Thesis Summary

Monitoring and Modelling of Microseismicity Associated with Rock Burst and Gas Outburst Hazards in Coal Mines

by

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Nomination for the Rocha Medal (2021) of the ISRM
Preface

The main body of the PhD thesis contains 60856 words and 241 pages. Results obtained in the course of this research have been presented in the following journal articles and conference papers, corresponding to different chapters of this thesis.

This thesis summary was produced with reference to the PhD thesis and the publications, and it contains 9979 words.

Chapter 3


Chapter 4


Chapter 5


Chapter 6


Chapter 7


**Chapter 8**


**Chapter 9**


• **Cao, W.***, Shi, J.Q., Durucan, S., Si, G., Korre, A. Gas-driven rapid fracture propagation under unloading conditions in coal and gas outbursts (*submitted to the International Journal of Rock Mechanics and Mining Sciences*).

(Note: corresponding authors are marked with *)
1. Introduction and objectives

1.1 Background

The advancement of mining technology allows coal mines to go deeper with ever increasing stress and gas emission conditions. The deep coal seams or rock masses are subjected to severe conditions compared to shallow ones, such as rock burst and gas outburst hazards. As the mining depth increases, these hazards become one of the urgent issues which are closely related to the effective and safe exploitation of underground resources and the stability of surrounding rock around the excavations.

It is generally recognised that dynamic hazards manifest themselves in different ways depending on variations in rock types and conditions of gas pressure and stress. In this respect, both dynamic phenomena in coal mining are considered as dynamic unstable failure problems because of the combined effects of rock/coal properties, stress and gas pressure conditions, geological structures and mining activities, with the ejected materials ranging from massive rock fragments to fine particles of coal accompanied with gas. Both underground seismic hazards, therefore, were investigated in this research in order to gain a better and more comprehensive understanding.

1.2 Knowledge gaps and research objectives

Despite extensive investigations in recent years, these hazards in deep coal mines have still not been fundamentally solved. Knowledge gaps on the following aspects still exist:

- seismic response of naturally fractured coal to stress and fracturing has not been well understood;
- not many long-term systematic field investigations have been conducted to reveal the role of stress concentration, fracture field, and mining intensity as contributors to microseismicity associated with longwall coal mining;
- no effective physics-based short-term forecasting methods are available for rock bursts and gas outbursts in coal mining;
- the synthetic microseismicity in a 3D numerical model has not been well developed and calibrated against recorded microseismicity;
- the role of dynamic stress perturbances induced by excavation unloading in contributing to unstable rock failure has not been quantified; and
- the accelerated propagation of gas-containing fractures subparallel to the unloading face in coal and gas outbursts has not been fully understood.

Targeting these knowledge gaps, the candidate carried out research and developed models to gain better insights into longwall coal mining induced microseismicity and dynamic unstable failure of rock/coal, as well as forecast underground seismic hazards and reduce the potential for those hazards.

The main structure of the thesis is depicted in Figure 1.
2. Previous research on underground hazards in coal mining

2.1 Rock burst hazards

Evaluation criteria for rock bursts evolved from the use of empirical thresholds to theoretical criteria. Most empirical thresholds consider both the state of *in-situ* stress in rock masses/coal seams and mechanical properties of rock/coal, and reflect the influence of deviatoric stress characteristics of the stress field. Theoretical criteria reflect not only the capacity to store strain energy in rocks, but also the environment for strain energy accumulation. Table 1 summarises some common empirical thresholds and theoretical criteria used for evaluation of rock burst risk.

2.2 Coal and gas outburst hazards

The major factors accounting for outburst occurrences are classified into intrinsic factors and extrinsic factors, as summarised in Table 2. Table 3 summarises some common empirical thresholds and theoretical criteria used for the evaluation of coal and gas outburst risks.

Many mechanism models for coal and gas outbursts were a combination of the pocket theory [1,2] and the dynamic theory [2,3]. In the 1980s, two principle models for outbursts were developed: coal destruction as result of shock-induced phase transition [4] and structural failure of coal induced by high gas pressure gradients [5]. It is generally agreed that outbursts are first initiated by dynamic failure of coal during stress changes ahead of the working face, and the rapid fracture extension and ensuing expulsion of coal and gas are driven by a large amount of desorbed gas from coal matrix [1,6].
Table 1. Empirical thresholds and theoretical criteria for rock bursts.

<table>
<thead>
<tr>
<th>Categories</th>
<th>Evaluation indices</th>
<th>Remarks/Evaluation criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress/stress</td>
<td>Stress-strength ratio index</td>
<td>$(\sigma_{\theta_{\text{max}}} + \sigma_{\theta})/\sigma_{\theta} &gt; 0.8$</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{\theta}/\sigma_{\theta} &lt; 2.5, \sigma_{\theta}/\sigma_{\theta} &lt; 0.16$</td>
<td></td>
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<tr>
<td></td>
<td>$\sigma_{\theta_{\text{max}}}/\sigma_{\theta} &gt; 0.55$ (heavy); $\sigma_{\theta}/\sigma_{\theta} &gt; 0.7$ (strong)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\sigma_{\theta}/\sigma_{\theta} &gt; 0.40$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\sigma_{\text{tm}}/\sigma_{\text{max}} &lt; 2$ (intensive)</td>
<td></td>
</tr>
<tr>
<td>Strength/stress</td>
<td>Excess shear stress (ESS)</td>
<td>$&gt; 15$</td>
</tr>
<tr>
<td></td>
<td>Brittle shear ratio (BSR)</td>
<td>$&gt; 0.7$</td>
</tr>
<tr>
<td></td>
<td>Coupled static and dynamic loads</td>
<td>The coupled static and dynamic loads exceed the critical stress limits of rock/coal</td>
</tr>
<tr>
<td></td>
<td>Tensile effective stress (TES)</td>
<td>The stress of a rock/coal element changes from compression to tension.</td>
</tr>
<tr>
<td>Brittleness</td>
<td>Brittleness</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Strain energy density (SED)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Burst energy coefficient ($R$)</td>
<td>$W_E/W_P &gt; 1$</td>
</tr>
<tr>
<td></td>
<td>Strain energy storage coefficient ($F$)</td>
<td>$&gt; 5$</td>
</tr>
<tr>
<td>Energy</td>
<td>Energy release rate (ERR)</td>
<td>$&gt; 4.7%$</td>
</tr>
<tr>
<td></td>
<td>Strain energy storage index ($W_E$)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Potential energy of elastic strain (PES)</td>
<td>$&gt; 150$</td>
</tr>
<tr>
<td>Fracture/damage</td>
<td>Fracture mechanics-based criterion</td>
<td>$K_I &gt; K_{Ic}$</td>
</tr>
</tbody>
</table>

Note: $\sigma_{\theta_{\text{max}}}$ is the maximum tangential stress of cross section in disturbed zone; $\sigma_{\theta}$ is the radial stress of cross section in disturbed zone; $\sigma_{c}$ is the uniaxial compressive strength; $\sigma_{t}$ is the tensile strength; $\sigma_i$ is the maximum principal stress of in situ stress; $\sigma_{\text{tm}}$ is the triaxial rockmass strength based on the Hoek-Brown strength criterion; $\sigma_{\text{max}}$ is the maximum horizontal stress on the boundary of an opening, $\sigma_{\text{max}} < \sigma_{\theta_{\text{max}}}$; $\phi$ is the frictional angle; $W_E$ is the elastic strain energy accumulated before rock failure; $W_P$ is the dissipated energy in the post-failure stage; $W_{sp}$ is the energy dissipated by plastic deformation during unloading process; $W_{st}$ is the stored energy in rock; $K_I$ is the stress intensity factor; and $K_{Ic}$ is the fracture toughness of rock.

2.3 Rock bursts and gas outbursts as dynamic unstable failure problems

As serious underground hazards frequently encountered in coal mines, rock bursts and gas outbursts share several similarities as follows:

1. Both hazards manifest as a dynamic type of violent failure phenomena.
2. More energy is released than absorbed during both hazards.
3. Both hazards can induce microseismic events and are usually preceded by cracking noises from within the rock mass or coal seam.
4. Both hazards can be either dynamically-induced or self-initiated.

However, it should be noted that the differences between these hazards also exist in some aspects, which are summarised as follows:

1. **Phenomenon.** Rock bursts result in rock ejection without gas involved, while a large amount of gas can be released in an outburst.
2. Rock/coal mechanical properties. Weak and friable coal contributes to the outburst proneness, while strong and hard rock/coal tends to have larger rock burst tendency.

3. Rock/coal integrity. Massive rock types are more liable to rock burst occurrences, while outburst prone coals are usually extensively fractured.

4. Energy source. Rock bursts result only from stored elastic strain energy of stressed rock masses, while internal gas energy principally contributes to outbursts.

Since both hazards are triggered under combined static and dynamic loads, they can be generalised as problems of dynamic instability under excavation unloading conditions: rock bursts are a violent failure of highly-stressed rock triggered by dynamic stress perturbations, while coal and gas outbursts are attributed to excavation unloading followed by gas desorption-driven rapid propagation of fractures.

<table>
<thead>
<tr>
<th>Categories</th>
<th>Factors</th>
<th>Sub-factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal type</td>
<td>Physical properties: coal rank, grain size, porosity.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mechanical properties: strength, Young’s modulus,</td>
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<tr>
<td></td>
<td>Poisson’s ratio, fracture toughness.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reservoir properties: permeability, Langmuir pressure and volume.</td>
<td></td>
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<tr>
<td></td>
<td>Mine depth</td>
<td></td>
</tr>
<tr>
<td>Intrinsic factors</td>
<td>Seam hardness</td>
<td></td>
</tr>
<tr>
<td>Seam thickness</td>
<td>Seamslope</td>
<td></td>
</tr>
<tr>
<td></td>
<td>In situ stress</td>
<td></td>
</tr>
<tr>
<td>Geological factors</td>
<td>Tectonic structures and discontinuities (faults, shear bedding zones, etc.)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tectonic activities (igneous intrusions)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gas content</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gas composition</td>
<td></td>
</tr>
<tr>
<td>Gas-related factors</td>
<td>Gas pressure</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gas pressure gradient</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gas adsorption/desorption rate</td>
<td></td>
</tr>
<tr>
<td>Mining methods</td>
<td>Thick seam longwall coal mining</td>
<td></td>
</tr>
<tr>
<td>Extrinsic factors</td>
<td>Multi-seam longwall coal mining</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sublevel caving coal mining</td>
<td></td>
</tr>
<tr>
<td>Stress regime generated</td>
<td>Face advance rate</td>
<td></td>
</tr>
<tr>
<td>Face advance rate</td>
<td>Pre-drainage</td>
<td></td>
</tr>
<tr>
<td>Gas control measures</td>
<td>Cross-measure boreholes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Protective mining</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Drainage borehole stimulation</td>
<td></td>
</tr>
</tbody>
</table>

2.4 Microseismicity associated with rock bursts and gas outbursts

Fracture-slip seismicity-generation mechanism: Mine-induced microseismicity is in essence the slippage of pre-existing subsurface fractures or flaws under the combined effects of tectonic and mining-induced stresses [7–9]. Therefore, the role of natural fractures throughout the active mining region needs to be highlighted in the explanation of microseismic response to coal extraction.
Correlation between microseismicity and rock bursts and gas outbursts: Induced microseismic characteristics are closely correlated with mining activity in both temporal and spatial sequences [10,11]. In coal mining, gas emission was also found to be associated with seismic events, with methane concentrations positively correlating with the acoustic emission rate [12].

Evaluation and forecasting of underground hazards using microseismic monitoring: The microseismic monitoring technique has been used as an effective passive seismological monitoring tool to identify regions prone to seismic-induced hazards in the field. The use of microseismicity as precursors to the occurrence of outburst and rock burst hazards has evolved through several stages, from the anomalous increase in seismic activity prior to mining hazards, to recognition of regularity patterns indicative of rock bursts, and then to comprehensive quantitative evaluation methods.

<table>
<thead>
<tr>
<th>Categories</th>
<th>Evaluation indices</th>
<th>Remarks/Evaluation criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength/stress</td>
<td>Protodyakonov strength</td>
<td>0.1–0.3</td>
</tr>
<tr>
<td></td>
<td>Drill-cuttings-to-hole volume ratio</td>
<td>&gt;3:1–7:1</td>
</tr>
<tr>
<td></td>
<td>Tensile effective stress (TES)</td>
<td>The stress of a coal element changes from compression to tension.</td>
</tr>
<tr>
<td></td>
<td>Unbalanced pressure driven force (UPDF)</td>
<td>The pressure gradient acting on a coal element overcomes the friction.</td>
</tr>
<tr>
<td></td>
<td>Gas volume</td>
<td>&gt;9 m³/tonne for CH₄ and 6 m³/tonne for CO₂ (Sydney Basin, Australia); 10 m³/tonne for CH₄ (China)</td>
</tr>
<tr>
<td>Gas</td>
<td>Gas pressure</td>
<td>&gt;= 0.74 MPa (China)</td>
</tr>
<tr>
<td></td>
<td>Gas desorption rate</td>
<td>3 cm³/35 s/10 g</td>
</tr>
<tr>
<td></td>
<td>Gas emission index</td>
<td>5-15 (liable); 15-20 (highly liable)</td>
</tr>
<tr>
<td></td>
<td>Permeability</td>
<td>&lt;= 5 mD (in situ); &lt;10⁻³ mD (core sample)</td>
</tr>
<tr>
<td>Fracture/damage</td>
<td>Fracture mechanics-based criterion</td>
<td>$K_I &gt; K_{ic}$</td>
</tr>
</tbody>
</table>

### 3. Seismic response and fracturing behaviour of coal under true triaxial stress conditions

To investigate seismic response of naturally fractured coal to stress and fracturing, laboratory experiments were carried out on two cubic coal blocks using a true triaxial rock testing machine, with the associated seismic response monitored using an ultrasonic monitoring system with active sources. To initiate fractures under laboratory conditions, internal stress was applied by injecting a hydraulic fluid to the centre of the coal blocks, rather than applying excessive external stress, which would have adverse effects to the experimental apparatus that was originally designed for hard rock testing. Recorded seismograms are correlated with the initiation of hydraulic fractures and interaction with natural fractures.

#### 3.1 Equipment and experimental procedure

The experimental set up (Figure 2a and b) used included a true triaxial rock testing machine (Figure 2c) to apply mechanical loads, an injection system (Figure 3) for hydraulic fracturing, and an ultrasonic monitoring system with active sources to record seismic response during the experiments.
Large coal blocks from an underground coal mine have been collected and cut to shape (300 mm cubes), ready for testing. The coal blocks had a few sets of natural fractures which outcrop at surfaces. Multi-stage triaxial testing was carried out for stress-strain-permeability characterisation of the coal used (Figure 4).

Brazilian tests were further carried out on six core samples to characterise the tensile strength and fracture toughness of the coal. The calculated mean tensile strength and fracture toughness values for the six samples were 0.47 MPa and 0.09 MPa·m$^{1/2}$, respectively.

3.1.1 Experimental procedure for the true triaxial tests

The experiments on two coal blocks were then carried out according to the following procedure. After being placed in the true triaxial apparatus, the coal block is first loaded to 3 MPa in three directions, and then unloaded to 2.22 MPa in the x direction, to create deviatoric stress conditions in favour of a fracture running perpendicular to the x direction. Silicon oil is then injected until leak-off occurs. Acoustic measurements are repetitively conducted at a 30 s interval until the shut-in.
Figure 3. (a) Transducer configuration used in the true triaxial experiment, and (b) trace types including straight transmission, oblique transmission and diffraction.

Figure 4. (a) 38 mm diameter core triaxial cell and stress-permeability testing components, and (b) axial stress-strain-permeability behaviour of coal determined through multi-stage triaxial testing.

3.2 Results and analysis

3.2.1 Stress and fracturing response

Figure 5 presents the mechanical behaviour of coal block 2 in response to loading and hydraulic fracturing. The borehole pressure increased quickly after the injection started, and an induced fracture was initiated. Leak-off happened when the borehole pressure reached the peak, which was 4.7 and 4.4 MPa for coal blocks 1 and 2, respectively.

3.2.2 Seismic velocity tomography

To analyse the change in seismic velocity over the hydraulic fluid injection process, seismic velocity tomography was performed for both coal blocks before and after hydraulic fluid injection using first arrival times in seismograms. Figure 6 illustrates the influence of hydraulic fracturing on the S-wave velocity tomograms. After the hydraulic injection into coal block 1, velocity-reduced regions extended roughly along the y direction (Figure 6c). The
location and orientation of velocity-reduced regions are consistent with those of the hydraulic induced fracture.

Figure 5. Stress, displacement and injection histories for coal block 2 during the true triaxial experiments.

Figure 6. S-wave velocity tomograms for coal blocks 1: (a) before hydraulic fracturing, (b) after hydraulic fracturing, and (c) the difference induced by hydraulic fracturing.

3.2.3 Seismic spectrograms

To investigate the temporal correlation between the fracturing behaviour and seismic response, seismic spectrograms were performed on recorded seismograms to obtain time-varying changes over the hydraulic fluid injection process. Figure 7 presents seismic spectrograms for three representative raypaths (stS, otS and dS) for coal block 1. Evident changes can be clearly identified in Figure 7(a) and (b) to correspond to the initiation of the injection-induced
fracture. This verifies that the induced fracture and fracturing fluid interfere with the propagation of stS seismic waves and influence seismic characteristics.

Figure 7. Examples of seismic spectrograms for different S wave raypath types for coal block 1: (a) straight transmission (stS), (b) oblique transmission (otS), and (c) diffraction (dS).

4. Field monitoring and analysis of microseismicity associated with longwall top coal caving mining

This chapter presents the analysis of recorded data from microseismic monitoring carried out at Coal Mine Velenje in 2011 and in 2016-2018. The respective role of stress concentration, fracture field, and mining intensity is investigated for their contribution to spatial, temporal and magnitude characteristics of microseismicity. Based on the monitoring results and the fracture-slip seismic-generation mechanism, a conceptual model was developed to explain the causes of anomalous microseismicity and statistical estimation of microseismicity to be triggered.

4.1 The field monitoring site

Coal Mine Velenje currently mines a lens-shaped deposit (Figure 8). The coal seam is 165 m thick in the central part and pinches out towards the margins.
4.2 Field implementation of the seismic monitoring technique

Around longwall panel K.-50/C in 2011: Continuous microseismic monitoring measurements were carried out at longwall panel K.-50/C during a four-month period from 27 April to 30 August 2011. These data were provided to the candidate early in his PhD research.

Around multiple longwall panels in 2016-2018: The microseismic monitoring system encompassed the nine LTCC panels in production around the central coal pillar (Figure 9).

4.3 Analysis of mining-induced microseismicity in 2011

4.3.1 Active time-lapse seismic tomography measurements

Figure 10 [14] presents the P-wave velocity tomograms for the tomography area. A relatively high velocity zone was detected diagonally across the centre of the tomography zone. This
heterogeneous zone is xylite-dominated coal with a relatively high strength, as compared to less strong detritic coal that also occurs in the coal deposit.

Figure 10. LTCC face K. -50/C P-wave velocity tomograms in X-component for the (a) 1\textsuperscript{st} and (b) 2\textsuperscript{nd} tomography campaigns (after [14]).

4.3.2 Continuous microseismic monitoring measurements

The microseismic events were analysed in terms of frequency-magnitude distribution and seismic energy distribution, focusing on the events recorded during twelve coal production weeks from 23 May to 30 August 2011.

A frequency-magnitude analysis was carried out on the recorded microseismicity around LTCC panel K. -50/C at Coal Mine Velenje. The fitted bi-weekly $b$ values were found to be fairly consistent with each other (~1.0) throughout the first eight weeks, until the xylite rich heterogeneous zone is approached (Figure 11).

Figure 11. (a) Frequency-magnitude plots, and (b) fitted $b$ values of the recorded seismic events over a 12-week period at LTCC panel K. -50/C, Coal Mine Velenje.
Gaussian distribution curves were fitted to the weekly histograms over the monitoring period between 27 April and 30 August 2011. A good fit was achieved for 10 weekly histograms. The goodness of fitting using the Chi-square test has shown that a $p$-value greater than 0.05 (95% confidence) was achieved for 8 out of the 10 weeks evaluated. The fitted mean value $\mu$ and the standard deviation $\sigma$ (Figure 12) remained fairly constant during the first eight weeks, and deviated after reaching the xylite-rich zone.

![Figure 12](image.png)

Figure 12. Fitted Gaussian distribution parameters for the microseismic event energy recorded during each production week of the study period at LTCC panel K. -50/C, Coal Mine Velenje.

## 4.4 Analysis of mining-induced microseismicity during 2016-2018

A total of over 17,000 microseismic events were identified around the nine LTCC panels. To facilitate analysis in this work, each microseismic event was to be associated with one of the nine panels, which is active and whose working face-line position is located closest to the event.

### 4.4.1 Spatial distribution

Figure 13 presents the mined-out area and distribution of the associated microseismic events for six longwall panels throughout the monitoring period. The majority of microseismicity is located within and close to the mined area. It is further noted that there was a kidney-shaped area where the density of the seismic events was relatively higher, indicating elevated stress concentration. A large part of this area is seen to overlap with the central coal pillar.

### 4.4.2 Energy magnitude and scaling

The frequency-magnitude relationship for all the microseismicity recorded was analysed. The shape of the frequency-magnitude distribution for each panel resembles that for the whole datasets.

Figure 14 shows the cumulative frequency-magnitude relationship of the recorded microseismicity. The $b$ value in the Gutenberg-Richter law fitted for seismic energy released for the whole dataset is 1, consistent with those around the six LTCC panels.

### 4.4.3 Evolutinal characteristics
Figure 15 plots the daily event number, seismic energy released and the distance to the closest face-line, together with the daily face advance rate at a representative panel K.-80/B. The results show that the daily microseismic intensity (top panel) closely follows the mine production schedule (bottom panel). In contrast, the average seismic energy and distance to the nearest face-line remained relatively consistent throughout. The latter suggests that the face advance rate had much less impact on the magnitude and spatial distribution of microseismicity.

Analyses of seismic energy, in terms of the estimation of $b$ value and the box-and-whisker diagrams, were performed based on weekly events. It is noted that the face advance rate had little impacts on either the $b$ value or the average seismic energy (Figure 16).
Figure 13. Spatial distribution of microseismicity associated with: (a) panel K.-80/E, (b) panel K.-80/B, (c) panel K.-80/D, (d) panel K.-80/C, (e) panel CD2, and (f) panel K.-95/E.

Figure 14. Frequency-magnitude relationship of the recorded microseismicity around: (a) all panels, and (b) each panel.

4.5 A conceptual model for mining-induced microseismicity

Since progressive longwall mining can be considered as a plane strain problem, a cross section of the multi-level LTCC mining layout is depicted in Figure 17. Pre-existing fractures within coal as potential sources of microseismicity are projected to the cross section as 2D fracture traces. Fractures are deemed to be activated in the form of microseismicity when the prevailing stresses satisfy the Mohr-Coulomb criterion. The change in shear stress $\Delta \tau$ along the fracture plane, i.e., the stress drop, can be approximated as the difference between the resistance $\tau_{sf}$ prior to slip and the dynamic strength $\tau_{df}$ of the fracture surface.
Figure 15. Evolitional characteristics of LTCC mining-induced microseismicity on a daily basis around panel K.-80/B.

Figure 16. Evolitional characteristics of LTCC mining-induced microseismicity on a weekly basis around panel K.-80/B.
Figure 17. Schematic illustrating longwall coal mining-induced microseismicity as a result of fracture slippage subjected to stress perturbations.

Figure 17 demonstrates possible causes for two types of anomalous microseismicity: elevated seismic energy level and heightened microseismic intensity. The elevated seismic energy level can be significantly attributed to: (1) large stress drop along the fracture surface during slip, and (2) source-scaling heterogeneity of fractures. Three possible reasons responsible for heightened microseismic intensity are: (1) the presence of highly fracture-populated regions, (2) weak fracture properties which lower the Mohr-Coulomb failure envelope; and (3) high stress concentration which brings the Mohr stress circle towards the failure envelope.

5. Development of a short-term statistical method to forecast microseismicity associated with longwall coal mining

Based on the conceptual model presented in Chapter 4, a data-driven yet physics-based methodology was developed to forecast mining seismicity hazards. The physical nature of the modelling approach originates from characteristics of pre-existing natural fractures throughout the coal seam, which dominate the resulting microseismic patterns.

5.1 A statistical model to forecast hazardous microseismicity

This work focuses on hazardous microseismicity having large energy release and occurring close to working faces or roadways. The real time forecasting of hazardous microseismicity becomes the problem of estimating the time-varying possibility that at least one large fracture slips in the vicinity of coal extraction over a certain period, given the local fracture field and...
production schedule (Figure 18). A flow chart of the forecasting methodology developed is presented in Figure 19.

Figure 18 Schematic diagram illustrating the physical basis of the statistical forecasting method for hazardous microseismicity.

5.1.1 Spatial, temporal and magnitude distribution

Event counts frequency: The generation of microseismicity can be approximately considered as a Poisson point process, which is described by the Poisson distribution. Figure 20 presents examples of the monitored and fitted event counts frequency of microseismicity around three LTCC panels at Coal Mine Velenje.
Figure 19. Flow chart of the forecasting procedure using microseismic sequence datasets with concurrent face advance records around a LTCC panel.

Figure 20. Frequency of daily microseismic event counts at three LTCC panels at Coal Mine Velenje (the connecting lines are only guides for the eye).
Since mining operation is a dynamic process, the ever-varying face advance rate is used as a tuning coefficient in the Poisson distribution to estimate the event counts frequency.

**Energy magnitude distribution:** The Weibull distribution achieves a good fit to empirical distribution of logarithmical seismic energy [10]. The CDF of the energy magnitude distribution can be fitted to estimate the probability of a large microseismic event over the next time interval $\Delta t$. Figure 21 presents examples of the frequency-magnitude distribution and fitted Weibull distribution for field microseismic monitoring data at Coal Mine Velenje.

![Figure 21](image1.png)

**Figure 21.** Examples of recorded and fitted energy magnitude distribution for microseismic events around different LTCC panels at Coal Mine Velenje: (a) histograms, and (b) cumulative distribution.

**Distance to the face-line position:** The spatial distribution of microseismicity with respect to the face-line is a continuous probability distribution and can be described by the Weibull distribution. The CDF of the spatial distribution of microseismicity with respect to the face-line can be fitted to estimate the probability of a microseismic event falling within a certain distance to the face-line over the next time interval $\Delta t$. Figure 22 presents examples of the spatial distribution with respect to the face-line and fitted Weibull distribution for field recorded microseismicity at Coal Mine Velenje.

![Figure 22](image2.png)

**Figure 22.** Examples of recorded and fitted spatial distribution with respect to the face-line for microseismic events around different LTCC panels at Coal Mine Velenje: (a) histograms, and (b) cumulative distribution.
5.1.2 Parameter estimation

The maximum likelihood method is applied to estimate relevant parameters. The method consists of calculating the maximum likelihood function, which is considered as the joint probability for sampling the set of observations. The parameters are estimated by maximising the likelihood function of the known distribution, given a sample of observations.

5.1.3 Risk assessment of hazardous events

It is justified to estimate the probability of hazardous microseismicity as the joint probability of event occurrence, the probability of an event being a large event, and the probability of an event being close to the longwall face. The probability that at least one hazardous event occurs over the next time interval $\Delta t$ is:

$$ P = \sum_{n} p(n) \left[ 1 - (1 - p)^n \right] $$

(1)

5.2 Application of the forecasting methodology at Coal Mine Velenje

The forecasting methodology developed was applied to longwall coal mining-induced microseismicity recorded during 2016-2018 at LTCC panel K.-80/B. The length of time window $\Delta T$ was determined as 14 days based on the event rate and mining schedule. The forecasted probability of hazardous microseismicity was updated daily ($\Delta t = 1$ day).

5.3 Results and analysis

Figure 23 presents the time-varying forecasted daily event number, and probability that large microseismicity, microseismicity close to the working face, and hazardous microseismicity occur on the day of forecasting for the three LTCC panels.

The forecasted daily event counts from the statistical model show excellent agreement with recorded numbers of microseismicity, with large event counts being forecasted at high face advance rates, and no events being forecasted when the coal production ceases.

The face advance rate affects the forecasted probability of large microseismicity $P_M$ by tuning the forecasted event counts. By comparison to $b$ values analysis for weekly microseismicity around the corresponding panel in Section 4.4.3, the evolution of $P_M$ and $b$ values display distinctly opposite trends.

The forecasted probability of microseismicity close to the working face $P_d$ was also tuned by the face advance rate ratio. More microseismicity were recorded close to the working face when the statistical model estimates a higher probability of such events.

The forecasted probability of hazardous microseismicity depends on all three aforementioned forecasted results. The forecasted probability of hazardous microseismicity closely follows the variation of that of large microseismicity ($P_M$) for the longwall panel, which means that the forecasting result is dominated by the impact of magnitude distribution of recorded microseismicity.
Figure 23. Forecasted daily event number, and forecasted probability that at least one large microseismic event, a microseismic event close to the face-line, and a hazardous microseismic event occurs on the day of forecasting around panel K.-80/B.

6. A DFN-based model to simulate microseismicity associated with longwall mining

A microseismicity modelling approach is developed based on the shear slip mechanism of mining-induced microseismicity and applied to longwall coal mining. The microseismic modelling approach developed is applied to simulate microseismic events induced by the progressive advance of the coal face over the twelve-week period in 2011 at Coal Mine Velenje. The results obtained are compared to the field monitored data.

6.1 Methodology development for microseismicity modelling in longwall coal mines

A numerical approach which considers fracture slippage based on the stress and failure state of the model is developed to generate microseismicity in longwall coal mining. Distinctive features of the developed methodology include the implementation of discrete fractures in numerical models and the use of a strain-softening constitutive model to better represent the effect of plastic zones on microseismicity distributions. The modelling is carried out by referring to the procedure presented in Figure 24.
6.1.1 DFN in FLAC\textsuperscript{3D}

Fracture intensity: The fracture intensity is determined through trial and error until a satisfactory match to the recorded field data is achieved in numerical simulations of microseismicity.

Fracture size range: The range of the fracture sizes can be constrained by the range of recorded energy release magnitude.

Fracture size distribution: The power law relationship, which more closely represents the natural distribution of fractures, was also in this work.

Spatial distribution of fractures: The fracture distribution is generated from a Poisson process.

6.1.2 Fracture slip evaluation

The Mohr-Coulomb slip condition is used to evaluate if a fracture has slipped or not. The resistance to slip is provided by the bonding and frictional properties of the fracture surfaces:

$$\tau_{sl} = \mu_{sf} \sigma + c_f$$ \hspace{1cm} (2)

where $\sigma$ is the normal stress on the fracture surface, and $\mu_{sf}$ and $c_f$ are the static friction coefficient and the cohesion along the fracture, respectively. The workflow implemented in this modelling work for examining fracture slip is presented in Figure 25.

Figure 24. Flow chart for the modelling procedure.
Figure 25. Flow diagram for the evaluation of a shear slip leading to microseismicity.

6.1.3 Microseismic energy release

The released kinetic energy $E_k$ from the fracture slip is proportional to the cube of fracture size (radius) and square of the stress drop:

$$E_k = \frac{4(1-\nu)\Delta \tau^2 R^3}{3G(1-\nu/2)}$$  \hspace{1cm} (3)

where $\nu$ is the Poisson’s ratio, $R$ is the fracture radius, and $G$ is the shear modulus. Equation (3) shows that the released kinetic energy is strongly affected by the fracture size and to a less extent by the rock strength (through stress drop) and mechanical properties.

6.2 Numerical modelling of microseismic events at panel K. -50/C at Coal Mine Velenje

6.2.1 Model set-up and generation of a discrete fracture network

A three-dimensional model was constructed in FLAC$^{3D}$ to represent the LTCC panel K. -50/C and surrounding strata. Strain-softening constitutive model was used to describe post-failure...
rock behaviour. When generating the DFN for modelling microseismicity, the recorded event energy range was used to estimate the range of fracture size using Equation (3) (Figure 26).

![Figure 26. Estimation of the range of fracture sizes through the event energy released during an eight-week period around panel K.-50/C at Coal Mine Velenje.](image)

6.2.2 Modelling of longwall top coal caving mining

The model run covered a period of eight weeks from 23 May 2011 to 17 July 2011. A total of eight longwall extraction steps were then modelled, each extraction step representing one production week. To account for the stochastic nature of the DFN, a total of five series of DFN realisations were generated and used in the model.

6.3 Model results and analysis

Figure 27 presents the frequency-magnitude distribution of the recorded and modelled microseismic events. The figure show that a relatively good agreement has been achieved between the model results and field observations.

![Figure 27. (a) Frequency-magnitude plots for microseismicity over 23 May to 5 June 2011, and (b) bi-weekly variation of $b$ values for recorded and modelled microseismic events around panel K.-50/C at Coal Mine Velenje.](image)
Curve fitting of a Gaussian distribution to the weekly histograms of the magnitude of microseismic energy predicted was also performed. As shown in Figure 28b, the simulated values are compared favourably with the field observations over the same period.

Figure 28. (a) Comparison of the recorded and modelled seismic energy released over Week 23 to 29 May 2011, and (b) fitted weekly mean value $\mu$ for recorded and modelled microseismic events at LTCC panel K.-50/C at Coal Mine Velenje.

7. Microseismic anomaly influenced by lithological heterogeneity in longwall coal mining

The modelling approach developed in Chapter 6 was applied to further model seismic characteristics during longwall coal extraction towards a heterogeneous zone. The rock strength of the elements and fracture attributes within the zone are varied, respectively.

7.1 Numerical model description

The numerical model was established based on the model developed in Section 6.2. The geometry of the xylite-rich zone inferred from the active seismic tomography measurements was digitalised from Figure 10 and implemented into the FLAC\textsuperscript{3D} model. The strength properties of xylite-rich coal were set to be one to two times those of detritic coal. Two groups of fractures were employed: one group for the xylite-rich zone (DFN 1), and the other for the remaining zones (DFN 2).

A total of twelve extraction steps were simulated, from 23th May to 28th August. Multiple runs were carried out with various rock strengths (compressive and tensile strength) for xylite-rich coal and fracture attributes (fracture intensity term and size distribution exponent) within the xylite-rich zone, respectively.
Figure 29. Mining geometry and geological implementation of the xylite-rich zone: (a) 3D model geometry, and (b) the central cross-section of the model along the face advance direction.

### 7.2 Results: Effect of rock strength on seismic response

Figure 30 presents the variation of fitted $b$ values from frequency-magnitude distribution of recorded and simulated microseismicity over the monitoring period. The reduction in $b$ values has a positive correlation with the increase in rock strength of elements within the xylite-rich zone.

The frequency-magnitude distribution of recorded and simulated microseismicity during 1 to 14 August 2011, when the xylite-rich zone was partly mined, was also analysed. It was noted that the $b$ value decreases with increasing rock strength of elements within the xylite-rich zone.
Figure 30. The bi-weekly $b$ values for frequency-magnitude distribution of the recorded and simulated microseismic events over the monitoring period.

The effect of rock strength on weekly histograms of the logarithmic event energy was analysed for the field data and modelling scenario $\sigma_{th} = 2\sigma_{ec}$, $\sigma_{th} = 2\sigma_{ec}$ before and after reaching the xylite-rich zone, respectively. The results indicated that both the elevation in energy levels and reduction in the number of seismic events after reaching the xylite-rich zone can be modelled by increasing the rock strength of elements within the xylite-rich zone. The decrease in the number of simulated microseismic events is believed to be due to a lower chance of slippage of fractures within the stronger xylite-rich zone.

Figure 31 shows the fitted Gaussian distribution parameters to the logarithmic event energy for the recorded and simulated seismicity over the monitoring period. Strong rock strength for xylite-rich coal leads to a marked increase in both $\mu$ and $\sigma$ when the xylite-rich zone is approached.
Figure 32a presents the variation of simulated weekly average resultant stress drop during face advance towards the xylite-rich zone. For the scenario with strong xylite-rich coal, the resultant average stress drop increases up to three weeks before the xylite-rich zone is encountered.

![Graph](image)

**Figure 32.** (a) Simulated average stress drops over the twelve-week monitoring period, and (b) examples of histograms of stress drops for the scenario $\sigma_{th} = 2\sigma_{cc}$, $\sigma_{th} = 2\sigma_{cc}$.

The histograms of stress drops during two typical production weeks for the scenario $\sigma_{th} = 2\sigma_{cc}$, $\sigma_{th} = 2\sigma_{cc}$ are plotted in Figure 32b. Stress drops form two clusters (one occurring in coal and the other in roof goaf) for the week 30 May to 5 June. In contrast, one more cluster corresponding to microseismic events occurring in the xylite-rich zone, is observed during the week 1 to 7 August. Therefore, the energy released from microseismic events is enhanced when the xylite-rich zone is reached.

### 7.3 Results: Effect of fracture attributes on seismic response

Figure 33a presents the variation of fitted $b$ values from frequency-magnitude distribution of recorded and simulated microseismicity over the monitoring period. For modelling scenarios with lower power law length exponent $a$ of embedded fractures within the xylite-rich zone, $b$ values of mining-induced microseismicity begin to decrease during 20 June to 3 July and reach the bottom just before encountering the xylite-rich zone.

Figure 34 presents examples of weekly histograms of the logarithmic event energy for the field data and modelling scenario $a_b = 1.8$, $\alpha_b = 0.7\alpha_c$ before and after reaching the xylite-rich zone, respectively. The rightward shift of bins to higher energy levels after encountering the xylite-rich zone can be simulated with lower $a_b$ values.

The effect of fracture attributes on fitted Gaussian distribution parameters to the logarithmic event energy was also analysed for the recorded and simulated seismicity over the monitoring period. Low length exponents $a_b$ of embedded fractures within the xylite-rich zone lead to a slight increase in $\mu$ and a noticeable increase in $\sigma$ when the xylite-rich zone is reached.
The slipped fracture size is closely associated with the seismic energy release. The weekly average slipped fracture size experiences an increase when approaching the xylite-rich zone for modelling scenarios with lower $a_h$ values.

Figure 33. (a) The bi-weekly $b$ values for frequency-magnitude distribution of the recorded and simulated microseismic events over the monitoring period, and (b) examples of $b$ values for the recorded and simulated microseismic events during 1 to 14 August 2011.

Figure 34. Examples of weekly histograms of the logarithmic event energy for the recorded and simulated seismicity for the scenario $a_h = 1.8$, $a_h = 0.7a_c$: (a) during Week 23 to 29 May 2011, and (b) during Week 1 to 7 August 2011.

The weekly histograms for two production weeks for the scenario $a_h = 1.8$, $a_h = 0.7a_c$ are plotted in Figure 35b. Results indicated that the less dominance of small slipped fractures within the xylite-rich zone (lower $a_h$ values) contributes to the increase in the average slipped fracture size when reaching the xylite-rich zone.
Figure 35 (a) Simulated average slipped fracture sizes over the twelve-week monitoring period, and (b) examples of histograms of average slipped fracture sizes for the scenario $a_b = 1.8$, $a_c = 0.7a_c$.

8. Unloading induced dynamic stress perturbations contributing to rock bursts

Excavation unloading induced dynamic stress perturbations as a source of vibration to trigger unstable rock failure is demonstrated through two theoretical examples designed by the author. The first example is the dynamic disturbance to adjacent pillars induced by dynamic pillar recovery, simplified to a problem of loading on a one-dimensional pre-stressed pillar. The second example is the dynamic disturbance to adjacent mine openings induced by dynamic excavation unloading, simplified to a problem of loading on a two-dimensional pre-stressed circular opening.

8.1 Dynamic stress disturbance induced by pillar recovery

8.1.1 Problem definition

Figure 36 illustrates the recovery process of underground pre-stressed pillars. From the perspective of dynamics, the response of neighbouring pillars is caused by unloading disturbance emanating from the removed pillar. Specifically, adjacent pillars are subjected to the combined effects of the initial vertical stress (Figure 36a), and dynamic disturbance of rock masses (Figure 36b). The dynamic response of pillar workings induced by pillar recovery can be simplified to a problem of loading on a one-dimensional pre-stressed pillar.

8.1.2 Dynamic instability criterion for pillar workings

In this work, rock/coal is considered to become unstable when the released energy exceeds the energy consumed in the failure process [15]. The criterion can be given by:

$$\frac{dU}{dt} = \frac{dU_a}{dt} + \frac{a_c}{a_c} > \frac{dU_f}{dt}$$

(4)
where $U$ is the total released energy, $U_s$ is the strain energy stored, $U_d$ is the external energy from the dynamic disturbance, and $U_f$ is the energy needed to be consumed in fracturing rock/coal.

For pillar workings under uniaxial compressive stress state, the criterion for dynamic instability can be simplified to:

$$\sigma_{\text{cri}} \leq \sigma_{\text{max}}$$

where $\sigma_{\text{cri}}$ is the pillar load under the critical equilibrium state.

Figure 36. Schematic of instantaneous pillar recovery and induced dynamic response of adjacent pillar workings: (a) before and (b) after pillar recovery.

8.1.3 Initial and transferred vertical pillar loads

The vertical pillar load $\sigma_v$ is related to the initial overburden loading and the near field extraction ratio $e$ [16]:

$$\sigma_v = \frac{\rho g H}{1 - e}$$

After pillar recovery, the load previously carried by the removed pillar will be redistributed and act on neighbouring pillars or surrounding rock. The transferred load can be given by the increment in the vertical load after adjacent pillar recovery.

8.1.4 Pillar recovery-induced dynamic stress
Figure 37 illustrates the dynamic response of a pre-stressed pillar subjected to a suddenly applied load. The induced disturbance can be characterised by the dynamic amplification coefficient $R$, defined as the ratio of the dynamic increased vertical pillar load to the final transferred load. The maximum vertical pillar load $\sigma_{v_{\text{max}}}^\Delta$ can be expressed in terms of $R_{\text{max}}$:

$$\sigma_{v_{\text{max}}}^\Delta = \Delta \sigma_d + \sigma_{v_0} = R_{\text{max}} \cdot \Delta \sigma_v + \sigma_{v_0}^0$$  \hspace{1cm} (7)

![Figure 37 Dynamic response of a pre-stressed pillar subjected to a suddenly applied loading.](image)

The pillar response to dynamic loads can be analysed by means of structural dynamics. Using the Duhamel integral equation [17] to obtain the total response by integrating all differential responses over the loading time, the maximum dynamic amplification coefficient $R_{\text{max}}$ is:

$$R_{\text{max}} = \max R(t) = \max \left[ \begin{array}{c} \frac{1}{t_0} \int_{t_0}^t \sin \left( \frac{2\pi}{T} t \right) dt \\
1 - \frac{T}{\pi t_0} \cos \left( \frac{2\pi}{T} \left(t - t_0\right) \right) \sin \left( \frac{\pi t_0}{T} \right) \\
\end{array} \right]$$  \hspace{1cm} (8)

where $t_0$ is the load transfer duration, and $T$ is the natural vibration period of the pillar.

As shown in Figure 38, instantaneous pillar recovery ($t_0 = 0$) yields a $R_{\text{max}}$ as large as 2. When the extraction time is longer than $T$, $R_{\text{max}}$ becomes 1, suggesting no evidence of dynamic effect. When $t_0$ ranges from $0.01T$ to $T$, $R_{\text{max}}$ falls in the range between 1 and 2.
Figure 38. Dynamic amplification coefficients of a pillar for different extraction time ($n = t_0/T$).

8.2 Dynamic stress disturbance induced by excavation unloading

8.2.1 Problem definition

This section focuses on the problem of underground excavation unloading impact on a neighbouring circular excavation. Figure 39 illustrates two circular excavations positioned at a certain distance in a hydrostatic stress state, where the one on the right is pre-existing and the one on the left to be excavated. The stress state of the rock/coal can be obtained via superposition of a static stress field and a tensile radial traction applied to excavation surfaces under unstressed conditions.

![Schematic illustration showing the superposition principle applied to the stress analysis of a pre-stressed excavation opening subjected to dynamic disturbance.](image)

8.2.2 Dynamic responses of an existing excavation under transient wave incidence

The dynamic response of an existing excavation can be simplified as an analysis of circular holes under cylindrical wave forces. A cylindrical tensile stress pulse arising from the new excavation boundary travels in the positive $x$-direction and envelops the existing excavation symmetrically from $\theta = \pi$. Because waves of any form can be decomposed to harmonic waves having different frequencies, one solution is to represent the effect of transient wave excitation in terms of the superposition of harmonic wave excitation, the solution of which has been given using the wave function expansion method by Mow and Pao [18].

The dynamic stress concentration factor (DSCF), i.e., the steady-state dimensionless tangential stress defined as the ratio of the tangential stress at the excavation boundary subjected to an incident plane $P$ wave over the radial stress at the same position without the circular excavation, was proposed to characterise dynamic perturbations at boundary of pre-existing excavations. The Fourier transform technique was applied to obtain the transient response (the transient dimensionless tangential stress) of an existing excavation from the steady-state response.

8.2.3 Results and analysis

Figure 40 presents DSCF variations around the existing excavation over time when $r_0/a$ is 5, 10 and 20. The dynamic response under plane wave excitation is also presented for comparison purposes [18].

As shown in Figure 40a, b, c, dynamic effects subjected to instantaneous unloading yield maximum values at $\theta = 0$, $\pi/2$ and $\pi$. When the normalised unloading time increases to $n_0 =$
the dynamic response becomes virtually unnoticeable. DSCF values at different locations converge to the static stress concentration factor after the passage of waves [18]. The analogous static solution for plane waves is Kirsch’s static solution for biaxial loadings, the far field stress \( P_0 \) in one direction, and stress caused by the Poisson’s effect \( P_0 \theta (1 - \nu) \) in the other direction [18].

Figure 40. Numerical results of the DSCF at the pre-existing excavation boundary.
9. Unloading induced gas-driven rapid fracture propagation in coal and gas outbursts

It has been recognised that the coal and gas outbursts are triggered by excavation unloading followed by gas-driven rapid propagation of a system of pre-existing or mining-induced fractures. Based upon this understanding, this chapter presents a coal and gas outburst model based on fracture mechanics and gas dynamics, where gas-containing fractures parallel to a working face experience opening first, then expansion and rapid propagation stages under unloading conditions.

9.1 A coal and gas outburst model based on fracture mechanics and gas dynamics

9.1.1 Conceptual model

Figure 41 illustrates a schematic of a coal seam with a working face and an induced failure zone ahead of the face. Here, the focus is on a newly formed penny-shaped fracture oriented parallel to the face, and its subsequent opening and propagation as the face advances.

![Figure 41](image)

Figure 41. Schematic representation of fracture opening in relation to effective stress changes ahead of a working face (modified after [19]).

9.1.2 Fracture behaviour subjected to intra-fracture effective stress

As the working face advances, a fracture in the vicinity is likely to experience opening first, then expansion and rapid propagation under the interplay of gas pressure and stress:

(1) Fracture opening triggered by excavation unloading. When the advancing face approaches, the change of stress conditions results in the opening of the fracture.

(2) Gas desorption and its migration into the fracture. Fracture opening results in an initial decrease in the intra-fracture gas pressure, which prompts the desorption of gas from the coal surrounding the fracture and its subsequent migration to the fracture. The fracture radius
remains constant \( (a_0 = a_1) \) at this stage, but the fracture volume continuously increases as gas pressure builds up.

(3) Fracture propagation. Once intra-fracture gas pressure reaches a certain limit, the fracture would begin to propagate immediately. The stress intensity factor criterion for the mode I \( (K_I) \) is used in the evaluation of fracture propagation:

\[
K_I \geq K_{Ic}
\]  

(9)

where \( K_{Ic} \) is the fracture toughness of coal.

The stress intensity factor \( K_I \) for a fracture embedded in an infinite domain can be expressed in terms of effective stress and fracture radius as:

\[
K_{I2} = 2(p_2 - \sigma_{min})(a_2 / \pi)^{1/2} = K_c
\]  

(10)

\( K_I \) monotonically decreases as the gas pressure decreases when \( p \geq \sigma_{min} \), which suggests that the propagation would cease at a state where the following equation is satisfied. On the other hand, once a fracture begins to propagate, it would keep on propagating, rather than reaching a state of equilibrium under continuous gas desorption conditions. As such, this would lead to successive propagation of fractures and coal expulsion, i.e., a coal and gas outburst.

9.1.3 Estimation of outburst threshold limits

The criterion for coal and gas outbursts can equally be expressed in terms of critical stress intensity factor \( K_I \) (Figure 42a) or intra-fracture gas pressure (Figure 42b). The latter means that a fracture with continuous inflow of desorbed gas is deemed to propagate if the critical intra-fracture gas pressure \( p_{lim} \) to drive fracture propagation is lower than that at adsorption/desorption equilibrium \( p_{equ} \).

9.2 Numerical implementation of the outburst model

Based upon the preceding analyses, a numerical model incorporating stress changes, gas desorption and fracture propagation was developed to simulate the initiation and temporal evolution of a coal and gas outburst triggered by coal extraction. Each element of coal seam
in the model is assumed to host a gas-containing micro-fracture of the same length, and the failure of model elements is governed by the propagated lengths of embedded fractures. The outburst modelling procedure developed is presented in Figure 43. The flow diagram for the implementation of the theoretical model is presented in Figure 44.

9.3 Model set-up for unloading-induced coal and gas outbursts

The roadway development used as an example to demonstrate the methodology developed in this work utilises the field data and layout from an outburst prone coal seam at Pniowek Colliery in Poland.

A three-dimensional geomechanical model was constructed using FLAC$^{3D}$ to simulate the roadway development and the assessment of coal and gas outburst potential. As illustrated in Figure 45, an outburst prone zone, represented by a much lower coal fracture toughness in the model, was placed in the coal seam. During geomechanical modelling, a total of five roadway development steps, each representing the removal of a 2 m length of the roadway, were modelled until the roadway reached the outburst prone zone.

To quantify their roles in evolution of coal and gas outbursts, parametric investigations were further performed by varying fracture toughness of coal, fracture radius, initial gas pressure, and in situ stress.

9.4 Results and analysis

9.4.1 Coal outburst behaviour of the baseline model

Figure 46 presents the evolution of intra-fracture gas pressure distribution 360 s after each roadway development step. As the development heading reaches the outburst prone zone, a
coal and gas outburst is initiated, whereby a steep gas pressure gradient forms at the outburst front.

![Flowchart Diagram]

- **Begin cycle**
- **Undisturbed (state_flag = 0)?**
  - No
  - Yes
- **Failed (state_flag = 2)?**
  - No
  - Yes
- If yes, enter the fracture expansion stage (state_flag = 1)
- Calculate $p_t$ after gas desorption
  \[ V_{e,t} = \frac{V_{e,eq}}{V_{e,eq}} \]
- Calculate $p_{eq}$ at equilibrium state
  \[ V_{e,eq} = m \left( \frac{V_{e,t}P_0 - V_{e+p,eq}}{P_0 + P_{eq}} \right) \]
- If $K_e \geq K_c$?
  - Yes
  - No
- Calculate $\alpha$ and $P_z$ after fracture propagation
  \[ P_z \geq P_{eq} ? \]
- Does propagation velocity increase?
  - Yes
  - Dynamic propagation
  - Quasi-static propagation
  - Reach equilibrium
    \[ P_z = P_{eq} \]
  - No
- $\alpha \geq \Delta t_{min}$?
- Enter the post-failure stage (state_flag = 2)
- Delete failed zones
- Update time since expansion begins $t = t + \Delta t$
- **End cycle**
Figure 44. Flow diagram for the calculation of the fracture expansion and propagation in a model element at time $t$.

Figure 45. General stratigraphy and model geometry of roadway development in the modelled coal seam.

Figure 46. Intra-fracture gas pressure distribution caused by gas desorption after each roadway development step (Unit: Pa).
Expulsion of coal at the working face causes the subsequent ejection of neighbouring coal elements by aggravating the release of *in situ* stress and facilitating gas desorption-driven fracture opening and propagation. As illustrated in Figure 47, the expansion of the outburst zone follows the same pattern as that represented by the onset of gas desorption from the coal elements.

![Image](image-url)

**Figure 47.** Time since fracture expansion begins and gas desorption from coal elements is initiated (only the left half of the outburst prone zone is shown).

Figure 48 illustrates the gas pressure variation associated with fracture behaviour in the proximity of the development face during the initiation stage of the outburst. The evolution of intra-fracture gas pressure corresponds to three stages of the fracture behaviour, namely fracture opening, expansion and propagation. It is noted that, a period of time is needed for the intra-fracture gas pressure to build up before it could initiate fracture propagation. This provides an explanation for the short time delay observed before coal and gas outbursts occur in the field, ranging from several to tens of minutes after exposure to an outburst prone zone [20].

![Image](image-url)

**Figure 48.** Evolution of intra-fracture gas pressure and associated fracture behaviour at a fracture.

### 9.4.2 Parametric investigations on coal outburst behaviour
Figure 49 illustrates effects of different influencing factors on the intensity of coal and gas outbursts, represented by ejected volume of coal over time. Large fracture toughness, fracture radius and initial gas pressure and low minor principal stress have favourable effects on the intensity of coal and gas outbursts.

![Figure 49](image)

Figure 49. Influences of (a) $K_{IC}$, (b) $d_0$, (c) $p_0$, and (d) $\sigma_i$ on the ejected volume of coal over time.

### 9.5 Discussion

The outburst model developed can explain several characteristics of coal and gas outbursts:

1. Coal and gas outbursts often happen not immediately but a period after the exposure of an outburst prone zone;
2. A coal and gas outburst usually initiates from a working face and manifests itself as surface stripping of coal slices;
3. A coal and gas outburst is continuous and dynamic failure of coal;
4. Low strength of coal adds to its proneness to coal and gas outbursts; and
5. Coal and gas outbursts tend to occur in highly fractured sites subjected to geological disturbance or intense mining-induced fracturing.

### 10. Conclusions

The main conclusions of this research are summarised as follows:
The active acoustic monitoring technique was found to be helpful to reflect the seismic response of coal to fracturing (both the fracture initiation and subsequent interactions with the natural fracture system in coal). This technique provides a new alternative to detect and analyse the fracturing behaviour in coal.

Long-term systematic monitoring of microseismicity around ten longwall panels has shown that microseismic event counts frequency is moderately correlated with mining intensity, while seismic energy magnitude and spatial distribution are poorly associated with mining intensity.

Analysis and interpretation of the long-term monitoring data led to the development of a conceptual model which describes mining-induced microseismicity as slippages of natural fractures in response to progressive longwall coal mining. The triggered microseismicity and associated energy release are described in terms of three mechanisms: fracture abundance, fracture slip criterion, and the resulting stress drop. Although microseismicity is induced by the longwall coal mining production, it was found that its energy and spatial distribution are controlled by the attributes of natural fractures throughout the coal seam.

Forecasting of hazardous microseismicity using the statistical short-term forecasting methodology, developed based on the conceptual model, was in good agreement with field observations. Forecasting results confirmed that the probability of hazardous microseismicity is the joint probability considering the event counts frequency, energy magnitude distribution and spatial distribution with respect to the closest longwall face. Forecasting results also suggested that the energy magnitude distribution of microseismicity plays a dominant role towards potential for hazardous microseismicity.

Numerical modelling of longwall coal mining induced microseismicity using the DFN-based microseismic modelling methodology, developed based on the conceptual model, has shown that a good match can be achieved between recorded and modelled microseismic events in terms of released energy and frequency-magnitude distribution. The energy released from a microseismic event is shown to be proportional to the cube of fracture size. The model findings indicate that the microseismic modelling methodology reflects the stochastic nature and magnitude characteristics of microseismicity, and that the power law fracture size distribution can be used to model microseismic generation around the longwall coal face.

Numerical modelling of microseismicity associated with the progressive advance of a longwall face towards a higher mechanical strength xylite-rich heterogeneous zone has shown a reduction in fitted b values and an increase in fitted Gaussian distribution parameters as the longwall face approached the heterogeneous zone. Both the high rock strength of xylite and low scaling exponent of fractures within the xylite-rich zone contribute to these deviations. The deviations in microseismic characteristics are believed to result from the combined effects of increased stress drops and slipped fracture sizes when the xylite-rich zone is approached.

Dynamic stress disturbances induced by underground excavations, including pillar recovery and large mine openings, contribute significantly to unstable rock failure such as rock bursts. The dynamic stress effect is closely associated with the extraction time. The maximum dynamic amplification coefficient $R_{\text{max}}$ on a pillar can exceed 1.5 or even approach 2 subjected to instantaneous recovery of an adjacent pillar, while the dynamic stress concentration factor (DSCF) around a mine opening can reach up to 18% subjected to instantaneous excavation of an adjacent mine opening. The findings indicate that
dynamic unloading disturbances should be considered when designing and supporting adjacent underground structures and openings in regions characterised by high levels of stress.

Coal and gas outbursts can be considered as a domino effect-type failure triggered by excavation unloading and propelled by gas desorption driven fracture propagation. The potential of coal and gas outbursts is governed by the threshold for fracture propagation, while the intensity is highly dependent on the gas desorption into fractures. Both the potential and intensity of coal and gas outbursts are dominated by four factors, namely fracture toughness of coal, fracture radius, initial gas pressure and in situ stress state. Furthermore, the delayed occurrence of coal and gas outbursts reported by many researchers may be associated with the gas desorption behaviour.

References