Study of Earthquake Clustering in the Rushan Area

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Abstract. Using the clumping earthquake identification method based on the nearest event distance algorithm by Zaliapin et al.[1-2] to investigate the characteristics of earthquake clumping for the Lushan earthquake swarm that occurred on October 1, 2013, the analysis of the results based on the calculated sequence development at different time periods shows that the seismic events in the Lushan earthquake sequence are basically still influenced by the larger earthquakes in the sequence as time passes, and the clumping of the sequence is obvious, with only a small fraction of “background earthquakes”[3-4] reflecting the regional stress state, with a clumping rate of 96%.

1. Introduction
The Rushan earthquake swarm has lasted for more than 5 years since October 1, 2013, with more than 13,000 small earthquakes, the largest of which was the 4.6 magnitude earthquake on May 22, 2015. Whether the continued activity of small earthquakes near the epicenter of this swarm is a continuation of the swarm sequence or a reflection of the background stress in the region is a pressing issue for current forecasting. Zaliapin et al. [1-5], introduced by Zheng Jianchang [4-5], developed a method to identify cluster earthquakes based on the nearest event distance algorithm, which effectively separates cluster earthquakes from background earthquakes and identifies background earthquakes that can reflect the trend of seismic activity. Zaliapin et al. [1,3] defined the nearest neighbor distance (NHD) between different events, and based on this method, they gave a method to analyze the clustered earthquakes and identify aftershocks. In this paper, we apply this method to study the development and evolution of the sequence activity of the Rushan earthquake cluster.

2. Zaliapin methodology
For a given earthquake catalog \( \{t_i, \theta_i, \phi_i, h_i, m_i\} \), \( i = 1, K, N \), where \( T \) is the moment of onset, \( \theta, \phi \) are the epicenter latitude and longitude, respectively, \( H \) is the depth of the source, and \( M \) is the magnitude of the earthquake. Without considering the depth, define the distance between two seismic events in the spatio-temporal energy domain [3],

\[
    n_j = \begin{cases} 
    c r_j^d 10^{-b(m_i-m_0)} & \tau_{ij} \geq 0 \\
    \infty & \tau_{ij} < 0 
    \end{cases}
\]

(1)

Where \( \tau_{ij} = t_j - t_i, r_j \) is the surface distance, \( m_0 \) is the reference magnitude, \( c \) is a constant factor, \( d \) is the fractal dimension of the epicenter distribution, \( b \) is the value of \( b \) in the G-R relationship (Without loss of generality, here we set \( c = 1, m_0 = 0 \)).
Define the nearest event distance in the given spatio-temporal range.

\[
    n_j^* = \min_j n_j
\]

(2)

Zaliapin et al [3] proved by theoretical analysis that under the assumption that \( N \) is a smooth stochastic
Poisson process with a certain probability density and that the magnitude scale $m_i$ is independent of the spatio-temporal scale $(t_i, x_i)$ and has an exponential distribution, then the nearest event distance $\eta^*$ satisfies the Weibull distribution and is independent of the lower bound on the magnitude of the process $N$.

Further define the time and space components of the nearest event distance $\eta^*$ normalized by the earthquake magnitude:

$$T_i = \tau_i 10^{-bm_i/2}, \quad R_{ij} = r_{ij}^d 10^{-bm_i/2}$$

(3)

$$\eta = TR$$

(4)

Numerical tests found that for a uniform Poisson process, the two-dimensional points of the spatiotemporal component $(T, R)$ of $\eta^*$ are concentrated along the straight line $10 \log_{10} T + 10 \log_{10} R = const$. The spatial and temporal components of the aftershock sequences that satisfy Omori's formula are distributed in a “cluster”.

When applied to the Southern California earthquake catalog, they found $\eta^*$ statistical distribution with a "bimodal" pattern, with one part corresponding to a cluster of earthquakes satisfying Omori's formula and the other part corresponding to a relatively independent so-called "background earthquake"; Also in the two-dimensional distribution of the spatial and temporal components $(T, R)$ of $\eta^*$, the “background earthquakes” and “cluster earthquakes” are concentrated on both sides of the line $10 \log_{10} T + 10 \log_{10} R = const$. Therefore, the "background earthquakes" and "cluster earthquakes" [6] can be effectively and statistically distinguished from each other in a physical sense.

Zheng et al [1] tested the method using three different models, including random data, swarm data, and data satisfying the ETAS model, and examined its discrimination between cluster and background earthquakes. Where the random data satisfying the uniform Poisson distribution conforms to the Weibull probability density distribution, The distribution of the spatio-temporal components of the distance to the nearest event is shown to be uniformly distributed on both sides of the fitted line, The swarm data are typical of cluster earthquakes, The statistical histogram shows a single-peaked distribution on the left side. In contrast, the data satisfying the ETAS model show a more pronounced bimodal pattern, and the experimental results show that the method is highly discriminatory.

3. Seismic activity analysis of the sequence of the Lushan earthquake swarm

In this paper, the results of the full sequence of the Rushan swarm are first calculated using the nearest event distance algorithm (Figure 1). The statistical histogram of the nearest event distance $\eta^*$ for this cluster shows a “peak” on the left side(Figure 1-a), and the contour pattern of the spatio-temporal component binary distribution in Figure 1-b also shows a "clumped" pattern in accordance with Omori's formula. The area of concentration of the contours is almost completely located at the lower left side of the line $x + y = 0$. The seismic activity shows obvious clustering characteristics.
Figure 1. Results of the nearest event distance method for the small earthquake activity of the Yushan earthquake cluster.

Using the nearest-neighbor event distance algorithm, a catalog of earthquakes in five different time periods since the occurrence of the Rushan earthquake swarm was selected, and the clumping of seismic activity in each time period was calculated and analyzed. Given the difference in activity intensity between the first and second phases of the sequence, the lower limit of magnitude was chosen to be less than 1.0. Based on the development of this earthquake sequence, the five time periods chosen respectively are as follows (Figure 2): ① October 2013 - June 2014; ② August 2014 - April 2015; ③ October 2015 - September 2016; ④ October 2016 - November 2017; ⑤ December 2017 - September 2018; and the results of the calculation of these five segments are shown in Figure 3.

Figure 2. Seismic sequence segmentation in Rushan.

As can be seen in Figure 3, the statistical histograms in Figures 1-a and 1-b show a "peak" on the left side, and the contour patterns in Figures 2-a and 2-b also show a "cluster" pattern in accordance with Omori’s formula, indicating that the seismic activity in the area at the beginning of the Rushan swarm is a cluster. The statistical histogram in Figure 1-c starts to show a small "peak" pattern on the right side, and the contour pattern in Figure 2-c starts to show a relatively small concentration of contours on the upper right side of the line x + y = 0, indicating that the analysis results from October 2015 to September 2016 show. The statistical histogram in Figure 1-d starts to show a "peak" pattern on the right side, and the contour concentration image in the upper right side of the line x + y = 0 in Figure 2-d is slightly more obvious than those in Figures 1-c and 2-c, indicating an increase in background seismicity from October 2016 to November 2017. The statistical histogram of Figure 1-e (December 2017 to September 2018) shows a more obvious "bimodal" pattern, but the peak on the right side is significantly smaller than that on the left side, and the concentration image on the upper right side of
the line $x + y = 0$ in the contour plot of Figure 2-c is not very dense. This indicates that although background earthquakes have occurred in this cluster area in the late stage of cluster development, the number of background earthquakes is relatively small and the cluster activity is still dominant.
4. Earthquake clumping rate
Using the straight line $x+y=0$ as the dividing line, we define the ratio of the number of earthquakes at the lower left of the line to the total number of earthquakes involved in the calculation as the earthquake clumping ratio ($cr$, cluster ratio), to calculate the earthquake sequence since October 2013 for the Rushan earthquake swarm, using a sliding number of equal events (window length 1000, step length 100), the calculation results show that the September 2014 earthquake The clumping rate shows a significant decrease, (23 earthquakes of magnitude 3 or higher with a maximum $M_L 4.7$ occurred from October 2013 to December 2014, of which three magnitude 4 earthquakes occurred before September 2014) and then fluctuates steadily, reversing in April 2015 to reach the highest clumping rate since the occurrence of the cluster, this may be related to the occurrence of the $M_{4.6}$ earthquake on May 22, 2015. The clumping rate $cr$ values continued at high levels until September 2015 (during which five magnitude 3 earthquakes occurred) and continued to decline after October 2015, with fluctuations from late 2015 to early 2016 that may be associated with two magnitude 3 earthquakes, $M_{3.1}$ on December 9, 2015 and $M_{3.0}$ on January 27, 2016. The clumping rate image shows that the earthquake clumping is continuously decreasing in 2017-2018, but the clumping rate is still above 96%. The figure shows that the seismic clumping rate in the epicenter region is significantly higher before the occurrence of larger earthquakes.

5. Conclusion
- The results of the full sequence calculation of the Rushan earthquake cluster shows that the
The statistical histogram shows a typical cluster model, and the contour pattern also shows a "cluster" pattern of aftershocks distributed in clusters satisfying the Omori formula, indicating that the Lactic Mountain cluster still persists.

- The results of the segment calculation: A small number of background earthquakes appear from the third segment, and in the last segment, the statistical histogram shows a "double-peak" pattern, but the peak on the right side is smaller than the peak on the left side, which indicates that there are background earthquakes, but the cluster activity is still dominant.

- The results of the settlement of the cluster rate show that although the cluster rate of 2017-2018 earthquakes has decreased compared with the beginning of the cluster, the cluster rate still reaches more than 96%, and the earthquake clustering is obvious.

6. References

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