 1999; Wiemer and Wyss, 2000) and (2) the magnitude of completeness by b-value stability (MBS) approach (Cao and Gao, 2002). Review and comparison of these and other methods for assessment of magnitude of completeness of earthquake catalogs is given in Mignan and Woesner, 2012.

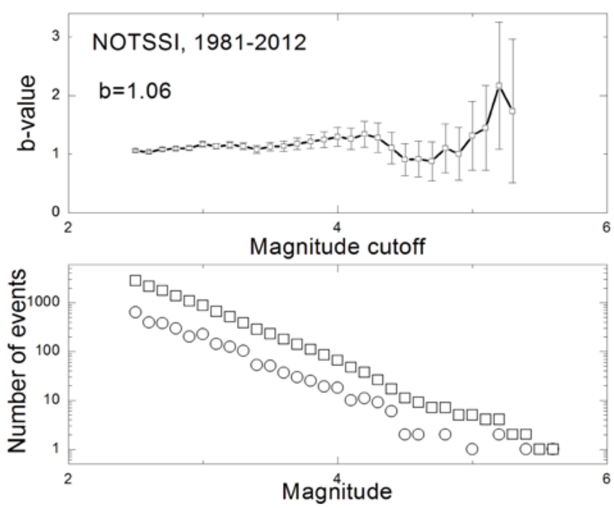

Figure 1. Completeness of the Bulgarian earthquake data over the period 1981-2012. Top: b-value estimate as a function of magnitude cutoff. Bottom: Non-cumulative (circles) and cumulative (squares) frequency-magnitude distributions.

The MAXC technique provides a fast and simple approach to estimate the magnitude of completeness of an earthquake catalog. This method relies on determination of the point of maximum curvature of the cumulative frequency-magnitude distribution which coincides with the magnitude bin of the non-cumulative frequency-magnitude distribution with highest number of observed events. MAXC technique generally provides lower estimate of the magnitude of completeness of earthquake catalogs than alternative techniques, including MBS

(Mignan and Woesner, 2012). MAXC method may underestimate the real magnitude of completeness, especially for gradually curved cumulative frequency-magnitude distributions (Mignan and Woesner, 2012). The MBS technique is based on determination of the b-value as a function of magnitude cutoff. The b-value estimate obtained using maximum likelihood technique (Aki, 1965) is low for magnitude cutoff lower than the magnitude of completeness. It increases for magnitude cutoff approaching the magnitude of completeness and remains stable for magnitude cutoff greater than the magnitude of completeness of the earthquake data. For very large magnitude cutoff the b-value estimate exhibits significant statistical fluctuations due to undersampling. The MBS technique is a conservative approach which generally provides higher estimate of the magnitude of completeness than other techniques (Mignan and Woesner, 2012).

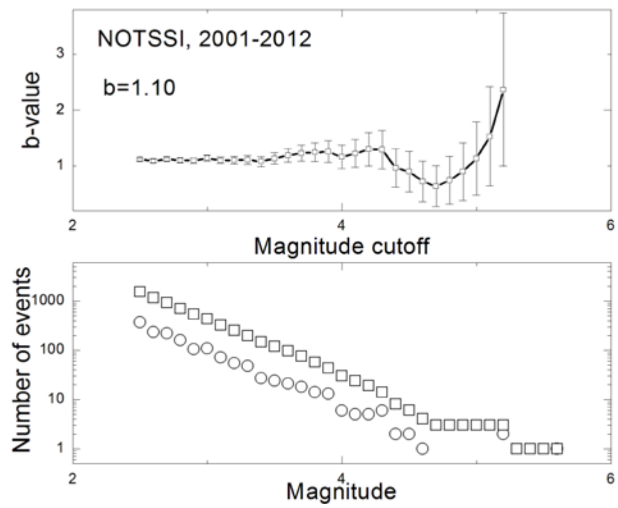

Figure 2. Completeness of the Bulgarian earthquake data over the period 2001-2012. Top: b-value estimate as a function of magnitude cutoff. Bottom: Non-cumulative (circles) and cumulative (squares) frequency-magnitude distributions.

Quality of the Bulgarian earthquake data increases dramatically after 1980 when National Operative Telemetric System for Seismic Information (NOTSSI) starts operating. Currently the Bulgarian National Seismic Network consists of 23 stations (16 permanent seismic stations and two local networks) (Botev et al., 2013). In year 2005 transition from analog to digital recording has been accomplished. For all registered earthquakes, duration magnitude is determined according to the formula obtained by Christoskov and Samardjieva, 1983.

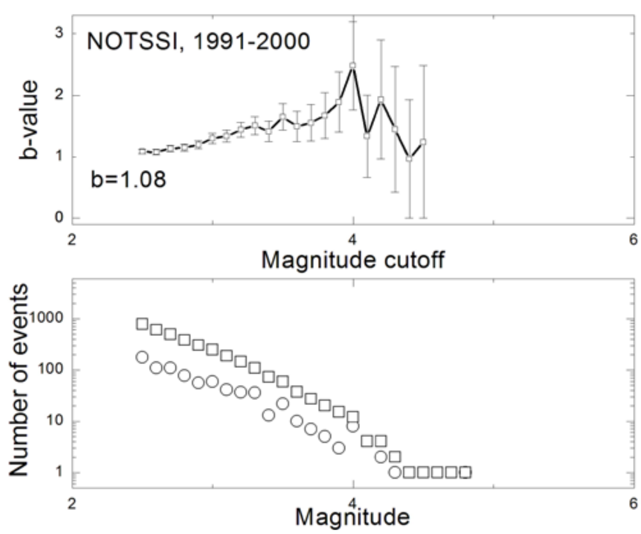

Figure 3. Completeness of the Bulgarian earthquake data over the period 1991-2000. Top: b-value estimate as a function of magnitude cutoff. Bottom: Non-cumulative (circles) and cumulative (squares) frequency-magnitude distributions.

We first analyze the completeness of Bulgarian earthquake data over the period 1981-2012. We consider all earthquakes on the territory of Bulgaria and adjacent lands (φ = 41.0-44.50N, λ = 22.0-30.0E) with M≥2.5 in the mentioned period (2778 events in total). In Figure 1 we present the results of application of MBS (top) and MAXC (bottom) techniques to these data. Observed number of events in a magnitude bin of given width increases systematically with decreasing the magnitude, indicating that the earthquake data are complete at least down to the threshold magnitude of 2.5. The MBS method confirms this finding. For small and moderate magnitude cutoff we do not observe any significant increase of the estimated b-value with increasing magnitude cutoff, indicating that the data are indeed complete down to magnitude 2.5. For large magnitude cutoff significant statistical fluctuations due to undersampling are observed. The b-value estimate for the period 1981-2012 is 1.06.

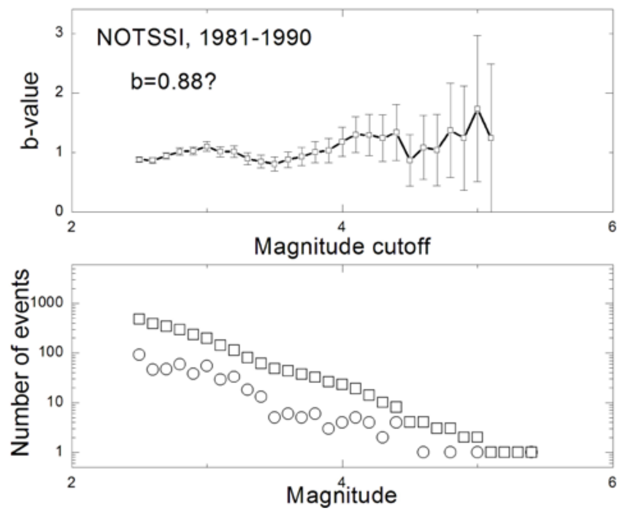

Figure 4. Completeness of the Bulgarian earthquake data over the period 1981-1990. Top: b-value estimate as a function of magnitude cutoff. Bottom: Non-cumulative (circles) and cumulative (squares) frequency-magnitude distributions.

To study possible temporal variations in the magnitude of completeness and in the b-value, we divide the 1981-2012 earthquake record into three segments (1981-1990, 1991-2000, and 2001-2012) and we apply the MAXC and the MBS methods to each segment separately (Figs. 2-4). For the time period 2001-2012 both techniques clearly indicate that the data are complete above magnitude 2.5 (Figure 2). The b-value estimate of 1.10 is similar to that obtained for the entire record. For the time period 1991-2000 both methods also indicate that the data are complete down to magnitude 2.5, though in this case the magnitude range for which the b-value is stable decreases (Figure 3). Since the number of moderate earthquakes in the period 1991-2000 is relatively low, significant statistical fluctuations due to undersampling are observed for relatively low magnitude cutoff, narrowing the stability range. The b-value estimate of 1.08 is also similar to the b-value obtained for the entire period 1981-2000. However, for the period 1981-1990 interpretation is not so straightforward. Initially, for magnitude cutoff lower than 3, the b-value estimate increases with the increase of magnitude cutoff, then decreases for magnitude cutoff between 3 and 3.5, and then increases again (Figure 4). Moreover, the b-value estimate of 0.88 obtained for magnitude cutoff 2.5 is significantly lower than the b-value estimates obtained for the other two periods (1991-2000; 2001-2012), as well as for the entire period 1981-2012. These results indicate that the Bulgarian earthquake data may not be complete down to magnitude 2.5 over the entire 1981-1990 period. We note that during the first 4 years of operation of NOTSSI, the annual number of observed earthquakes with M>2.5 is lower compared to the later years (Botev et al., 2013).

To confirm that the data are not complete above M=2.5 over the period 1981-1984, we apply the MAXC and MBS methods to the NOTSSI data from this period. Both methods suggest that over the period 1981-1984 Bulgarian earthquake data are complete only down to magnitude 2.8 (Figure 5). Since the number of events recorded over the period 1981-1984 is considerably smaller than the total number of earthquakes registered over the entire 1981-2012 period, the incompleteness of data in the period 1981-1984 does not affect significantly completeness estimates based on data for the entire period, leading to false conclusion that the data are complete above M=2.5 over the entire period 1981-2012. In fact, they are complete down to magnitude 2.5 only over the shorter period 1985-2012.

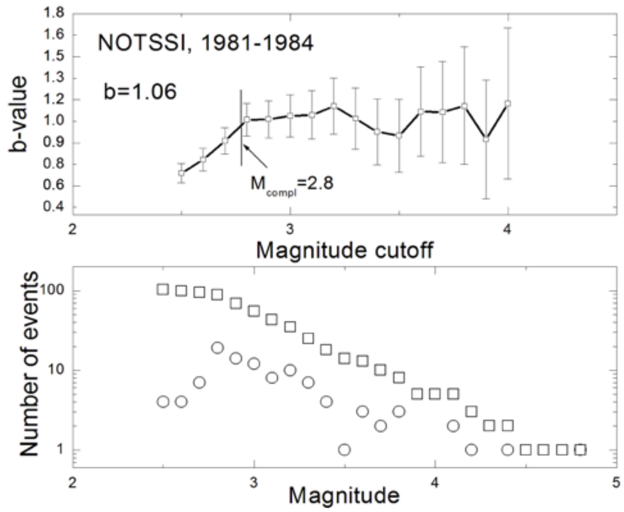

Figure 5. Completeness of the Bulgarian earthquake data over the period 1981-1984. Top: b-value estimate as a function of magnitude cutoff. Bottom: Non-cumulative (circles) and cumulative (squares) frequency-magnitude distributions.

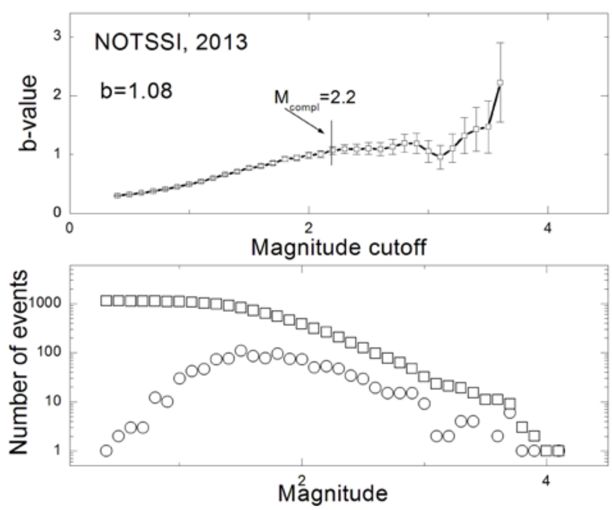

Figure 6. Completeness of the Bulgarian earthquake data for year 2013. Top: b-value estimate as a function of magnitude cutoff. Bottom: Non-cumulative (circles) and cumulative (squares) frequency-magnitude distributions.

To study whether recent Bulgarian earthquake data are complete to even lower magnitude than 2.5 we consider all 1124 events with epicenters within the region defined by φ = 41.0-44.50N, λ = 22.0-30.0E, registered in 2013 by the Bulgarian National Seismic Network. Lowest magnitude of registered earthquakes in 2013 is M=0.4. In Figure 6 we present the results of application of MBS (top) and MAXC (bottom) techniques to these data. The MBS method indicates that the data from year 2013 are complete down to magnitude 2.2. The MAXC method suggests even lower magnitude of completeness. Moreover, for magnitude cutoff lower than 2.2 the slope of the b-value curve decreases slowly with decreasing magnitude cutoff, indicating possible spatiotemporal variability of the magnitude of completeness and even lower than 2.2 magnitude of completeness for certain earthquake zones in Bulgaria. Indeed, for the Rhodopes the magnitude of completeness is 1.9 (see the paper M. Tsekov, E. Botev, Seismicity of the Rhodope zone over the period 1980-2014, in this volume).

Prior to 1980 the quality of the Bulgarian earthquake data deteriorates. The primary source of earthquake information for Bulgaria prior to 1980 is the catalog, compiled by Grigorova et al., 1978. From this catalog we analyze only earthquakes located in the zone φ = 41.0-44.50N, λ = 22.0-29.0E, covering Bulgaria and close surroundings. Moreover, since large portion of the events in this catalog are aftershocks of several very strong earthquakes from the beginning of the 20th century, we consider only independent events. To this end we decluster the catalog using the classical spatiotemporal window method (Gardner and Knopoff, 1974) with window parameters proposed by Christoskov and Lazarov, 1981. We also consider only events from the 20th century, since for previous centuries the data are scarce.

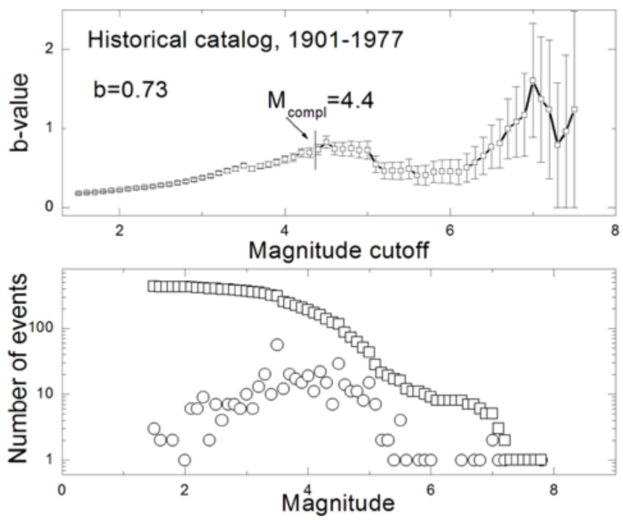

Figure 7. Completeness of the Bulgarian earthquake data over the period 1901-1977. Top: b-value estimate as a function of magnitude cutoff. Bottom: Non-cumulative (circles) and cumulative (squares) frequency-magnitude distributions.

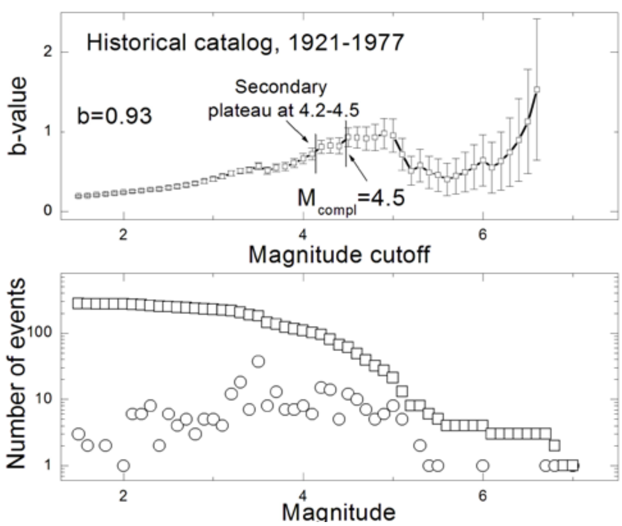

Figure 8. Completeness of the Bulgarian earthquake data over the period 1921-1977. Top: b-value estimate as a function of magnitude cutoff. Bottom: Non-cumulative (circles) and cumulative (squares) frequency-magnitude distributions.

In Figure 7 we present the results of application of MBS (top) and MAXC (bottom) techniques to the declustered historical catalog for the period 1901-1977. The MBS method indicates that the data are complete down to magnitude about 4.4. This finding is in disagreement with previous reports that after year 1900 historical Bulgarian earthquake data are complete above magnitude 4.0 (Christoskov, 2005; Solakov et al., 2009). The MAXC method also indicates that the magnitude of completeness for the period 1901-1977 is considerably higher than 4.0. Obtained b-value estimate of 0.73 is significantly lower than the obtained b-value estimates for recent seismicity (greater than 1.0). This lower b-value estimate corresponds to the large magnitude range of observed earthquakes in Bulgaria during the first three decades of the 20th century.

Next, we consider separately the shorter time periods 1921-1977 and 1941-1977 (Figs. 8 and 9). For both periods magnitude of completeness is also clearly greater than 4.0. For the period 1921-1977, the MBS method gives an estimate of 4.5 for the magnitude of completeness. Secondary plateau region is observed for magnitude cutoff between 4.2 and 4.5 (Figure 8), indicating that for part of the time period 1921-1977 the earthquake data may be complete above M=4.2. Indeed, the MBS method indicates that during the period 1941-1970 the earthquake data may be complete above M=4.2 (Figure 9). However, the gradual change of the slope of the cumulative magnitude-frequency distribution for 4.0<M≤4.6 contradicts this finding and suggests that the magnitude of completeness for the period 1941-1970 may be higher than M=4.2. Finally, we consider the completeness of the earthquakes during the period 1901-1930 characterized by occurrence of several strong earthquakes on the territory of Bulgaria (Figure 10). Both methods indicate that the data are complete only down to magnitude 4.4 or 4.5.

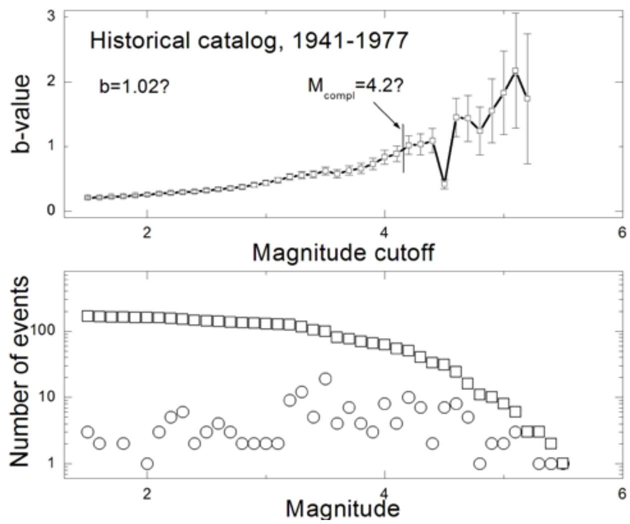

Figure 9. Completeness of the Bulgarian earthquake data over the period 1941-1977. Top: b-value estimate as a function of magnitude cutoff. Bottom: Non-cumulative (circles) and cumulative (squares) frequency-magnitude distributions.

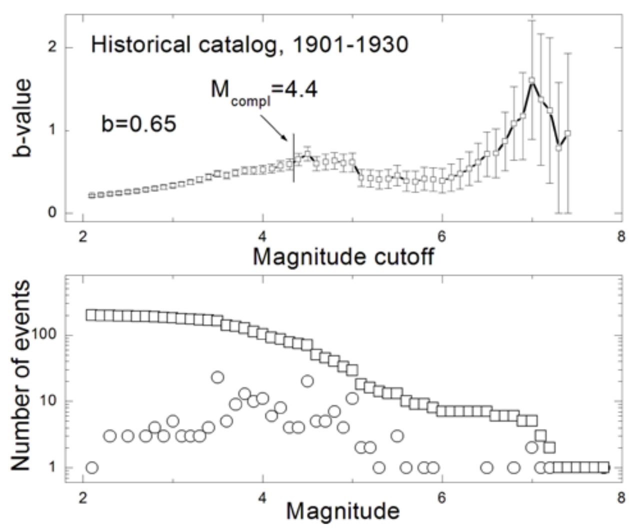

Figure 10. Completeness of the Bulgarian earthquake data over the period 1901-1930. Top: b-value estimate as a function of magnitude cutoff. Bottom: Non-cumulative (circles) and cumulative (squares) frequency-magnitude distributions.

Our findings can be summarized as follows. For the period 1985-now the magnitude of completeness of Bulgarian earthquake data is at least 2.5 (and maybe even lower). However, in the first years of operation of NOTSSI (1980-1984) the magnitude of completeness is 2.8. Recent earthquake data (for year 2013) are complete to even lower magnitude scales (M=2.2). Our results also indicate possible spatiotemporal variability of the magnitude of completeness, which we will study in a future work. The quality of the Bulgarian earthquake data prior to 1980 is much lower. For the historical data we obtain higher estimate of the magnitude of completeness than previously reported estimates (Christoskov, 2005; Solakov et al., 2009) based on the Stepp's method (Step, 1972). However, we note that Figure 2.2, upper left panel of Solakov et al., 2009 may be considered as evidence based on the Stepp's method that historical Bulgarian earthquake data are not complete down to magnitude 4.0 until recently. Visual inspection of this figure suggests a kink in the scaling curve at x=30 years, indicating that the Bulgarian earthquake data are not complete down to magnitude 4.0 prior to the last 3 decades.

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