A modification of the nearest neighborhood triggering mechanism in longwall mining: do seismic events only triggered by its closest neighbors?

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ABSTRACT: A common approach in seismology is to use the nearest neighbours method to identify the spatial and temporal relationships between events and select the closest event pairs to identify the triggering cascade. However, in mining engineering, due to the continuous triggering from dynamic mining development as well as the complex geological conditions (e.g., faults), the mining seismic events may not be purely triggered by one prior event, but by a triggering group of a few different events. In this study, we modify the event-event triggering identification approach applied in longwall seismic events. We find that high-energy events can be triggered by previous low-energy events, with clear foreshadowing events. High-energy events can be related to a few low-energy events whose mechanism is based on mining activities.

Keywords: Longwall mining, Seismicity, rock mechanics.

1 INTRODUCTION

Owing to the substantial spatiotemporal features between seismic events, the analysis of their spatial and temporal sequence plays a significant role in seismology (Si et al. 2020; Wang et al. 2021). The spatiotemporal characterizations reveal the essence of seismic events either by the 'cascade' or 'stick slip' theory, benefiting the understanding of earthquake formation (Davidsen et al. 2021). In longwall mining, the occasionally happened rock bursts and coal bursts accidents, analogously to earthquakes, also indicate a strong spatial cluster and temporal sequence (Holub et al. 2011). Hence, the spatiotemporal analysis of seismicity induced by longwall mining events is essential to workplace safety and mining productivity.

Multiple approaches to analyzing seismic inter-event triggering achieved considerable outcomes in the understanding of seismic temporal cascade (Gu et al. 2013). One of the most important methods is the Omori-Utsu law, whereby the event triggering rate after the source events can be empirically predicted. According to the Omori-Utsu law, the triggering seismic events followed by the source events show an exponential decay, where the triggering rate of seismic events is the highest right after the occurrence of source events and decreases gradually with time (Davidsen et al. 2017). The Omori-Utsu law provides a stable foundation of seismic temporal triggering sequence, whereas the spatial sequence of seismic events also attracts considerable attention. The location of seismic events indicates the breakage of rock mass or the instability (e.g., slippage) of pre-existing discontinuities, which has been proved by extensive research both in laboratory tests or site observations (Wang et al. 2021; Li et al. 2022, 2023). In the laboratory UCS and triaxial tests, the position of the inclined failure plane coming from an intact rock sample is aligned with the cluster of acoustic emission events. In addition, site monitoring systems also indicate that pre-existing faults are more likely to induce seismic events. A quantified analysis of seismic events, namely the fractal dimension, exhibits the fractal features of seismic event clusters. In three-dimensional space, the randomly distributed events illustrate a fractal dimension of three, while a planar event distribution indicates a fractal dimension of two. The change of fractal dimension indicates the variation in the spatial correlation of seismic events.

By combining the abovementioned spatial and temporal relationships of seismicity events, the spatiotemporal analysis of seismicity events provides a more comprehensive analysis. Such as a previous study (Si et al. 2020) performed by our research group, which applies the principal component analysis (PCA) to transform the 4D seismic information (location X, Y, Z and occurrence time) into 2D parametric data. We noticed that the high-energy seismic events occur within the high-density area of 2D parametric data. We also notice that the famous Epidemic Type Aftershock-Sequence (ETAS) model can be used to regulate the triggering rate of seismic events after source events considering the space-time-magnitude distance (Gu et al. 2013). Most importantly, the nearest neighbour method calculates the spatiotemporal distance between the seismic events and finds out the most likely triggering source of individual seismic events (Davidsen et al. 2021). The advantage of the nearest neighbour method is that all of the seismic events are separated into triggering and non-triggering catalogues. For the triggering catalogue, the nearest neighbours method enables us to understand the detailed triggering sequence of seismic events and how the cascade episode is formed. However, in longwall mining, the continuous resource extraction activities induced a dynamic triggering of seismic events in a longwall panel. Hence the triggering source may not only be the nearest neighbours but the comprehensive effect of multiple seismic events. Therefore, the application of the nearest neighbour method may lose valuable data about the true formation of seismic incidents.

In this study, considering the shortcomings mentioned in the nearest neighbour method, we modify the method to show all potential triggering sources for high-energy seismic events. The results show that the high-energy events occurring with a large number of precedent events cannot be identified by the nearest neighbour events.

2 METHODOLOGY

2.1 Nearest neighbour method

A spatiotemporal distance is identified to compare the spatiotemporal relationships between two existing seismic events. The proposed spatiotemporal relationships should consider the Gutenberg-Richter (GR) law (Gu et al. 2013; Davidsen et al. 2021), where the distribution of seismic moment follows a reciprocal law ($N(>m)\sim 10^{-bm}$). $N(>m)$ is the number of seismic events with the magnitude larger than m, and b is the b value, showing the seismic magnitude distribution among all seismic events. Following the famous GR law, the spatiotemporal distance between two seismic events can be written as (Gu et al. 2013; Davidsen et al. 2021):

$$n_{ij} = c\left(\vec{x}_{ij}\right)^{D_f} t_{ij} 10^{-bm_i} \tag{1}$$

where, $\vec{x}_{ij}$ is the distance between seismic events i_{th} and j_{th} and t_{ij} is the difference in occurrence time between events i_{th} and j_{th}. D_f is the fractal dimension of seismic events, related to the spatial distribution of seismic events. Most importantly, the i_{th} event is considered as the base event (triggering source) ($j > i$), whose occurrence time is earlier than the event (j_{th}). Frome the defined spatiotemporal distance, a high magnitude event (i_{th}) will introduce a lower spatiotemporal distance (n_{ij}) which indicates there is a higher possibility to trigger an event (j_{th}).

For a given dataset of time-space-magnitude distance n_{ij}, the nearest neighbourhood method regulates that the seismic events are only triggered by the closest precedent event pair. For the source event i_{th}, if the following up events j satisfies $n_{ij} = min_{(k<j)}(n_{kj})$, the event i and j are considered as the closest event pair. We write the distance between the closest event pair as n_i^*. If the distance between the closest event pair is low, the relationship between the source event i and j is closer and vice versa.

For all of the closest event pair n_i^*, some of them indicate a triggering relationship namely that the occurrence of such two seismic events is spatiotemporally related. On the other hand, some events are considered as background events without any precedent related events. Hence, to separate the event catalogue into triggering events and non-triggering events, a threshold is set as n_{thre} above which the seismic event pair is unrelated. Yet, if the spatiotemporal distance between two seismic events is lower than the threshold, the event pair then follows a triggering relationship from event i to event j.

2.2 Modified nearest neighbour method

The nearest neighbour method mentioned in Section 2.1 provides a solid foundation regarding how to identify the triggering cascade for the event i_{th}. However, by reviewing the spatiotemporal distance presented in Equation (1), we found that Equation (1) comes from aftershock perspective indicating when searching for the potential triggering events of i_{th} event, we do not involve the magnitude of triggering events (j_{th}), which is a foreshock sequence. In addition, some high energy events may abruptly occur without any precedent triggering source or maximumly triggering by one closest precedent event, owing to that only aftershock triggering mechanism is considered in Equation (1). However, seismicity incidents in longwall mining engineering may be triggered by face advance or slippage on pre-existing faults, which should be related to multiple seismic events concentrating on the fault or longwall face.

Hence, considering the nature of mining seismicity and the modified spatiotemporal relationship listed in Equation (1) can be written as:

$$n'_{ij} = c\left(\vec{x}_{ij}\right)^{D_f} t_{ij} 10^{-bm_j} \tag{2}$$

The only difference between Equation (1) and (2) is that the magnitude of the source event (m_i) is replaced by the magnitude of precedent events (m_j). Also, for Equation (2), we attempt to find the precedent triggering source of each individual events j_{th}, by involving events ($i < j$). High magnitude events are more likely to become the triggering source of following-up seismic events.

2.3 Introduction of the case study site

Seismic data applied in this study is collected from Henan province, China, owned by Yima Coal Group Company. The depth of coverage of the study mine is beyond 1000 meters, where high in-situ stress, high temperature, complex geological conditions and high disturbance from the longwall face advance induce severe seismicity hazards. The seismic incidents reduce the productivity of longwall mining activities and threaten underground worker safety.

In order to understand the mechanism of seismic events in the study mine and mitigate the influence of seismic incidents, a 16-channel seismic monitoring system (Poland, EMAG) is installed to collect valuable seismic waveforms from the mining face. To ensure the completeness of seismic data, only seismic events monitored by at least eight geophones are located and inversed. The waveforms collected by the geophones are directly processed in Insite Geo software by Itasca. The waveform is filtered, and the seismic events are located with the P wave velocity field of 4000m/s.

3 RESULTS AND DISCUSSION

To better present the spatiotemporal relationship of seismic events, we separate the spatiotemporal distance into two different parameters (T_i^* and L_i^*). The physical meaning of T_i^* is the temporal distance between two seismic events and the meaning of L_i^* is the spatial distance of distance. The expression of the two abovementioned parameters is:

$$T_{ij}^* = t_{ij}10^{-\frac{bm_j}{2}} \tag{3}$$

$$L_{ij}^* = \left(r_{ij}\right)^{D_f}10^{-\frac{bm_j}{2}} \tag{4}$$

The separation of spatiotemporal distance into two parameters T_{ij}^* and L_{ij}^* indicates $n_{ij}^* = T_{ij}^* \times L_{ij}^*$. And the results of the study site are plotted in Figure 1. The logarithmic scale is applied to illustrate the distribution of spatiotemporal distance among seismic event pairs. Then, a threshold is set to separate the entire event catalogue into triggering and non-triggering catalogues. Since there is no clear boundary between triggering and non-triggering events in Figure 1, a pragmatic approach is to use the Trial and error method. Different threshold values are considered and also, and we performed Bi-test on the triggering catalogue and non-triggering catalogue to see the deviation of the selected catalogue from a homogenous Poisson test (see (Davidsen et al. 2021)). Finally, we found that $n_{thre} = -0.36$ is selected to be the best value to separate the entire data set.

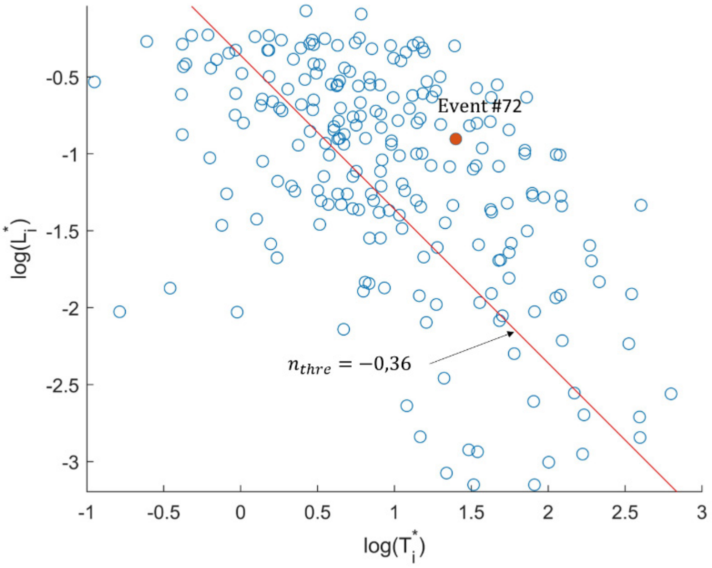

Figure 1. Triggering analysis for the seismic events at the study mine. The scatter plot indicates the spatiotemporal distance between two seismic events. A red line is set as the threshold, above which the seismic event pair is considered as non-triggering without spatial and temporal independence. And the event pairs below the threshold are triggering events, illustrating a closer spatiotemporal correlation. The highlighted event# 72 is a high energy event.

Interestingly, we find that there is a high energy event #72 (seismic moment =2032N.m) that is not triggered by any other precedent events. This observation indicates that high energy events ‘appear out of thin air’. It is not comprehendible in longwall mining engineering that the continuous triggering of mining activities can easily become the ‘triggering source’ of subsequent seismic events.

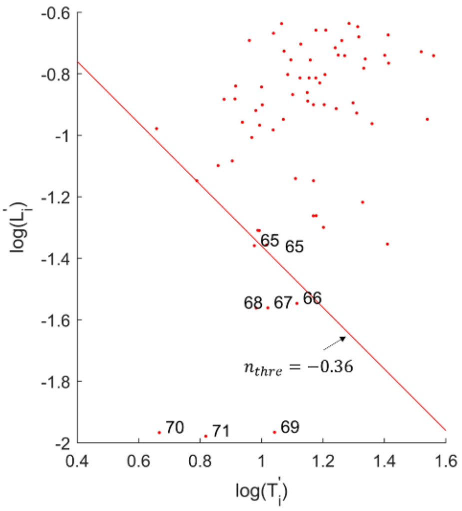

Figure 2. Modified triggering analysis for event #72. The scatter plot indicates the spatiotemporal distance from event #1 to event #71.

Figure 2 follows the modified spatiotemporal distance mentioned in Section 2.2 and we find that there are some precedent events below the triggering threshold. In other words, there may be a triggering relationship between those precedent events and event #72. Event #72, in this stage, seems to be related to other seismic events and be triggered by other events.

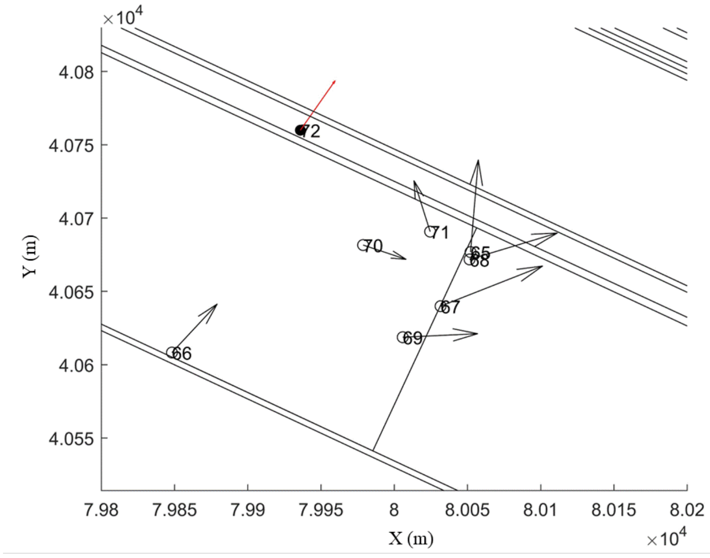

Figure 3. Potential triggering events of event #72. The longwall heading position at the occurrence time of event #72 is also plotted. The arrows indicate the 2-dimensional rupture direction of each seismic event.

The potential precedent events (triggering source) of high energy event #72 are plotted in Figure 3, where we observe that the location of triggering sources of event #72 clusters around the longwall face. This indicates that high energy event #72 is related to the mining activity. This result is consistent with our understanding that mining activity can induce local instability of rock mass or discontinuities and then the seismicity incident can be triggered. Hence, we confirm that the method we mentioned in Section 2.2 can assist in the identification of precedent triggering events of seismic incidents.

4 CONCLUSION

In this study, we propose a modified nearest neighbour method to find the potential precedent seismic event of seismic incidents. We find that some high energy seismic events in longwall mining engineering could ‘appear from the thin air’ according to the analysis by the nearest neighbours method. After using the modified nearest neighbours method mentioned in this study, the precedent triggering source of high energy events can be found, and the mechanism of the seismic triggering is owing to the longwall mining activity. The application of the modified nearest neighbours method can compensate for the shortcomings of the nearest neighbours method and provides more information about the mechanism of seismicity events.

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