Void detection at an anthracite mine using an in-seam seismic method

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Abstract

An in-seam seismic (ISS)-based void detection technique was developed at Penn State University. Among various features, the most important one is its capability of acquiring high quality and broadband signals ranging from 50 to 5000 Hz. This feature is essential for acquiring and analyzing signals for a thin seam condition. The technique was tested at an underground anthracite mine. It successfully detected a mined out void at a distance of 46 m (150 ft) from the coal face. The seam height at the test site was 1.4 m (4.5 ft) on average. The transmission surveys generated well developed Love seam waves. This made it possible to reliably assess the dispersion characteristics of Love waves for this particular site. The Airy-phase had a typical frequency range of 400–600 Hz with a fairly stable velocity of 975 m/s (3200 ft/s). An elliptical method was used for void mapping in order to accommodate highly irregular sensor and source locations. The mapping error was within ±4.6 m (15 ft) based on the test results.

Keywords: Void detection; Mine safety; Inundation; In-seam seismic; Love waves; Dispersion

1. Introduction

In 2002, nine miners at the Quecreek Mine in Pennsylvania were trapped underground for 72 h after accidentally cutting into a water-filled abandoned mine. The incident as such, known as inundation, is not a rare event for the mining industry. It is one of the main safety problems faced by the mining industry worldwide. For the coal mining industry in the United States alone, more than 100 incidences of cutting into abandoned mines have been reported since 1995 (Gardner and Wu, 2005).

One of the underlying problems of the Quecreek incidence was the lack of convenient and reliable void detection techniques for detecting old mine workings. In response to the Quecreek incidence, the U.S. Congress appropriated $10 million for mine mapping and void-detection research, and MSHA promptly established the geophysical void detection program, aimed at advancing the current state of practice for detecting underground mine voids (Gardner and Wu, 2005). An in-seam seismic (ISS) based void detection technique was proposed by the Penn State Researchers. This article discusses the testing result of the technique at an anthracite mine.

1.1. Concept of the ISS based void detection technique

In-seam seismics (ISS) conventionally refers to methods which utilize channel or seam waves that are “trapped” in a weak seam and “sandwiched” by strong ones. The advantage of using “trapped” waves is that their energy is better preserved and therefore these waves can be detected over much larger distances in comparison with those radiating three-dimensionally.
The ISS technique originated from Evison’s in-seam experiment which showed that a coal seam could serve as a waveguide and “guided waves may find useful applications in mining” (Evison, 1955). Following Evison’s discovery, Krey carried out a systematical study on the theory of in-seam seismics (1962, 1963, 1976a,b). During the past fifty years, in-seam seismics has grown into a recognized science and engineering discipline. The basic theory and method of the ISS technique were well summarized by Dresen and Ruter (1994).

The ISS based void detection technique, in essence, is a reflection technique. The difference between this technique
and conventional reflection surveys is the type of waves utilized. With conventional reflection surveys, body waves are utilized, which can be either P- or S-waves or both, while with an ISS technique, Love waves are used. Love waves are a special type of channel or seam waves.

The operational principle of the ISS based void detection technique is illustrated in Fig. 1, where both sensors and seismic sources are placed in the middle of the seam. When the seismic source is generated, Love waves will be developed, traveling two dimensionally within the seam. Some of them will be reflected at the void and received by the sensors. The void boundary can be delineated based on the travel time and travel velocity of the Love waves as well as the locations of seismic sources and sensors. Note that the source and the sensors are located on a straight line and the sensors are equally spaced. However, it is important to point out that these arrangements were made for simplicity and are not required conditions for the ISS based void detection.

1.2. Experimental design

The ISS-based void detection includes three main aspects: experimental design, signal processing and void mapping. Experimental design is the first and probably the most critical step for the ISS-based void detection technique. Many factors, including both theoretical considerations and practical problems, have to be taken into account. The basic objective of experimental design is to create the best technical environment for acquiring high quality signals. Other important considerations include providing an adequate coverage for the area to be surveyed, facilitating data analysis, and creating a stable mathematical system. In this section, four components of experimental design will be discussed, namely: testing layout, data acquisition system and sensors, sensor installation, and seismic sources.

1.3. Testing site layout

The testing site utilized for the study was the Harmony Mine, an anthracite mine, located near Mt. Carmel in east central Pennsylvania. The Harmony Mine is a modern and efficient underground coal mine, where the room-and-pillar mining method is utilized to extract the coal. The production of the mine has ranged from 160 to 195 kt/year for the past 10 years, making it the largest underground anthracite mine in North America.

Fig. 3. Experimental layout of the test site. The setup includes a sensor array (AB), three source sections (1, 2, 3) for transmission surveys and two source sections (4 and 5) for reflection surveys. Details of the sensor array (AB) are given at the bottom of the figure.
The anthracite seam at the mine site varies from less than 0.3 to over 4 m (1–13 ft) thick, averaging 1.37 m (54 in). The seam is overlain by 69 to 122 m (255–400 ft) of overburden. The immediate roof and floor is a light-gray to yellowish-brown conglomeratic sandstone with uniaxial compressive strength greater than 82 Mpa (12,000 psi). The immediate roof conglomerate is 9 to 20 m (30–65 ft) thick and the floor conglomerate is 3 m (10 ft) thick. The mine is level in pitch, operating on the apex of an anticline.

A total of three field tests were carried out at the mine at two different locations, Site I and Site II. Fig. 2 is a mine map showing the approximate locations of these two test sites. Site I was located in the middle of a long pillar, which was about 18 m (60 ft) wide. Site II was a much larger pillar with a width of 46 m (150 ft). To make the paper concise, only the data from Site II were utilized as this site is more representative in terms of the size. For simplicity, Site II will be referred to as the test site in the rest of the text.

The test site is illustrated in Fig. 3. There were one sensor array and five source sections. The sensor array was located at the lower right corner of the pillar and consisted of 16 sensor holes. All boreholes were drilled in the center of the seam to a depth of 1.5 m (5 ft) from the face. This arrangement was used to avoid near-face fracture zones, one of the measures necessary for improving the coupling effect. Angled sensor holes were
used to enhance polarization analysis. The sensors installed in paired sensor holes S4/S5, S8/S9 and S12/S13 were used to simulate biaxial sensors.

The two source locations at the south side of the pillar (4 and 5) were used for reflection surveys. A total of 16 reflection surveys were carried out using these two locations. It is interesting to note the irregular sensor and source locations. These source sections and the sensor array were not in a straight line. Source Section 4 was significantly off the sensor line. In fact, even the sensor

Fig. 6. Love waves from the transmitted signals associated with Event 89.
line itself was not straight. Furthermore, the spacing of the sensors was highly irregular. For the ISS based void detection, it is common to have irregular sensor and source locations and irregular sensor spacing. These irregularities have an important impact on the mapping method to be used for void detection.

The three source locations on the north side of the pillar (1, 2 and 3) were used for transmission surveys. Sites 4 and 5 which were designed for reflection surveys also provided transmission data since they were not on the same line as the sensor section. With the transmission data available from all five source locations, the test site was well covered in terms of both ray directions and ray traversing areas.

1.4. Data acquisition system and sensors

A 16-channel ESG Hyperion seismic monitoring system was used for data acquisition. The system has a 16-bit resolution with a maximum sampling rate of 40 kHz per channel. During the operation, one channel connected to a wire-breaking recording device was used for triggering. The other fifteen channels were used for recording seismic signals. A sampling rate of 20 kHz was used for data recording at the Harmony Mine.

Sensors utilized for the study were ESG A1030 accelerometers, uniaxial sensors with a sensitivity of 30 V/g and a flat response (plus or minus 3 db) within the bandwidth 50 to 5000 Hz. The sensors are 10-cm (4 in) long and 2.54-cm (1 in) in diameter.

A noticeable feature of the overall monitoring system is its broadband capability, ranging from 50 to 5000 Hz. This is very different from the frequency range used for conventional reflection surveys. This capability is necessary for several reasons. First, the coal seam at the Harmony Mine is thin, 1.37 m (4.5 ft) on average. Considering that the period of Love waves is in the same order of the seam height, the expected signal frequency of Love waves would be at least several hundred. In fact, the typical frequency for the Airy phase at the mine site is 400–600 Hz, and some are close to 1000 Hz. Second, the signal frequencies for the body waves transmitted through the country rock are even higher, typically in a range of 2000–3000 Hz. A system which can record these high frequency signals is extremely helpful for the data analysis. Third, if the system is used for void detection for a non-coal mine condition, where in-seam body waves have to be used, the expected signal frequency could be even higher. For instance, the signals used for void detection in trona mines have a typical frequency range of 3000–5000 Hz (Ge, 2006).

1.5. Sensor installation

The signal travel distances at the test site ranged from 46 to 61 m (150–200 ft) for transmission surveys and over 91 m (300 ft) for reflection surveys. The ability to detect high frequency signals over these distances in coal was a major challenge for the project. The basic strategy in dealing with this difficulty was to maximize sensor coupling. First, the sensor sections were placed at locations where the coal seam was relatively uniform and competent, and free of major structures. Second, to avoid near-surface fracture zones, sensors were installed...
in boreholes which were drilled beyond these zones. Third, and most importantly, a retrievable sensor installation technique was developed, allowing repeated use of sensors and sensor boreholes and assuring a firm installation of sensors (Ge, 2006).

With the retrievable sensor installation technique, the sensor anchor, a screw assembly, is first cemented at the end of the sensor hole with a special type of resin. The sensor is then attached to the anchor by associated screw (Fig. 4). The anchorage strength of an installed sensor is measured by the amount of force needed to pull the anchor out. Laboratory testing showed that the "pull-out force" for a sensor installed in anthracite coal is at least 100 kg (250 lbs).

The technique enables the sensor to effectively detect high frequency signals yet is simple and convenient for both installation and retrieval operations. The technique has been used at seven different sites. Sensors installed in the prescribed manner have exhibited predictable, consistent, and repeatable performance.

Fig. 8. A typical transmission signal and Love wave component observed at the Harmony site and the dispersion curve for the Love wave component.
1.6. Seismic sources

Detonation caps and dynamite in the amount of 40, 80 and 120 g were used as the seismic sources. The use of 80 and 120 g appeared too strong for the site, resulting in saturation of the recording system. The explosives were installed at the bottom of specially prepared blasting holes. These holes were 3.8-cm (1.5 in) in diameter and 1.2-m (4 ft) long, drilled in the middle of the seam at right angles to the coal face. Each blasting hole was sealed by

Fig. 9. Processing reflected Love waves with a bandpass filter and wavelet transform.
a 61-cm (24 in.) long plug of stemming clay, which was tightly tamped against the borehole bottom.

2. Analysis of transmitted and reflected Love waves

The ISS-based void detection technique relies on the travel time information of Love waves. Unlike body waves, for which the velocities can be assumed constant for most engineering applications, the travel velocity of Love waves is a function of the associated signal frequency, a phenomenon known as dispersion. Since the dispersion characteristics are governed by site conditions, such as seam height, and densities and S-wave velocities associated with both seam and country rock, field studies are essential in order to acquire this site sensitive information. As a result, signal analysis in ISS-based void detection technique is usually a two-step process. The first is to determine the dispersion characteristics of Love waves associated with the site under study. Since this study relies on transmission data, a transmission survey is an essential and important part of the ISS-based void detection technique. The second step is the identification of the reflected Love waves from the reflection survey.

2.1. Love waves observed at the Harmony Mine site

In order to determine the dispersion characteristics of Love waves associated with the Harmony Mine site, a detailed transmission survey was carried out. This included a total of 28 surveys with sources located at the five general locations (Fig. 3). Love waves were observable from all surveys and many of them, such as event 89, were well defined.

By design, event 89 was a reflection survey. The layout of the survey is shown in Fig. 5, where R8 denotes the location of the seismic source which is 40 g of dynamite. Two sets of ray paths are shown in the figure. One (AC) is for the transmitted Love waves from R8 to the sensor array, and another one (ABC) is for the Love waves reflected from the other side of the pillar. The focus at this point is transmitted Love waves.

The waveforms of the transmitted signals are presented in Fig. 6, where Fig. 6a is the original record and 6b is the original signal processed by a 200–600 band pass filter. The trend of the Love waves is quite evident even for the original one. For the convenience of discussion, two bands were marked in Fig. 6b. The first one is S-waves transmitted in coal. The width of this band is nearly constant. The second band delineates the approximate location of Love waves with the Airy-phase at the center. This band clearly shows a dispersion effect: the band is getting wider as the distance increases. The figure also shows that Love waves are quite resilient. In comparison with the body waves which arrive earlier, these Love waves have a relatively high amplitude and a much longer duration. A close-up

![Fig. 9 (continued)](image-url)
of these Love waves also shows that even their appearances are very similar (Fig. 7).

2.2. Characteristics of dispersion curves

Theoretically, Love waves may travel with a wide range of velocities, from a low value somewhere about 70% of the S-wave velocity of the seam to an upper limit equal to the S-wave velocity of the country rock (Arnetzl and Klinge, 1982). For the ISS-based void detection, one is interested in the dispersion curve with the velocity near and below the seam S-wave velocity. The velocities above the S-wave velocity of the seam are highly unstable and have no practical application in the ISS-based void detection technique. Because of this, the dispersion curve for the Harmony Mine site was restricted to a section where the velocities are near and lower than the S-wave velocity of the seam. Such an example is given in Fig. 8.

The dispersion curve in Fig. 8c is representative for the Harmony site. The original waveform and the zoomed Love wave portion are given in Fig. 8a and b, respectively. The shape of the Love wave shown in Fig. 8b is typical for the Harmony site. It is also typical from a theoretical point of view: a relatively high-amplitude, high-frequency component preceded by a series of low-amplitude, low-frequency components. The former is known as the Airy phase.

In general, the Love waves observed from the transmission surveys had a frequency range of 300–900 Hz with a velocity range of 1372–914 m/s (4500–3000 ft/s). The typical frequency range for the Airy phase is 400–600 Hz. The velocity for the Airy phase, however, is quite stable, with a typical value of 975 m/s (3200 ft/s).

2.3. Identification of reflected Love waves

After the dispersion characters of Love waves are determined, the next step in the ISS-based void detection technique is to identify reflected Love waves. Because reflected Love waves are, in general, much weaker than the transmitted ones, various processing methods, such as band pass filters, have to be used to enhance their appearance. For the test site at the Harmony Mine, a 200–600 Hz band pass filter was found adequate for most cases. As an example, the original reflected signals of event 89 are presented in Fig. 9a. Although the trend of the reflected Love waves is detectable, as shown by a dashed line, it is weak. However, the trend becomes much clearer after applying a 200–600 Hz band pass filter (Fig. 9b). The trend may be further enhanced or studied by other methods, such as cross correlation, hodogram and wavelet analysis. Fig. 9c is the result of a wavelet transform.

3. Void mapping

After the reflected signals have been identified and their arrival times have been determined, the next step is
void mapping. Conventionally, delineating a structure by the ISS technique relies on the method of signal stacking. In order to use a stacking method, receivers and sources have to be on a straight line and to be equally spaced. These conditions are generally not met during ISS based void detection. At the test site, two source locations used for reflection survey were not in line with the sensor section and one of these was significantly off the line. In fact, due to the site constrain, even the sensors were not on a straight line and were spaced irregularly.

The elliptical mapping method is inherently compatible with the conditions associated with the ISS-based void detection technique (Ge, 2006). The principle of the method is illustrated in Fig. 10. It is known that reflection surveys rely on two pieces of information: locations of seismic sources and receivers, and signal travel distances between sources and receivers. If we consider a source and a receiver as the foci and use the signal travel distance as the sum of the distances, it is immediately known that an ellipse is uniquely defined and that the reflection point must be on the ellipse. According to the analytical geometry, the ellipse not only defines the trace of the potential reflection point, but also the direction of the reflector, which is the tangent line of that point. Therefore, the void boundary is delineated by the common tangent line to these ellipses.

In order to use the elliptical mapping method, it is necessary to utilize three pieces of information: sensor and source coordinates, signal travel time, and the corresponding velocity. As an example, the mapping data associated with event 89 are listed in Table 1. The travel times are the differences between the signal arrival and initial times. The travel distance is the product of the travel time and the velocity. The velocity of the site specific Airy phase used for the calculation is 975 m/s (3200 ft/s). The mapping result is presented in Fig. 11 which shows that the void boundary at AB was delineated fairly accurately, within few meters in this case.

The elliptical mapping method offers a number of advantages for the ISS-based void detection technique. First, it is very flexible in accommodating various site conditions as it places no requirement on the locations of sensors and sources. Second, the method is robust for data processing in that it can utilize all reflected signals for void mapping regardless of the locations of sources and receivers, the type of signals, and the survey sequence. Third, as the method represents the reflection data directly, it avoids many mathematical manipulations.

Fig. 11. Void mapping with the elliptical method using Event 89 data. (The locations of the sensor array and the seismic source are denoted by Sensors and R8, respectively. The void line is denoted by vv'.)
which may otherwise be required. Finally, the method is simple, intuitive, and easy to use.

4. Conclusions

An ISS-based void detection technique was tested at the Harmony Mine, an anthracite mine located in Pennsylvania. The testing site was a 46-m (150 ft) wide pillar, where the coal seam varied from 0.9 to 1.8 m (3–6 ft) and was sandwiched between massive sandstone roof and floor.

The characteristics of Love waves were studied through the data from the transmission survey, which ranged from 46 to 61 m (150–200 ft). Love waves were readily observable for most cases without using a filter. Dispersion curves, which were abstracted from individual traces, were analyzed. The study of the dispersion curves showed that the Love waves at the Harmony Mine site had a frequency range of 300–900 Hz with a velocity range of 1372–975 m/s (4500–3200 ft/s). The Airy phase had a typical frequency range of 400–600 Hz with a fairly stable velocity of 975 m/s (3200 ft/s).

The reflected Love waves were much weaker than the ones observed from the transmission survey and had to be processed to enhance their appearance. For the Harmony site, a 200–600 Hz band pass filter was found suitable for most cases.

The elliptical mapping method was used for void delineation. This method is useful for ISS based void detection due to its flexibility to accommodate irregular locations of sensors and sources. In addition, the method offers several other advantages, such as its robustness in data processing, and its simple means of representing data. It is not only easy to used but also avoids heavy mathematical manipulations. The mapping error at the site was in the order of ±4.6 m (15 ft).

The retrievable sensor installation technique made it possible to acquire broadband and high quality signals, which was critical to the success of the project.

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