INVESTIGATING THE POTENTIAL FOR LOCATING TRAPPED MINERS USING A PRE-EXISTING MICROSEISMIC MONITORING SYSTEM

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Whilst some research has been completed in the area, the industry still does not have an accepted reliable means of locating trapped miners. A technique for locating trapped miners was developed in which miners would hit the wall or support of an excavation with a hammer or similar sized object, which would then be detected by the (pre-existing) microseismic monitoring system in the mine. As part of the project, field testing was carried out at three underground mines in Australia in conjunction with the Institute of Mine Seismology. The collected data was processed and subsequently analysed using statistical tools. Back analysis of the data from Tasmania mine was used to estimate the detection reliability as a function of distance from the sensors. A reliability of 100% was achieved up to 65 m, 90% at 84 m and 0% further than 250 m. For test sites with three sensors within 200 m, the location of the miner could be located within 46 m of accuracy 90% of the time and within 35 m 80% of the time. The average location accuracy over all located test sites was 23 m. The experience of the field testing and the results suggest that the technique could be implemented in operating underground mines (which use a microseismic monitoring system) without significant cost or effort.

INTRODUCTION

Incidents in underground mines causing workers to be trapped can pose a significant risk to human life and an operation’s profitability. Recent collapses in mine workings (such as San Jose, Chile in 2010, Crandall Canyon, USA in 2007 and Beaconsfield, Australia in 2006) have shown the potential for serious incidents to trap and fatally injure mine workers. Whilst a seismic system was used to detect signalling miners in the Quecreek mine disaster (US MSHA2002), no effort has been made to locate trapped miners in a rescue situation.

The concept of locating trapped miners using a microseismic monitoring system was first tested in the 1970’s with a surface based seismic system with portable surface mounted sensors (Westinghouse Electric Corp1971, Durkin and Greenfield1981, Kovac et al.1994). Whilst these systems had some promising results in the field of coal mines, according to a report by J. Davitt McAteer, the system is now “old, outmoded, cumbersome and time consuming to deploy” (McAteer et al.2006).

In 1974, research was conducted with a system in which the sensors were located in the underground workings and were buried under several inches of dirt to create coupling with the ground. Detection of hammer blows was possible between 305 and 457 m, but no attempt was made to locate the source (Powell and Watson1976).

General problems with a temporary system consisting of surface mounted sensors are that they take too long to deploy in a rescue situation and, due to the poor coupling with the ground, can be susceptible to noisy conditions in the surrounding area (Coal News2007). Furthermore, surface systems above the mine would have poor resolution in the vertical direction. In a tabular, sub-horizontal reef scenario (as is the case for coal mining where the systems were tested) accuracy in the vertical dimension may not be of great concern. This is, however, important in most hard rock mines.

There is a clear benefit in being able to 1) detect, and 2) locate signalling trapped miners by using an already existing micro-seismic system. This paper reports on a pilot study that aimed at determining the viability of detecting and locating a trapped miner with existing in-mine microseismic systems.

This work differs from previous work, mainly in the fact that it uses previously existing systems that were already in use for routine seismic monitoring. As a result, most of the sensors used were grouted inside a borehole in order to create quality coupling with the rock mass.

For the purpose of detecting and locating weak signals from miners, the in-mine seismic system needed to be operated in a “continuous monitoring mode”, rather than the standard triggering mode.

A consistent finding of the previously mentioned research was that wave manipulation tools, such as notch filtering, and wave stacking could improve the signal to noise ratio (SNR) of the seismic waves. As the work presented here was a pilot study, it did not make use of either of these and further improvement of the results is therefore possible.
FIELD TESTING

The basic concept for locating trapped miners with the use of the seismic system is that, a trapped miner would generate seismic waves by hammering against a tunnel wall. These waves would then be detected and located giving valuable information to aid the rescue operation.

The field tests consisted of repeatedly hammering against the walls of excavations and recording the waveforms which were later processed to obtain locations for the original hammer blows.

As the wall striking source (WSS) blows are unlikely to trigger enough sensors required to obtain an accurate location, continuous monitoring mode was used, with all of the continually sampled data written to disk.

A series of test sites were chosen which would be hit by the WSS. Each test site was marked and surveyed by mine survey personnel so that the exact location of each site could be used in location error analysis.

Before striking the test site, loose rocks around the area were scaled down to reduce the risk of rocks falling and causing injury.

The test sites were then hit at regular intervals of approximately 0.5 to 1 sec with the WSS. A variety of surfaces and WSS’s were used (such as a number of hammers and a rock) in the tests in order to see the efficacy and suitability of these surfaces and sources for the generation of locatable waveforms.

A small geophone, herein referred to as a WSS sensor, was connected to the nearest Geophysical Seismometer (GS box) and was used to record the exact time that the WSS struck the wall. This enabled easy identification and isolation of the waveforms for the purpose of the study. The WSS sensor was connected using ordinary copper pair wire (such as bell wire) hung, where possible, on mesh to keep it clear of any passing vehicles. The bell wire (which was connected to the WSS sensor) was connected to the GS box by either using a spare seismic channel or replacing one component of a tri-axial sensor. During testing, the WSS sensor was simply held up against the rock approximately 1 to 3 m away from the test site whilst the test site was being struck by the WSS.

Figure 1 shows an example of a test site being hit with a geological pick, while another member of the testing team holds the WSS sensor against the wall.

Field tests were performed at MMG’s Golden Grove and BCD Resources’ Tasmania mine as well as another Australian hard rock mine, herein referred to as Mine C.

At Golden Grove and Mine C, part of the in-mine system was isolated from the mine wide system. As the mines were in operation, only 3–4 sensors could be used at any one time for the field trials, otherwise the sensitivity of the mine wide seismic monitoring system would be reduced.

The testing at Tasmania mine coincided with the end of production at the mine which provided a unique opportunity to use the full seismic system for the test and to have an emergency like situation where the mine was not in operation.

The sensors which were isolated from the mine system and used in the testing recorded the waveforms created by the WSS. The recorded data was downloaded to the system computer (in the case of Tasmania Mine) or a USB flash drive (Golden Grove and Mine C).

Figure 1. Action shot of testing

DATA QUALITY AND PROCESSING

The quality of the WSS blow in the seismograms varied widely, with some test sites having very clear P- and S-waves (Figure 2) while other sites had quite poor SNR, making it difficult to distinguish the waveforms from noise (Figure 3).

This effect was particularly pronounced in one area of Mine C, where the sensors used for testing were wall mounted. Whilst the mine has had good results using the sensors for seismic processing in the past, the SNR appeared to be worse than that of other tests. Despite the lack of mining activity, the SNR for the waveforms from Tasmania mine was no better than that of the other tests. The contributing factors to the SNR are noise at the sensor location, distance to the sensor and amplitude of the signal created at the source (by the WSS).

Systematic noise sources could be problematic as they can easily mask or be mistaken for the waveforms generated by a signalling miner. Figure 4 shows and example of a sensor recording a systematic noise. This problem, however, can easily be mitigated by providing the miners with a signalling procedure. Such a signalling procedure could include the number of blows and time interval between blows that defines a packet of signals and the time interval between packets, thus creating a signal pattern easily recognisable.
DETECTION AND LOCATION

Detection of WSS Blows

In order to examine the reliability of the system in detecting trapped miners, an empirical back analysis was conducted based on the distance to the sensor.

The definition of detection used in this back analysis was a sensor being used in the processing of the event for eventual location. This may be a somewhat conservative definition, as it may be possible to identify that a miner is signalling even if the seismogram is not suitable for use in event location.

For all events that were located, the distance to each sensor and whether the sensor detected the signal was tabulated. Due to the smaller scale of the tests at Golden Grove and Mine C, only the test for Tasmania mine had the required range of data to complete this analysis.

The distances were binned by log distance, with 10 bins per order of magnitude change in distance. The percentage of events detected in each bin was calculated in order to find the relationship between probabilities of detection and distance (Figure 5).

The results of the relationship were then calculated based on the mine plans and sensor locations of Tasmania mine (Figure 6) to give a probability of detecting a single blow at any given point in the mine. The probability of detection in the working levels to the east of the mine could be improved by installation of a sensor at approximately 1070 RL further to the east of the mine. In order to achieve 90% confidence in detecting an event, an inter-sensor spacing of 120 m would be needed. Mines in production could undertake this sort of analysis in order to understand where their system has areas of low sensitivity to trapped miner detection (and potentially trapped miner location).

Graphs of distance versus peak particle velocity (PPV) were used in order to investigate the impact of using different WSSs and strike surfaces on the system’s ability to detect a signalling miner. Examples are shown in Figures 7 and 8. The detectability of a trapped miner is insensitive to the choice of WSS and striking surface. This is significant, as it means a miner does not have to carry specialised equipment with them underground in order to be detected.

Location of WSS Blows

Processing of WSS blows followed the same general approach used for routine seismic event processing, namely identifying the arrival times of pressure and shear waves (P- and S-waves) on the seismograms. No wave manipulation (such as filtering or wave stacking) was used when processing the data.
Figure 5. Distance-probability relationship

Figure 6. Probability of detection, Tasmania mine
At the time of writing the paper processing was performed manually only, which was a time consuming endeavour. The processes necessary for detection and location of trapped miners need to be streamlined and some development of seismic monitoring software is necessary to achieve this.

Several hammer blows were processed at different sites, examples of which are shown in Figure 9. The figure shows examples of the best results and ‘typical’ test results obtained at each of the mines where testing took place. There are some events at the bottom of Figures 9c and 9d which are not in a similar location to the majority of the “events” and could be considered outliers.

Removal of Outliers

The distance between the location of each “event” and the median location of the set of “events” were used as a basis for determining outliers. Chauvenet’s criterion, a test which finds the probability of an observation being at a certain distance from the mean (assuming a normal distribution), was then applied to determine which events were outliers (Taylor 1997). For a set of events (corresponding to a single test site) to have any outliers assigned, the set needed to have a standard deviation of at least 5 m. This was to avoid events which are a short distance away from the median being tagged as outliers due to a very small standard deviation. Outlier removal was also not performed on very small sets (less than 5 events).

Figures 10 and 11 show the effect of removing outliers for a particular test site, with the mean location having a lower absolute error after excluding the outlier.

Absolute Location Accuracy

The absolute location accuracy is the distance from the event location (or a mean location) to the actual test site location which was surveyed.

A potential source of error in the location accuracy was an incorrect velocity model, particularly for Beaconsfield and Golden Grove, due to the large volume of voids in the testing areas. Calibration of the velocity models however, was outside the scope of the study and thus was not taken into consideration in the analysis of location error.

To find the absolute location error, the (arithmetic) mean location for each test site was calculated after the outliers were removed. As the signalling miner has to be within the development of the mine, the mine development provides a further constraint on the location of miner. The nearest point on the development survey string to the mean location was assumed to be the location of the trapped miner. Setting the miner’s location to the nearest point on the development string resulted in absolute error values which were on average about 4.5 m less than for the mean locations.

Even without the use of any wave manipulation techniques or wave stacking, a reasonable degree of accuracy can be achieved. Figure 12 shows the distance to the third closest sensor (D3) for each test site plotted against the absolute error of the nearest survey point for that specific test site. D3 is used as three sensors are usually needed to get an accurate location using a seismic monitoring system. Whilst there is no clear relationship between the variables (as evidenced by the five point moving average line), it is clear that test sites which are far from the sensors (i.e. D3 greater than 200 m) have a large absolute error. The shapes of the points are determined by the number of events used in the mean location calculation.

A cumulative plot was made of the absolute error of the test sites, excluding those which were further than 200 m from the third closest sensor (Figure 13). Of the data presented in Hudyma 2008, 80% had an inter-sensor spacing of less than 200 m in Australian and Canadian mines and so a D3 of greater than 200 m can be considered a sparse sensor array. Again, the shapes correspond to the number of events used in the mean location calculation. With D3 less than 200 m, 90% of test sites had an error of less than 46 m, 80% less than 35 m and 60% less than 20 m. The average error was 23 m.
Figure 9. 3D View of best and ‘typical’ test sites at participating mines

Golden Grove (a-best, b-typical)

Tasmania Mine (c-best, d-typical)

Mine C (e-best, f-typical)

= Sensor  = Event  = Test Site
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Figure 10. 3D view of outlier removal looking SW

Figure 11. 3D view of outlier removal looking SE

Figure 12. Distance to 3rd sensor vs error
Figure 13. Cumulative plot of error for D3 < 200 m

Figure 14. Comparison of different WSSs
Influence of Different WSS and Strike Surfaces

Given that the WSS blows could be detected and located, one would not expect a significant variation in the absolute location error from different WSS’s or striking surfaces. This can be seen in Figure 14 and Figure 15 showing the mean locations (after excluding outliers) for different wall striking sources and different strike surfaces. Figure 14 shows the mean absolute error of blows with different WSSs for each test site. Whilst the mean error for test site IDs 186 to 202 is large, this is because the D3 value for the test sites is large (greater than 250 m) and there is no conclusive difference between the two WSS’s used for each of these test sites.

Similarly, there was no noticeable difference in the absolute error between different surfaces that were struck. Figure 15 shows the error of each test site, plotted by which surface was struck.

In general it appears that there need not be any stringent requirement on the type of WWS or surface that should be used by trapped miners, when trying to locate.
Stability of Location Estimate

For this analysis, it was assumed that the data collected was representative of the range of different quality and locations of individual hammer blows (events). The uncertainty and variation in the location accuracy can then be studied by performing repeated analysis by sampling different subsets and permutations from the original dataset. By using different permutations and subsets of these events, the expected variation in the mean location can be quantified. From this analysis the number of events needed to find a stable mean location (i.e. a mean location that does not vary greatly in position with the addition of more events) can be found.

For each test site, a random order was assigned to the events. The mean location (excluding outliers) was calculated for the set of events 1 to \( x \), where \( x \) varies between 1 and \( n \) (\( n \) being the total number of events for that test site). The difference between the absolute error of each set and the “final” set (i.e. \( x = n \) ) was calculated.

Figure 16 is a cumulative plot of this difference, grouped by the number of events used to calculate the mean location. There were 200 random orders of the arrival times sampled (with replacement) for each test site.

Although a larger number of hammer blows will result in a more stable mean location, a stable mean location can be established with as few as 5 WSS blows. After 5 blows 90% of combinations had a mean location with an error which is within 6 m of the final stable location.

Modified Location Method

In an attempt to improve the event locations and provide a more flexible method for locating trapped miners, a modified algorithm was used to calculate the event locations. The same P- and S-wave picks were used for both the conventional and modified location methods. The modified method involved evaluating each point on the development floor string of the mine as a potential source for the event, instead of calculating the source as a point in space. The residual at each of these points was calculated, giving a contour plot of the mine.

The advantage of this location method is that it gives not only a single location for the trapped miner, but indicates the relative likelihood of them being located at any point in the mine. As an example, for the 3D contour plot in Figure 17, the rescue team could focus their efforts on the “hot” levels, instead of just a single point given by conventional location methods. The residual is purely a measure of the uncertainty in the algorithm used for location. The residual varied widely between test sites and as such only indicates the relative probability of a single event being located at that survey point.

Figure 17. Contour Plot of Residual (looking NW)
The point on the development string with the lowest average residual was set as the location of the trapped miner for absolute location error analysis. The absolute location accuracy using this method was found and compared with conventional methods. Figure 18 is a plot of distance to the third sensor and the difference in absolute location error between the modified and the conventional location methods (positive indicates that the modified method is more accurate, negative that the conventional method is more accurate). It was found that on average, there is no significant difference between the two methods in terms of accuracy and so the modified location method would be the preferred method to use in an emergency situation, as it gives rescue crews a broader picture of where the miner may be.

CONCLUSIONS AND RECOMMENDATIONS

The results of this pilot study show that trapped miners striking the wall of an excavation can be detected and successfully located using a standard in-mine micro-seismic system. Further development is however, necessary to streamline the process to be used under an emergency situation.

As was expected, the SNR is better for fully grouted sensors than for wall mounted sensors.

All test sites which have been analysed and processed to date were detected by at least one sensor. Back analysis of the data from Tasmania mine resulted in a relationship between distance and probability of detection which was 100% up to 65 m, 90% at 100 m and dropped to 0% at 250 m.

Test sites with a D3 of over 200 m had a large location error, however test sites where there were three sensors within 200 m could be located within 45 m with 90% confidence, 35 m with 80% confidence, 20 m with 60% confidence and the average error was about 25 m.

A variation of the location algorithm was used in order to generate a contour plot of residual for the mine. This modified location method produced results which were, on average, as accurate as the conventional location method. The advantage of using the modified location method is that it provides an indication of the confidence in the location and, in an emergency situation, rescue teams can focus their efforts on a wider area which may include multiple levels, instead of just a single point in the mine development.

In order to implement the technique at an operating mine, seismic monitoring software would need to include a “continuous monitoring” mode where all of the data is recorded and can be easily viewed. A signalling procedure would need to be defined so that the miner’s blows can be more effectively differentiated from repeated noise on some of the sensors. This signalling procedure should include a minimum of five blows in order to get an accurate location for the miner.

No significant difference was found in the PPV generated by different WSSs. There was no difference in the PPV generated by striking different surfaces. If detection was possible, there was no noticeable variation in the location accuracy with different WSSs or with different surfaces that were struck. The significance of this is that a miner can be detected and located without the need to carry specific equipment, even a rock will suffice.

If possible, the modified location algorithm should be used in order to give rescue crews a broader picture of where the miner may be signalling from.
Overall, the changes needed to implement this system in a mine which currently uses a microseismic monitoring system would require minimal cost and effort.

Further improvement in the detection sensitivity and the location accuracy of a signalling trapped miner can be expected with the use of techniques to improve the signal to noise ratio.

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