Mine Void Detection Demonstration Projects

George H. Gardner, PE
Senior Civil Engineer
Mine Safety and Health Administration
Mine Waste and Geotechnical Engineering Division

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Lebanon, Virginia
Presentation Outline

• Mine Safety and Health Administration (MSHA)
• Impetus for Void Detection Demonstration Projects
  – Problems with abandoned mine voids of unknown location and extent
    • Subsidence Events
    • Impoundment Breakthroughs
    • Mine Inundations
• Demonstration projects

Reports on MSHA website:
High-Profile Incidents Related to Underground Mines

• Impoundment Breakthrough Incidents
  – Miller’s Cove, Lee Co. VA, August, 1996
  – Miller’s Cove, Lee Co. VA, October, 1996
  – Buchanan, Buchanan Co. VA, November, 1996
  – Big Branch, Martin Co., KY, October, 2000

• Mine Inundation
  – Quecreek No. 1 Mine Inundation and Rescue, July 2002
Martin County Coal Company

Big Branch Refuse Impoundment

October 2000

Approx 300 Million Gallons of Coal Slurry Released
Discharge Exited Mine at No. 2 North Portals

Approx. limit of inundation in North Mains

Discharge Exited Mine at South Mains Portal
South Mains Portal

Eroded by slurry discharge
Coldwater Creek
Reuter - Oct. 18th - “A massive spill of slowly spreading coal slurry triggered water shortages and school closings across eastern KY...prompting the governor to declare a state of emergency.”

“Communities throughout the affected 10 county area were forced to close off water intake pipes.

“Some public schools were forced to close indefinitely pending restoration of safe water supplies...
Example of potential for breakthrough created by mine workings located near an impoundment.
October 11, 2000 -- Once the breakthrough was discovered, dozers were used to push overburden into the impoundment to attempt to stop the discharge.
## Abandoned Coal Mines

<table>
<thead>
<tr>
<th>State</th>
<th>No. of Abandoned Mines</th>
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<tbody>
<tr>
<td>Kentucky</td>
<td>150,000</td>
</tr>
<tr>
<td>West Virginia</td>
<td>100,000</td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>40,000</td>
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<tr>
<td>Virginia</td>
<td>6,000</td>
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Impoundments and Mining

• 220 Impoundments in Appalachia built over or adjacent to mine workings.
• MSHA rated and prioritized impoundments in terms of potential and consequences of failure.
• 54 Sites had a high potential for breakthrough.
• One of the greatest challenges is to determine the extent of mining. In many cases mine maps have proven to be unavailable, inaccurate, or incomplete, especially near the outcrop.
• Mine Operators were required to evaluate potential for breakthroughs and design to prevent them.
Congressional Study

• National Research Council, Committee on Coal Waste Impoundments.
• $2,000,000 Budget.
• Assembled team of experts.
• The council recommends that demonstration projects using modern geophysical techniques be funded, and that results be widely conveyed to the mining industry and to government regulatory personnel through workshops and continuing education.
High-Profile Incidents Related to Underground Mines

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#1 Rescue Well

Approximate Location of 6" Drillhole

1 Left Section
No. 1 Borehole Drilling
Started at 8:00 PM, Breaks into Mine at 10:16 PM

No. 2 Borehole Drilling
Stopped 204 Feet

204 Feet  240 Feet
Active Mines: Inundation Accidents
Magnitude of the Problem

- From 1995 through June 2002, mine operators reported 181 mine inundations.
- Of these, at least 107 were unplanned cut-throughs that resulted in water inundations.
House/Senate Conference Agreement

"$10,000,000 for digitizing mine maps and developing technologies to detect mine voids, through contracts, grants, or other arrangements, to remain available until expended."

- MSHA Allocation:
  - $3.9M to Mine Mapping
    - Grants to States
  - $6.1M to Void Detection
    - Contracts
    - Projects to Demonstrate available technologies for void detection.
Mine Mapping

$3.9 million in State Grants to establish an electronic system of collecting, georeferencing, digitizing, and delivering underground maps for abandoned mines, helping to ensure miner safety nationwide.

– West Virginia $1.2 Million
– Kentucky $1 Million
– Pennsylvania $1 Million
– Virginia $317,000
– Ohio $52,000
– Utah $52,000
– Illinois $52,000
– Indiana $52,000
– Colorado $51,000
– Alabama $51,000
– Maryland $50,000
– New Mexico $50,000
– New York $25,000
U.S. DEPARTMENT OF LABOR
MINE SAFETY AND HEALTH ADMINISTRATION
1100 WILSON BOULEVARD
SUITE 2132
ARLINGTON, VIRGINIA 22209-3939
Request for Proposals
Geo-physical Void Detection Demonstrations
RFP# MSHA J53R1011
Darrell A. Cooper, MBA, CPCM
Director,
Acquisition Management Division
(202) 693-9831
Fax (202) 693-9826
cooper.darrell@dol.gov
Purpose: “The U.S. Department of Labor, Mine Safety and Health Administration is seeking sources to conduct demonstration projects for advancing the current state of technology in detecting underground mine voids.”
Timeline of Demonstration Projects

- Pre-solicitation Notice
- Request For Proposals
- Objective Scoring System Developed
- MSHA Contracted with outside technical reviewers
- Review Teams Formed
  - MSHA Representative
  - Other Government (generally USACE) Representative
  - University Professor of Geophysics
- Initial Selection process (5/26/2004)
  - 11 Respondents to receive further consideration
- Negotiations on scope and price
- Final Selections
- Project Execution (2004-2007)
- Project Completion (2007)
Response to RFP

- 58 Proposals
- 23 Sources
- Methods Covered
  - Surface Seismic Reflection
  - Inseam Seismic Reflection
  - DC Resistivity
  - Seismic Land Streamer
  - Synthetic Aperture Radar
  - Underground Electromagnetics
  - Microgravity
  - SASW
  - Ground-penetrating Radar
  - Look-Ahead Radar
  - Forward-Looking Seismic
  - Mobile Field Robotics (dry voids)
  - Mine Fish (wet voids)
  - Gravity Gradiometer
  - Time Domain Electromagnetics
  - Airborne Electromagnetic Conductivity
  - Drillstring Radar
  - MASW
  - 3-D Sonar
  - Cross-hole Seismic Tomography
  - Radio Imaging
  - 3-D Downhole Laser
  - Residual Potential Mapping
14 Selected Projects

- Surface Seismic Reflection (2)
- Borehole Seismic Tomography (2)
- Vertical Seismic Profiling (1)
- In-seam Seismic (ISS) (various seismic sources/receivers) (4)
- Electrical Resistivity (1)
- Time Domain Electromagnetics (1)
- Look Ahead Radar (1)
- Borehole Radar Tomography (1)
- Delta EM Gradiometry (1)
Elements of Each Project

- Site Selection
  - To address particular issue
    - Strata
    - Depth
    - Void Characteristics (air-filled, water-filled)
  - Partnered with Mining Company
- Demonstration of Technology
- Post-processing of Data
- Ground-Truthing / Field Verification
- Draft Report
- Review
- Final Report
- Dissemination of Information
Surface Seismic Reflection

**Advantages:** No interference with active mining operation, relatively low cost.

**Disadvantages:** Surface Access issues, terrain above the mine can complicate data collection/processing, background “noise” from the mine, attenuation of signal through soft surface deposits.
Surface Seismic Reflection

Blackhawk (Division of Zapata Engineering)

- 2-D surface array of geophones (1050 x 150 feet) was to create a 3-D view at the coal seam.
- Unique seismic source actuator created both P (compression) and S (Shear) waves.

L.M. Gochioco & Associates

- Single line of geophones were set at equally spaced intervals along the ground surface.
- Seismic source was created by a “seisgun,” which consisted of a pipe inserted into the ground with a 12-gauge shotgun shell discharged through the pipe.
Field Demonstration Results – Surface Seismic Reflection

- Surface ranged from flat with minor vegetation to rolling/steeply sloping with areas of heavy vegetation. Depth to coal seam was between 220 – 270 feet. Both demonstrations were over flooded mines.

- **LM Gocchioco:** Mine boundaries were successfully detected. Individual entries could not be discerned.

- **Blackhawk:** Mine boundaries were successfully detected. Anomalies outside mine works that couldn’t be fully explained.
Advantages: Does not interfere with active mining operation.

Disadvantages: More labor/cost intensive than surface techniques, surface access issues, background “noise” from the mine.

Coal seams and voids are detected using the velocity contrasts measured versus the surrounding strata.
Borehole Seismic Tomography

Blackhawk (Division of Zapata Engineering)
- Hydrophone receivers were lowered down one borehole and a seismic source is generated at various depths in another borehole.
- Distance between boreholes was between 160 – 200 feet, depth was 80% of seam depth.
- Testing performed at a coal mine in Illinois

Colorado School of Mines
- Technology was the same, but holes were separated by 35 feet and were drilled to full depth of target void (11’X11’).
- Test was run at a hard rock mine (Edgar Experimental Mine)
Field Demonstration Results – Inseam Seismic

• Surface ranged from flat to gently sloping.

• **CSM:**
  – Flooded void was detected, the elevation was off by 3 feet.
  – Dry void was detected, the elevation was off by 8 feet. (Borehole Spacing 35 feet)

• **Blackhawk:** tests with borehole spacing approaching 200 feet was unsuccessful. No mine voids were detected in this project.
VSP & RVSP

**Advantages:** No interference with active mining operations.

**Disadvantages:** More labor intensive than strictly surface techniques, Right-of-entry issues, background “noise” from the mine.

Approximate Borehole Spacing 1 to 2 x Target Depth

Multiple lines of boreholes and geophones can be deployed to provide subsurface 3-D images

- Geophone
- Seismic Source
- Reflected Wave Path from RVSP

| Void       | Coal Seam |
Vertical Seismic Profiling & Reverse Vertical Seismic Profiling

L.M. Gochioco & Associates (VSP)

• Hydrophone receiver string in borehole and a seismic source is generated along the ground surface.
• Seismic source on surface “seisgun,” which is a pipe inserted into the ground and a 12-gauge shotgun shell fired through the pipe.

Blackhawk (Division of Zapata Engineering) (RVSP)

• Seismic source was lowered down a borehole and activated at different elevations. The geophone receivers were set up in a single line along the ground.
• The seismic source was an air gun actuated by an air compressor.
  – Generated both P and S waves.
Field Demonstration Results – VSP/RVSP

• Surface was flat with minor vegetation. Seam depth ranged from 150 – 260 feet. All voids were flooded.

• Gocchioco (VSP): demonstration used sources spaced at 50 foot centers and geophones at 3 foot intervals extending up 100 feet from target depth. Voids were undetected with boreholes at 80 feet and 50 feet away.

• Blackhawk (RVSP): demonstration used geophones spaced at 10 foot centers and source was activated at 5 foot intervals within a borehole 80% of target depth. Voids were detected with boreholes between 25 – 35 feet away to an accuracy of 3-5 feet.
Blackhawk
(Div. of Zapata Eng.)

Data depicted in this slide includes only the solid green line.
Four of the demonstration projects involved variations of inseam seismic reflection.

**Advantages:** Simplified data processing (homogeneous material – channel waves).

**Disadvantages:** Impact on mining operation may need to be considered. Safety of contractors working in the mine.
In-Seam Seismic Reflection

L.M. Gochioco & Associates
Geophones mounted in the face and ribs. Seismic source was created by striking a plate on the coal rib with a sledge hammer.

Penn State University
Geophones mounted in the face and ribs. Seismic source created by detonating a blasting cap within the rib. Demonstrations at Pennsylvania Anthracite mine and Wyoming Trona Mine.

Marshall Miller & Associates

Coal Outcrop

Seismic Energy

Transmitted Ray

Reflected Ray

Geophone (string)

Inaccessible Mine Void

Coal Barrier

Triggering Device

Seismograph
Geophones mounted across the margin between active mine and abandoned mine.

Seismic vibration associated with the underground mining (continuous miner) passively recorded across the string of geophones.

Conceptually based on successful prior investigations done with Tunnel Boring Machines (TBM)
The red line indicates the geophone number in which this data was collected.

Black arcs represent the scattered waves being reflected up from the old mine voids.

Blue line represents the direct wave arrival at this geophone.
Field Demonstration Results – Wright State - Inseam Seismic

• Flooded mine entries were detected within 90’ at a distance of 1200’.

• Dry mine voids were not successfully detected.
LM Gocchioco In-Seam Seismic results

- Target mine works (#6 seam) is black dashed lines

- Pink outline of #7 seam works, 45’ above #6 seam

- 1200’ avg. horizontal distance to #6 works

- #7 seam works reflected better than #6 seam (G, see notes below)
Blue dots are the measured reflection points of the #7 seam old mine works (dashed outline)

#7 reflection results were highly accurate, although the #6 seam works was original target
Field Demonstration Results – Gocchioco - Inseam Seismic

- Generally successful in detecting mine voids at distances between 200 and 1000 feet away.

- In one case, erroneously detected mine voids in an overlying mined seam.
Figure 10: Stacked In-Seam Reflection Line 2
(Combination of 37 Individual Edited Reflection Gathers)

Zone exhibiting Strongest Stacked Reflections

ISR Line 2 Stack
In seam seismic projection – line 2 results
Field Demonstration Results – Inseam Seismic

• **Pennsylvania State University:**
  – Air-filled mine voids were detected (within 30 feet) at a distance of 400 feet at an anthracite coal mine.
  – Air-filled mine voids were not detected at distances of 300-400 feet at two bituminous coal mines.
  – Both air-filled and water-filled entries were detected (within 40 feet) at a distance of 1700 feet at a trona mine.

• **Marshall Miller Associates / Virginia Polytechnic Institute:**
  – flooded voids were not detected.
  – Air-filled voids were detected, but distances were not reliable. This was reportedly due to the angle between the outcrop and the abandoned mine boundary.
Electrical Resistivity

**Advantage**: No adverse impact on the mining operation. Can be effective when run vertically from above the mine or horizontally from coal outcrop (around refuse impoundments).

**Disadvantage**: Effectiveness of the technology decreases with depth, if water is not present in/around the void and with complicated terrain.

D’Appolonia Engineering,
Division of Ground Technology Inc.

This project applied a surface-based method that measures the response of sub-surface materials to induced electrical currents to detect underground mine voids. By deploying electrodes on the ground surface, inducing electrical current into the ground, and measuring the voltage difference at the receiving nodes, the resistivity of sub-surface materials were measured and compared to known resistivities.
Electrical Resistivity Current Electrode and Survey Line
SYSCAL Junior Resistivity Meter and Data Collector
Partially flooded mine voids identified by electrical resistivity survey (shown as blue/green) and confirmed by drilling.
Damp or dry mine voids not readily discernable from solid coal.
RESISTIVITY DISTRIBUTION OBTAINED FROM USING THE WENNER CONFIGURATION ALONG EXPERIMENTAL DC RESISTIVITY PROFILE CC-1 FOLLOWING THE OUTCROP OF THE LEWISTON COAL (for additional information see D'Appolonia, 2006)

LEGEND
- Red triangle: Corehole
- Blue dot: Air rotary boring
- Red dot: Air rotary boring with mine void

Layout of mine entry from laser imaging system surveyed by Workhorse Technologies - note that results identify a previously unknown tunnel extending into area of resistivity anomaly.
Field Demonstration Results

- Ground surface was flat to slightly sloping. Target voids were 5 feet high by 20 feet wide, and ranged in depth from 20 to 60 feet. Voids were air filled but wet.

- Demonstration results varied, detecting some mapped entries, but not others. Interpretation of the results relied heavily on the mine maps.

- Use of the underground laser imaging during confirmation drilling confirmed some previously unknown/unmapped voids, discovered from the electrical resistivity results.
Electromagnetics

D’Appolonia Engineering, Division of Ground Technology Inc.  
(Time Domain EM)

Signal source from a wire/cable loop on the ground surface - receiver located approximately 15 meters away from the source. Subsurface conductors produce electromagnetic waves when a current is sent through the source wire loop. The receiver measures the secondary decaying electromagnetic waves.

Stolar Research Corporation (Delta EM Gradiometer)

A rod is carried horizontally across the ground surface. This rod had receivers located at each end which measured the gradient between two simultaneous signals. The primary wave is rejected while measuring the gradient of the secondary scattered EM wave.
Electromagnetics

Colorado School of Mines – Crosshole Radar Tomography
Pulses of radio energy are transmitted into the subsurface and reflected pulses received (borehole method). Transmitted pulses are received across the void (crosshole method). The wave scatter (reflection, refraction, and diffraction) from the interfaces of materials with differing electromagnetic properties are measured.

Stolar – Look-Ahead Radar (LAR)
This technology involves deploying a portable radar antenna against a coal seam, transmitting electromagnetic waves through the coal, and recording wave reflections indicative of a void. The distance to any detected void is determined by the velocity of the wave and the time between transmission and reflection. Ultimately, the contractor plans to develop a unit to mount on a continuous miner and provide real-time data.
D’Appolonia - TDEM
Conclusion - TDEM

- The TDEM technique was only able to image areas of extensive wet or moist mine workings.

- The method did not identify dry mine workings where they were known to exist.

- The degree of resolution was not high enough to image individual mine workings.
Stolar - Delta EM Gradiometer
Magnetic field induced into the ground by a 30-inch diameter loop (left) or a 31-foot diameter loop (right).
Stolar - Delta EM Gradiometer (Re-designed)
Conclusions – Stolar Delta EM Gradiometer

• 43 traverse lines were run

• 190 null points – Overlain by mine maps.
  – 142 (75%) over coal/air boundaries
  – 35 (18%) over coal pillars
  – 13 (7%) over no obvious feature
Crosshole / Borehole Radar

** Advantage:** No adverse impact on the mining operation.

** Disadvantage:** Requires Surface Access. More labor/cost intensive than surface techniques/

**Colorado School of Mines,**

Borehole method – pulses of electromagnetic energy are sent and received in the same borehole. The received signal is from reflection off the target. Requires at least one hole.

Crosshole method – pulses of electromagnetic energy are generated in one borehole and received at another borehole. The boreholes are on opposite sides of the target. Requires at least two boreholes.
Borehole radar data for the air filled void condition (transmitter and receiver placed in the same hole)
CSM - Field Demonstration Results

• Boreholes were approximately 35 feet apart on opposite sides of the target void. Boreholes extended to target depth of >200 feet.

• The borehole demonstration detected the void, but the depth was off by 10 feet.

• The crosshole demonstration detected a void, but the data quality was poor and the specific location could not be determined.
Stolar (LAR)

**Advantage**: No adverse impact on the mining operation. Real-time information is provided to miner operator about conditions ahead of mining. Provides last line of defense against completely unexpected conditions.

**Disadvantage**: Detection distance is limited to approximately 30 feet. Technology has not progressed to the continuous miner application.
Stolar - Field Demonstration Results

- The air-filled void demonstration detected an 8 foot void at a distance of 30 feet.
- The current unit used in the demonstration is too large to mount on a mining machine.
- The data required some post-processing.
LAR – Field Demonstration Results

• A variety of antennas were investigated (dielectrically loaded horn, dual sleeve dipole, folded RMPA, Spiral)

• One static LAR test was completed which detected an air-filled void at a distance of 30 feet.

• A portable system was successfully demonstrated but the machine-mounted and handheld units were elusive.

• The information collected led the developer to conclude that the desired data is present and may be extracted if specific design changes are made to the antenna.
Borehole Laser
Borehole Sonar

Workhorse Technologies Inc.
Downhole Laser and Video Camera
Workhorse Technologies, LLC downhole laser image of mine voids located by borings B34 and B31 on perimeter of Lots Branch Impoundment.
General Observations

• Projects exhibited varying degrees of success.

• Based on the number of variables that exist at each mine site, no one technology can be used with 100% certainty to find all potential voids.

• Although several technologies produced good results under the given circumstances, a “tool box approach”, using the strengths of one technology to fill in for the weaknesses of another is the most logical approach.

• Field verification through confirmation drilling is, of course, always necessary.
Complete Reports are available on the MSHA Website: