Overmining low factor of safety coal pillars using an enhanced monitoring system

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Abstract

Prior to the Coalbrook disaster in 1960, bord-and-pillar mining of the number two seam in the Witbank coalfields often resulted in small pillars with low factors of safety. At the Goedehoop Colliery, number two seam pillar stability is also affected by top and bottom coaling, while at Greenside Colliery, stability was further reduced by additional loading from a surface mineral residue deposit. This compromised the stability of the number two seam workings, impacting the safe mining of the overlying number four seam reserves. To extend the life of mine of both operations, an alternative risk management approach using designated enhanced monitoring districts was implemented to safely mine the number four seam reserves. This paper presents the use of geophone arrays to monitor micro-fracturing in number two seam pillars and the interburden between number two seam and number four seam, thereby enabling early detection of potential instability during overmining of the number two seam. Risk was assessed using fault and event tree analyses to determine acceptable failure probabilities. Automated seismic data processing distinguished micro-fracturing from noise, supported by extensive evacuation procedures for effective risk management. This approach facilitated the safe extraction of 4.70 Mt of number four seam coal. The study quantifies the efficacy of geophone monitoring in optimising coal recovery over low factors of safety pillars and assesses the application of Van der Merwe's (2019) time-based formulae for pillar stability analysis for this project.

Keywords

overmining low factor of safety coal pillars, seismic monitoring system, crack counting, fault and event tree analysis, evacuation procedures

Introduction

Prior to the Coalbrook disaster in 1960, bord-and-pillar coal mining in the Witbank Coalfields resulted in smaller pillars, typically left at extensive mining heights during top and bottom coaling. This means that the long-term strength and load-carrying capacity of the pillars were not considered during mining operations.

Failure of the pillars in a lower-lying seam can cause uncontrolled deformation, thereby impacting the potential mining of the upper seams. The impact of potential subsidence on the number five seam (S5) and the number four seam (S4) is shown in Figure 1.

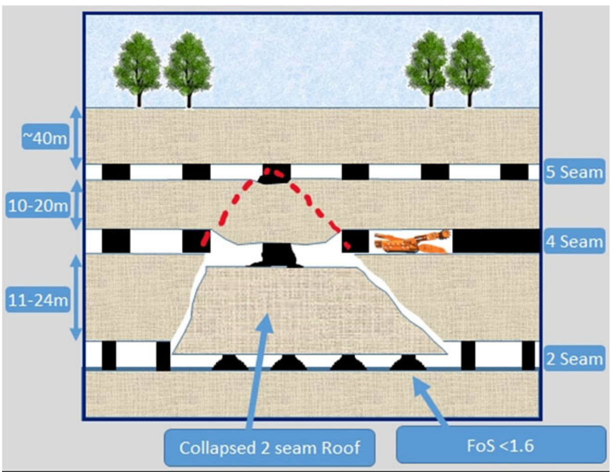


Figure 1—Schematic of the impact of a pillar failure in S2 on the mining of S4 and S5

Overmining low factor of safety coal pillars using an enhanced monitoring system

At the Goedehoop and Greenside Collieries the seams were mined with bord and pillar layouts. The number two seam (S2) at Goedehoop Colliery was mostly mined out in the early 1960s and at Greenside Colliery between 1930 and 1960.

Top and bottom coaling were carried out at Goedehoop to maximise extraction. This reduced the pillar system factors of safety (FoS) as the width-to-height (W:H) ratio decreased. The potential future mining of the other seams, overlying S4 in this case, was not considered during the extraction of the S2.

As Goedehoop's reserves dwindled in the mid-2010s, the life-of-mine became heavily dependent on mining the S4 reserves. However, in extensive areas, the underlying S2 was not considered safe to overmine, leading to potentially sterilised reserves.

At Greenside Colliery, some of the S4 resources were underlying the Greenside surface mineral residue deposit (MRD). However, the stability of the historical S2 workings underlying the planned S4 reserves was impacted by additional loading imposed by the MRD.

At both operations, analysis of the S2 stability was conducted using the most accepted pillar design formulae in South Africa. At Goedehoop Colliery, these initially included those developed by Salamon and Munroe (1967) and Van der Merwe (2013a; 2016). In addition, post-analysis at Greenside Colliery in 2020 also utilised the Van der Merwe (2019) formulae.

To optimise the life-of-mine at both operations, the risks had to be properly quantified, and effective mitigation strategies implemented.

The cracking of pillars was confidently considered as a potential precursor to pillar failure, therefore monitoring the behaviour (cracking) of the pillars and roof would provide warning of pillar failure and ultimately of interburden instability. Several monitoring options were considered:

➤ Crack counting, such as the Goaf Warn, and seismic monitoring systems were assessed to give an indication of possible imminent failure in the rock mass (roof and pillars of the S2). The Goaf Warn system was used in longwall coal operations with limited success. As the majority of the S2 at both operations were inaccessible, the placement of these units would be problematic and not adequate to monitor the onset of failure.

➤ Extensometers were also considered to indicate signs of roof beam failure. These were installed previously at Goedehoop to monitor intersection stability in the S2. However, they can only monitor failure or displacement in the roof in the immediate area of its installation, e.g., the intersection. As such, the large number and cost of the extensometers precluded their use. Additionally, remote real-time monitoring was not proven in our scenario.

Geophones are widely utilised in the deep-level hard rock mines of South Africa to monitor mining induced seismicity. Geophones have not been extensively used in South African coal mining, due to the low risk of seismic events associated with the shallow nature of the underground workings. However, the ability of these devices to detect micro fracturing would indicate possible pillar and interburden instability.

This paper aims to share learnings in managing the associated risks when overmining previously mined bord-and-pillar workings with a low safety factor using arrays of geophones to detect the possible onset of pillar and/or roof instability.

The use of this monitoring system in the application of the Van der Merwe 2019 pillar design formulae that utilises a time-based stability approach is also discussed.

Although this paper will touch on some practical issues, it will not go into depth on how it was managed on the operations; the main aim of the paper is the assessment and mitigation strategy in the overmining of the Low FoS pillars.

Background

General

Coal pillar design aims to satisfy industry-accepted FoS, and more recently, probability of stability (PoS) criteria. These minimum criteria were developed based on the long-term stability requirements of the panels. In this context, these criteria are used to validate the stability requirements of historically mined S2 panels and thereby assess the probability of safely overmining such workings.

Goedehoop Colliery

The S2 at Goedehoop was mined in the early 1960s. After depletion of the S2 reserves, top coaling was carried out in several areas and, in some cases, bottom coaling was done on the retreat out of panels. At the time, the overlying S4 reserves were not considered economically viable, and therefore, no consideration was given to the impact of the low safety factors on future mining of the overlying seams.

The secondary mining (top and bottom coaling) in the late 1980s resulted in FoS that were below the industry-accepted criteria (FoS <1.6, down to 0.8) and low W:H ratios (≤ 2) for extensive areas

Table 1

Example of FoS and PoS of S2 cells at the corridor area at Goedehoop Colliery

Block no.	FoS (S&M)	FoS (VdM2013)	FoS (VdM2016)	FoS (VdM2019)	PoS (%) (VdM2016)	PoS (%) (VdM2019)
32a	1.30	1.20	0.68	1.47	16.57	99.20
32b	1.34	1.25	0.72	1.54	20.25	99.72
32c	1.43	1.32	0.75	1.62	24.25	99.93
32d	1.36	1.25	0.71	1.52	18.96	99.60
31a	1.19	0.99	0.48	1.09	3.96	73.83
31b	1.39	1.21	0.65	1.45	13.35	98.97
31c	1.38	1.22	0.66	1.47	14.52	99.20
31d	1.49	1.29	0.68	1.52	16.33	99.61
33a	1.57	1.38	0.74	1.64	22.85	99.95
33b	1.12	0.95	0.48	1.06	3.85	69.95
33c	1.54	1.39	0.79	1.73	28.56	99.99
33d	1.54	1.39	0.79	1.73	28.56	99.99

of S2 pillars. This effectively sterilised the S4 reserves above, as these areas were considered unsafe to mine.

Additional analyses were done in 2017 utilising the Salamon and Munroe (1967), Van der Merwe (2013a), and Van der Merwe (2016) pillar design formulae to assess the stability of the pillar systems. Note that the pillar design is done on the system and not an individual pillar – so more or less rectangular analysis blocks (cells) were evaluated where the cell length is at least equal to the panel width. A sample of the results obtained for these cells in the so-called corridor area is shown in Table 1. Even though not available at the time, the results, when utilising the Van der Merwe (2019) formulae, have also been added to Table 1.

The results show that, using the Van der Merwe (2019) formulae, a number of cells have an FoS and a PoS above the minimums of 1.60% and 99.00%, respectively, compared to the other formulae. The Van der Merwe (2019) methodology builds on the time-based probabilistic approach that was developed by Van der Merwe (2016). The 2019 formulae utilise the expected pillar size at failure by accounting for the expected scaling between the onset of mining and failure. This results in the statistical expectation of FoS of 1.0, corresponding to a probability of failure of 50% (Van der Merwe, 2019).

In the mid-2010s, with dwindling S4 reserves, two more areas (so-called blocks G and H) were earmarked for over-mining at Goedehoop that met the minimum FoS criteria of 1.2, using Van der Merwe (2013). These are shown in Figure 2.

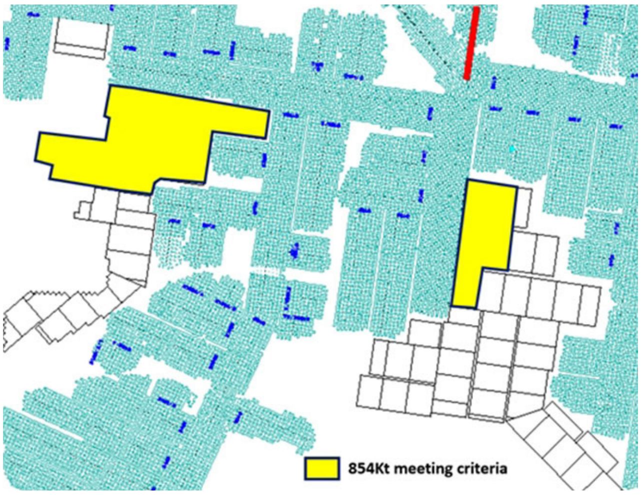


Figure 2—Proposed S4 blocks G and H for overmining low safety factor areas in relation to mined S2 workings

Greenside Colliery

The S2 at Greenside Colliery was mined from the early 1930s to the mid-1960s. The average S2 mining height was approximately 2.40 m. At these relatively low mining heights, S2 pillar stability was historically not considered to pose a safety risk to future S4 mining.

In the early 1930s, a surface mineral residue deposit (MRD) consisting of waste material generated during coal processing was started. The initial expansion of the MRD did not consider S4 as viable at the time. In 2019, the height of the MRD extended 57 m above the surface, with the S4 panels located around 40 m below the surface. The additional loading imposed by the MRD potentially negatively impacted the stability of the S2 workings. A stability analysis was conducted in 2019 by splitting the area under the dump and under the planned S4 panels into several cells. By splitting the area in cells, factors such as changes in S2 pillar dimensions, depth below surface, and MRD height variations could effectively be accounted for during analysis. These cells, in relation to the historically mined S2 working and planned S4 panels, can be seen in Figure 3.

Figure 3—Stability analysis cells in relation to mined S2 workings

Table 2

FoS and PoS for S2 cells below planned S4 panels at Greenside Colliery

Cell no.	FoS (S&M)	FoS (VdM2013)	FoS (VdM2016)	FoS (VdM2019)	PoS (%) (VdM2016)	PoS (%) (VdM2019)
C10	1.29	1.41	0.92	1.76	47.64	100.00
C11	1.26	1.41	0.95	1.80	52.12	100.00
C12	1.95	2.19	1.47	2.79	99.18	100.00
D10	1.19	1.32	0.87	1.66	39.96	99.97
D11	1.26	1.41	0.95	1.80	52.03	100.00
D12	1.65	1.82	1.18	2.24	85.06	100.00
E10	1.15	1.27	0.84	1.60	35.51	99.90
E11	1.35	1.51	1.01	1.93	62.59	100.00
E12	1.28	1.41	0.92	1.74	47.47	99.99
F9	1.16	1.30	0.87	1.66	40.58	99.97
F10	1.15	1.27	0.84	1.60	35.41	99.90
F11	1.34	1.50	1.01	1.92	62.02	100.00
F12	1.30	1.51	1.04	1.95	66.70	100.00
G9	1.18	1.17	0.79	1.61	28.22	99.92
G10	1.26	1.41	0.95	1.80	52.44	100.00

For each cell, the corresponding FoS and PoS were calculated utilising different industry-accepted formulae. The results can be seen in Table 2, with the red-coloured values being less than the industry-accepted minimum stability requirements.

The following findings were derived from the stability analysis:

➤ Both the Salamon and Munroe (1967) and Van der Merwe (2013a) pillar design formulae indicated only two S2 cells (C12 and D12) exceeding the minimum required FoS of 1.60. These cells were located at the edges of the dump footprint and therefore subjected to less loading than the adjacent areas.

➤ The Van der Merwe (2016) formula indicated that the FoS and PoS of the entire area underneath the Greenside MRD fell below the minimum requirements of 1.60 FoS and 99.00% PoS. This methodology considers the time-dependent behaviour of the pillar and its impact on pillar strength since mining of the S2 workings took place.

➤ The Van der Merwe (2019) formula indicated both an FoS and PoS that met the minimum industry requirements. This method utilises the reduction in pillar sizes due to scaling within the statistical analysis.

Overall, formulae prior to Van der Merwe (2019) indicated FoS values less than industry requirements. A decision was made that to safely overmine the S4 workings below the MRD, the same methodology employed at Goedehoop Colliery, utilising strategically installed geophones, would be utilised.

Defining risk

Before the start of the project at Goedehoop Colliery, a joint session

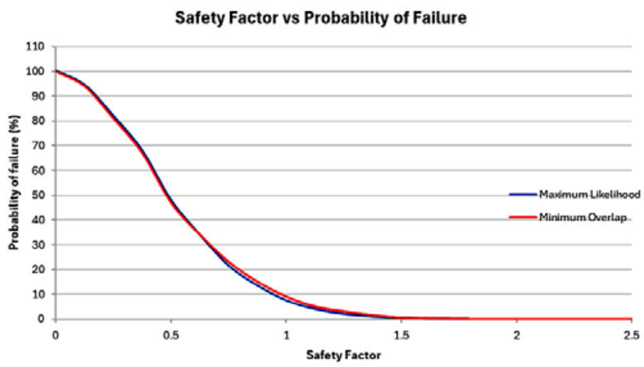


Figure 5—Factor of safety vs probability of pillar failure (Van der Merwe, Mathey, 2013b)

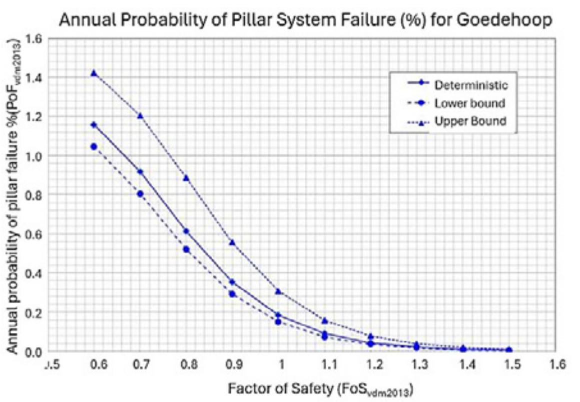
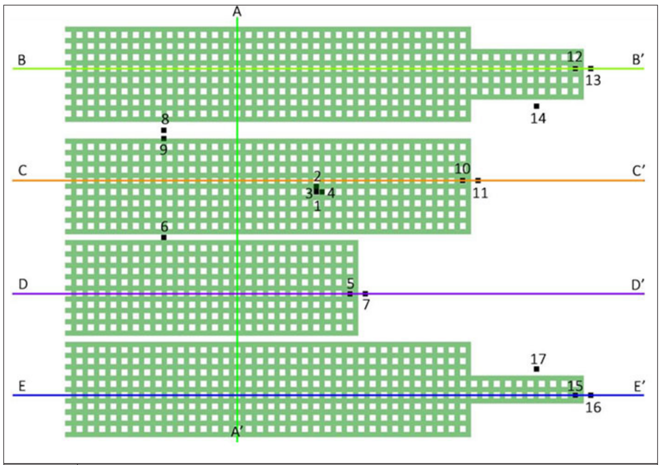


Figure 6—Annual probability of pillar system failure on S2 for Goedehoop Colliery, as derived by SRK Consulting



1	Pillar centre in middle of panel
2	Bord centre in middle of panel
3	Pillar edge in middle of panel
4	Bord edge in middle of panel
5	Pillar behind lagging panel
6	Narrow barrier pillar centre (one pillar width)
7	Abutment ahead of lagging panel
8	Wide barrier pillar (two pillar widths) centre
9	Wide barrier pillar (two pillar widths) edge
10	Pillar behind leading panel
11	Abutment ahead of leading panel
12	Pillar behind five roadway width panel
13	Abutment ahead of panel (five roadway widths)
14	Abutment on the side of (five roadway width panel) 4
15	Pillar behind panel (three roadway widths)
16	Abutment ahead of panel (three roadway widths)
17	Abutment on the side of (three roadway width panel)

Figure 7—Map3D conceptual model showing positions at which stress changes were monitored at different levels below the S4

was held with several rock engineers from various mining houses and consulting agencies. The aim of this session was to discuss possible rock mass responses, failure mechanisms, and possible monitoring strategies.

The session output and several follow-up discussions further guided the requirements for quantifying the risk and probability of failure that could result in an unwanted event during the overmining of the S4.

Probability of failure

An evaluation of the annual pillar probability of failure (PoF) was one of the most critical inputs to the risk assessment. While the FoS of a pillar gives an indication of relative pillar stability, the degree to which a pillar is stable cannot be quantified from FoS alone. However, a link between the FoS and PoF had been established by comparing the observed number of failures with a predicted number of stable cases for each safety factor across the entire population of pillars in South Africa (Van der Merwe, Mathey, 2013b).

Using statistical methods, maximum likelihood, and minimum overlap, the work done by Van der Merwe and Mathey (2013b)

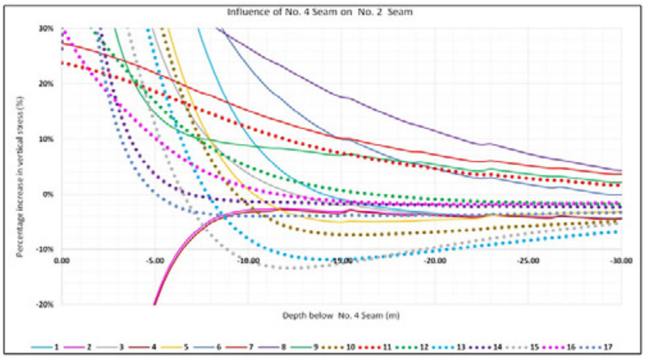


Figure 8—Increase in vertical stress at different middlings and locations due to overmining of S4 workings

yields a PoF of 7.7% for FoS = 1, and not 50% as predicted by the typical probability theory by Van der Merwe (2019). It is also interesting to note that the FoS coinciding with a PoF of 50% is just less than FoS = 0.5 (Van der Merwe, Mathey, 2013b). This can be seen in Figure 5.

The annual PoF was calculated using an approach developed by SRK Consulting, based on a site-specific relationship between PoF and FoS by using the Van der Merwe (2013a) formulae for S2 in the Witbank area. The annual probability of failure for pillar system failure on S2 can be seen in Figure 6.

Adjustments required for pillar behaviour, taking into account abutment stress

Mining of S4 will cause a redistribution of abutment stresses, which could affect the stability of S2. Map3D (a numerical modelling code) analysis done by SRK Consulting for Goedehoop Colliery showed that the magnitude of these stresses on S2 will be a function of the interburden between the seams and the mining geometry of the S4 panels. Additionally, adjustments were made to account for increased pillar loading due to overmining. The positions at which these stress changes were assessed are shown in Figure 7. The percentage increase in vertical stress acting on the pillars at each position is shown in Figure 8.

In the aforementioned analysis, adjustments for additional time-dependent deterioration of the workings are incorporated into the various pillar design formulae.

The probability of failure was determined using a fault tree. The risks were then determined using an event tree, after which they were evaluated against predefined acceptable levels of risk.

Fault tree concept

The concept of the tolerability of risk is considered before presenting the results. Risk thresholds, indicating the tolerability of risk, are plotted in terms of local acceptability of fatalities from industrial and other accidents. This is shown in Figure 9.

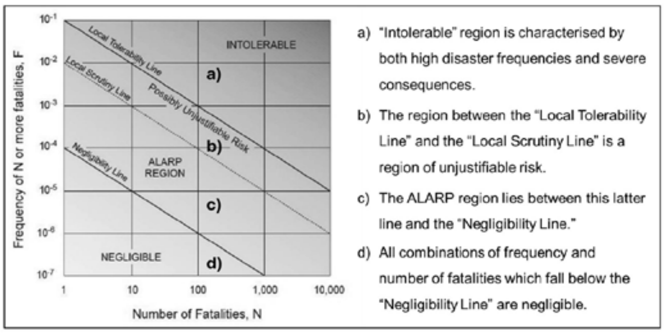


Figure 9—Indicative frequency-fatalities curve indicating the tolerability of risk from industrial and other accidents (Lamb, 1997)

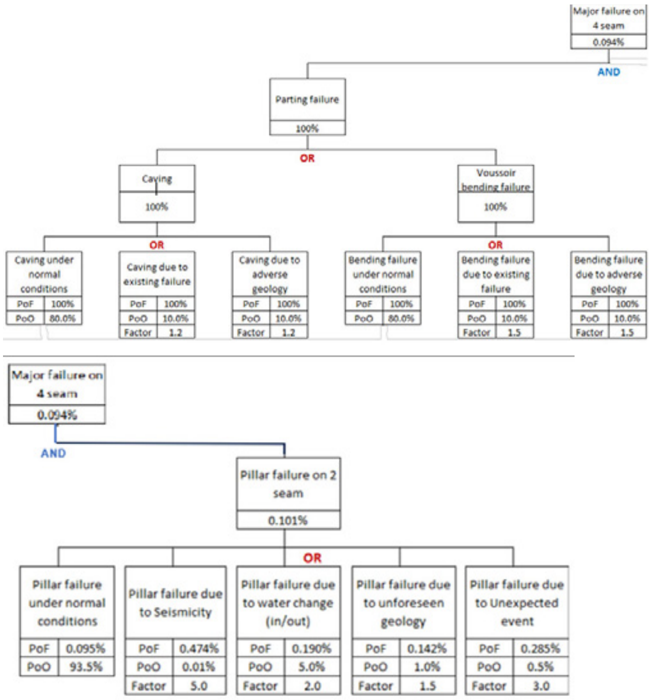


Figure 10—Fault tree analysis of major failure of S4

Fault tree analysis

The most undesirable event identified in the fault tree analysis was a major failure on S4. The events leading to such a major failure would be a result of multiple pillar failures on S2 and the parting between S4 and S2. Each event is split into probability of failure (PoF) and probability of occurrence (PoO), as can be seen in Figure 10.

Each of the potential modes of failure (caving and beam failure) was evaluated using the mining layouts, borehole lithology data, and back analysis of the subsidence data provided by Goedehoop Colliery.

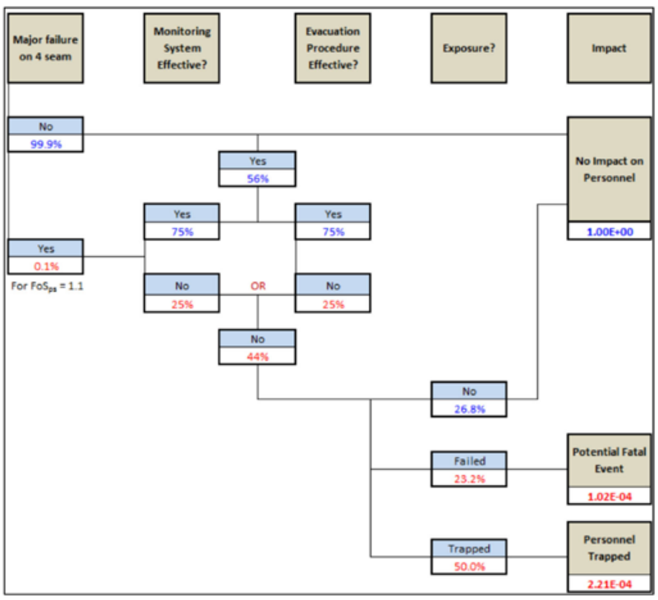


Figure 11—Event tree of major failure on S4

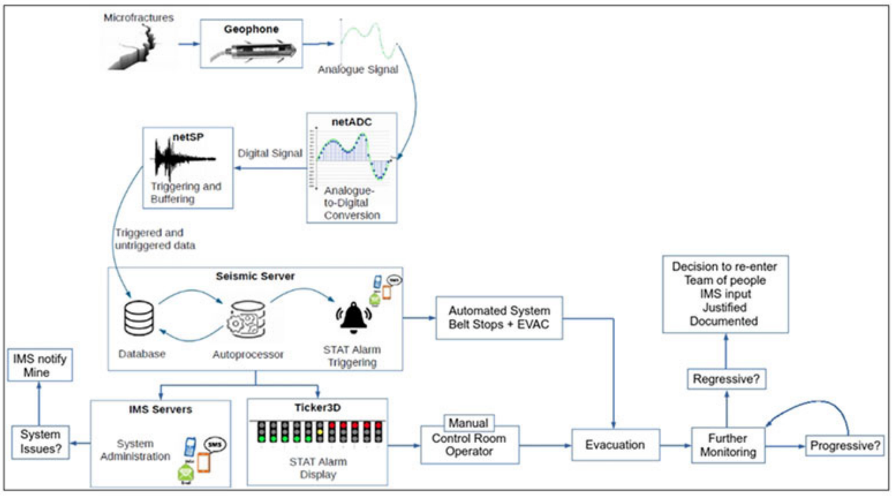


Figure 12—Process flow indicating the steps to be followed when micro-fracturing is detected

Probability of fatality

Event tree

The main purpose of the event tree is to estimate the probability of fatality or injury caused by a major failure on S4. The event tree developed during the joint workshops is shown in Figure 11.

The components of the event tree address the following:

- ➤ Whether the monitoring systems in place can detect impending failures.
- ➤ Whether the evacuation procedures will be effective.
- ➤ Whether people are exposed.
- ➤ Whether there is at least one injury or fatality.

Monitoring

The ability to give timeous warning of possible instability or a failure in the monitor system were essential for safely overmining the Low FoS areas. The areas to which the above procedures were applicable were called enhanced monitoring districts (EMD).

Crack counting process

The objective of the seismic monitoring system was to monitor an area that might be susceptible to pillar failure. When pillar instability is detected, the Mine Control Room and responsible mine personnel are informed so that appropriate and immediate action can be taken.

The Institute of Mine Seismology (IMS) previously developed an early warning system based on the concept of "crack counting" (Lynch, 2002), which used a seismic sensor to trigger alarms based on predefined criteria. However, a key limitation of this system was that it did not allow for the classification of the recorded waveforms.

In a mining environment, many signals recorded by seismic sensors originate from non-seismic sources, such as underground machinery, mine personnel, or even surface activity, especially in shallow mining operations. Without waveform classification, these signals cannot be reliably distinguished from actual seismic events. For the alarm system to be effective—capable of detecting early signs of pillar instability while avoiding excessive false alarms—accurate waveform classification is essential.

The classification or processing of the seismic data needs to be fast and accurate. Automatic processing is preferred over manual processing as it is much faster and can be carried out at a lower cost. Another advantage of using automatic processing is that, if the mine experiences connectivity issues, the alarm system can still run locally on the mine site, and mining operations can continue.

The automatic processor needs to be able to distinguish between three classes:

- ➤ Noise generated by underground mining activities.
- ➤ General noise, caused by activity on surface and other environmental factors.
- ➤ Seismic cracks – pillar- or interburden-related.

For the classification, there are two types of machine learning techniques, namely supervised and unsupervised. With supervised machine learning, the training set (waveforms, in our case) will already be classified into the three classes. In this case, these labels were not available. Unsupervised machine learning does not use labels; instead, it attempts to detect clusters for classification. Simple algorithms were developed based on pattern recognition to specifically detect waveforms that were generated from underground machinery, mining activities, and possible cracking of rock.

The short-term activity tracker (STAT), as per Mendecki (2016), can be used to trigger an alarm, which might indicate pillar instability. This method can run automatically in real time on IMS software at the Mine Control Room. The STAT gives the probability that the current activity rate is higher than the reference activity rate. If the reference activity (i.e., events per hour) is too

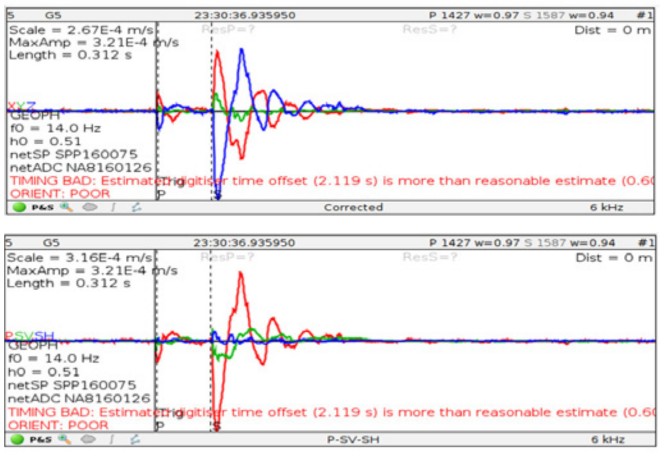


Figure 13—The top signal visually looks like a seismic crack, but rotated only once (bottom signal), it is clear that this signal is not a seismic event

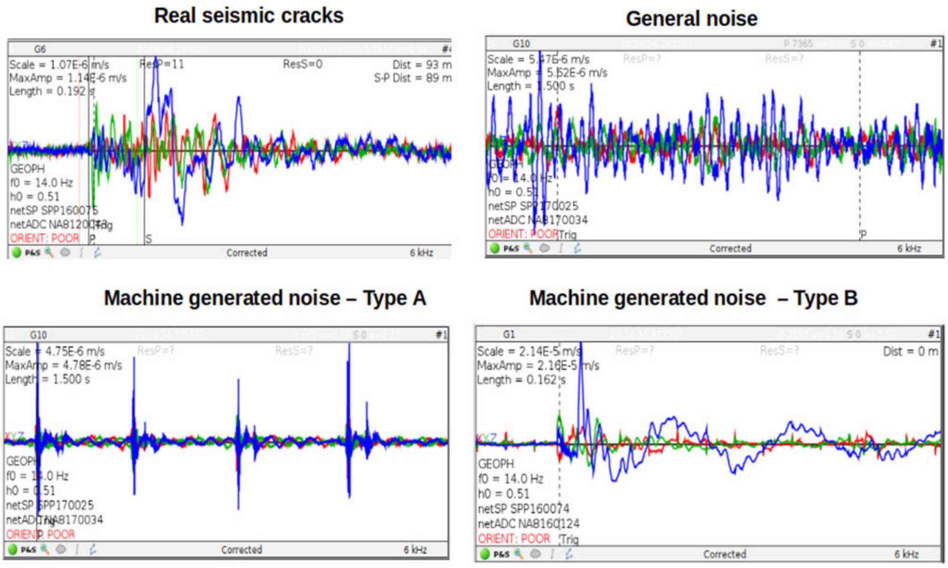


Figure 14— Examples of data recorded at Goedehoop Colliery in 2017

high, then actual instability may not be detected. However, if the reference activity is too low, then false alarms will be generated. An illustration of the process flow when micro fracturing is detected is shown in Figure 12.

Geophones

As the objective of the monitoring was crack counting and not event location, there was not a real need for tri-axial geophones, however tri-axial geophones are required to calculate the directivities. The directivity of the particle motion of the P-wave and S-wave is orthogonal. This can be useful in classification and to distinguish, if possible, whether arrivals are indeed P- and S-waves. The waveform shown in Figure 13 looks visually like a seismic crack, but only after rotating the waveform is it clear that the two arrivals are P-waves.

Once an automatic P-wave pick has been made, the variability in the recorded waveform around that pick can be analysed. By applying a standard statistical technique, principal component analysis (PCA), the waveform is rotated into a new coordinate system that better separates the different wave components. In this transformed system, the first principal component typically aligns with the direction of wave travel, and is expected to contain only P-wave energy. The remaining two components are then expected to represent the S-wave energy. This separation helps assess whether the identified P- and S-wave arrivals are likely to be correct.

Automatic processor

In Figure 14 examples of data recorded at Goedehoop Colliery are shown. The top left example is a real seismic crack recorded on 1 September 2017 at 01:00:48, the top right waveform an example of general noise recorded on 1 September 2017 at 00:38:54, the bottom left waveform is from a crusher on 6 September 2017 at 09:04:34, and the waveform displayed in the bottom right was generated from material moving over a broken bolt on a conveyer belt and was recorded on 5 April 2017 at 20:34:53.

Following here, the algorithms are explained in more detail on how to detect the different noise types, including machine-generated noise or possible seismic cracks.

Type A

A standard statistical measure can be used to assess how much the recorded signal fluctuates relative to its average level. Figure 15 shows a waveform generated by a hydraulic hammer, with motion

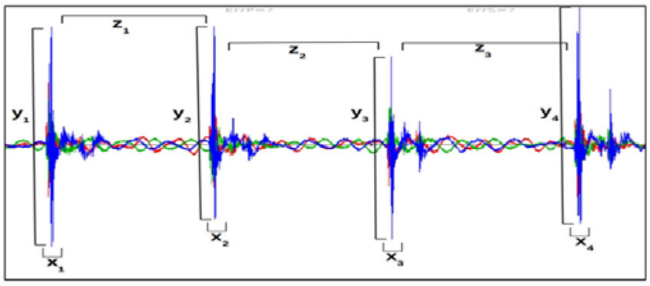


Figure 15—The waveform produced by a hydraulic hammer

recorded in three directions (x, y, and z). For signals of this type, the variation in all three directions is typically low. When the measured variation in each direction falls below a certain threshold, the signal is classified as noise or non-seismic and is excluded from further analysis.

Type B

In Figure 16 a waveform is shown that looks like a possible seismic crack but turned out to have been generated from material moving over a broken bolt on a conveyer belt structure. Around early September 2017 many alarms were triggered, and the waveforms produced looked seismic, but all the waveforms that activated the alarms were very similar. Further, as soon as underground personnel evacuated, these signals stopped. After investigation, a broken roller was discovered that triggers these waveforms when material moves over the roller. Waveform similarity techniques,

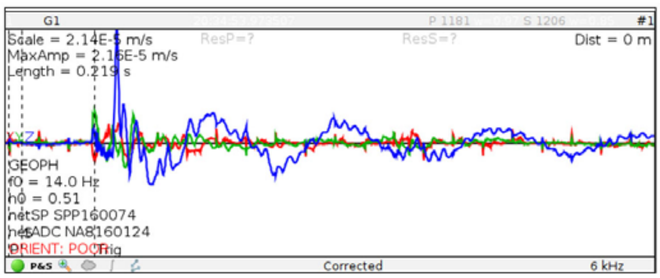


Figure 16—Example of a waveform that was generated by a broken bolt on a conveyor belt

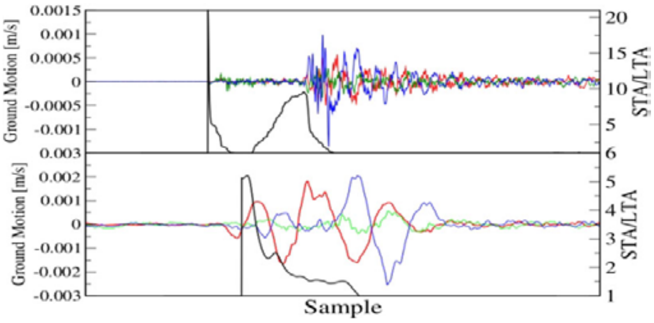


Figure 17—Waveform of a seismic crack (top) with clear phase arrivals and a waveform that was generated from an unknown source but only has a p-wave. Note the difference between the STA/LTA curves (black lines) of the two signals

such as cross-correlation, can be used to detect the second type of machine-generated noise. If the Pearson correlation coefficient of all three components is above some threshold, then the recorded data is classified as reject.

Seismic cracks

Simple pattern recognition techniques are used to classify recorded data as seismic. Seismic events typically have visible pressure (P) and shear (S) wave arrivals, and signal-no-noise (SNR) with not too many other spikes. The different characteristics/features can be measured as the number of spikes (arrivals), nspikes, signal-to-noise, SNR, short-term average (STA) and long-term average (LTA) ratio of the signal, STA/LTA, and dominant frequency of the signal, fdom. The STA/LTA of the signal is a means of obtaining the number of arrivals a signal has; this ratio tends to increase rapidly close to a phase arrival – Baer and Kradolfer (1987). This can be used to determine if a likely arrival (P-wave) is followed by another phase arrival (S-wave). These features can be used to detect possible seismic cracks.

In Figure 17, two waveforms are shown: the top waveform has a clear P- and S-wave arrival, while the bottom waveform does not. The STA/LTA curve (black line) has a sharp increase near the P-wave arrival, then drops during the P-wave coda, then increases near the S-arrival, and then finally dropping towards the S-wave coda. This is clearly different from the bottom curve.

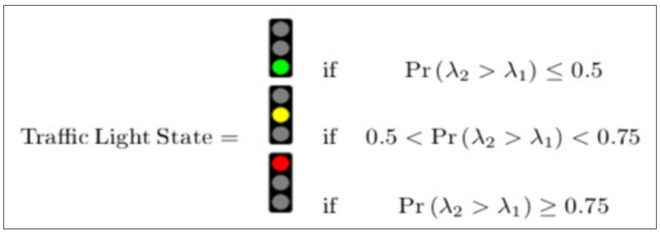


Figure 18—The STAT traffic light system. An alarm is raised when the probability is larger than 0.75

Short-term activity tracker

To avoid unnecessary false alarms, the activity level is compared to a reference value. This reference value is calibrated based on historical alarm rates to achieve a manageable false alarm rate while not missing alarms associated with actual pillar failure. These rates are compared probabilistically. If this probability exceeds a pre-defined level, an alarm is raised. In this case, the short-term activity tracker (STAT) gives the probability (for each seismic sensor) of the current activity rate (lambda$_2$) being larger than the reference activity (lambda1). The STAT probability, as per Mendecki (2016), is given in terms of: $N_1 = 20$ is the reference number of events per time Δt_1, N_2 is the number of classified seismic cracks in the last Δt_2 hours, $\Delta t_1 = \Delta t_2 = 1$ hour, and k = 1.

STAT is implemented in the IMS software Ticker3d and runs in the mining operation's control room. If the STAT probability of a sensor is smaller than 0.5, then a green light is assigned, if the probability is between 0.5 and 0.75, an orange light is assigned, and if larger than 0.75, then an alarm is raised, as indicated in Figure 18.

To reduce the number of false alarms, the alarm threshold, i.e., N1 increases when machine generated noise is detected. Typical machine-generated noise has low recorded ground motion (< 1e^{-5} m/s). The machine-generated noise may appear very similar to seismic events and this may cause false alarms. When the automatic processor classifies data (with low ground motions) as seismic, and machine-generated noise was detected in the past 15 minutes, then it will be saved as seismic with a 0.2 probability. This effectively increases the alarm threshold during times when machine noise is detected.

Results and alarm statistics

In Figure 19 the histogram of the triggers per hours (left) and accepted events per hour (right) is shown for all data recorded between commissioning of the seismic system and decommissioning at Goedehoop Colliery. As can be seen, a reference activity rate of 20 will not produce many false alarms but seems low enough to detect real alarms.

Connectivity and evacuation

Each installed geophone was linked to a seismic enclosure (container). The enclosures were then linked to the Institute of

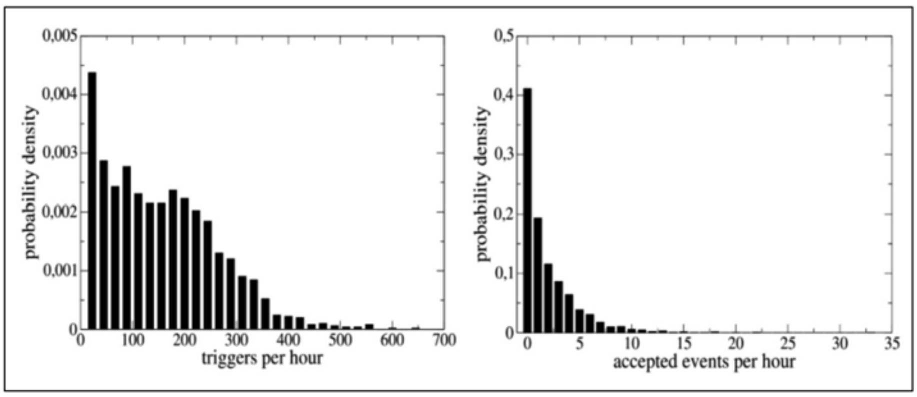


Figure 19—Histograms of the number of triggers per hours (left) and the number of accepted events per hour (right) are shown for all data recorded between commissioning of the seismic system and decommissioning

Mine Seismology (IMS) and the Mine Control Room using fibre connectivity. A dedicated desktop computer in the Mine Control Room updated the status of the geophones in real time.

To reduce the risk, strict access controls to the EMD blocks were required. A dedicated guard stationed at the EMD Waiting Place was responsible for issuing a set number of access tags. The EMD Waiting Place was in a safe area outside of the EMD blocks with an open communication line to the Mine Control Room.

The evacuation procedure specified the response taken based on the triggered alarm condition. When the number of accepted triggers exceeded the threshold limit of 20, a robocall was received by all responsible parties and the Mine Control Room desktop flagged it as a so-called Red TARP alarm. This led to the Mine Control Room immediately phoning the Section Waiting Place to initiate an evacuation of the crew. In addition, the Control Room remotely activated an audible alarm in the Section and enforced a stoppage of all mining activities by stopping the section conveyor. This ensured that even if the phone went unanswered, personnel would still be aware of the required evacuation.

During the evacuation, all personnel were expected to gather at the EMD Waiting Place. When all personnel had been accounted for using the tag system, the guard notified the Mine Control Room that the area was clear. The location of the triggered sites allowed the Rock Engineering Department to determine the affected areas, and the required extent of the evacuation. Personnel were only allowed to return to the affected areas when triggers had reduced to below the set accepted trigger threshold. This upliftment needed to be authorised in writing by the Mining Manager after consultation with the Rock Engineering Department. A dedicated WhatsApp group per site was used for swift communication. Overall, this resulted in an automated evacuation process with several additional manual controls to enforce compliance. Re-entry required management involvement to ensure full positive communication by all responsible parties.

If real-time connectivity to the geophones was lost due to network issues or a power failure, a 15-minute time window was given for restoration. When the system was not restored to real-time connectivity within this time frame, an evacuation of the affected areas was ordered. When connectivity to IMS was lost but not to the Control Room desktop, the so-called 'Hawkeye' response was activated. This involved a trained mine supervisor being stationed at the Mine Control Room desktop to manually alert the response team to any triggers or system downtime.

Exposure of people

The event tree shown in Figure 11 indicates the probability of mine personnel being exposed to pillar system failure over time and space if people had not been evacuated. Although a failure could occur at any time, underground personnel will only be exposed for a limited time during each shift.

Exposure of personnel is dependent on:

- Category of mine personnel (production and non-production)
  The number of mining and engineering personnel allowed in each section will depend on the risk analysis for that section, ensuring the risk remains ALARP. This is done by relating the frequency (per year) to the number of possible fatalities (F-N assessment).
- Time exposed to the risk in the working area

$$\text{Exposure per worker} = \frac{\text{Total number of hours worked per worker in each zone}}{\text{Total number of hours each year}} \qquad [1]$$

Assuming 299.8 working days per year.

$$\therefore \text{Exposure per worker} = \frac{\text{Time spent in the area}}{24} \times \frac{299.8}{365} \qquad [2]$$

- Area within the working area where the person will work
  Face Area – The length of the face area was taken as the distance from the face to the feeder breaker (3 rows back), typically around 52 m (dependent on pillar sizes).

Back Area – This was defined as the total area from the waiting place to the face area.

- Probability of spatial coincidence of personnel exposed to the failure.
  This is dependent on the space occupied by a failure.

$$\text{Probability of spatial coincidnece} = \frac{\text{Area of the collapse}}{\text{Total area of the working place}} \qquad [3]$$

The probability for intersection collapse will be low but might be high for multiple pillar failure of the S2. A failure that affects the face area's consequence will be more severe as all the workers could be affected because they are concentrated within the face area.

Evaluation of risk

The process described in the aforementioned 0was used to determine the risk against accepted risk levels (ALARP) and is expressed as individual risk per annum and plotted using an F-N graph. The input parameters account for the abutment loading, exposure parameters, coincidence, and an evacuation success rate. The parameters can be seen in Table 3.

The exposure of different mining personnel (Table 4) and visitors were calculated for the different areas within the working area for both day and night shift. The annual exposure of mining personnel calculated for day shift can be seen in Table 4.

The data was then plotted on an F-N graph against acceptable risk levels. An example of such a plot for different mining commodities done by SRK Consulting can be seen in Figure 20.

Should the risk exceed the acceptable risk levels then the following should be considered:

- Reduce the number of people allowed in the section.
- Reduce the exposure time by changing the duration of the shifts and / or eliminating the night shift.
- Reduce the exposed area by reducing the number of roadways (width and ultimately the exposed area).

Table 3
Example of general inputs into the F-N graph

Input parameters	
Effective monitoring	90%
Effective evacuation	90%
Ineffective monitoring and evacuation	19%
Abutment adjustment to FoS	15%
Workdays per year	299
Days in a year	365
High exposure (min)	3 hrs / day
Coincidence parameters	
Exposure length	800 m
Face exposure length	52 m
Collapse length	200 m

Table 4
Annual exposure of mining personnel within the working area for day shift

Personnel designations	Average hours/day			Total	Annual exposure
	Day shift				
	Face area (normal)	Face area (breakdown)	Back area		
CM Operator 1 Day	10.0	4.0	0.0	14.0	11.95%
CM Operator 2 Day	10.0	4.0	0.0	14.0	11.95%
CM Cable 1 Day	10.0	4.0	0.0	14.0	11.95%
CM Cable 2 Day	10.0	4.0	0.0	14.0	11.95%
S/C 1 Day	10.0		0.0	10.0	8.53%
S/C 2 Day	10.0		0.0	10.0	8.53%
S/C 3 Day	10.0		0.0	10.0	8.53%
R/B 1 Day	10.0		0.0	10.0	8.53%
R/B 2 Day	10.0		0.0	10.0	8.53%
LHD driver 1 Day	2.0		0.0	2.0	1.71%
LHD driver 2 Day	2.0			2.0	1.71%
Faceboss Day	9.0	4.0		14.0	11.95%
Electrician Day		6.0		6.0	5.12%
Fitter Day		6.0	0.0	6.0	5.12%
Shiftboss Day	3.0			3.0	2.56%
Foreman Day	3.0			3.0	2.56%

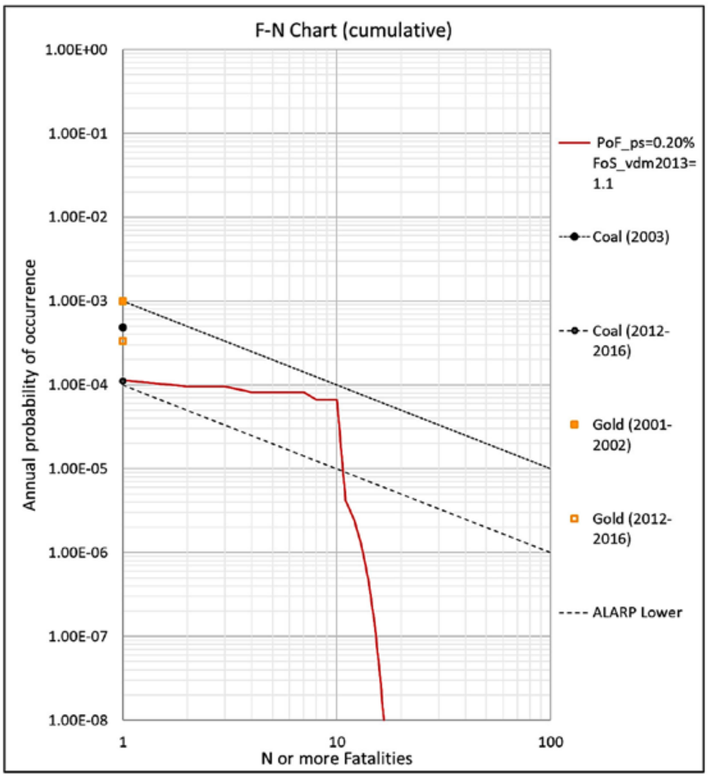


Figure 20—Example of an F-N Chart comparing outcome of the analysis with different mining commodities

Operational implementation

Goedehoop Colliery

Corridor area

For the trial to commence, a suitable low factor-of-safety block had to be chosen. The site needed to have access to the S2 pillars for visual assessments during overmining, should fracturing be detected by the seismic system. The only S2 block fulfilling these criteria was located at Simunye Shaft. The so-called corridor area is shown in Figure 21.

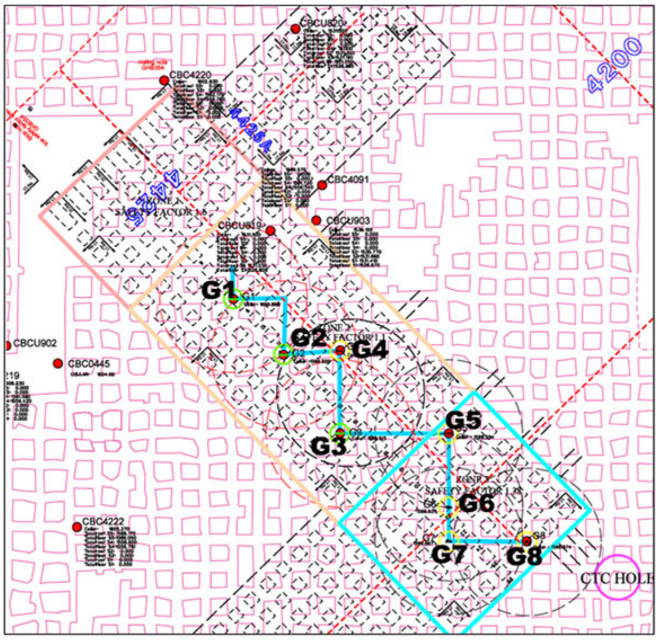


Figure 21—Geophone layout in the corridor area

To ensure that micro-cracking of the S2 pillars was detected, the geophones were installed 100 m apart. Installation initially occurred from the accessible S2 workings by drilling and installing the geophones 10 m into the roof. Each geophone was grouted in place so as to ensure positive contact with the surrounding rock mass. For this initial trial, the geophones were connected to NetADC's and NetSP in underground seismic enclosures within the accessible area.

As the S2 workings in the corridor area were accessible, all triggers exceeding the 20 acceptable triggers per hour threshold were visually inspected. No cracking of pillars was observed following the alarms, which indicated that the triggers were not linked to pillar straining. Analysis by the Rock Engineering Department and IMS indicated that the triggers were caused by machinery and other activities within the S4 workings. As the project progressed, the trigger algorithms were adjusted to refine the system and exclude any false triggers. The evacuation and re-entry procedures employed during these alarms proved highly successful, with all personnel safely evacuating to the designated waiting area.

Blocks G and H

The focus then shifted to Block G and Block H, geophones were installed from the surface, as the S2 workings were not accessible. The seismic stations, communication infrastructure, and security systems were all placed on surface. The length of cabling to the geophones had to be limited to approx. 400 m, as the signals weakened due to voltage drop and signal attenuation. Two separate seismic enclosures had to be installed for Block G and Block H, due to these distance requirements. Both Block G and H were successfully mined with no alarms linked to pillar instability.

Square Block

Lastly the S4 reserves at the so-called Square Block were successfully mined using EMDs. No alarms related to pillar instability were detected. The remaining geophones were subsequently switched off and all hardware on the surface was reclaimed.

Greenside Colliery

A total of four panels at Greenside Colliery were classified as EMDs. The sites were drilled from the top of the Greenside MRD and connected to two seismic enclosures. Even though the initial project plan was for the distance between sites not to exceed 100 m, this proved challenging due to drilling constraints on the dump. The unconsolidated nature of the fine waste material led to drill rods getting stuck and holes being abandoned before the natural ground elevation could be reached. As a result, several planned locations had to be shifted.

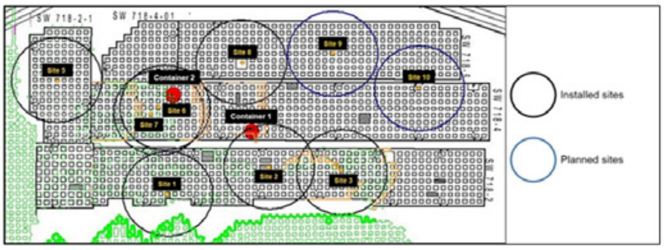


Figure 22—Final positions of the installed sites and enclosures at Greenside Colliery

Table 6

Issues and learnings from the EMD project

Issues	Learnings
Long lead time on hardware components in relation to expected time of mining.	All hardware components, including geophones and seismic stations, must be ordered and installed in advance of overmining.
Analysis and risk assessment process of EMD panels taking too long.	All EMD panels and the expected time of mining must be planned to allow for diligent S2 pillar stability analysis and risk assessments.
Surface rights may not belong to the mine. Negotiation with landowners and leases for access and drilling are required.	Consult landowners in advance to allow for drilling of boreholes, site preparation, and installation of seismic stations on surface. Free access to the stations should be arranged to address hardware issues.
Detailed monitoring procedure is not in place. Control Room personnel are not adequately trained to exercise the procedure.	All Control Room personnel should be trained in advance to prevent any confusion. Creation of a simple but detailed Trigger Action Response Plan (TARP) visible at the Control Room assists the operators with the required steps.
Unauthorised personnel entering the EMD panels.	Guard should be stationed at a single-entry point into the EMD panels, with a pre-determined number of access tags.
Confusion of section personnel when an alarm is triggered.	Setup of evacuation and re-entry procedure. All section personnel must undergo training and participate in emergency evacuation drills.

By the end of the project, eight of the planned ten sites were installed. The final locations of the installed sites and the abandoned positions of sites 9 and 10 are shown in Figure 22. The installation of sites 9 and 10 were abandoned due to a decision that sufficient data had been gathered and the highest risk areas had been safely mined.

Several alarms occurred during the project. The Rock Engineering Department set up the Greenside Evacuation Procedure based on the proximity of the alarming site/s to each panel.

Most of the TARP alarms that occurred could be linked to a trigger mechanism that had not been accounted for and subsequently excluded from the accepted trigger range. These include triggers caused by surface re-mining activity occurring on the MRD above.

Immediately after Site 6 was commissioned in panel SW718-4, it began to set off alarms. After a hardware issue was excluded by IMS, underground and surface visits were conducted, but did not indicate any clear cause. The surrounding sites did not register the same accepted triggers, and a decision was made to install a new geophone at Site 7 within a 16 m centre distance of Site 6. When Site 7 did not register the same triggers appearing in Site 6, a decision was made to decommission the unit.

By the end of the project, none of the TARP alarms could be linked to instability from the S2 pillars.

Learnings

Several learnings were made during the EMD project. A summary of issues and subsequent learnings can be seen in Table 6.

Conclusion

- ➤ Approximately 4.70 Mt of coal, which was previously declared as sterilised, was successfully mined between operations using a thorough risk assessment and mitigation process.
- ➤ Fault and event tree analyses were done to ensure the risks were kept ALARP and within acceptable limits.
- ➤ The factors identified that could cause instability in the S4 was a failure of either the pillars in the S2 or the parting between the S2 and S4.
- ➤ Coal reserves overlaying perceived low FoS coal pillars can potentially be safely extracted utilising geophone arrays by implementing the following:
  - Automated seismic data processing that gives timeous warning of possible micro-crack formation and pillar failure.
  - An effective evacuation procedure.
  - Ensuring limited exposure of personnel to the perceived level of risk.
  - Ensuring the risk levels were ALARP and within acceptable limits.
- ➤ Mining of the S4 reserves were done in areas where pillar failures could be expected, based on the FoS calculations at the time. Following the success of mining these areas without failure indicated that the historical formulae used (post 1960) may be conservative.

Recommendations

- ➤ Enhanced monitoring is recommended if overmining of potentially unstable coal pillars is planned that fall outside of the scope of this paper.
- ➤ Even though the results of this project might assist in validating that the Van der Merwe (2019) formulae better represent actual pillar strength over time, closer scrutiny of the available data is recommended.

Acknowledgements

We would like to thank Thungela Resources for their support in carrying out this project at both Goedehoop and Greenside Collieries. We would like to acknowledge SRK Consulting for the work done on annual PoF derivations for the Goedehoop Colliery, F-N modelling, as well as analysis on abutment stress interaction on S2 from the mining of differently structured S4 panels. We would also like to thank the Institute of Mine Seismology (IMS) for the extensive work done as only briefly outlined in this paper. Finally, we would like to thank all other stakeholders, including the rock engineering personnel from various mining houses for their participation in the concept formulation.

References

Baer, K., Kradolfer, U. 1987. An automatic phase picker for local and teleseismic events. *Bulletin of Seismological Society of America*, vol. 19, no. 6, pp. 1437–1445. Available at: https://pubs.geoscienceworld.org/ssa/bssa/article-abstract/77/4/1437/119016/An-automatic-phase-picker-for-local-and?redirectedFrom=fulltext

Lamb, J. 1997. *Risks and Realities - A Multidisciplinary Approach to the Vulnerability of Lifelines to Natural Hazards*. Centre for Advance Engineering CAE, New Zealand. ISBN: 0-908993-12-9.

Lynch, R.A. 2002. Col816: *Develop specifications for a portable counting seismometer to be implemented routinely in mines underground.* Safety in Mines Research Advisory Committee. Available at: https://www.mhsc.org.za/sites/default/files/public/research_documents/COL816%20Report.pdf

Mendecki, A.J. 2016. Mine Seismology Reference Book: Seismic Hazard. Institute of Mine Seismology, ISBN 978-0-9942943-0-2, www.imseismology.org/msrb/, 1 edition, May 2016. URL https://www.imseismology.org/imsdownloadsapp/webresources/filedownload/Mendecki(2016)-MSRB-Seismic-Hazard.pdf

Salamon, M.D.G., Munro, A.H. 1967. A study of the strength of coal pillars. *The Journal of The Southern African Institute of Mining and Metallurgy*, vol. 68, no. 2, pp. 55–67. Available at: https://journals.co.za/doi/pdf/10.10520/AJA0038223X_3918

Van der Merwe, J.N., Mathey, M. 2013a. Update of the coal pillar strength formulae for South African coal using two methods of analysis. *The Journal of The Southern African Institute of Mining and Metallurgy*, vol. 113, pp. 841–847. Available at: https://www.scielo.org.za/pdf/jsaimm/v113n11/09.pdf

Van der Merwe, J.N., Mathey, M. 2013b. Probability of failure of South African coal pillars. *The Journal of The Southern African Institute of Mining and Metallurgy*, vol. 113, pp. 849–857. Available at: https://www.saimm.co.za/Journal/v113n11p849.pdf

Van der Merwe, J.N. 2016. A three-tier method of stability evaluation for coal mines in the Witbank and Highveld coalfields. *The Southern African Institute of Mining and Metallurgy*, vol. 116, pp. 1189–1194. Available at: https://www.scielo.org.za/pdf/jsaimm/v116n12/16.pdf

Van der Merwe, J.N. 2019. Coal pillar strength analysis based on size at the time of failure. *The Southern African Institute of Mining and Metallurgy*, vol. 119, pp. 681–692. Available at: https://scielo.org.za/pdf/jsaimm/v119n7/12.pdf ◆