Modelling the influence of heterogeneity on microseismic characteristics in longwall coal mining

Wenzhuo Cao, Ji-Quan Shi, Sevket Durucan, Guangyao Si, Anna Korre
Department of Earth Science and Engineering, Royal School of Mines, Imperial College, SW7 2AZ, London, United Kingdom

ABSTRACT: Mining-induced microseismicity has been extensively used to evaluate the potential for rock bursts and coal and gas outbursts in underground coal mines. In a research project completed a few years ago, it was observed that characteristics of microseismicity around a longwall working panel were fairly consistent over the monitoring period until a heterogeneous zone with a relatively high coal strength was reached. The current research presented in this paper aims at achieving a better understanding of the effect of heterogeneity on microseismic activity in longwall coal mining. A microseismicity modelling approach which combines deterministic stress and failure analysis together with a stochastic fracture slip evaluation was used to simulate the evolution of microseismicity induced by the progressive face advance passing through a heterogeneous zone. The heterogeneous zone was taken into account by varying the material strength of the elements within the high strength zone and the fracture attributes within this zone. Results have shown that both the high rock strength of coal lithotype and low fracture intensity within this zone contribute to the decrease in seismic event counts, and that the increase in energy released results from the combined effects of increased stress drops and slipped fracture sizes when the high strength zone is approached.

1. INTRODUCTION

Underground mining activities are usually accompanied by microseismic events. Extraction of large volumes of rocks at depth brings about changes in stress conditions around mine openings and beyond. It has been widely accepted that microseismicity is predominantly caused by slip of pre-existing planes of weakness (e.g. fractures) and geological discontinuities (e.g. faults) (Stiller et al., 1983; Spottiswoode, 1984).

Seismic events are typically characterised by the magnitude of released energy, event counts, and the scaling of microseismic event magnitude. Energy released from a microseismic event is predominantly dependent on fracture size, stress drop along the fracture surface, and rock properties (Salamon, 1993). The stress drop is in turn affected by the prevailing stress conditions and rock properties.

Occurrences of microseismic anomaly have been reported to be associated with geometric and structural complexities, such as bedding shear zones in coal seams and stiff structures in hard rock mines. The presence of these geological structures influences the rock mass response to loading conditions, and thus microseismic characteristics. For example, Sato and Fujii (1988) reported that the seismic energy release rate was significantly suppressed before passing through a fault in the hanging wall. It has been observed that the largest seismic events tended to fall into the largest vein in an American deep hard rock mine (Swanson, 1992). It was also reported that two stiff reef structures led to decreases in both seismic event rate and seismogenic movement rate in an Australian gold mine (Abolfazlzadeh and Hudyma, 2016).

The impact of local heterogeneity in rock properties such as permeability and strength on the response of rock masses to excavation has been studied numerically. An and Cheng (2013) adopted a one-dimensional flow model with a low-permeability zone to study the gas distribution patterns, and showed that both the magnitude of permeability and the extent of the low-permeability zone affect the abundance of gas in the coal seam. Using a coupled fluid flow-geomechanical model, Si (2015) simulated the advance of a development heading approaching two different types of local heterogeneities, i.e., a low permeability zone representing a tectonic intrusion, and an elevated-strength zone, to study the impact of local heterogeneity
on gas emission and outburst tendency. The simulation results have shown that the presence of a low permeability area results in an increased gas pressure gradient with the approaching of the heading, and an increase in the outburst tendency shortly after the passage of the heading; meanwhile, the presence of an enhanced strength region leads to a significant suppression in gas emission when the heading approaches, and a rapid increase in gas emission with the passing of the development heading.

The impact of material heterogeneity arisen from geological structures such as faults or shear zones has been investigated by a number of researchers. Lei et al. (2004) conducted triaxial loading experiments on rock samples containing pre-existing joints with various healing strength and asperities, and found that while the failure of homogeneous faults gives no clear early warning signals and is unpredictable, heterogeneous faults fracture after a crack nucleation phase with distinct statistical variation of AE activity parameters. Sainoki and Mitri (2014) used a transversely isotropic, linear elastic model to verify the increase in fault-slip potential as a result of heterogeneity of shear stiffness in the weak zone. Zhao et al. (2014) modelled the response of the rock mass containing a brittle fault zone in TBM excavations, in which the Mohr-Coulomb yield criterion was adopted to evaluate the failure of the fault zone, and interface elements were used to represent the interaction between the fault and the rock mass. Xu et al. (2015) used an equivalent continuum approach to model a cavern excavation near an interlayer shear weakness zone, where the thickness, strength and orientation of the zone were characterised.

In a research project completed a few years ago, continuous microseismic monitoring was performed around a working longwall panel at Coal Mine Velenje in Slovenia. During a monitoring period of twelve weeks in 2011, a seismic anomaly characterised by a decrease in event counts and an increase in the average seismic energy released was observed from the eighth week onwards (Si et al., 2015a). This anomaly has been attributed to a xylite-rich zone with relatively high strength in an area dominated by detritic coal (Si et al., 2015a).

In a more recent research by the authors, a numerical modelling approach which includes sequential stress analysis and fracture slip evaluation was developed to model the microseismicity generation in longwall coal mining. The modelling approach was then applied to simulate microseismic occurrence and associated energy release prior to the seismic anomaly at Coal Mine Velenje. The model results were compared to field observations in terms of logarithmic event energy and frequency-magnitude distribution of microseismic events.

In this study, the modelling approach developed is applied to model seismic characteristics during longwall coal extraction towards a heterogeneous zone inferred from time-lapse seismic tomography. The rock strength of the elements and fracture attributes within the zone are varied, respectively. The induced microseismicity are investigated in terms of event counts and weekly released energy. This model provides a tool to obtain a better understanding of factors influencing mining-induced microseismicity, and lays a foundation for the prediction of rock bursts or coal and gas outbursts using recorded microseismic data.

2. RECORDED MICROSEISMIC EVENTS AND ANALYSIS AT COAL MINE VELENJE

Coal Mine Velenje is located on the largest coal deposit in Slovenia. The multi-level mining combined with the longwall top coal mining (LTCC) method is used at Coal Mine Velenje to mine a coal seam which is up to 160 metres thick in the centre of the coalfield (Si et al., 2015a).

During LTCC extraction at longwall panel K. -50/C, time-lapse seismic tomography was performed over a 100 m × 141 m area ahead of the advancing longwall face (Si et al., 2015a). Specifically, a total of 40 receiver and 40 source boreholes were placed along the intake and return gateroads with a regular spacing of around 2.5 m. Each receiver was equipped with 3 receiver components, i.e., X-, Y- and Z-components, monitoring the P-wave velocities parallel to the gateroad, perpendicular to the gateroad and in the vertical direction, respectively. During the survey, explosives in boreholes were used to generate P-waves, and P-wave velocities were computed and interpolated to produce velocity tomograms for every receiver component. During the first of two campaigns, when the monitored zone was 95 m ahead of the advancing face, a relatively high velocity zone was detected diagonally across the centre of the area, as presented in Fig. 1. This heterogeneous zone is considered to be xylite-dominated coal with a relatively high strength, as compared to less strong detritic coal that also occurs in the coal deposit. The unconfined compressive strength of xylite in the mine is known to be around twice of that for detritite.

In order to assess the dynamic behaviour of the coal seam in response to longwall mining, continuous microseismic monitoring measurements were carried out at the same panel during a 12 week period from 23 May to 28 August 2011 (Si et al., 2015a). When the longwall face reached the xylite-rich zone, a decrease in microseismic event counts accompanied by an increase in the average released seismic energy was observed (Fig. 2).
The analysis of the microseismic data has shown that the bi-weekly frequency-magnitude distribution of recorded microseismic events follows the Gutenberg-Richter relationship, with the $b$ value reflecting the scaling of microseismic event magnitude. In addition, the weekly histogram of the released seismic energy follows a Gaussian distribution, which is characterised by the mean of the distribution $\mu$, and the standard deviation $\sigma$. It was observed that these features of microseismic events were quite steady in the first eighth weeks, and deviated after reaching the xylite-rich zone (Fig. 3 & Fig. 4).

Considering that microseismic events primarily arise from fracture slippage, the $b$ value for the Gutenberg-Richter relationship is related to the scaling of fracture sizes in the coal seam. Similarly, the fitted mean value $\mu$ and standard deviation $\sigma$ of the Gaussian distribution are associated with the fracture sizes and size distribution, respectively.

In view of the consistency in $\mu$, $\sigma$ and the $b$ values during the first eight weeks, it was assumed that the fracture sizes and size distribution within the coal panel were consistent over this period. The deviations in the $b$, $\mu$ and $\sigma$ values, event counts and average energy release when approaching the xylite-rich zone suggest that, except for rock strength, the fractures within the xylite-rich zone differ from those in the coal seam. Based on the modelling work of triaxial loadings to fractured rock mass embedded with DFN following a power law size distribution using a coupled DEM-DFN model, samples with lower fracture intensity has higher rock strength and elastic modulus, and samples with lower fracture size distribution exponent $a$ tend to have greater rock strength (Harthong et al., 2012). In this respect, it is deduced that fractures within the xylite-rich zone have lower intensity and power-law exponent $a$ related to the size distribution.

3. MODELLING METHODOLOGY

In this study, a numerical approach which considers fracture slippage based on the stress and failure state of the model is applied to generate microseismicity in longwall coal mining. Salamon (1993) and Board (1994) were the first to implement fractures along which slip can take place to form a microseismic event in elastic models. The authors of this paper developed their model in FLAC3D and incorporated a strain-softening
constitutive model to describe the post-failure behaviour of the rock mass realistically. The modelling is carried out by referring to the following procedure:

(1) Model construction and fracture implementation.
A model is first established in FLAC3D to represent the longwall panel layout and surrounding strata. Mechanical and strength properties are assigned to elements representing different geological structures, and an elasto-plastic constitutive model is applied to represent the rock mass failure behaviour in response to coal extraction. The initial and boundary conditions are then set up to simulate the *in situ* stress field in the coal mine.

The pre-existing fractures are implemented as potential microseismic hypocentres in the model domain. This is realised by the built-in discrete fracture network (DFN) logic in FLAC3D. The embedded fractures are planar and disk-shaped. The fracture attributes consist of fracture intensity, orientation, size range and size distribution. Considering shear slip as a predominant microseismicity mechanism, the fracture intensity can be estimated by event counts of recorded microseismicity. The fracture orientation can be specified according to field scanline surveys, or randomly sampled from a Gaussian distribution. The fracture size range and distribution can be estimated by the range and distribution of the recorded microseismic events.

(2) Stress and failure analysis.
Progressive longwall mining is simulated by sequential excavation steps. At one excavation step, the elements representing both the coal to be extracted by the shearer and the caved top coal are “removed” from the model domain. The stress calculation and failure analysis are then performed alternately throughout the modelling process to update the stress state and determine if plastic failure occurs in response to coal production. In this way the influence of post-failure behaviour of the rock mass on stress redistribution around excavations is taken into account. The running stops when no failure zones form and new stress equilibrium is reached. At the next excavation step, the removed elements are “reinstated” by assigning mechanical and strength properties of caved goaf materials to them.

(3) Microseismicity generation and calculation of released energy.
After the stress equilibrium is reached in the model, all the fractures located in the elastic zone are traversed to check if fracture slippage takes place to generate a microseismic event. In view that fracture sizes may exceed those of zone elements, nine stress calculation points on each fracture surface, including eight uniformly located on the fracture circumference and one at the centroid of the fracture, are used. The stresses applied for evaluation are extracted from those for zone elements closest to these stress calculation points. Once the slip criterion at any stress calculation point is met, the fracture is considered to have slipped over the whole fracture surface and a microseismic event is thus formed. The adopted fracture slip criterion is the Mohr-Coulomb slip condition, i.e., the fracture slippage is considered to take place once the prevailing shear stress along the fracture plane exceeds the shear strength. The released seismic energy from the stress drop is calculated by

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

(1)

where $\nu$ and $G$ are the Poisson’s ratio and the shear modulus of the host rock respectively, $\Delta \tau$ is the stress drop magnitude and $R$ is the fracture size.

In this study, fractures that have slipped once are marked and not allowed to slip in the following modelling steps.

4. NUMERICAL SIMULATION OF LONGWALL COAL MINING-INDUCED MICROSEISMICITY

4.1. Numerical model description
A 3D model was constructed according to the geological conditions around the longwall panel K. -50/C. The length, width and height of the model are 300 m, 350 m and 200 m, respectively. As illustrated in Fig. 5a, the panel K. -50/C has a thickness of 20 m and a width of 150 m, including both the intake and return gateroads. The panel was underlain by 100 m thick floor coal, and overlain by a 20 m thick mixed roof layer, half of which was clay on the intake gateroad side, and the other half was caved roof goaf on the return gateroad side. A further 50 m thick clay layer was on the top of the mixed layer. The geometry of the xylite-rich zone inferred from the active seismic tomography measurements was digitalised from Fig. 1 and implemented into the FLAC3D model, assuming full penetration within the coal panel.

The geological structures used in the model consisted of coal, clay, failed clay (for caved roof goaf) and xylite (for the xylite-rich zone). Material properties of the first three structures were obtained from laboratory tests on samples from Coal Mine Velenje and are shown in Table 1. The elastic properties (bulk modulus and shear modulus) of the xylite were set to be the same as those of coal, and strength properties (compressive and tensile strength) of xylite were set to be one to two times those of coal.

The rock strata behaviour was modelled using the strain-softening constitutive model. In the post-failure stage, it was assumed that the residual cohesions of coal, clay
and xylite reduce with increasing plastic strain, and that residual values of 17% of initial cohesions are achieved when the plastic strain reaches 0.001.

Fig. 5. Mining geometry and geological implementation of the xylite-rich zone: (a) 3D model geometry, and (b) a cross-section of the model along the face advance direction.

The bottom of the model was fixed, and the normal stresses were applied on other boundary faces to simulate the in situ stress field. The initial vertical stress was estimated from the weight of overburden, and the initial horizontal stress was calculated based on the Poisson’s effect under vertical gravity loading.

After geometry construction of the model, fractures were embedded into the model domain. Given the frequency-magnitude distribution of recorded microseismic event, the fracture sizes were assumed to follow a power-law distribution, which is given by

$$n(l) = \alpha \cdot l^{-a}$$  \hspace{1cm} (2)

where $n(l)$ is the number of fractures with size in the range $[l, l+dl]$ per unit volume, $\alpha$ is the fracture density term, and $a$ is the size scaling exponent which determines the relative number of fractures with different sizes.

In this study, two sets of fractures were employed: one set for the xylite-rich zone (Set 1), and the other for the remaining zones (Set 2). For both fracture sets, the fracture positions and orientations were set to be random, and the fracture radii ranged from 0.9 m to 9 m. A fracture number of 69,545 and scaling exponent $a=3.0$ were applied for the Set 2 to calibrate the synthetic microseismic intensity and size distribution to the recorded ones. The fracture number and scaling exponent for the Set 1 were varied during modelling, and will be introduced in Section 4.2.

4.2. Modelling scenarios

A total of 12 extraction steps were simulated (from right to left in Fig. 5b), from 23th May to 28th August, with an interruption of a two-week period starting from 16th July. To take into account the impact of previous mining activities, the intake and return gateroads at the panel and the elements representing one week coal production (12 m long, 150 m wide and 20 m thick) before the initial face-line were extracted. In this study, each excavation step represented coal extraction for one week. After stress equilibrium was reached at each excavation step, the stress and failure states of elements hosting fractures were checked if fracture slippage had taken place to register microseismic events, as described in Section 3.

Multiple runs were carried out with various rock strengths for xylite and fracture attributes within the xylite-rich zone, respectively:

1. The geometry parameters for fractures in the heterogeneous zone remain the same as those in the coal seam, and three scenarios were considered by varying compressive and tensile rock strength of elements within the heterogeneous zone: (a) $\sigma_{ch} = \sigma_c$, $\sigma_{th} = \sigma_{ce}$; (b) $\sigma_{ch} = 1.5 \sigma_c$, $\sigma_{th} = \sigma_{tv} \sigma_{ch} = \sigma_{tv}$; and (c) $\sigma_{ch} = 2 \sigma_c$, $\sigma_{th} = 2 \sigma_t \sigma_{clh} = \sigma_{ct}$.

Table 1 Rock mechanical properties used in the K.-50/C LTCC model (after Zavšek, 1993; Si et al., 2015b)

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Bulk modulus (GPa)</th>
<th>Shear modulus (GPa)</th>
<th>Cohesion (MPa)</th>
<th>Internal friction angle (°)</th>
<th>Tensile strength (MPa)</th>
<th>Residual cohesion (MPa)</th>
<th>Residual tensile strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>0.90</td>
<td>0.19</td>
<td>2.10</td>
<td>23</td>
<td>0.92</td>
<td>0.35</td>
<td>0.52</td>
</tr>
<tr>
<td>Clay</td>
<td>1.10</td>
<td>0.24</td>
<td>1.90</td>
<td>30</td>
<td>0.92</td>
<td>0.63</td>
<td>0.52</td>
</tr>
<tr>
<td>Failed clay</td>
<td>0.77</td>
<td>0.17</td>
<td>0.63</td>
<td>30</td>
<td>0.92</td>
<td>0.63</td>
<td>0.52</td>
</tr>
</tbody>
</table>
where $\sigma_{cc}$ and $\sigma_{tc}$ are respectively the compressive and tensile strengths of the coal seam, and $\sigma_{ch}$ and $\sigma_{th}$ are those of the heterogeneous zone.

(2) The rock strength of the heterogeneous zone remains the same as that of the coal seam, and three scenarios were considered by varying the fracture intensity term and size distribution exponent of fractures hosted by the heterogeneous zone: (a) $a_h = 3.0$, $\alpha_h = \alpha_c$; (b) $a_h = 2.5$, $\alpha_h = 0.7\alpha_c$; and (c) $a_h = 2.0$, $\alpha_h = 0.4\alpha_c$.

where $a_h$ is the power-law distribution exponent for the heterogeneous zone, and $\alpha_c$ and $\alpha_h$ are the fracture intensity terms for the coal seam and heterogeneous zone, respectively. Since the fracture density term $\alpha$ is proportional to the fracture number in a certain volume, $\alpha_h$ is controlled by changing the total number of fractures assigned to the heterogeneous zone. The fracture distribution for the scenario (c) is presented in Fig. 6. The model results and analysis are presented in Section 5.

5. MODEL RESULTS

5.1. Influence of rock strength on seismic response

(1) Stress and failure zone distribution

The distribution of failed zones in response to coal production is shown in Fig. 7. It can be observed that during 30 May to 5 June, when the face-line is far away from the xylite-rich zone, the failed zone extends to around 40 m ahead of the longwall face. When the xylite-rich zone is encountered during 11 to 17 July, the failed zone propagation is heavily confined by the boundaries of the xylite-rich zone.

(2) Event counts and released microseismic energy

Fig. 9 shows the variation of microseismic event counts against time. When the rock strength of elements within the xylite-rich zone is the same as that of coal, event counts are quite consistent over the coal production period. When the rock strength of elements within the xylite-rich zone is stronger than that of coal, there is a notable reduction in the event counts from up to four weeks before to one week after reaching the xylite-rich zone. A slightly more reduction is observed for the scenario $\sigma_{ch} = 2\sigma_{cc}$ than that for $\sigma_{ch} = 1.5\sigma_{cc}$.

The stress distribution ahead of the face-line as mining progresses is plotted for four typical production weeks in Fig. 8. It is shown that the major principal stresses peak at the failed zone edge. In the first two production weeks, the abutment stress concentration is as far as 40 m ahead of the longwall face. As the longwall face approaches the xylite-rich zone during 11 to 17 July, the abutment stress concentration region is limited to be in front of the xylite-rich zone, suggesting an apparent stress disturbance resulting from the material heterogeneity.
The weekly released seismic energy during the coal production period is presented in Fig. 10. With the same rock strength for coal and xylite, both the total and average released energies are fairly consistent during the twelve weeks modelling period, fluctuating around 5,500 kJ and 45 kJ, respectively. In contrast, strong rock strength for xylite leads to a marked increase in both the total and average released energies when the xylite-rich zone is approached. The total and average released energies peak at around 11,600 kJ and 124 kJ respectively one week before reaching the xylite-rich zone, and gradually decline until the end of the monitoring period.

In order to analyse the magnitude distribution of stress drops during coal extraction, the histograms of stress drops during two typical production weeks for the scenario $\sigma_{1h} = 2\sigma_{1c}$, $\sigma_{2h} = \sigma_{2c}$ are plotted in Fig. 12. It can be seen that stress drops form two clusters for the week 30 May to 5 June. Considering various rock strength properties for different geomaterials, it is deduced that stress drops from events occurring in coal and clay range from 0.80 to 1.12 MPa, and that those from events taking place in roof goaf are between 0.32 and 0.48 MPa. In contrast, one more cluster ranging from 1.76 to 1.96 MPa, corresponding to microseismic events occurring in the xylite-rich zone, is observed during the week 11 to 17 July. The average stress drop in this cluster is around twice that from events happening in coal and clay. In addition, the number of events that occur in coal and clay decreases remarkably. Therefore, the average released energy from microseismic events is enhanced when the xylite-rich zone is reached.
5.2. Influence of fracture attributes on seismic response

(1) Event counts and released energy of microseismicity

Fig. 13 presents the variation of event counts over time for different fracture attributes within the xylite-rich zone. It is noted that mining-induced seismic event counts have a positive correlation with embedded fracture numbers. In addition, the occurrence of microseismicity is suppressed up to four weeks prior to encountering the xylite-rich zone.

Fig. 13. The weekly microseismic event counts over time.

Fig. 14 shows the weekly released event energy during the coal production period for different scenarios. With the same fracture attributes for coal and xylite \((a_n = 3.0, \sigma_{ch} = \sigma_{co})\), both the total and average released energies are fairly consistent over the coal production period. When the xylite-rich zone is reached, more energy is released for the scenario \(a_n = 2.0, \sigma_{ch} = \sigma_{co}\). This is the result of increased slippage chance of relatively large fractures within the xylite-rich zone given a lower \(a_n\) value. However, the variation in released energy is not quite obvious for the scenario \(a_n = 2.5, \sigma_{ch} = \sigma_{co}\). It is also noted that there are great fluctuations in the released event energy between the first eight production weeks when the xylite-rich zone has different fracture attributes from the coal seam. These are probably because of the intrinsic stochastic nature in size distribution and spatial distribution of embedded fractures.

Fig. 14. The weekly released energy over time: (a) total released energy, and (b) average released energy.

(2) Average slipped fracture size

The slipped fracture size is closely associated with the seismic energy release. It can be observed that the variation of weekly average slipped fracture size is quite consistent with that of weekly average released energy (Fig. 15): fairly steady over the whole coal production period for the scenario \(a_n = 3.0, \sigma_{ch} = \sigma_{co}\) not obvious variation and a remarkable increase when approaching the xylite-rich zone for the scenario \(a_n = 2.5, \sigma_{ch} = \sigma_{co}\) and \(a_n = 2.0, \sigma_{ch} = \sigma_{co}\), respectively.

Fig. 15. Average fracture size evolution over the coal production period.

In order to analyse the distribution and variation of slipped fracture sizes, the weekly histograms for two production weeks for the scenario \(a_n = 2.0, \sigma_{ch} = \sigma_{co}\) are plotted in Fig. 16. A right shift of the bin with the maximum event counts can be noticed from the week 30

---

Fig. 12. Histogram of stress drops during different production weeks for the scenario \(\sigma_{ch} = 2\sigma_{co}, \sigma_{ch} = 2\sigma_{co}\): (a) week 30 May to 5 June 2011, and (b) week 11 to 17 July 2011.
May to 5 June to the week 11 to 17 July. In addition, the maximum slipped fracture size also increases from less than 7 m to around 8.5 m.

![graphs](image)

(a) 30 May to 5 June 2011  (b) 11 to 17 July 2011

Fig. 16. Histograms of average slipped fracture size for different production weeks for the scenario $\alpha_x = 2.0$.

6. DISCUSSION

Material heterogeneity and geological discontinuities can contribute to rock failure and even increased hazard potential. However, there are no systematic investigations regarding the influence of material heterogeneity or geological discontinuities on microseismic occurrences and evolution as most current numerical modelling research are based on continuum mechanics which is limited to deterministic stress and fracture analyses. Research presented in this paper models microseismic occurrences by taking the stochastic nature of microseismicity into account.

A higher strength xylite-rich coal zone was detected in the K.-50/C LTCC panel at Coal Mine Velenje during active seismic tomography research. It has been observed that, during the week 11 to 17 July 2011, the largest microseismic events were recorded in a region 40 to ~60 m ahead of the advancing face, overlapping with the xylite-rich zone. This region was also overlapping with the front abutment stress zone, as illustrated in Fig. 8. It has also been noted that the microseismicity underwent a reduction in event counts but an increase in average released energy during this period.

As shown in Eq. (1), the seismic energy released is proportional to the square of stress drop. Given that the strength of xylite is higher than that of detritic coal, less fracturing would be expected to take place in xylite, and thus less intensity in microseismicity, than in detritic coal under the same stress conditions. However, once failure has occurred in the xylite-rich zone, the associated stress drop, and thus seismic energy released, would be much larger than those in the surrounding coal.

Similarly, the seismic energy released is proportional to the cube of fracture size (Eq. 1). Given that less fractures are embedded within the xylite-rich zone, less microseismic events would occur in xylite under the same stress conditions. In addition, a larger proportion of large fractures within the xylite-rich zone would lead to a larger slippage chance for large fractures, and thus increased seismic energy release under the same stress conditions.

It is noticed that the increase in average released energy (Fig. 10 and Fig. 14) and decrease in event counts (Fig. 9 and Fig. 13) begin several weeks before reaching the xylite-rich zone in the models. Considering that mining-induced microseismic events can take place up to 80-100 m ahead of a longwall face-line, seismic characteristics of events from a heterogeneous zone can be detected before the zone is reached. In this respect, seismic anomaly may be utilized as a precursory indicator for abnormal geological stratum or fracture attributes.

7. CONCLUSIONS

In the present study, the progressive advance of a longwall face towards a xylite-rich coal zone during a 12 week period at Coal Mine Velenje was simulated in FLAC3D. A newly developed DFN-based numerical approach combining stress analysis and fracture evaluation was utilized to simulate the induced microseismic occurrences and associated energy release.

The heterogeneity of the xylite-rich zone was taken into account by varying rock strength of the xylite and fracture attributes within the xylite-rich zone, respectively.

When the longwall face-line is far from the xylite-rich zone, the event counts and weekly energy release are fairly consistent during the coal extraction period, which is in agreement with the field observations. Once higher strength properties were assigned to xylite zone or fractures with lower fracture intensity and scaling exponent were embedded within the xylite-rich zone, a reduction in microseismic event counts and an increase in average released energy were observed as the longwall face approached the heterogeneous zone.

Therefore, both the high rock strength of xylite and low fracture intensity within the xylite-rich zone contribute to the decrease in event counts. In addition, the increase in weekly released energy is believed to result from the combined effects of increased stress drops and slipped fracture sizes when the xylite-rich zone is approached. The results of this study can provide implications for a precursory detection of abnormal geological strata and fracture attributes.

ACKNOWLEDGEMENTS

This research is carried out as part of the project “Monitoring, assessment, prevention and mitigation of
rock burst and gas outburst hazards in coal mines (MapROC)” funded by the European Commission Research Fund for Coal and Steel (RFCS), Grant No: RFCR-CT-2015-00005. The authors would like to express their gratitude to the European Commission for funding this research.

REFERENCES


