A non-invasive approach for quantitative evaluation of geological deformations and dynamic disasters in complex mining environments

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Summary

The escalating demand for deep underground energy sources, driven by the depletion of shallow resources, has raised concerns about the occurrence of dynamic disasters, which pose significant societal risks. In the context of engineering excavation processes, the presence of pre-existing and excavation-induced fractures significantly influences the evolution of complex geological disasters associated with mining activities. Traditional approaches to disaster prediction rely heavily on physical models and numerical simulations. However, these methods often suffer from limitations such as time-consuming and uneconomical drilling tests, as well as restricted coverage. To overcome these challenges, this study introduces a novel methodology that enables comprehensive imaging of the geological response, deformation patterns, and dynamic disaster prediction within the entire minefield of underground engineering works with a special emphasis on steeply inclined and extremely thick coal seams (SIETCS).

Introduction

With the progressive excavation, the reorganization of the in-situ stresses and formation of high stress concentration regimes complicate the mining operation which result in the movement of coal/rock layers leading to dynamic disasters including coal-rockburst, outburst, and collapse [1,2]. Among these, the rockburst is globally considered as the most dangerous dynamic disaster and frequently occurring in Chinese as well as worldwide coalmines. Before a rockburst event occurs, a seismogenic process takes place, leading to the formation of numerous micro-fractures and the gradual release of microseismic energy during the failure process [3]. Therefore, characterizing these fractures and monitoring the released energy can help in comprehending the early warning of rockburst disasters. For this purpose, traditional monitoring methods including stress monitoring [4], drilling cutting methods [5], geophysical monitoring including microseismic technology [6,7], acoustic emission [8] and electromagnetic technology [9] are commonly applied to engineering excavation works for early warning monitoring. In the past, these methods were applied to underground engineering excavation projects to decipher rockburst indexes and prediction of dynamic disasters [10-13]. The existing literature predominantly focuses on traditional coal seams, characterized by horizontal and gently inclined formations. However, there is a notable scarcity of comprehensive studies on steeply inclined and extremely thick coal seams (SIETCS). The mining conditions and environments associated with SIETCS are highly complex, which gives rise to ongoing debates and uncertainties surrounding the identification and prediction workflows for dynamic disasters such as rockbursts. Moreover, the unique geological background shaped by regional tectonics further complicates the task of developing a definitive workflow for accurately identifying and predicting rockburst-driven dynamic disasters in SIETCS. Therefore, the development of new integrated methodologies is crucial to precisely evaluate failure zones and mitigate dynamic disasters in these intricate mining environments. This research provides a newfangled and integrated workflow based on non-invasive geophysics for the identification and prediction of rockburst prone regions in a typical SIETCS mine of northwestern China.

Theory and/or Method

In-situ passive seismological observations have been made for a period of 24 months in a SIETCS mine in China. The data were processed for noise removal by rock mass signal analysis, event recognition, and source parameters estimation [14]. The seismic energy is computed by the following equation:

\[
E = -2\gamma_{\text{eff}} + \frac{1}{2} \int \Delta \sigma_{ij} u_i n_j dA + \int dt \int \sigma_{ij} T_{ij} dA \quad (1)
\]

Where, \(2\gamma_{\text{eff}}\) is the effective surface energy, \(\Delta \sigma_{ij}\) shows the stress difference, \(n_j\) represents unit vector perpendicular to the fracture plane, \(\delta\) represents the area of the fracture with displacement \(u_i\), \(\sigma_{ij}\) shows the traction rate, and \(T_{ij}\) characterizes the source duration.

After the acquisition, processing and source location identification, the events location information is sorted chronologically. A python-based script is designed in this study to identify the initiation of endpoints of the fractures by connecting the events located in the same direction (codirectional events) and similarly poly-directional (new fractures). This iterative process of tracking codirectional and poly-directional events is repeated several times to confirm the events are correctly mapped using the basic principle of fracture mechanics. Then, the regional lineaments are interpreted using the basic principles of lineaments geology. The model validation is performed and a correlation between lineaments and seismic energy is established. The released energy is a physical parameter while fracturing is a mechanical process during mining operations which are resulted due to in-situ disturbance of
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the coal-rock mass, thus, we believe that there exists a certain relationship which is one of the main motives of this research. After establishing such a correlation, different risk zones are identified which represent the deformation (rockburst) in that particular region. This method has been proven to be effective for disaster identification and prediction and for determining the deformation propagation. Additionally, dynamic disaster prediction indicators have been computed and compared through conditional probability [15].

Discussion of Results

The Steeply Inclined and Extremely Thick Coal Seam (SIETCS) mines are more complicated due to abrupt changes in rheological properties, complex stress-state environments, irreversible deformation, intense brittle failure and wider influenced area. Since its commencement, microseismic technology has brought new capabilities for the characterization of fracture propagation and modeling schemes to predict such disasters. Some of these new advancements mainly developed and investigated in this study are addressed.

The general evaluation of induced-microseismic response suggested that with the increasing mining depth and excavation rate, the stress transformation occurred between two active coal seams. The 3S seismology theory helped in imaging the stress transformation process (Figure 1). The uneven distribution of microseismic events and rockbursts is ultimately the combined result of mining activity and the non-uniformity between the geological structure and stress distribution. The change of cumulative events with time can be divided into three processes, namely, quiet period (S1), active period (S2) and transition period of microseismic activity (S3). These three stages (S1, S2 and S3) correspond to the stress evolution process of engineering rock mass, namely stress concentration stage, stress weakening stage and stress transition stage. One of the rockburst events occurred during the stage S2 which is marked by arrow in Figure 1. Thus, a sharp increase and sudden decrease in the number of seismic events can provide a clue to understand microseismicity and thus prediction of rockburst. In the northern half of the mining area, the number of fractures and the length are comparatively small as compared to the central and southern half. This might be indicative of resistive coal-rock layers having comparatively more strength and less stress accumulation than the other parts of the mining area. The statistic of the few selected fractures is shown in Table 1.

The lineament's identification and interpretation involve tracking the propagation pathways of the fractures, which can be done based on the configuration, orientation and geometry of the mapped induced fractures. Figure 3 represents the interpreted lineaments for the Layer-1 as indicated by dotted lines with seismic energy correlation. The lineament's propagation follows the mining direction in general, however, some of the lineaments are oriented in different directions especially along the working face between 1600 m to 2000 m and 900 m to 1300 m (northeast to southwest). In the zone of rockburst events and high energy tremors, the lineaments are quite closely connected and merging towards a particular portion which confirms the occurrence of dynamic disaster occurred in the study area. Our proposed novel method of fractures and lineaments mapping helped in imaging the entire fracturing processes during active mining phases (Figure 2 and 3). The mapped fractures are shown in blue color where the induced rockbursts and high energy tremors are also displayed (Figure 2). The mapped fractures are unevenly distributed along the two working faces with maximum density of the fractures concentrated in B3+6 coal seam and rock pillar in between the two coal seams.

![Figure 1: The stress transformation process using 3S theory.](image)

The predicted dangerous zones in the central part are characterized by high energy levels while the other two predicted zones in the southwestern part of the mining area shown different patterns. Thus, it can be concluded that the released seismic energy during the active excavation process depends on the mining intensity, rock type, lithology, and stress concentration as well as stress transformation process. In general, in underground engineering, point-scale observations are made while our method provides a detailed picture of the entire minefield which could be helpful in upcoming disaster prediction. The decreasing occurrence frequency of fractures and lineaments is introduced as the new prediction indicator for dynamic disasters. The source parameter averages, variation in seismological parameters, maximum potential magnitude, and probability theory suggested unique criteria for disaster identification and prediction. The prediction probabilities of the four indexes are calculated respectively and compared with the prediction result for validation purposes.
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Table 1: Statistics of the selected mapped fractures, S= starting, E= ending, L=length, E=Energy, X and Y=coordinates.

Conclusions

This study analyzed the identification and prediction of rockburst prone regions subjected to excavation of SIETCS mine in northwestern China (Wudong coalmine). The study makes use of traditional disaster prediction indicators coupled with novel geophysical approach of fractures mapping for accurate prediction of dynamic disasters in underground engineering excavation. The case-study identified stress transformation between two steeply inclined coal seams which is inferred to be the result of non-uniformity between geological structure and mining activity. Based on the 3S theory, it is deduced that the regional stress was much higher in weakening stage resulting in number of high energy tremors. The newly introduced Seismo-Frac method helped in mapping induced fractures, lineaments and their correlation with released seismic energy. The mapped fractures and lineaments are unevenly distributed along the two working faces. By analyzing the fracture network before and after the rockburst, it is concluded that the decrease in occurrence frequency of the fractures can provide guidance about the dynamic disaster prediction and deformation propagation direction. Before the occurrence of rockbursts, the calculated source parameters showed an abnormal change. It is deduced that sharp increase in the number of microseismic events and released elastic energy can be used as precursors to rockburst whereas a sharp decrease in the seismological parameters can be used as one of the predictors. Such a holistic geophysics-based approach provides new avenues for geological disasters prevention and safe yield of energy resources in worldwide SIETCS mines with broader applications to geotechnical and civil engineering works.

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