Evaluation of Mine Subsidence Conditions using Borings and Downhole Investigation Techniques

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ABSTRACT

A properly planned and executed mine subsidence investigation is critical to understanding subsidence issues and mitigation. Typically, it includes:

- Desktop assessment of potential subsidence types, such as if sinkholes from roof falls or trough subsidence from pillar failure, or both could occur.

- Developing an investigation program to assess subsidence varies with the anticipated subsidence type(s) as follows:

  - Sinkholes – Borings typically target open rooms and conditions where sinkholes are more likely to develop.

  - Troughs – Separate borings typically target pillars to assess if crushing has occurred and an adjacent room to assess mined conditions and caving.

- Drilling borings using coring or air rotary, or in combination with each other. In addition to obtaining samples of the subsurface materials, valuable information can be obtained during drilling, such as the presence of voids being indicated by tool drops and fractures and voids indicated by the loss of water or air return. All borings should be cased in the soil zone to allow for further investigation with downhole techniques and mitigation. Borings should also extend into the mine floor and into harder rock units if pillar punching is an issue.

Downhole techniques to supplement borings include:

- Downhole geophysical techniques
- Borehole camera
- Cavity scanning
- Borehole sonar
- Borehole imagery
- In-Seam

The information obtained from the investigation can then be used to assess if subsidence has occurred or not, future subsidence deformations, and mitigation options and quantities.

In summary, a mine subsidence investigation needs to consider expected mine subsidence types, mine conditions, and information needed to assess subsidence and mitigation.

1. Introduction

A properly planned and executed mine subsidence investigation is critical to understanding subsidence issues and mitigation.

2. Mine subsidence background

"Mine subsidence is the downward movement of the ground surface due to gravity in response to a loss of support at mine level. The ground surface and whatever is constructed upon it is supported by a structural system that comprises the overburden (the soil-mantled sequence of rock strata situated between ground surface and mine level), the coal pillars, and mine floor. Excessive deformation or failure of one or more of these components over time can result in mine subsidence." (Bruhn et al., 1978). Subsidence can occur as sinkholes or troughs, as shown on Figure 1. Ground cracks can sometimes form around troughs.

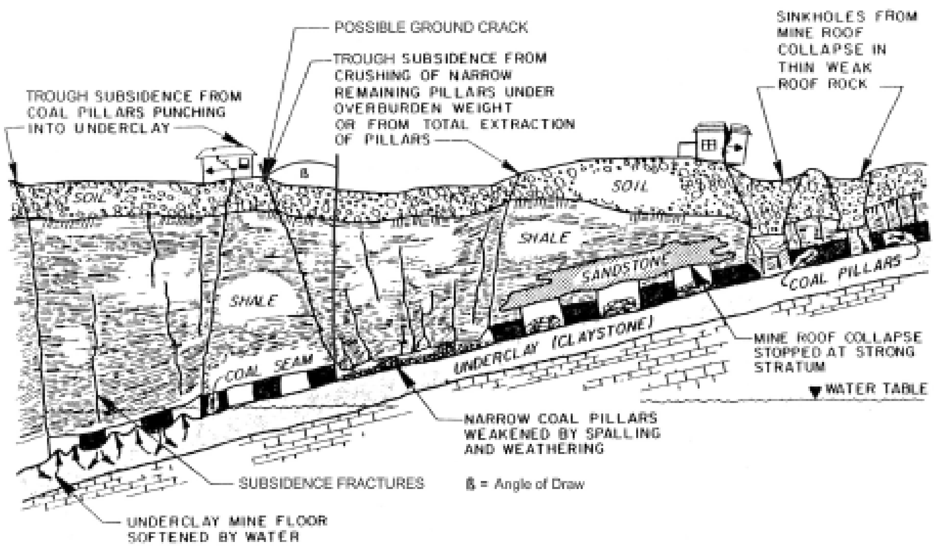


Figure 1 Types of subsidence (modified from Bruhn et al, 1978)

3. Desktop Assessment

Desktop assessment should include review of potential subsidence types, sinkholes from roof falls or trough subsidence from pillar failure, or both may occur. Obtaining information on over - burden thickness, rock types, geologic structure, mining conditions, and previous subsidence events will help with this assessment. Tying the mine map to the surface is a key task. If coordinates are available, they can be used to tie the mine map to the surface. If they are not available, surface features, such as roads, streams, oil and gas wells, and mining infrastructure can be used.

4. Investigation Planning

Developing an investigation program to assess subsidence varies with the anticipated subsidence type(s) as follows:

- Sinkholes – Borings typically target open rooms and conditions where sinkholes are more likely to develop.

- Troughs – Separate borings typically target pillars to assess if crushing has occurred and an adjacent room to assess mined conditions and caving.

In addition, a variety of conditions can be encountered at mine level as shown in Figure 2.

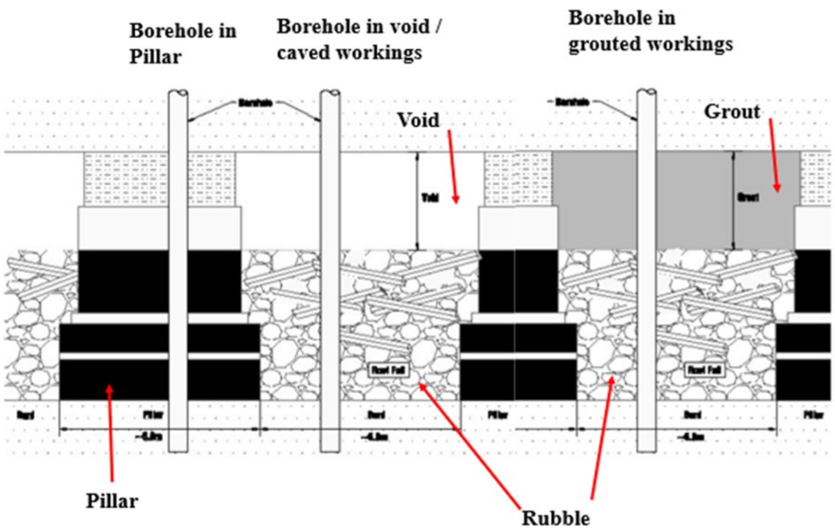


Figure 2 Typical mine level conditions encountered in drilling (Knott et al, 2016)

Some safety considerations also need to be considered at this time, such as:

- Gases that are potentially explosive and / or dangerous may emanate from the borehole;
- Artesian water from the mine workings may be encountered; and
- Sinkholes can occur from soil flowing into a mine void in an uncased borehole.

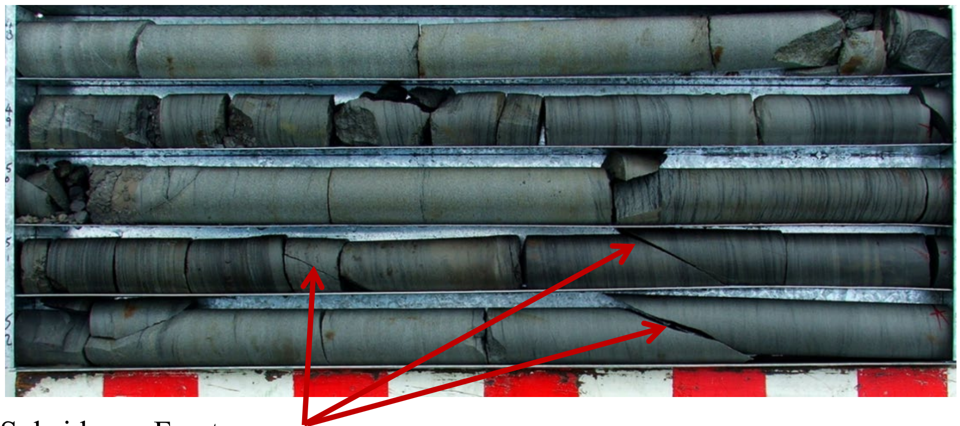
5. Investigation Methods

5.1.1 Borings

Borings are typically drilled using coring or air rotary, or in combination with each other on larger projects. In addition to obtaining samples of the subsurface materials, valuable information can be obtained during drilling, such as the presence of voids as indicated by tool drops and fractures and voids indicated by the loss of water or air return. All borings should be cased in the soil zone to allow for further investigation with downhole techniques and mitigation. Borings should also extend into the mine floor and below soft rock units if pillar punching is an issue.

5.1.1.1 Cored rock borings

In cored borings, rock is generally recovered, allowing an assessment of the rock types, discontinuities, and subsidence fractures. Some downhole techniques can also be used to obtain this information as indicated below. Figure 3 illustrates an example of rock cored where a trough subsidence event has occurred. The boring encountered fracturing above the coal due to pillar crushing at mine level.



Subsidence Fractures

Figure 3 Typical trough subsidence fractures above Borehole Coal Seam, Newcastle, Aus where a trough subsidence event occurred in 1896, shortly after mining, Core depth is 157.5 ft to 173.9 ft (48 to 53m), with the top of the seam at 212.8 ft (64.87 m) (Knott et al, 2012)

5.1.1.2 Air Rotary Borings

As the drill bit grinds up the rock with air rotary drilling, only chips of rock or dust may be recovered; which is why they typically have a lower cost than cored borings. However, they are beneficial in helping to provide data on coal depth, voids, and overburden conditions. An example of air rotary drilling is provided in Figure 4.

Figure 4 Air rotary drilling Note, in many cases a water well drilling rig is used (note dust) Aqua earth website

5.2 Downhole techniques

5.2.1 Downhole geophysical techniques

Downhole geophysical logging is commonly used in resource exploration. It can also be used in mine subsidence assessment / mitigation to:

- Assess seam thickness and pillar crushing by determining the top and bottom of the coal seam in areas of poor recovery;
- Pick up voids and material properties in zones of "no return";
- Assess the effectiveness of subsidence mitigation work, such as the presence of cement fly ash grout in verification holes; and
- Assess if a "void" is open or filled with "soft" material which can impact grout volumes and effectiveness.

Tools that measure density, velocity, borehole deviation, and natural gamma are used in mine subsidence assessments, but due to space constraints, we will focus on density and deviation.

5.2.1.1 Density

Density measurement is the most common and valuable method. It picks up variations in rock density by measuring average density of the material using high energy gamma rays emitted from a source that pass through the rock surrounding the boring following Short and Long spaced travel paths to be measured at two receptors as shown in Figure 5. The tool is useful for distinguishing between voids and coal as they have a lower density than the other rock types as shown in Figure 6.

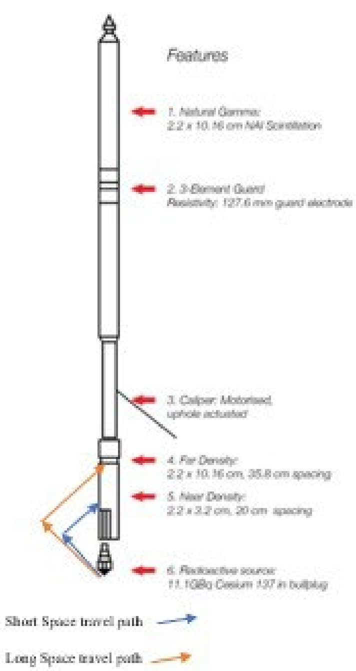


Figure 5 Density Tool

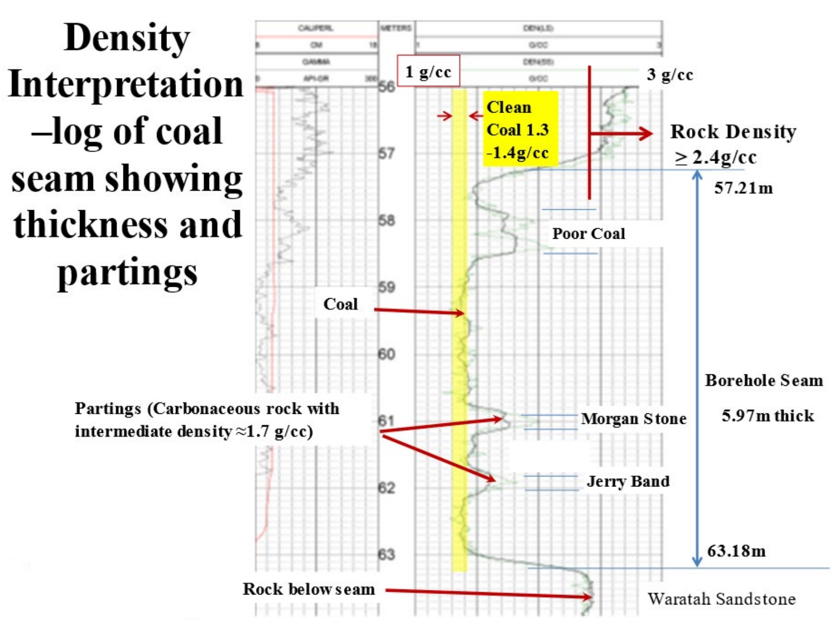


Figure 6 Density Interpretation –log of coal seam showing thickness and partings

Borehole sidewall stability is a key issue in the use of the device as getting a radioactive source lost in a boring is a major issue. This results in the two following cases:

- Unstable Boring – Where the boring penetrates unstable ground, such as caved material from subsidence, the tool is lowered down the casing with the drill rig over the hole to reduce the potential for the tool being stuck in the ground as shown in Figure 7.
- Stable Boring – Where the ground is stable, the device can be used after the boring is completed, provided the soil zone is cased as shown in Figure 8.

If the density is measured through steel casing, the impact of the steel density on the readings must be accounted for in data processing.

Figure 7 Unstable borehole conditions - Lower device through drill rods with rig on the borehole

Figure 8 Stable borehole conditions - Lower device through casing in soil zone after drilling

5.2.1.2 Deviation

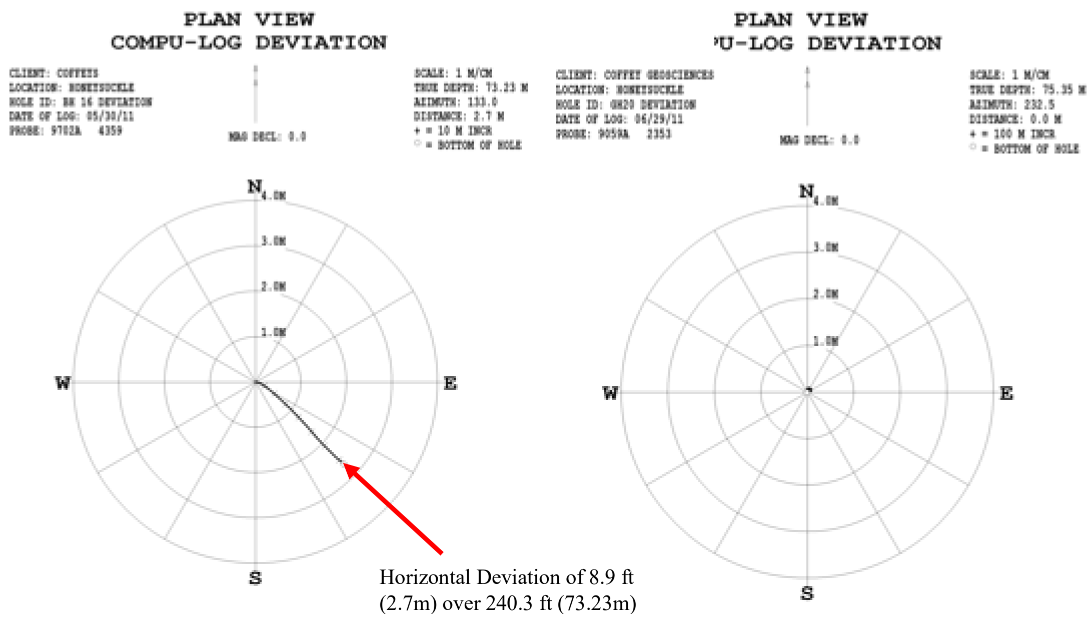
Assessing deviation is important as borings can veer from their intended straight path during drilling due to subsurface conditions such as boulders and / or fractured zones. Also, an accurate location aids in assessing the position of the mine level target with respect to the surface. The device is lowered down the hole and provides measurement of hole position with depth to an accuracy of ± 2° for the bearing and ± 0.5° for the slant angle. The type of device used depends on if the boring is open or has steel casing as follows:

- Open Hole – Magnetic deviation tool

This tool contains a magnetometer and inclinometer package that records the tools inclination and bearing at specific depths. From this data, an azimuth with corresponding inclination which relates to the starting and end-point are calculated.

- Cased Hole - Gyroscope Tool

This tool produces the same basic data as the magnetic deviation package and is processed in a very similar manner except that a gyroscope is used due to the steel casing impacting the readings. An example of the output is provided in Figure 9.



Planned vertical grout hole that missed target due to deviation of 8.9 ft (2.7m at 73.23m) depth during drilling (driller had to redo hole at his own expense)

Grout hole "right on the money" at 240.6 ft (73.35m)

Figure 9 Typical Deviation Plots

5.2.2 Borehole camera

The first author has used borehole cameras on projects since 1987 and found them extremely beneficial in interpreting subsidence and mine level conditions. Conditions in the rock overburden and at mine level can be viewed above and below the groundwater level. For the first author, the real need for using a camera extensively was identified on a mine grouting project in West Virginia in the early 1990s when a 16ft (4.9m) high "void" was reported based on air rotary drilling. It was thought the grout hole would be a "big taker"; however, it took very little grout. Apparently, the hole contained soft material, possibly claystone roof fall and gob (poor material in the coal left in the mine). A camera would have picked up that the "void" was not open, but filled. Borehole cameras are used extensively in Australia. Papers of interest are provided in Pells et al (1988), Rouvray and Davies (2005), Kingsland et al. (2004), Fennell (1997), and Millar and Holz (2011).

The use of an appropriate camera is important. At times, sewer inspection cameras have been used for mine subsidence work due to availability or low cost. However, sometimes the results were not good, as in one case where poor lighting and shadows resulted in images that were so bad that it appeared that more voids were present than encountered during the drilling.

Features of importance for a camera include:

- Hole Size – It should be able to be used in an HQ (3.78 in, 96mm) OD or smaller hole to avoid having to ream out the hole.
- Have a tilting head to allow side and downhole viewing as well as the ability to rotate upwards and view the roof in voids. If a tilting head camera is not available, attachments for simultaneous downhole and side-hole viewing with a mirror, compass and side view lens for void viewing are beneficial.
- Adequate light, as mine voids tend to "soak" up light and many features are lost in the dark. This may require adding better lighting to the camera.
- Ability to focus near (i.e. side of borehole to see rock types and discontinuities) and far (to assess voids and pillar conditions).
- Camera orientation with a compass is useful to map the direction of workings and pillar ribs to tie the workings to the surface.

Current cameras provide color images, such as the GeoVisionTM, which has a rotating head that allows 360° viewing and 170° of tilt as shown in Figure 10 and Figure 11. It can fit in a 1.75 in (44.5mm) diameter hole and has a minimum focus distance of 1.5 in (38mm) and a maximum focus distance of 5 ft (1500mm).

Figure 10 View of camera equipment

Figure 11 View of camera

The camera is useful during the investigation phase to assess caving and mine level conditions, such as the orientation and openness of the workings, and pillar integrity as shown in Figure 12 through Figure 16. The camera also allows the true height of open voids to be assessed, as the roof rock may be pushed down as a result of drilling pressure. Borehole cameras are also of use to assess the effectiveness of grouting as illustrated in Figure 17. Millar and Holz, (2011) also have images of mine level grout placement.

The camera can also be used to assess groundwater conditions. Groundwater inflows can be" friend" or "foe", as small flows may help to clean the sides of the hole, while heavy inflows generally make mine level viewing difficult, as it is like looking through a waterfall.

Several factors that help with viewing are as follows (Knott and Streater, 2017):

1. Case the hole in the soil zone – This helps to keep "mud" from migrating down the sides of the hole in the period between drilling and viewing and keep the borehole open. Note the borehole should also be capped to reduce the potential for material falling into the borehole and reduce air flow in and mine gas flow out of the borehole for safety reasons.

2. Flush the hole with water for flooded and non-flooded conditions, as this helps to remove cuttings from the sides of the hole and flush sediment from the hole. This may lead to quicker viewing time below the water level as there are less particles to settle. Also, if too many suspended solids remain in the borehole, when they settle it will "fill" part of the hole so that the bottom of the hole may not be able to be viewed.

3. For below water viewing, unless good flushing is performed, two days to several weeks may be needed to allow suspended particles to settle. Flocculants have also been used to help settle suspended solids quicker, but environmental impacts need to be assessed. Flowing water in the workings also helps to clear the water as sediments from drilling are flushed from the area of interest.

4. Suspended particles can be easily stirred up and it is better to look at features of interest on the way down rather than waiting to check on the way back up as particles may become resuspended once the camera passes thought them.

5. Adjust lighting as needed to improve viewing.

6. Pan slowly when viewing sideways and pause at features of interest.

Some disadvantages associated with using borehole cameras include:

1. Waiting time for suspended solids to settle.
2. Difficulty judging distance and the size of objects.
3. Some camera operators will not lower device into a void due to a fear of getting it stuck.
4. Debris at mine level, such as rubble, blocking sideways view.
5. Insufficient light, particularly underwater to illuminate features of interest in the distance.
6. Lowering the camera too fast and missing features of interest.

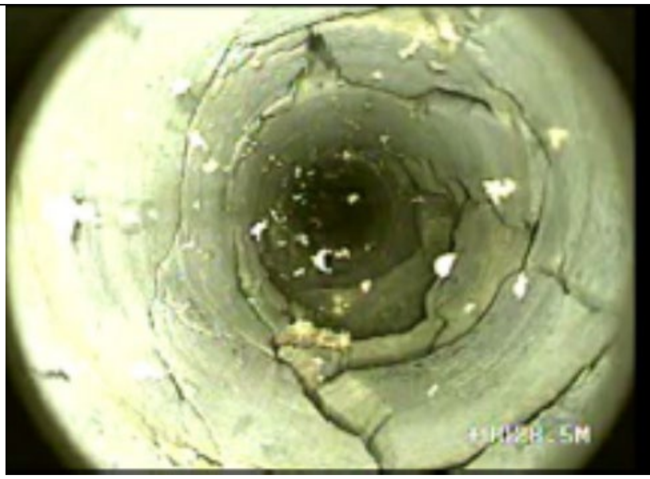


Figure 12 Underwater image of broken rock due to caving (Note suspended particles)

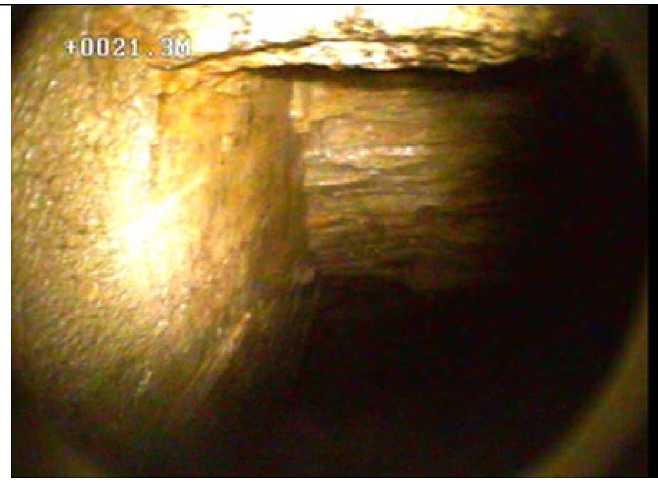


Figure 13 Side view of roof joint intersection in unflooded workings

Figure 14 Borehole encountering edge of pillar and room (underwater)

Figure 15 Downward looking underwater view of in place coal in Yard Seam, Newcastle, Aus at 84.3 ft (25.7 m) depth (borehole encountered

Figure 16 View of light lowered into another borehole about 100 ft (30m) away indicating open haulageway

Figure 17 Grout enveloping conveyor in haulageway (Knott et al, 2013)

5.2.3 Void scanning

Laser surveys are generally conducted in air-filled voids / cavities and sonar surveys in water-filled voids (see next section). Modern 3D scanner technology provides superior qualitative and quantitative information than other cavity survey methods with deployment at any level in boreholes which penetrate cavities, including abandoned mines. The complete tool length does not need to be deployed into most mining cavities; thereby mitigating the risk of getting stuck inside the void. The scanning devices rotate 360 degrees in the horizontal plane and tilt in the vertical plane to produce 2D vertical and horizontal sections, 3D point cloud models and volume estimations. Typically, rotating scans record horizontal sections data in 2° azimuth increments and tilting scans of vertical sections data in 3° increments. The data are viewed in real time. For both systems, the clear "line of sight" survey distance range is 6 inches (150 mm) to a maximum of 196.9 ft (60m) for the laser, and > 656 ft (200 m) for the sonar. Accuracy is 1/1000 of object distance; e.g., ¾ inch (2 cm) for a 65.6 ft (20 m) distant target. The volume precision is typically +/- 1.5%. However, both reduce where the incidence angle on the void wall is small and there are remnant items present, such as pit props, etc.

This survey example is of an abandoned 1930s coal mine slope entry (inclined access) located in an Australian urban area. It was surveyed to establish the physical conditions and dimensions for remediation grouting.

A Flodim SARL high-definition, color video camera and 3D laser tool was used in a 3-3/8 in (96 mm) diameter borehole drilled into the cavity, with the setup of the tool prior to deployment in the cased borehole as shown in Figure 18 and a diagram of features in Figure 19. A sinker bar is attached to the top of the tool to prevent rotation during horizontal section surveys. The data were acquired using a truck-mounted, Century Geophysical LLC-equipped, slimline logging unit.

Video and still images were recorded concurrently with the 3D laser survey which provided valuable information on the physical condition of the slope in real time. Figure 20 indicates physical deterioration with spalling of the slope roof and walls and fallen material on the floor.

The 3D laser survey results indicated that the slope is backfilled to a depth of 17.1 ft (5.2 m) below ground level (mbgl) and it has a volume of 97.8 cy (74.8 m3) (Figure 21). It dips to the east at a grade of 3H:1V or 18° and had a maximum void height of 6.6 ft (2.0 m) (Figure 22) and is oriented east / west (Magnetic North) as shown on Figure 23.

Oriented, superposed horizontal sections shown in the plan diagram (Figure 23) show the areal extent of the slope entry. The width was between 5.9 ft (1.8 m) and 8.2 ft (2.5 m) with widening to 11.5 ft (3.5 m) in one area in the NE quadrant. The inclined length was 79 ft (24 m).

Figure 18 Logging unit setup with laser / video

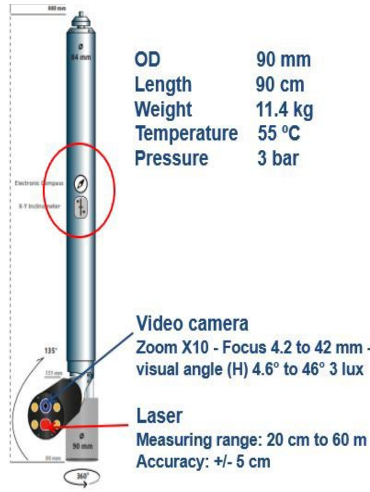


Figure 19 Laser tool diagram

Figure 20 Image from laser / video looking down-gradient from the west.

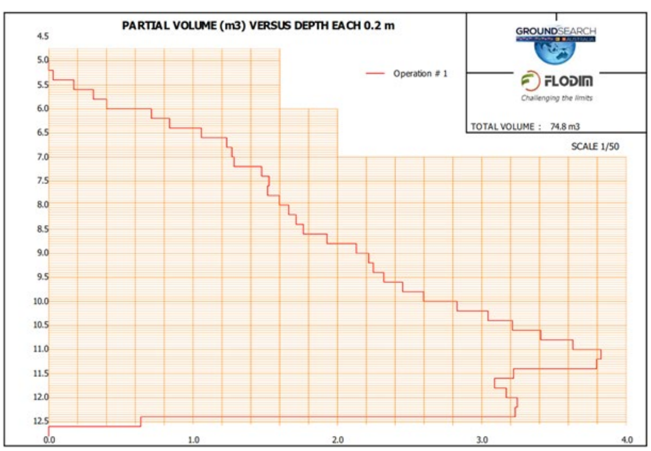


Figure 21 Partial volume (X axis) versus depth (Y axis) at 7.8 in (0.2 m) intervals.

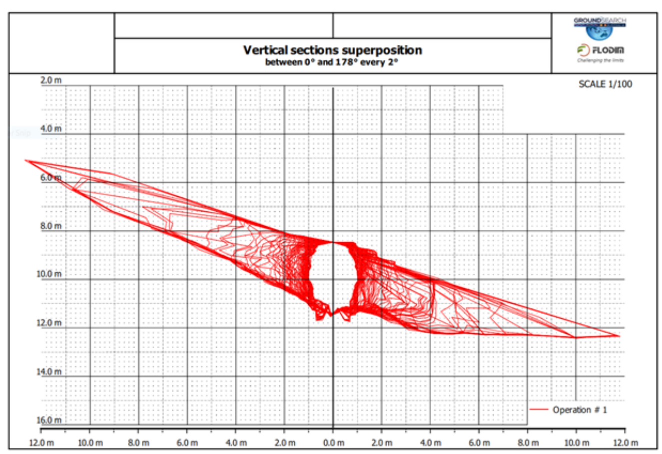


Figure 22 Superposed vertical sections showing the cavity height, distance from survey borehole (X axis) and depth (Y axis).

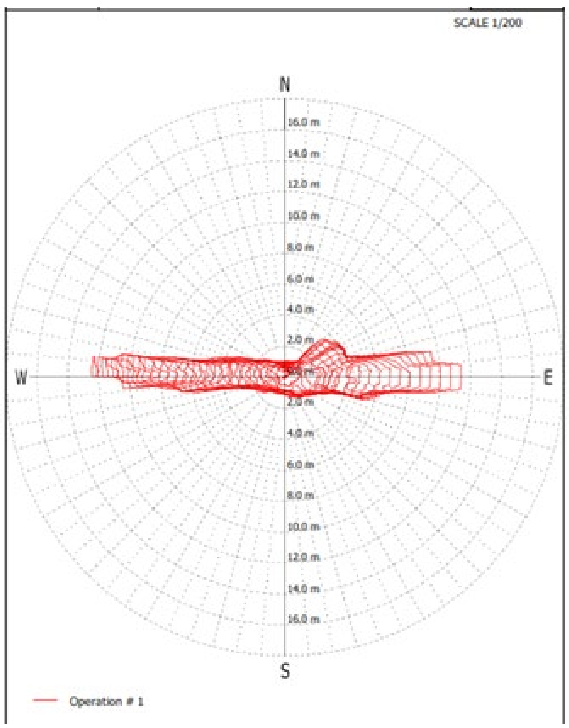


Figure 23 Superposed horizontal sections showing the areal extent and orientation of the cavity.

Models of the cavity were created from digital horizontal and vertical point data cloud slices. Figure 24 represents cardinal point viewpoints. The distance from the survey point is represented in separate coloured zones.

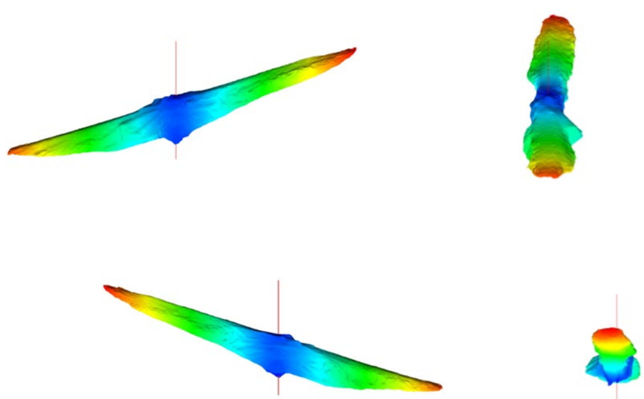


Figure 24 Cavity models – Views in clockwise direction from upper left showing view from North, East, West, and South

5.2.4 Borehole sonar

5.2.4.1 2D Sonar

The sonar device is typically lowered down a vertical hole into a flooded mine void and will scan a horizonal cross-section of the void surfaces in 360° at depths of interest. Voids less than 1 ft

(300mm) high are difficult to image. It should be noted that the imaged void may be in the roof overlying the mined workings and not the mined interval due to roof fall; therefore, it may not give the actual mined width, but the smaller caved width of the roof void. A view of the device is provided in Figure 25 with a view of the output showing the configuration of the mine workings in Figure 26, and a view of the mine map at the corresponding location of the boring indicating a "match" in Figure 27.

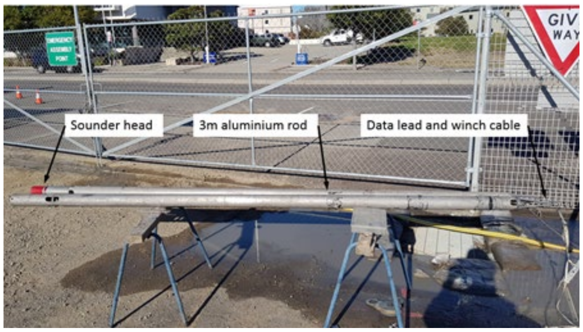


Figure 25 Downhole sonar setup with 10 ft (3m) rod attachment

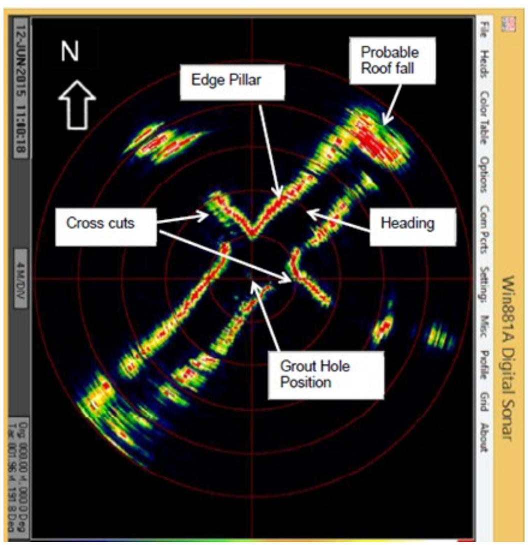


Figure 26 Sample sonar output

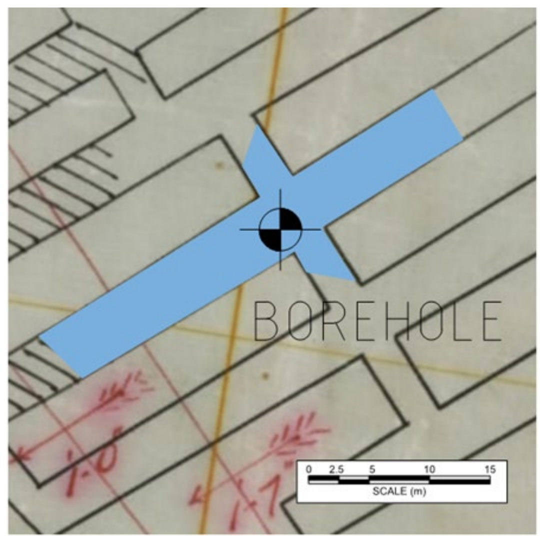


Figure 27 View of mine map corresponding to sonar output

5.2.4.2 3D Sonar

As indicated in a previous section, 3D sonar systems use a scanning to develop a 3D model of the void. They are deployable in >H-size (3-3/8 in (96 mm)) boreholes.

As an example, the device was used in the assessment of a void in abandoned mine workings in the about 20 ft (6 m) thick Borehole Seam, in Newcastle, Australia (Figure 28). The mine workings were completed prior to 1908 and are below sea level and therefore flooded, as mining ended prior to about 1916 (Hawkins and Harvey, 2001). The 3D sonar survey was performed using Flodim SARL 3D sonar technology since the workings were underwater and it could provide an image in areas with poor water clarity. The results indicate that the cavity roof was at a depth of 249.7 ft (75.8 m) and had a maximum void height of 6.6 ft (2.0 m) (Figure 29), the volume of the cavity was 123 cy (94.1 m^3) (Figure 30), and is oriented southwest / northeast (Magnetic North) as shown in Figure 31. The mine workings were flat-lying, as would be expected based on geologic conditions, with all surfaces uneven. The survey took 3.5 hrs.

Figure 28 Sonar survey equipment before borehole deployment.

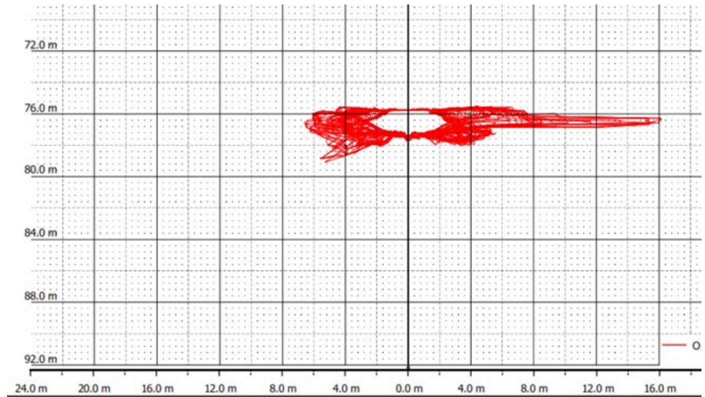


Figure 29 Superposed vertical sections showing the cavity height, distance from survey borehole (X axis) and depth (Y axis).

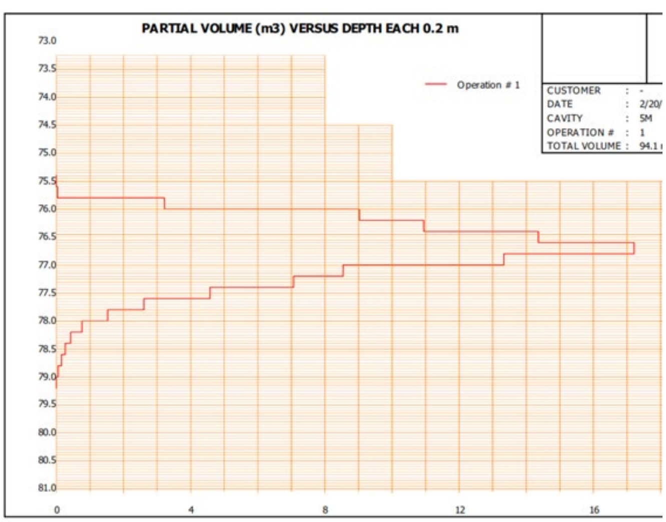


Figure 30 Partial volume (X axis) versus depth (Y axis) at 7.8 inch (0.2 m) intervals.

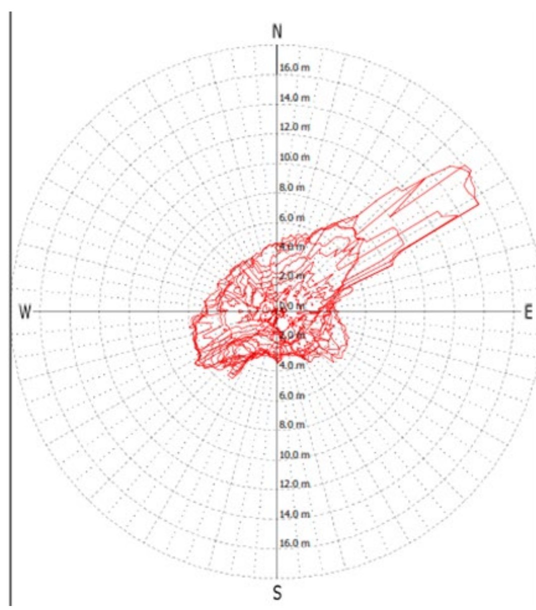


Figure 31 Superposed horizontal sections showing the areal extent and orientation of the mine void between 248 ft (75.6 m) and 258,5 ft (78.8 m) depth.

Models of the void can also be created from digital horizontal and vertical point data cloud slices similar to those previously provided in Figure 24.

Figure 32 shows the sonar data overlaid on the mine map. It indicates that the mine map is accurate in this area. The data provide the detail required to optimize the stabilization of the mine workings, thus resulting in savings to the client.

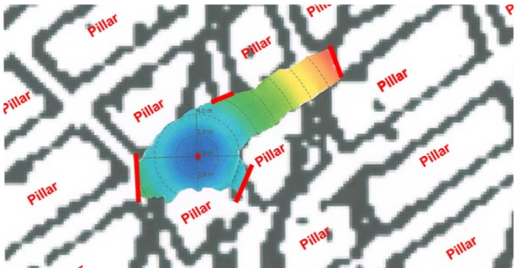


Figure 32 The overhead solid model shows the areal extent and orientation of the void with respect to the mine workings. Mine plan (RC, 1908).

5.2.5 Borehole Imagery

Acoustic Televiewer (ATV) and Optical Televiewer (OTV) scans of a borehole wall are centralized, depth-based, continuous, fully oriented 360° images enabling identification and analysis of planar features such as:

- Lithology characterization;
- Bedding planes (including separations and dip and strike);
- Fractures / joints / cleats (including frequency and orientation);
- Aperture;
- Veins and mineralization; and
- Borehole breakout and other borehole anomalies.

Typical applications include:

- Borehole core orientation / provide information in core loss zones;
- Geotechnical site investigations (including cuts and tunneling);
- Open cut and underground mines;
- Hydrogeology (secondary permeability / casing inspection);
- Structural geology (hydrocarbons and mineral exploration);
- Mine subsidence investigations (overburden characteristics);
- Increased understanding and confidence in computer-generated models.

Acoustic scanners use high-resolution sound waves and operate only in water-filled boreholes without the need for clear water. Logging speeds are 3.3 ft/min (1 m/min) for 2.5/64 in (1 mm) sample interval and 14.8 ft/min (4.5 m/min) for 3/16-inch (5 mm) sample interval. Boreholes with diameters from 3 inch (75 mm) to 9 inches (230 mm) are logged generally. Data are viewed in real time with processing in commercial software.

Optical scanners use a precision, wide-angle lens and a camera to capture a high-definition video image and operate in both air and water-filled boreholes with clear water only. Logging speeds are from 3.3 ft/min (1 m/min) to 19.6 ft/min (6 m/min) depending on required vertical resolution. Boreholes with diameters from 1.9 inch (48 mm) to > 19.6 in (500 mm) are generally logged. The image is oriented to Magnetic North (or to the high side of the borehole) using a 3-axis magnetometer and accelerometer in the tool as shown in Figure 33. The scanner data interpretation procedure is based on the on-screen, manual superposition of sine curves onto features. The height of the sine curve determines the dip and the trough indicates the dip direction. Using automatic picking software to assess discontinuities can miss critical discontinuities. Figure 34 and Figure 35 represent the output from the devices. Data analyses and graphical representations such as contoured plots can be produced.

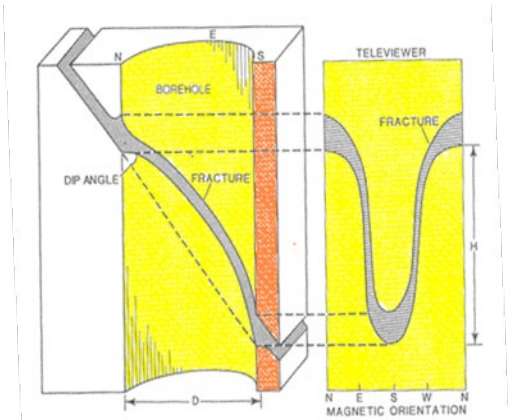


Figure 33 Diagram of borehole feature (left) as represented in flattened, 360° scanner view.

Figure 34 Flattened, 360° ATV image showing fractures in coal measures interburden.

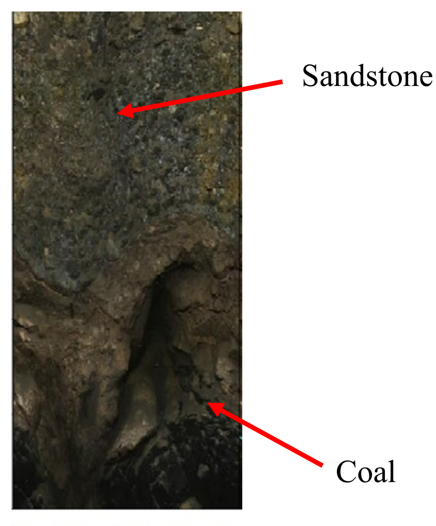


Figure 35 Flattened, 360° OTV image showing overburden and coal seam contact with the top of the coal dipping at 47° in the dip direction of 132° magnetic north.

The scanners are a cost-effective and accurate tool to measure borehole breakout which can be a reliable indicator of the orientation of the in situ, maximum horizontal stress (SH). They can also be seen with a borehole camera.

ATV and OTV surveys provide accurate and reliable identification of planar features that intersect borehole walls providing valuable in situ data in zones of geological, hydrogeological and geotechnical significance. Ultimately these surveys increase data confidence for project design, development and costings.

5.2.6 In-Seam

Radio Imaging Method (RIM) technology uses EM (radio signal) waves between separate borings, one with a transmitter antenna and the other with a receiver antenna, drilled into a coal seam. The signal strength between borings can be used to assess if mining has occurred or not as indicated in Figure 36.

The antennas are lowered to the middle of the seam in both the transmitter and receiver borings, and the signal propagates through the coal seam waveguide as the signal is bounded by the over and underlying rocks due to their differing electrical conductivities. The receiver unit measures the signal strength. It is important to have available accurate seam depth information to position the antennas in the appropriate part of the coal sequence. However, irrespective of the provided depth information, experimentation in the field by the RIM engineer will confirm the position of the antenna in the seam (moving of the probes out of the coal will result in a noticeable decrease in signal strength).

The detection of voids within a coal seam using RIM is based entirely on the waveguide behavior of the coal seam itself. The RIM EM wave travels in a "trapped" mode in the coal between the conductive roof and floor material. The EM wave travels along a "ray path" or "wave front" from transmitter to a companion receiver, decaying in signal strength as a function of distance. In homogeneous conditions, the rate of this decay is consistent and predictable beyond the near field of the transmitting antenna. In a homogeneous coal seam, an EM wave attenuates (decays) with distance traveled at a fixed rate; this is termed the attenuation rate. If a geological anomaly exists along the ray path, the receiving antenna will measure lower signal strength (increased attenuation rate). Geological anomalies that will affect the RIM signal include faults, dikes, paleochannels, seam thinning, and increased water in the seam. Non-geological anomalies that may affect the RIM signal include abandoned mine workings. If a portion of that seam waveguide is water-filled or air-filled, the rate of decay changes.

The RIM downhole instrumentation consists of a multi-frequency transmitter and receiver units designed for borehole applications. The antennas consist of wound ferrite cores powered by downhole batteries and phase linked by a fiber-optic synchronization cable. The field procedure is to set up transmitter and receiver units in adjacent boreholes and measure the decay of the RIM signal over distance (the "measured signal strength").

In general, RIM equipment should be deployed into vertical boreholes lined with PVC casing, never metal casing. Casing prevents damage or loss to the system resulting from hole collapse or debris. If the geology is exceptionally competent, the probes can be used without PVC casing.

The borehole depths can be a minimum of 20 ft (6 m) and a maximum of 1500 ft (457 m). (Note this section was based on information extracted from Stolarczyk and Peng (2003)).

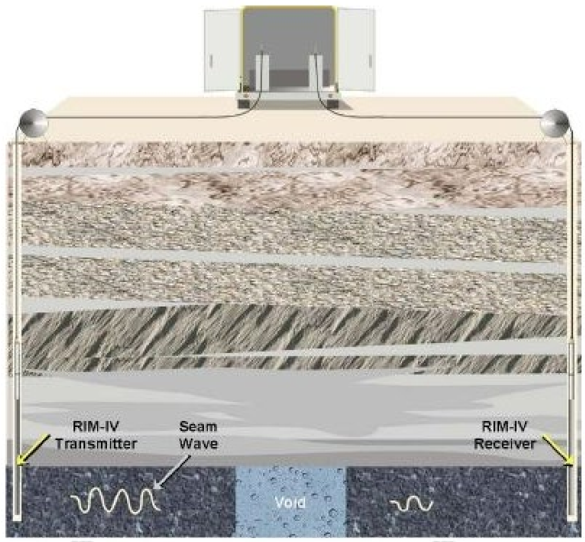


Figure 36 Illustration of the RIM setup and EM wave propagation

6 Assessment of Subsidence

The information obtained from these techniques can then be used to assess if subsidence has occurred or not, and help assess mitigation options and quantities. For example, an accurate measure of coal seam thickness can indicate if a seam has been crushed or not and void height and extent can be obtained.

7 Summary

In summary, a mine subsidence investigation needs to consider expected mine subsidence types, mine conditions, and information needed to assess subsidence and mitigation. The following tools can be used to supplement the information obtained from borings:

- Density - Assess rock types and the presence of voids and coal seams and the presence of grout;
- Deviation – Assess boring drift with depth;
- Borehole Camera – View the strata encountered in the boring, including fractures and mine level conditions;
- Laser surveys - Provide a 3D image of air-filled voids; workings are generally conducted in cavities and: sonar surveys in water-filled cavities. Laser and sonar data can be combined into a single model as can multiple location surveys. In addition, the 3D laser and sonar technologies are important tools for the cost-effective, remote determination of the in-situ void conditions and dimensions thereby enabling a highly accurate void volume determination for subsequent assessments.
- 2D sonar – Used to assess the extent of underwater voids, with the data taken in horizontal planes.

- 3D sonar – Used to assess the extent of underwater voids, with the data taken in all directions.
- Borehole Imagery – Can be used to provide data such as strike, dip, and width of discontinuities encountered in the boring.
- In-Seam – Can assess if mining has occurred between two borings.

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