Attenuation and duration of seismic signals generated from controlled methane and coal dust explosions in an underground mine

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1. Introduction

1.1. Statement of the problem

Seismic monitoring provides a useful means for detection and evaluation of events resulting from mining activity. Seismic signature characteristics such as arrival times, amplitudes, duration and frequency content can indicate the nature and location of the source. In the past, most mining-related seismic measurements have focused on events such as rockbursts, production blasts from quarries, roof falls and rock fractures [1,2,3,4]. However, little or no effort has been expended towards examining the characteristics of a signature emanating from a methane and coal dust explosion in an underground mine. The Sago Mine disaster in 2006 provides an example of why these particular signatures should be researched. A small amplitude signal was identified on records of the regional seismic network stations that were closest to the mine [5]. The epicentral location of the small amplitude signal was at the Sago Mine. However, it was unclear whether the signature represented the explosion itself or another type of mining-related seismicity such as a large roof fall. This paper presents findings from a study aimed at examining seismicity from methane and coal dust explosions by analyzing the attenuation and duration of seismic signatures collected from controlled methane and coal dust explosions, with potential applications to forensic studies of mine explosions such as the Sago Mine disaster.

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1.2. Proposed solution and objective

The Lake Lynn Experimental Mine (LLEM) is a facility associated with the National Institute for Occupational Safety and Health's (NIOSH's) Office of Mine Safety and Health Research. The research facility has conducted controlled methane and coal dust explosions since 1983. These experiments provide insight into the behavior and prevention of underground mine explosions [6,7]. This facility provides an ideal location and opportunity to monitor the seismicity from controlled explosions in an underground mine. A seismic monitoring system was installed at the Lake Lynn Experimental Mine to collect seismic signatures emanating from controlled methane and coal dust explosions. Seismic signatures were analyzed to begin to understand their characteristics from the different explosions. These types of measurements could not be found in other literature and characteristics found in the signatures are hoped to provide better understanding of these events when captured in the far-field. For this paper, the results and conclusions discuss the attenuation and durations of the seismic signatures. The attenuation of the seismic signatures was studied by observing the maximum amplitude at different distances away from the source. The durations of the seismic signatures were investigated to determine if the impact of the varying experimental designs can be observed. The objective was to determine if the attenuation and duration characteristics could give insight into seismic signatures measured on a regional seismic network station in the future.

Although the accessibility of the LLEM allowed for the unique opportunity to monitor methane and coal dust explosions in an underground environment, control of the experimental designs was not made available. Therefore, the presence of explosion-containment structures and the amount of initial explosive fuel used during the experiments was based on research needs related to mine seal design and was not controlled for the purposes of this study. Ideally, experiments with replicated designs would be monitored; however, this was not an option. Thus, this study was considered to be an exploratory project where any finding or observation made from the seismic signatures would be considered to be beneficial for further research.

2. Materials and methods

2.1. Lake Lynn Experimental Mine and instrument locations

The Lake Lynn Experimental Mine is a full-scale, underground mining research facility on the site of a former limestone quarry. The facility is located approximately 96 km (60 miles) southeast of Pittsburgh, PA, and 16 km (10 miles) northeast of Morgantown, WV. The west side of the facility, known as the old workings, was mined when limestone was produced commercially from the site. This area of the research facility resembles a layout typical of an underground room and pillar stone mine. The dimensions of entries in the old workings are 15.2 m (50 ft) wide by 9.1 m (30 ft) high. The east side of the facility contains mine drifts that are dimensioned to match configurations found in longwall coal mines. The dimensions of these entries are 6.1 m (20 ft) wide by 2.0 m (6.5 ft) high. The size of the pillars in the simulated longwall gate roads is 24×12 m (80×40 ft). A-, B-, C- and D-Drifts are approximately 480–495 m (1575–1630 ft) long. E-Drift, which connects the entries at the inby end, is 155 m (510 ft) long. Instrument rooms in the mine are located approximately three-fourths of the way down C- and D-Drifts. These rooms are protected from the entry via blastproof doors. A 70-ton bulkhead door with a steel framework is located between C- and E-Drift and is closed during all of the explosions. The mine layout is shown in Fig. 1, including both uniaxial and triaxial geophone locations used for this experiment.

Geologically, the mine is located in the Greenbrier limestone formation [8]. A borehole drilled into the roof approximately 9.1 m (30 ft) high in the old workings of the mine showed the different formations at the test site. The data from the borehole were obtained from the NIOSH engineers who conducted the borehole logging. The geology observed from the borehole logs in the old workings was confirmed to be approximately the same geology in the area where the explosions were ignited and most of the measurements were taken. From the surface of the roof to 4.3 m (14 ft) above the mine is a fine-grained limestone. A shale/claystone formation is located between 4.3 and 6.1 m (14 and 20 ft). Between 6.1 and 9.1 m (20 and 30 ft), which is at the end of the observation hole, is a fine-grained limestone.

The methane and coal dust explosions conducted at LLEM were ignited at the inby end of A- or C-Drift. The chosen locations of the geophones were distributed around the explosion at various distances. The locations of both uniaxial and triaxial geophones are indicated on the mine map in Fig. 1. Over the time interval of the experiment, nine triaxial and three uniaxial geophones were utilized. Geophone 7 is not listed on the mine map because it is a "dummy" geophone used for testing purposes. Geophone 13 was installed on a limestone outcrop outside of the mine to collect data away from the source. Not all geophones were present for each test monitored at LLEM. The geophone placement became more proactive as the study progressed; i.e., additional geophones were added to the existing array in specific locations as a response to new findings in the data. In some cases geophones had to be removed due to their locations interfering with other experiments at LLEM. In addition to the seismic system at the mine location, the nationwide US Geological Survey (USGS) stations were studied at the time of the explosions. The closest

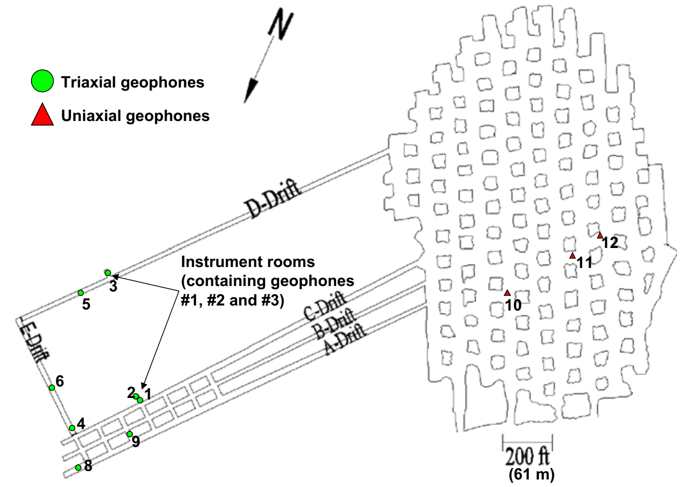

Fig. 1. Layout of the Lake Lynn Experimental Mine with geophone location and instrument room locations highlighted.

USGS station to LLEM is located at Mt. Chateau, WV, which is approximately 16 km (10 miles) south of the mine.

2.2. Methane and coal dust explosions

The Lake Lynn Experimental Mine can accommodate a variety of explosion configurations. The explosions[1] can be located in A-, B-, C- or D-Drifts, and a typical explosion consists of natural gas ($\approx$ 98% methane) injected into an ignition chamber at the face of the drift. A mine ventilation brattice is draped across the entry to contain the methane in the ignition chamber. An electric fan with an explosion-proof motor housing mixes the natural gas with the air to result in an approximate 9.5% methane-air concentration. The flammable natural gas-air volume is ignited using a triple-point ignition source. This ignition source consists of three sets of two 100 J electric matches that are equally spaced at mid-height across the closed end of the drift and ignited at the same time. Five barrels filled with water, located near the outby end of the ignition chamber, act as turbulence generators to achieve a projected pressure pulse. To increase the explosion pressure, either the ignition chamber was lengthened or pulverized coal dust was suspended on shelves from the mine roof starting just outside of the ignition chamber.

For this study, the size of the explosion was defined as the peak pressure generated in the drifts of the mine. Pressure measurements were taken in the C-Drift or A-Drift ribs, depending on whether the explosion took place in C-Drift or A-Drift. The data were sampled at 1500 samples per second and were obtained from the LLEM staff. The pressure measurements were not on the same time scale as the seismic measurements. An example of a pressure–time curve is plotted in Fig. 2. In the figure, the multiple curves represent the different locations where the pressure measurement was taken along the drift. The peak pressure generated for this example is around 0.38 MPa (55 psi), which would be considered the size of that particular explosion. A total of 19 explosions were analyzed for this paper, summarized

[1] Mine shot numbers 506–524 were conducted for purposes other than this study. Mine shot numbers 506–507 are referenced in Refs. [9] and [10]. Mine shot numbers 508–509 are referenced in Ref. [11]. Mine shot numbers 513, 514, and 516–19 are referenced in Ref. [12]. Mine shot numbers 523 and 524 are referenced in Ref. [13]. Mine shot numbers 520–522 are not yet published; however, the work was completed by Ken Cashdollar, Eric Weiss, and Sam Harteis as part of the mine explosion program for the NIOSH Office of Mine Safety and Health Research's then Disaster Prevention and Response Branch.

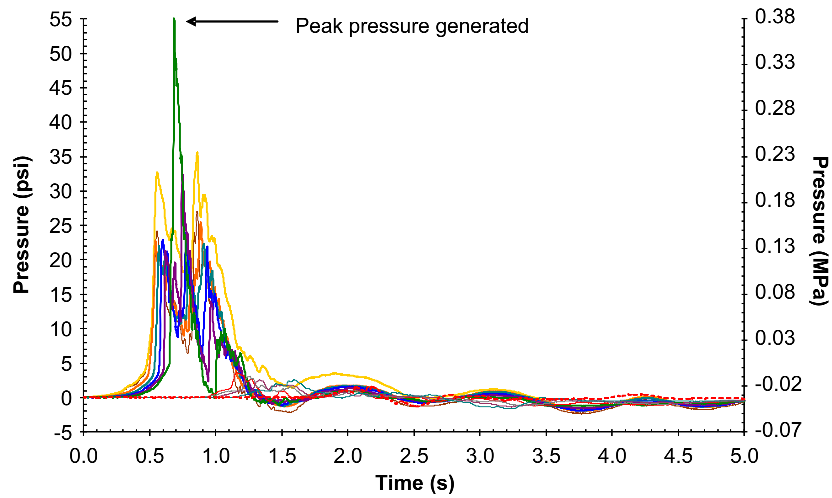

Fig. 2. Example of pressure–time curves used to obtain the size of the explosion, as defined by the peak pressure generated.

Table 1
Summary of explosions analyzed during the study.

	Size of explosion (MPa)	Size of explosion (psi)	Ignition location	Containment geometry
Mine shot #503	1.20E-01	17.4	C-Drift face	Explosion contained within sealed area
Mine shot #504	1.37E-01	19.9	C-Drift face	Explosion contained within sealed area
Mine shot #505	3.80E-01	55.1	C-Drift face	Explosion ignited in sealed area, seal in entry destroyed
Mine shot #506	6.17E-01	89.5	C-Drift face	Explosion ignited in sealed area, seal in entry destroyed
Mine shot #507	1.47E-01	21.3	C-Drift face	First three crosscuts sealed, no seal in path of explosion
Mine shot #508	3.46E-01	50.1	C-Drift face	Explosion contained within sealed area
Mine shot #509	6.31E-01	91.5	C-Drift face	Explosion ignited in sealed area, seal in entry destroyed
Mine shot #510	1.01E-01	14.6	A-Drift face	All crosscuts sealed, no seal in path of explosion
Mine shot #513	9.56E-02	13.9	A-Drift face	All crosscuts sealed, no seal in path of explosion
Mine shot #514	1.03E-01	15.0	A-Drift Face	All crosscuts sealed, no seal in path of explosion
Mine shot #516	8.98E-02	13.0	A-Drift face	All crosscuts sealed, no seal in path of explosion
Mine shot #517	9.27E-02	13.5	A-Drift face	All crosscuts sealed, no seal in path of explosion
Mine shot #518	9.16E-02	13.3	A-Drift face	All crosscuts sealed, no seal in path of explosion
Mine shot #519	1.72E-01	24.9	A-Drift face	All crosscuts sealed, no seal in path of explosion, however last two seals in the crosscuts failed
Mine shot #520	1.07E-01	15.6	A-Drift face	First five crosscuts sealed, no seal in path of explosion
Mine shot #521	1.10E-02	1.6	A-Drift face	All crosscuts sealed, no seal in path of explosion
Mine shot #522	1.09E-01	15.8	A-Drift face	First five crosscuts sealed, no seal in path of explosion
Mine shot #523	3.09E-01	44.8	A-Drift face	Explosion contained within sealed area
Mine shot #524	5.52E-01	80.0	A-Drift face	Explosion contained within sealed area

in Table 1. The table indicates the size of the explosion, whether the explosion took place in A- or C-Drift, and the containment geometry.

The containment geometry is a reference to whether a mine seal was in the propagation path of an explosion down the length of the entry and whether seals were within the crosscuts. Fig. 1 indicates the location of the mine seal in the propagation path of the explosion in the A- or C-Drift entry and the location of mine seals in the crosscuts, which are all represented by small thick black lines. The seals in the propagation path of the explosions were approximately 115 m (375 ft) away from the face of the drifts. In most scenarios during the study, seals were also constructed in the crosscuts between A- and B-Drifts and B- and C-Drifts. Table 1 explains the locations of crosscut seals in more detail. For example, for mine shot number 503, Table 1 indicates that the explosion was contained within a sealed area and that the ignition location was at the C-Drift face. Therefore, the explosion was contained within the area created by the first three sealed crosscuts in B- and C-Drifts, a mine seal in the C-Drift entry, and a bulkhead door between C- and E-Drifts (however, the explosion did not destroy any of the seals). In this study, five experiments were conducted where an explosion was fully contained within a sealed area either in A- or C-Drifts. Four experiments were conducted where an explosion was ignited within a sealed area in C-Drift and the pressure wave from the explosion destroyed the seal.

2.3. Seismic monitoring system

Geophones were chosen as the seismic transducer to record seismic waves emanating from the methane and coal dust explosions. The geophones surrounded the area of the methane and coal dust explosions at the Lake Lynn Experimental Mine. Geophones 1, 10, 11, 12 and 13 were anchored onto the mine floor while the rest of the geophones were anchored to the mine roof. No grout was used while anchoring the geophones to the roof or floor. Both the triaxial and uniaxial geophones had a natural frequency of 4.5 Hz. The output chart provided by the manufacturer only includes responses up to 90 Hz; nevertheless, for this study, it was assumed that the response was constant but that spurious responses could occur. Surface measurements approximately 60 m (200 ft) above the mine were taken near the end of the study using a three-component digital output seismometer. The instrument was installed at a depth of one meter below the ground surface above the A-Drift face. The instrument was set to sample at 500 samples per second and was oriented in the same manner as the geophones installed inside of the mine. Data from this seismic instrument were only available for mine shot numbers 523–524. The seismic monitoring system was installed within the existing structure of LLEM. The two A/D converters used in the study, named MS boxes and QS boxes, both had a sampling rate of 2000 samples per second and contained six channels for input. The MS boxes had 22-bit resolution (14 bit A/D with 8 bit gain) and the QS boxes had a 24 bit resolution. The seismic monitoring system was a trigger-based system, in contrast to a real-time continuous monitoring system. This system only recorded and saved data based upon two or more geophones being triggered by an event.

2.4. Method for determining amplitude

The maximum amplitudes of the seismic signatures were studied in order to calculate the attenuation factor. The maximum seismic wave amplitudes were converted into units of m/s from the original digital counts. The maximum ground velocity, or amplitude, is a reference to the peak particle velocity, not the velocity of the seismic wave traveling through the medium.

2.5. Method for determining attenuation

The attenuation of the seismic signatures was studied to determine how much the amplitude decays as the seismic wave travels through the limestone. The attenuation was calculated in terms of decibels, which compares the ratios of amplitudes observed at different locations within the mine. The formula used to calculate attenuation is

$$dB = 20\log\left(\frac{V_1}{V_2}\right) \quad (1)$$

where V_1 is the measured input (volts), and V_2 is the reference input (volts). Since amplitude is linearly related to the voltage from the geophone, a ratio of measured and reference amplitude values are used in the decibel calculation instead of volts. The measured input is the measured amplitude at different distances away from the source. The reference input would be related to an initial amplitude observed at zero distance away from the source of the explosion. However, since a geophone was never present at the location of the source, this parameter had to be estimated from the seismic data for each explosion. An example is shown for mine shot number 506 in Fig. 3. For this example, the *x*-axis is on a logarithmic scale. The amplitude of ground velocity was observed to decrease exponentially with distance. The reference input, V_1, can be estimated at 0.053 m/s based upon where the regression line crosses the *y*-axis

Once the reference points were calculated for each mine shot, the attenuation for each mine shot was calculated and plotted. An example demonstrating the attenuation of amplitude for mine shot number 506 is plotted in Fig. 4. For this example, the *x*-axis is on a logarithmic scale.

2.6. Method for determining duration

The overall duration of the mine shots helps give insight into how the experimental design may affect the seismic signatures observed at different locations. For example, when a mine seal is in the path of the explosion, if a signature is significantly longer in duration than when the mine seal is not there under similar conditions, then it can be inferred that the seal had a significant effect on the signature. The time frame of the seismic signature was defined by the window between the first arrival and when the signature was believed to drop back into the background noise. Due to the complexity of the seismic signatures, the method of analysis was conducted in a qualitative manner. In some cases, this was difficult to observe so bandstop filters were applied to the noisy waveforms in an attempt to evaluate the signature further. In addition, in some cases reflections of the pressure wave hitting the mine face or mine structures were observed. However, these events were not included in the duration calculation, with only the seismic signature from the explosion being of interest. In cases where the explosions and reflections were merged together and inseparable, the full duration was reported.

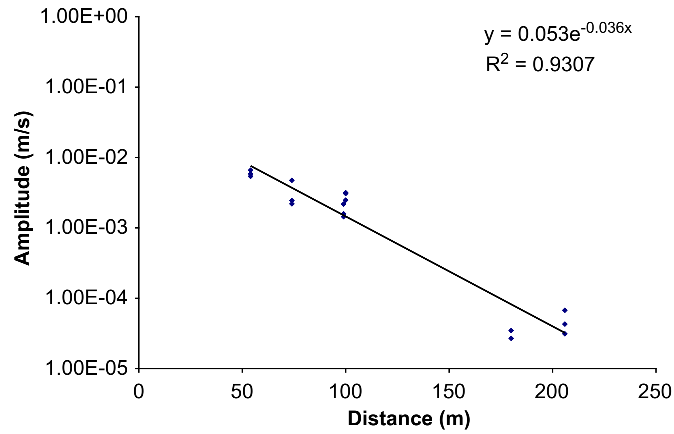

Fig. 3. Plot of amplitude versus distance for mine shot #506.

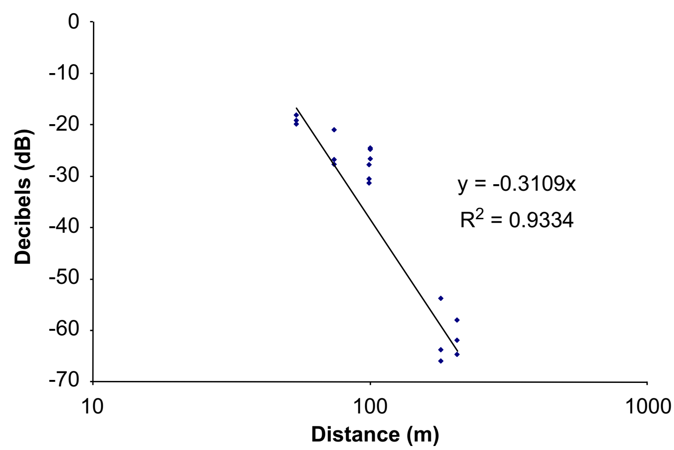

Fig. 4. Plot of attenuation for mine shot #506.

3. Results and discussion

Table 2 shows a summary of the attenuation factors for the mine shots analyzed. The attenuation factors shown in Table 2 were calculated by the same method described earlier for mine shot number 506. The maximum pressure from each explosion is also given. No correlation could be made between the size of the explosion or experimental design and the attenuation factors observed, as seen in the scatter plot in Fig. 5. In this scatter plot, the confined explosions are represented by a diamond shape and the unconfined explosions are represented by a square shape. The lowest attenuation factor was observed for mine shot number 509, the largest explosion based on the maximum pressure generated. The highest attenuation factor was observed for mine shot number 505, one of the largest explosions. The average attenuation factor for the fourteen mine shots studied was

−0.20 dB/m with a standard deviation of 0.080 dB/m. For each explosion, it appears that the amplitude of ground velocity attenuates very quickly.

One goal for the study was to collect the signatures on a regional scale using the USGS seismic networks; however, signatures could not be identified for any of the explosions at regional distances. The attenuation factors explain why the shots were not observed on the Mt. Chateau regional seismic network, 10 miles south of the mine. Geophone 13 was installed outside of the mine to collect data for mine shot numbers 510–520; however, explosion vibrations were not sufficient to trigger the sensor. This geophone was over 500 m away when the explosions were ignited inside of A-Drift.

Although attempts were made to monitor the explosions from greater distances, the signal attenuated into the background noise. The geophones in the old workings were connected to the system after mine shot number 506 and were over 500 m away from the source. They were triggered on mine shot numbers 508 and 509, each of which generated pressures on the order of 0.35 MPa (50 psi). Although the largest explosions were able to destroy mine seals, they were unable to be seismically observed at the regional network due to the seismic wave attenuation.

Another fact to keep in mind is that these explosions are largely decoupled from the limestone. The explosion was ignited in an open space and the transfer of the energy occurred as the expanding pressure wave interacted with the surrounding rock. This is very different from other types of seismic sources such as an earthquake or a roof fracturing in an underground mine where the source is direct rock-on-rock contact. Even with a quarry blast, the explosive fuel is packed tightly into the rock. Therefore, the transfer of seismic energy from methane explosions into the rock is significantly less than other mining-related mechanisms that create seismic signatures. For a mine explosion to be observed on a regional network, a large amount of seismic energy (stemming from the explosion itself or subsequent roof falls/seal destruction) would have to be transferred into the rock so that the seismic signature does not attenuate into the background noise. Based on the attenuation measurements from this study, for the Lake Lynn Experimental Mine or similar circumstances where an explosion is ignited in an open space inside of a volume similar to the ignition chamber, an explosion significantly larger than 0.62 MPa (90 psi) would be required to generate enough seismic energy for the signature to be observed at a regional seismic network station 16 km (10 miles) away.

Duration trends were better observed for the seismic signatures when groups of geophones between 0 and 150 m and over were analyzed separately. These trends are likely because at close distances, the P-, S- and body waves are not as fully separated as they are at further distances. Also, the complexity of the seismic signatures provided another degree of difficulty in determining the signal duration. To demonstrate, the LLEM supervisor indicated that it is possible that the pressure wave from the explosion moved into each crosscut as it traveled down the drift, reflecting within the crosscuts. It is possible that these reflections were detected by the closest geophones to the explosion and not by the geophones at a further distance.

Four mine shots conducted in C-Drift were selected to compare the durations of seismic signatures of methane and coal dust

Table 2
Attenuation factors and size of the explosions for each mine shot during the study.

	Size of explosion (MPa)	Size of explosion (psi)	Attenuation factor
Mine shot #503	1.20E-01	17.4	−0.152
Mine shot #504	1.37E-01	19.9	−0.239
Mine shot #505	3.80E-01	55.1	−0.381
Mine shot #506	6.17E-01	89.5	−0.311
Mine shot #508	3.46E-01	50.1	−0.209
Mine shot #509	6.31E-01	91.5	−0.084
Mine shot #510	1.01E-01	14.6	−0.193
Mine shot #513	9.56E-02	13.9	−0.168
Mine shot #514	1.03E-01	15.0	−0.211
Mine shot #516	8.98E-02	13.0	−0.167
Mine shot #517	9.27E-02	13.5	−0.137
Mine shot #518	9.16E-02	13.3	−0.114
Mine shot #519	1.72E-01	24.9	−0.161
Mine shot #520	1.07E-01	15.6	−0.273
Average			−0.200
Standard deviation			0.080

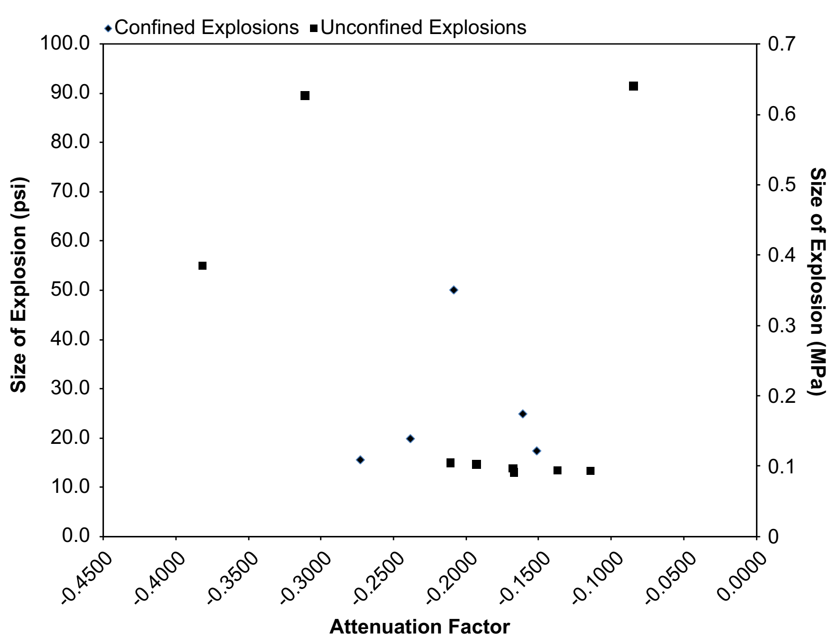

Fig. 5. Scatter plot showing no correlation between the attenuation factors and size of the explosion. The confined explosions and unconfined explosions are distinguished from one another by different symbols.

explosions with and without the destruction of mine seals. These experiments included two explosions in which a mine seal in the path of the explosion failed (mine shot numbers 506 and 509), one in which a mine seal was in the path of the explosion but it did not fail (mine shot number 508), and one in which no obstruction was in the path of the explosion (mine shot number 507). For geophones 1 and 2, located less than 150 m away from the source in the C-Drift instrument room, data were not available for mine shot number 508. The average durations are reported in Table 3. The averages were taken using data from two geophones on all three components, thus giving a total of six samples. Table 3 also indicates whether a seal was in the propagation path of the pressure wave and if it was destroyed. As the table shows, when a mine seal is in the path of a pressure wave, a longer duration is recorded and the structure has a direct effect on the seismic duration. The longer duration was attributed to the destruction of the mine seal and impacts of the seal fragments against the mine roof, rib and floor. The standard deviations indicate that the differences in the average durations are statistically significant. Representative signatures from the data reported in Table 3 are plotted in Figs. 6 and 7. The signatures are for mine shot numbers 507 and 509 and are from geophone 2 located on the C-Drift roof.

The average durations for geophone numbers 3 and 5, located over 150 m away from the source in D-Drift, are reported in Table 4. Similar observations as before can be made where a longer duration is observed when a mine seal is in the path of the explosion. The duration is observed to be longest when the explosion is confined within the sealed area without destroying the seal. In this scenario, the pressure pulse is reflected repeatedly between the structure and mine face. Not enough data were available from E-Drift (geophones 4 and 6) to calculate significant averages.

For mine shot numbers 510–521, three geophones were located within 150 m of the explosions, which were the closest geophones to the source. These instruments were geophones 2, 4 and 6. Table 5 shows the average durations observed in the seismic signatures from these geophones and their standard

Table 3
Average durations from geophones 1 and 2 for mine shot numbers 506–509.

	Mine seal	Average duration (s)	Standard deviation (s)	Number of samples
Mine shot #506	Yes-destroyed	3.10	0.21	6
Mine shot #507	No	1.86	0.25	6
Mine shot #509	Yes-destroyed	3.95	0.23	6

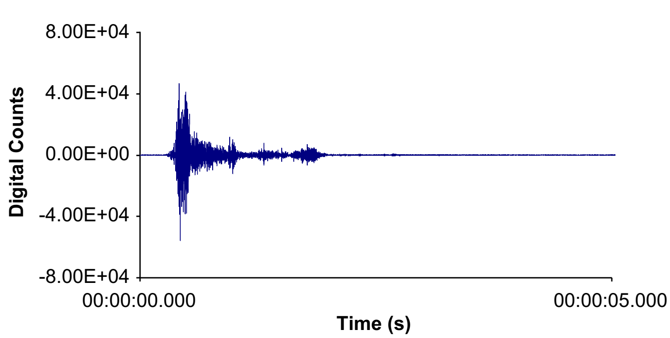

Fig. 6. Representative waveform from Geophone 2 for mine shot number 507. The two lines indicate the interval which determined the duration. For this experiment, the explosion was able to move freely down C-Drift.

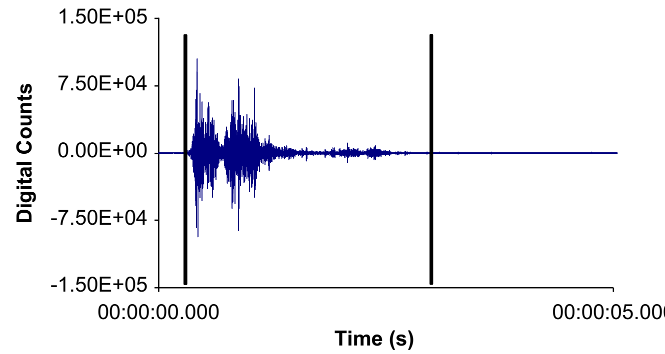

Fig. 7. Representative waveform from geophone 2 for mine shot number 509. The two lines indicate the interval which determined the duration. For this experiment, the explosion destroyed a seal in the C-Drift entry.

Table 4
Average durations from geophones 3 and 5 for mine shot numbers 505–509.

	Mine seal	Average duration (s)	Standard deviation (s)	Number of samples
Mine shot #506	Yes-destroyed	3.56	0.13	6
Mine shot #507	No	2.26	0.14	6
Mine shot #508	Yes	4.22	0.14	6
Mine shot #509	Yes-destroyed	3.50	0.08	6

Table 5
Average durations from the closer geophones during mine shot numbers 510–519.

	Mine seal	Average duration (s)	Standard deviation (s)	Number of samples
Mine shot #510	No	1.92	0.17	3
Mine shot #513	No	2.08	0.07	3
Mine shot #514	No	1.48	0.39	9
Mine shot #516	No	2.09	0.04	3
Mine shot #517	No	1.89	0.23	9
Mine shot #518	No	1.76	0.19	3
Mine shot #519	No	3.83	0.95	6

deviation. The only outlier appears to be mine shot number 519, which showed a duration approximately twice as long as the other mine shots. This particular explosion was almost twice as large as the other explosions in Table 5. Also, during this mine shot number 519, the seals located in the final two crosscuts between A- and B-Drifts failed (Table 1), which most likely was captured in the seismic signatures. The seal in crosscut six was cracked and some blocks were displaced, while the seal in crosscut seven was completely destroyed and some of the blocks were blown into C-Drift. The displaced blocks were a potential source of seismic energy as they contacted the mine roof, rib and floor, likely causing a longer duration in the seismic signatures for mine shot number 519.

Geophones located further away, specifically geophones 3 and 5 located in D-Drift, showed durations which were in the same

Table 6
Average durations from the far-away geophones during mine shot numbers 510–519 and 521.

	Mine seal	Average duration (s)	Standard deviation (s)	Number of samples
Mine shot #510	No	2.20	0.09	3
Mine shot #513	No	1.93	0.05	6
Mine shot #514	No	2.25	0.05	3
Mine shot #516	No	2.06	0.08	6
Mine shot #517	No	2.09	0.10	6
Mine shot #518	No	1.85	0.10	3
Mine shot #519	No	2.29	0.10	6
Mine shot #521	No	0.61	0.01	5

Table 7
Average durations for the closer geophones during mine shot numbers 523 and 524.

	Mine seal	Average duration (s)	Standard deviation (s)	Number of samples
Mine shot #520	No	3.72	0.25	9
Mine shot #522	No	5.41	0.32	6

range, as reported in Table 6. These geophones, which are further beyond the near-field environment, are not affected by factors such as reflections or crosscut seal interactions. Mine shot number 521 showed the shortest duration of any methane and coal dust explosion, with an average duration of 0.61 s. This explosion was very weak in comparison to the others, as indicated by its maximum pressure value of approximately 0.014 MPa (2 psi) (Table 1).

Mine shot numbers 523 and 524 were the only experiments conducted in A-Drift where the explosion was contained within a sealed area. During these two experiments, seals were placed in the crosscuts and a seal blocked the propagation path of the explosion. In both cases, the seals were able to withstand the pressure wave. Seismic data from inside of the mine were only available from the geophones located far away from the source in D-Drift. Compared to the durations observed for tests without seals, the effect of the seal placement in the entry appears to have a direct effect on the duration of the seismic signature (Table 7). When Table 7 is compared with Table 6, the explosions are up to and over one second longer in duration when contained within a sealed area versus freely moving down the entry. This difference in duration was observed for the same geophones when the tests were conducted in C-Drift (Table 4). Again, it is believed that when the explosion is contained within a sealed area, the pressure pulse is reflected repeatedly between the seal structure and mine face.

In order to validate the pressure pulse reflection between the structure and the mine face, a seismometer was placed on the ground surface above the A-Drift face for mine shot numbers 523 and 524. Again, during this shot, the explosion was ignited at the A-Drift face and a seal was placed in the propagation path of the explosion (however, the seal was not destroyed). The pressure pulse reflection could be observed extremely well when a low-pass filter set at 15 Hz was applied to the signature from the surface seismometer. The lowpass filtered waveform from the surface seismometer for mine shot number 523 is plotted in Fig. 8. During mine shot number 524, the same period could be observed on the surface seismometer and could also be seen on the signatures collected from inside the mine.

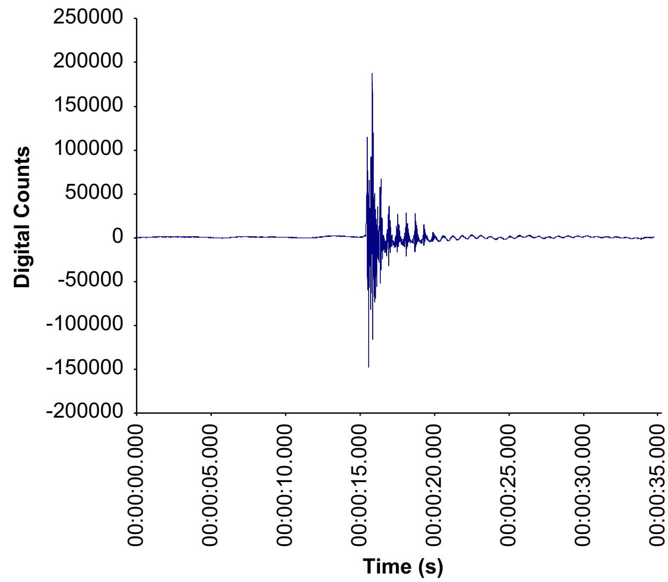

Fig. 8. Filtered waveform from the surface seismometer during mine shot number 523.

Fig. 8 shows that after the initial explosion, the signature contains a repeatable period at 0.62 s on average and lasting over 15 s. This observation can be attributed to the pressure wave being confined within the sealed area. As an example, Zipf et al. considered the scenario of an explosion in a mine entry with both ends closed and filled with an explosive methane–air concentration [14]. Initially, the slow deflagration stage involves a laminar flame speed of approximately 3 m/s (10 ft/s). As the deflagration accelerates, the turbulent flame speed increases to approximately 305 m/s (1000 ft/s). The pressure in the burned gas behind the flame increases and an acoustic wave propagates to the speed of sound. For this study, it is assumed that the pressure wave traveling down the mine entry has a velocity comparable to the speed of sound in air. The speed of sound in air is a function of temperature, which for the mine, at 286 K (55° F), would be approximately 335 m/s (1100 ft/s). The mine seal is located approximately 115 m (375 ft) away from the source location where the explosion ignites. If the pressure wave travels 230 m (750 ft) (twice the distance of the mine face to the mine seal) at 335 m/s (1100 ft/s), it should come in contact with either the mine seal or mine face approximately every 0.68 s. This value is approximately the same as the period observed in Fig. 8, which is on an average 0.62 s. This implies that the pressure wave was bouncing back and forth within the sealed area, creating a seismic signal either when the wave came into contact with the mine seal or the mine face. However, it cannot be determined which of the wave reflections is causing the seismic signature.

The final major observation was for mine shot numbers 520 and 522, where the explosion was allowed to enter different parts of the mine due to open crosscuts between A- and B-Drifts. This allowed the explosive pressure wave to possibly enter into B- and C-Drifts. An example of the possible path of the explosion is shown in Fig. 9, where the closest geophones are indicated by green dots. An example of a signature from the closer geophones from this type of geometry is shown in Fig. 10. The experimental design causes a more complex scenario than the previous experiments. The signatures observed from the closer geophones, located in the C-Drift instrument room and E-Drift, appeared to be affected by interactions of the pressure wave entering into the B- and C-Drifts. Table 8 indicates the average duration of the signatures observed from these geophones for the two mine

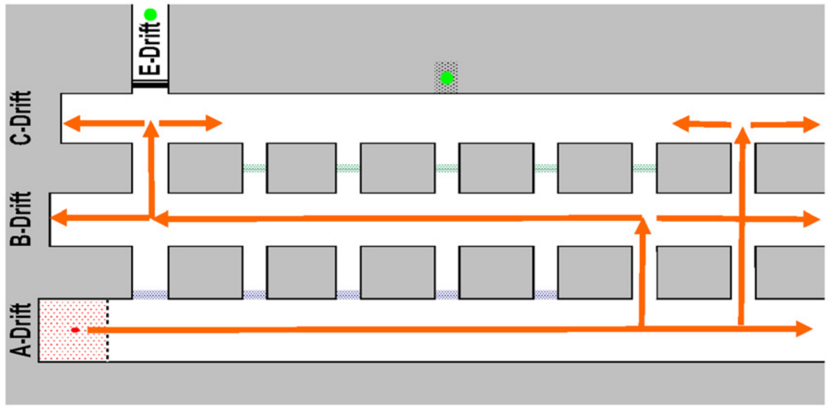

Fig. 9. Schematic of the experimental design for mine shot numbers 520 and 522. The design indicates that the propagation path of the pressure wave was allowed to enter into B- and C-Drifts. The green dots indicate the geophone locations within the bounds of the figure. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

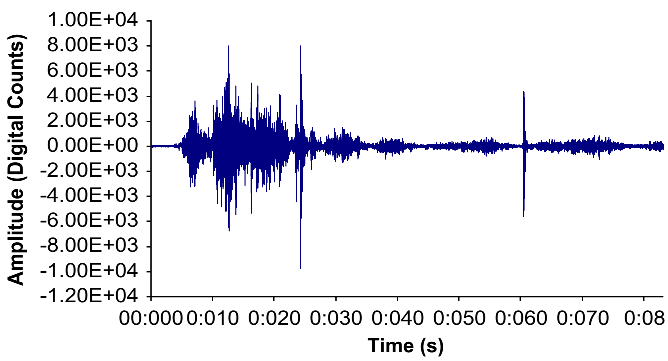

Fig. 10. Example of a seismic signature collected during mine shot number 522 by geophone 2. The signature appears to contain multiple reflections as a result of the pressure wave from the methane and dust explosion entering into B- and C-Drifts.

Table 8
Average durations for the closer geophones during mine shot numbers 520 and 522.

	Mine seal	Average duration (s)	Standard deviation (s)	Number of samples
Mine shot #523	Yes	3.62	0.26	6
Mine shot #524	Yes	3.08	0.03	6

shots. These durations are significantly longer than those that were previously observed. The seismic signature of the methane and coal dust explosion could not be differentiated from the seismicity of the pressure wave interacting with the ribs and mine structures as it entered into B- and C-Drifts, as seen in the example of the signature complexity in Fig. 10. Not enough data are available to compile significant findings for the geophones further down D-Drift.

4. Conclusions

Seismic signatures emanating from controlled methane and coal dust explosions at the Lake Lynn Experimental Mine were studied. The objective was to determine if the attenuation and duration measurements could give insight into future seismic signatures measured on a regional seismic network station.

A total of nineteen explosions were monitored between the different stages of this study. No correlation could be made between the size of the explosions and attenuation factors for the different mine shots. The average attenuation factor for all the mine shots was -0.20 dB/m. The explosions were monitored by seismic instruments locally at distances of 500 m (1640 ft) and through a regional seismic network station 16 km (10 miles) away, but no signatures could be observed at those distances. The measured attenuation factor explained why the signatures were not observed at far-away distances. The methane and coal dust explosions were ignited in an open space and the transfer of the energy occurred as the expanding pressure wave interacted with the surrounding rock. This situation is very different from other types of seismic sources such as an earthquake or a roof fracturing in an underground mine, where the source is direct rock-on-rock contact. Therefore, the transfer of energy from methane explosions into the rock is significantly less than other mining-related mechanisms that create seismic energy. For the Lake Lynn Experimental Mine, an explosion significantly larger than 0.62 MPa (90 psi) would have to be conducted in order to observe the seismic signature on a regional scale.

The duration of the seismic signatures was shortest for explosions with no seals in the path of the pressure wave and longest for those where a seal blocked the propagation path of the explosive pressure wave. For the experiments where the explosion was confined within the sealed area, a geophone on the surface of the mine observed signal durations for up to 15 s. The containment geometry also played a role in the duration of the seismic signatures. When the explosion was contained within a sealed area, the seismic signatures oscillated with a period corresponding to the pressure wave reflecting between the mine seal and mine face. The signatures were also observed to be very complex when crosscuts were opened and the explosive pressure wave entered into different areas of the mine, causing reflections between drifts and crosscuts.

The preliminary results identify the potential of seismic data to be useful in forensic studies of mine explosions such as the Sago Mine disaster. The results show that the introduction of a mine seal had a direct effect on the seismic signature, causing a longer duration, potentially due to the destruction of the seal. Also, there were different characteristics observed in the seismic signatures when comparing experiments where the seal was destroyed and when the seal contained the explosion in a tunnel-like environment. Finally, the signature was most complex when there were no seals and the explosion moved freely between the crosscuts and drifts.

Currently, it is very difficult to separate the seismic signature into different events such as the explosion itself, reflections of the pressure wave within the crosscuts, and the destruction of the seal. Further research, including the use of more geophones on the surface above the mine or placing geophones in a borehole, could minimize the complexity within the signatures. This would also give more opportunity to characterize the effect of a mine explosion or destruction of a mine seal on a seismic signature.

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