Engineering Geophysical Application to Mine Subsidence Risk Assessment

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GEOHAZARDS IMPACTING TRANSPORTATION IN THE APPALACHIAN REGION

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Focus

- Project Background
  - Purpose and objectives

- Abandoned Mine Subsidence Challenge
  - The problems
  - The risk assessment

- Engineering Geophysical Investigation – Multi-phase Approach
  - Geophysical methodology
  - Exploratory borings
  - Void imaging and mapping

  - Geotechnical Evaluation of Subsurface Conditions
    - Characterization of failure / failure modes
    - Assessment of relative subsidence sinkhole risk levels

- Numerical Modeling Analysis (LaModel)

- Integrated Results

- Conclusions and Recommendations
Purpose

Conduct multi-phase investigation to determine mine subsidence risk along pipeline/utility corridors leading to nearby power plant

Objectives

- Delineate the mine workings areas with potential subsidence risk that could effect the structural integrity of the corridors
- Determine the zones under the corridors where mitigation efforts should be directed
- Determine mitigation techniques for ground stabilization of the remaining mine voids and caved areas beneath the corridors
Abandoned Mine Subsidence Challenge

Why abandoned mine subsidence so complex to solve

The Problem
Many unknown conditions...!

Subsurface
- Strata
- Geologic setting
- Mining depth

Mine workings
- Dry and/or flooded
- Stable
- Collapse / rubble / gob

Voids / openings
- Location & orientation
- Size
- Lateral extent

Mine records / maps
- Incomplete
- Incorrectly geo-referenced
- Nonexistent

Extraction rate
- 40% to 70%
- 80% to 100%

Time-dependent
- Integrity of coal
- Integrity of roof structure

The Solution
- Accurate risk assessment
- Cost-effective mitigation techniques
but what will be the acceptable subsidence risk level…..

Extreme to high?

High to low?

Low to negligible?

The Solution

- Accurate risk assessment
- Cost-effective mitigation techniques
Geotechnical Evaluation

- Failure modes evaluation
- Subsidence risk assessment
- LaModel analysis:
  - Pillar safety factor
  - Subsidence displacement
  - Roof bending stress

Multi-phase Approach

Phase I

Geophysical Study
(Five lines: 7,236 linear ft)

- MASW (Multi-channel Analysis of Surface Waves)
- Seismic Reflection

Phase II

Exploratory Borings Program
(14 drillholes)

- Drill cutting logging
- Geophysical logging
- HQ core

Phase III

Integrated Results

- Potential subsidence/sinkhole areas
- High risk zones
- Mitigation techniques, plan & cost

Void Imaging
(Video camera & laser)
Mine Layout – Typical Geologic Setting

- Mining method: Room-and-pillar
- Operation: 1919-1922
- Coal seam thickness: ~ 8ft
- Seam strike and dip: N 23° W, 7° W
- Depth: 50 – 100 ft
- Critical pipe & utility corridors buried 8 ft bgs
Sinkholes Development
Geophysical Field Setup

- Site conditions: Open and rocky
- Geophysical survey: Simultaneous acquisition of surface MASW and reflection data sets using the same geophone arrays
- Five survey lines totaling 7,236 linear ft

Acquisition Parameters

**Recording vehicle:**
- Geometric Geodes, 24 bid A/D
- 72 active channels
- 0.5 ms sample rate

**Seismic source:**
- iVi EnviroVibe
- 15,000 lbs peak ground force
- Geometry: 12-ft spacing
- Sweep frequency:
  - MASW 6 to 80 Hz
  - Reflection 60 to 260 Hz

**Geophones:**
- Geospace GS20D, 8Hz single element
- Geometry: 6-ft spacing
Geophysical Survey layout

- **MASW**: Provides bulk estimates of shear wave velocity (Vs) with depth, which is indicative of relative strength of overburden. Low “Vs” may indicate zones where sinkhole-type subsidence is propagating toward the surface.

- **Seismic Reflection**: Provides high-resolution imaging at the mine workings horizon. The presence or absence of coherent mine floor reflectors allows discrimination between un-collapsed workings and rubble zones.

- **Combined MASW & Reflection**: Identified anomalies potentially indicative of near surface subsidence zones and open mine workings. Focused subsequent exploratory borings for ground truthing.
Line 1
Low velocity anomaly between ST’s 445 – 470 (150’)
BH-01 & BH-11 show disturbed / rubblized mine roof, reducing rock shear strength & decreasing its Vs (weak rock).

Line 2
Anomalies characterized by velocity reversal
Results of thin but hard sandstone layers above the mine workings.

Low Vs / weaker rock (strata)
High Vs / harder rock (strata)
Shear wave velocity variation

- **Slower Vs** can be the result of:
  - Fractured rock where subsidence has already occurred
  - Naturally occurring changes in the strata that affect the overburden competence (i.e. less hard sandstone vs. more soft shale)
  - Sinkhole-type subsidence propagating to the surface

- **Faster Vs** is indicative of harder strata with higher beam strength
Seismic Reflection Data Interpretation

Reflection Profile – Line 1
(Interpretation focuses on the presence or absence of mine floor reflectors)

- Compressional acoustic energy (P-wave) transmits more effectively through intact pillars & empty air spaces
- Presence of mine floor reflector (yellow) is indicative of intact pillar and open mine workings
- Absence of a mine floor reflector is indicative of rubble (acoustic energy is scattered in all directions, and does not return to the surface as a coherent echo)
Geotechnical Evaluation of Subsurface Conditions

Ground Truthing of the Geophysical Investigation and Void Mapping
14 Exploratory Borings, Laser / Video Void Imaging, & Borehole Geophysical Logging

Exploratory Boring Program – Field Setup

Drilling

Laser Scanning

Video Imaging

Checkshot Survey

BH-07: HQ Core, Sandstone (100% RQD)

BH-07: HQ Core, No. 7 Coal Seam

Borehole BH-10

Ground Surface Elevation: 6990 FT
0 to 250 (10 Interval) 0 to 200 (20 Interval) 0 to 5 (1 Interval) 0 to 10 (1 Interval)

Lithology

Coal
Rubble
Sandstone
Not Specified
Shale
Void

Geophysical Logs

Conductivity (M/s/m)
Natural Gamma (CPS)
Density (g/cc)
1-Arm Caliper (in)

www.zapeng.com
Geotechnical Evaluation of Subsurface Conditions

Geologic Cross Sections

No. 7 seam strike ~ N 23° W, dipping 7° to the west
Geotechnical Evaluation of Subsurface Conditions

Laser Void Mapping Results – Boreholes BH-01 & BH-02

BH-01 (SW of Line 3) @ depth 90 ft

- Open mine workings (12 ft high):
  - Void extensions: 25’ N-S direction
  - 14’ E-W direction

BH-02 (NE of Line 1) @ depth 61 – 73 ft

- Open mine workings (12 ft high):
  - Two lateral void extensions: NW & NNE ~ 10’ W x 45’ L
  - South void extension: ~ 15’ L x 18’ W
  - Mine map re-alignment (room & haulageway)
Geotechnical Evaluation of Subsurface Conditions

Video Camera Void Mapping Results – Borehole BH-02

Open mine workings (12 – 15 ft high):
- Large void @ 64’, indicative of a room and/or haulageway
- Mine roof failure to ~ 7’ forming a new roof line
- Large rock pile on mine floor
- Coal rib, indicative of remaining stable coal pillar
- Overall void height, including coal pillar and roof fall, is ~ 15'

NOTE: Opening height (including pillar and roof fall) is estimated at approximately 15 ft.
Geotechnical Evaluation of Subsurface Conditions

Characterization of Failure / Failure Modes and Risk Levels

- Based on the ground conditions seen in each of the 14 borings (drill logs, core samples & physical properties, borehole video records) and void mapping, four principle failures / risk levels were characterized and ranged from:
  - Conditions of a complete caving and collapse of mine workings with strong intact overburden materials, characterized by Failure Mode 1…to
  - Unstable mine workings (such as intact pillar, and/or partially mined, weak roof, and void/rubble) with shallow soft/weak overburden materials, characterized by Failure Mode 4

- Failure Modes and Associated Relative Risk Levels:
  - Failure Mode 1 – Risk Level Negligible
  - Failure Mode 2 – Risk Level Very Low
  - Failure Mode 3 – Risk Level Moderate
  - Failure Mode 4 – Risk Level High
Geotechnical Evaluation of Subsurface Conditions

Relative Subsidence Risk Levels

Failure Mode 1 – Negligible to Failure Mode 2 – Very Low
Geotechnical Evaluation of Subsurface Conditions

Relative Subsidence Risk Levels

Failure Mode 4 – High
Geotechnical Evaluation of Subsurface Conditions

Probability of Sinkhole (Caved Zone) Development Reaching Surface
As a Function of Overburden Thickness

Assuming:
- Angle of draw: 19° (margin of safety in sinkhole size estimation, American West ranges from 12° to 16° (Peng, 1978)
- Void size: 7 ft H x 10 ft W

Probability of Sinkhole Development:
- Area within BH-14: >100% probability forming a sinkhole at the surface
  - Surface settlement will have propagated 8 ft from the edge of the void space
- Area within BH-01 & BH-06: <10% probability forming a sinkhole

Survey Index
**Numerical Modeling**

**LaModel Analysis**

**Purpose:** Determine areas of potential subsidence – Present & future trough or sinkhole due to the time-dependent deterioration of the coal pillar

**Input parameters & materials properties**

<table>
<thead>
<tr>
<th>Parameters/Material Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overburden thickness or depth of cover (ft)</td>
<td>0 to 300</td>
</tr>
<tr>
<td>Mining seam height (ft)</td>
<td>7.75</td>
</tr>
<tr>
<td>In-situ coal strength @ various stages of deterioration (psi)</td>
<td>900, 775, 650, 525, &amp; 400</td>
</tr>
<tr>
<td>Elastic modulus (E) for coal (psi)</td>
<td>300,000</td>
</tr>
<tr>
<td>Poisson’s ratio (ν) for coal</td>
<td>0.33</td>
</tr>
<tr>
<td>E for overburden (psi)</td>
<td>500,000</td>
</tr>
<tr>
<td>ν for overburden</td>
<td>0.25</td>
</tr>
<tr>
<td>Overburden lamination thickness (ft)</td>
<td>10</td>
</tr>
<tr>
<td>E for gob (initial/final) (psi)</td>
<td>50/50,000</td>
</tr>
</tbody>
</table>

**Output**

1) **Pillar safety factor** Indicates where additional pillar failure might occur
2) **Surface subsidence** Indicates the present subsidence and changes in subsidence due to deterioration in coal strength
3) **Roof bending stress** Indicates areas of present and/or potential roof failures due to access tensile, compressive, or shear stresses – Sinkhole development
Numerical Modeling

Digitized Mine Map and Topography

Coal seam grid: 3-ft square elements in a 1,000 by 660 element (3,000 by 1,980 ft)
Intermediate Roof Stresses for 650 psi Coal

- Potential delayed subsidence areas are located at the *edge of the major gobs*
  - Prone to continued failure and sinkhole development
- Seven of the ten sinkholes observed over the modeled area are located at the edge of a gob

High stress areas:
- Would have failed during initial mining

Intermediate stresses 200 to 800 psi
- Causing delayed subsidence

Low stresses:
- Has no affect on roof integrity
Integrated Results / Conclusions and Recommendations

Potential Trough and/or Sinkhole Subsidence Risk Zones under the Pipeline/Utility Corridors

“Identified four zones with risk levels ranging from relatively negligible to very low at the west site (overburden ~ 90’ thick), to high at the east side (overburden ~ 50’ thick)

Conclusions
Assessment of four identified risk zones:
- Zone 1: Potential sinkhole development – requiring mitigation
- Zone 2: Potential subsidence development-requiring mitigation
- Zone 3: Low subsidence risk – requiring test borings
- Zone 4: Negligible subsidence risk – requiring test borings
Recommended Mitigation Technique

- Foamed-sand slurry backfilling technique for ground stabilization of Zones 1 & 2 beneath the corridors

**Project Example**
Abandoned Coal Mine beneath Residential Area, Colorado Springs, CO

Video snapshot images during the foamed-sand backfilling
Thank You!