Spatio-temporal Analysis on the Aftershocks of January 24, 2020, Mw6.8 Sivrice-Elazığ (Turkey) Earthquake

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Abstract
A statistical analysis on the aftershock sequence of January 24, 2020 Sivrice-Elazığ (Turkey) earthquake was performed by using well-known parameters such as b-value and p-value. Aftershock catalog was taken from KOERI and includes 4458 aftershocks in one year after the mainshock. b-value was computed as 0.82±0.02 by considering the magnitude of completeness value as Mcomp=1.9. It is smaller than typical b-values. The highest p-values were observed in and around the mainshock and the lowest b-values. The highest p-values were observed in and around the mainshock including Pütürge and Erkenek segments. These findings indicate that there is a relation between the largest aftershocks and the lowest b-values. The regions with the smallest b-value and the largest p-value have large stress and coseismic deformation, respectively. Stress variations and coseismic deformation are highly effective on the b-value and p-value variations. Thus, earthquake hazard may be evaluated with the aftershock hazard parameters and spatio-temporal analysis of aftershocks is suggested for a preliminary assessment after the mainshock.

1. Introduction
Analysis of spatio-temporal behaviors of aftershock sequences can be considered as one of the significant tools for the understanding of earthquake mechanisms because aftershock occurrences supply potential information about the nucleation of earthquakes and physical characteristics of materials in the earthquake fault zone [1]. Aftershock occurrences provide a detailed source of information on the Earth's crust, fault geometry, stress distribution after the mainshock and earthquake source properties as well as the aftershock hazard in comparison with mainshock hazard [2]. Thus, aftershock sequences continue to exist as the key features of earthquake activity and hence, evaluation of aftershock sequences have been gained increased attention in recent years.

A large earthquake (with an intensity of Io=IX), which struck the Pütürge segment in Elazığ, with moment magnitude Mw=6.8 (local magnitude M=6.6) at a depth of 4.8 km which has left lateral strike slip faulting mechanism, occurred on January 24, 2020 between the southern Elazığ and Malatya provinces at local time 20:55:11.0 (17:55:11.0 UTC). This earthquake was one of the largest earthquakes affecting the EAFZ since 1971 (M6.8 Bingöl earthquake) and affected four cities surrounded the mainshock epicenter. The main shock directly caused heavy damages and resulted in 41 causalties with hundreds of injured people. After the earthquake, 1540 buildings were damaged moderately, while 8519 buildings were damaged heavily and collapsed.

The principal purpose of this study is to make an evaluation of the aftershock sequence following the January 24, 2020 Mw6.8 Sivrice-Elazığ earthquake. For this purpose, a statistical analysis including characteristic aftershock parameters such as the b-value in the Gutenberg-Richter formula, p-value in the modified Omori law was achieved by using 4458 aftershocks described in one year from the mainshock. ZMAP software package [3] was used for all estimations of aftershock parameters.

2. Methods
Magnitude-frequency distribution of aftershock occurrences was given by Gutenberg and Richter (1944) [4]. This basic form is well known in earthquake statistics and empirical equation can be given as follow:

\[ \log_{10} N(M) = a - bM \]  

where N(M) is the cumulative number of aftershocks with magnitudes larger than or equal to M, a-value and b-value are positive constants. Changes in a-value depend on the observation period, size and seismicity of study region, and it exhibits important variations for different regions. b-value defines the magnitude-frequency relation of aftershocks and, tectonic structure of study area effects the region-time changes in b-value. Utsu (1971) [5] suggested that b-values changes mostly between 0.3 and 2.0. A negative correlation exists between b-value and stress distribution and, b-value shows the ratio between the relative numbers of small and large earthquakes in the region [6].

Temporal decay rate of aftershocks can be defined by a power law named as the modified Omori law or Omori-Utsu law [7]. Aftershock decay rate with time after the mainshock can be given by following scaling law:
where \( n(t) \) is the number of aftershocks (aftershock decay rate per day) per unit time \( t \) (days) after the mainshock. \( p, c, \) and \( K \) values are empirically derived positive constants. They depend on the activity rate in the earliest part of the sequence and the total number of aftershocks in the sequence, respectively. \( K \)-value, stated as aftershock productivity, is controlled by the total number of events in the sequence. It is a normalizing parameter and depends on the total aftershocks number and the threshold magnitude. \( c \)-value is dependent on the aftershock activity rate in the earliest part of the sequences and incomplete detection of small aftershocks in the early stage of sequence effects \( c \)-value estimation \([8]\). Fast decay rate of aftershocks has large \( p \)-value but slow decay of aftershock sequences has small \( p \)-value. It is stated that \( p \)-value generally varies from 0.5 to 1.8 for different aftershock occurrences in the world. Changes in \( p \)-value may be associated with fault heterogeneity, slip distribution or crustal heat flow but it is not clear which condition among them is more effective in \( p \)-value changes.

3. Results and Discussion

Aftershock catalog were supplied from the Bogazici University, Kandilli Observatory and Earthquake Research Institute (KOERI). The aftershock region were limited by taking into account the different studies and reports and thus, the area between the coordinates 38.3°E-39.7°E and 38.0°N-38.7°N was selected (Fig. 1). Aftershock catalog is homogenous for local magnitude, \( M_r \), and consists of 4458 events with magnitudes 0.65≤\( M_r \)≤5.7. There are 4165 events with magnitude \( M_r \)≤3.0, 246 events with 3.0≤\( M_r \)≤4.0, 41 events with 4.0≤\( M_r \)≤5.0, 6 events with \( M_r \)≥5.0 and aftershock with \( M_r \)≥5.7 is the biggest of all. The highest density of aftershocks (all size of events in general) was recorded in all the parts of the aftershock region whereas the larger aftershocks (\( M_r \)≥4.0), including the biggest event, were especially observed in and around the mainshock, in the northeast part of the mainshock and southwest end of the aftershock region (Fig. 1).

\[
n(t) = \frac{K}{(t + c)^p} \quad (2)
\]

For the estimation of aftershock parameters, two important inputs must be organized to ensure the completeness: (i) minimum magnitude threshold, \( M_{min} \), and (ii) a minimum time threshold, \( T_{start} \), i.e. excluding the first hours to days from the mainshock. As a simple rule, \( M_{min} \) can be considered for the shortest \( T_{start} \).and thus, this approach uses the highest magnitude completeness (\( M_{comp} \)) value, described for the earliest part of the sequence \([9]\). This magnitude level can be simply defined as the lowest magnitude in the catalog and is based on the assumption of Gutenberg-Richter scaling law distribution of magnitudes. \( M_{comp} \) value includes 90% of the earthquakes that can be sampled with a scaling law \([10]\) and shows spatial and temporal changes according to different networks and catalogs. For the aftershock sequence of Sivrice-Elazığ earthquake, \( M_{comp} \) value was taken as 1.9 in the estimation of both the \( b \)-value and \( p \)-value. Although the maximum number of aftershocks is recommended to be used, the amount of available data is reduced with this application. Thus, for the aftershock sequence of Sivrice-Elazığ earthquake, \( M_{min}=1.9 \) and \( T_{start}=0.01 \) were used to calculate the aftershock decay parameters. \( c \)-value is measured in time unit, days for example. After some big earthquakes, some delay (usually small) can be seen in the aftershock sequences. It can be observed in the aftershock decay curve with time. In many cases, however, a large incompleteness can be seen in the catalog at earliest part of the aftershock sequence and therefore, an artificial large \( c \)-value can be computed. In fact, there is no upper limit of \( c \)-value. However, this value is generally suggested as small or very small: for example, around 0.01. In this study, it is aimed to remove these types of uncertainties on the estimations by considering \( M_{min}=1.9 \) and \( T_{start}=0.0 \). With this approach, the earliest part of the sequence is included in the analyses and completeness was provided although the number of aftershocks strongly decreased. Thus, in order to estimate the decay parameters of the modified Omori law, 2235 aftershocks were used with \( M_r \)≤1.9.

Fig. 2 shows the cumulative number of aftershocks in one year after the Sivrice-Elazığ mainshock. Considering the slope of the cumulative number of aftershocks curve, two subregions may be defined on Fig. 2. The first two months can be considered as the first part and the rest ten months as the second region. 2537 aftershocks were recorded in the first two months from the mainshock and there are totally 1921 aftershocks in the remaining time period. Aftershock activity after the first two months is relatively constant and indicates a slower decrease by comparison with the activity of the first two months.

Gutenberg-Richter relation and magnitude-frequency distribution of aftershock sequence was given in Fig. 3. \( M_{comp} \) value was taken as 1.9 and \( b \)-value was calculated as 0.82±0.02 by using the maximum likelihood solution. This \( b \)-value is relatively smaller than the average \( b \)-value of 1.0 which is observed worldwide. However, as seen in from Fig. 3, magnitude-frequency distribution of Sivrice-Elazığ aftershock sequence is well represented by Gutenberg-Richter scaling law with an average \( b \)-value close to 1.0. Frochlich and Davis \([11]\) suggested that some factors such as the higher stress concentration or high strain in the region, low heterogeneity degree of medium can cause decreases in \( b \)-value. Bender \([12]\) provided a detailed study on the dependence of \( b \)-value to the data fitting techniques, relative number of small and large earthquakes, maximum magnitude in the catalog, the interval size and sample size. Low \( b \)-value is related to the great number of large earthquakes, whereas high \( b \)-value indicates that there are many small earthquakes rather than great earthquakes in the catalog. As given in data section, there are 246 aftershocks with 3.0≤\( M_r \)≤4.0 and 47 aftershocks with \( M_r \)≥4.0. Thus, this low \( b \)-value may be related to relatively large number of aftershocks with \( M_r \)≥4.0.
The modified Omori law fit to the cumulative numbers of aftershock sequence observed from mainshock time of January 24, 2020 Sivrice-Elazığ earthquake and estimated aftershock decay parameters for different starting times with the magnitudes $M_{\text{comp}} \geq M_{\min}$ were plotted in Fig. 4. All aftershock parameters including $p$, $c$, and $K$-values in the modified Omori formula, their standard deviations, the minimum magnitude, starting time for the data and the number of aftershocks were also given. For the calculation of $p$, $c$ and $K$-values, the maximum likelihood approach was used, and the aftershock sequence was modeled by the modified Omori model, closely following the modified Omori law with a clear exponential decay. $p$-value was calculated as $0.80 \pm 0.02$ was estimated for the sequence by using $M_{\min}=1.9$, $T_{\text{start}}=0.01$ days since these input parameters are more satisfying than other input parameters. According to the Dieterich (1994) [13], if a main shock is modeled as a dislocation, aftershock rate within a finite time interval and region decays with the $p$-value about 0.8, due to a nonuniform stress change around the mainshock. Helmstetter and Shaw (2006) [14] stated that a heterogeneous stress distribution produces a power law decay with a $p$-value smaller than 1.0 (the more heterogeneous the stress is; the larger $p$-value is (closer to 1). According to these results, there is a low stress heterogeneity in the Sivrice-Elazığ aftershock sequence. A smaller $p$-value for an aftershock occurrence also indicates a slow decay rate and thus, the aftershocks sequence of the Sivrice-Elazığ earthquake has a relatively slow decay rate (as seen in Fig. 2).

Figure 3. Gutenberg-Richter relation and magnitude-frequency distribution of aftershock sequence

To obtain regional changes of $b$-value and $p$-value, aftershock area was divided into rectangular cells separated 0.02° in latitude and longitude. The closet nearest epicenters (number of events, $N_e$) was taken as 350 aftershocks for each cell and the minimum nearest epicenters ($N_{\text{min}}$, minimum number of events $> M_{\text{comp}}$) was taken as 100 events. Then, regional variations of $b$-value and $p$-value were mapped considering the number of aftershocks between 100 and 350. Next, as an important input data, $c$-value was taken as 0.279 days and $T_{\text{start}}=0.01$ days since these input parameters are more satisfying (Fig. 4) for the regional imaging of $p$-value.

Regional changes of $b$-value and $p$-value for aftershock sequence were shown in Figs. 5 and 6, respectively. $b$-value show regional changes between 0.5 and 1.2, and regional variations in $p$-value vary from 0.5 to 1.1. Aftershock activity (including all size of aftershocks with $M_c < 5.0$) was densely occurred in and around the mainshock, in the northeastern and southwestern parts of the mainshock (Fig. 1). Also, the largest aftershocks with $M_c > 5.0$ show a high density around the mainshock epicenter and in the southwestern end of the sequence. $b$-value changes can be thought as three groups: (i) the smallest $b$-values ($< 0.8$) to the north and south direction from the mainshock epicenter (including Gülmahmut, Ağaçkızı, Sivrice, Uluölük and Kavaklıdöy) and in the southwestern end of the region (including Erkenek segment, Pütürge, Unutans, Baştuzra and Pelitli); (ii) intermediate $b$-values (between 0.9 and 1.1) to the northeast and southeast direction from in Pütürge segment (including Harabeykaya, Akuşçağı, Yangınıkonak, the north and south parts of Hazar Lake); and (iii) the highest $b$-values ($> 1.1$) to the northeast end of the region (including Değirmenönü, Durmuştepe and Çayırköy). The smaller $b$-values were generally computed in the larger aftershock ($M_c > 4.0$) regions, whereas the biggest $b$-values are related to the regions in which aftershocks with $M_c < 3.0$ generally observed. Regional changes of $p$-value for aftershock sequence have both low and high values in all aftershock area. The largest $p$-values ($> 1.0$) were found in the north and south parts of the mainshock epicenter (in and around the mainshock including Uluölük, Kavaklıdöy and Aladıkme) and there is a faster decay of aftershock activity in these areas. On the contrary, lower $p$-values ($< 0.7$) were obtained in the south parts of the Hazar Lake, northwest part of Pütürge segment and southwest end of the aftershock region (including Durmuştepe, Çakırköy, Yangınıkonak, Erkenek segment, Baştuzra, Pelitli and Erenli). These small $p$-values mean that aftershock decay rate is slower in these parts rather than in the other parts of the region. Thus, aftershock activity decays faster in and around the mainshock epicenter ($p < 1.1$) than that of along the rest parts.

Figure 4. The modified Omori law fit to the observed data and aftershock decay parameters starting 0.01 days after the mainshock

Figure 5. Regional variations of $b$-value. $b$-value was plotted by sampling the nearest 350 aftershocks with cells spaced 0.02° in latitude and longitude. Star shows the mainshock

Figure 6. Regional variations of $p$-value. $p$-value was plotted by using the same grid and number of aftershocks with cells spaced as in the case of $b$-value map. Star shows the mainshock

Following the January 24, 2020 Sivrice-Elazığ earthquake, several studies including geotechnical evaluations were made and different parameters such as coseismic slip distribution and displacement, post seismic deformation, mainshock faulting, rupture kinematics, dynamic modelling and stress distribution were analyzed and discussed. Obtained results in this study among $b$-value, $p$-value, stress distribution and coseismic deformation are supported by the general results provided by literature.

4. Conclusions
Spatio-temporal evaluation of aftershock parameters following the January 24, 2020, Me=6.8 Sivrice-Elazığ earthquake was made by considering the b-value of Gutenberg-Richter relation and p-value of the modified Omori model. Results include that the variations in b and p-values are highly affected the stress distributions and coseismic deformation after the mainshock. Hence, considering the aftershock hazard after the mainshock, evaluation of the spatio-temporal parameters of the aftershock sequences may give preliminary, reliable and useful results for the fast evaluations of real time aftershock hazard.

Declaration of Conflict of Interests

The author declares that there is no conflict of interest. He has no known competing financial interests or personal relationship that could have appeared to influence this paper.

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