Engineering Geophysical Application to Mine Subsidence Risk Assessment

By:

Kanaan Hanna, Sr. Mining Engineer
Steve Hodges, Sr. Geophysicist
Jim Pfeiffer, Sr. Geophysicist

ZAPATA
TRUST · INTEGRITY · QUALITY

Dr. Keith Heasley, Professor
West Virginia University

GEOHAZARDS IMPACTING TRANSPORTATION IN THE APPALACHIAN REGION

TDOT MARSHALL UNIVERSITY.

August 2-4, 2011, Chattanooga, TN

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

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

The Solution

- Accurate risk assessment
- Cost-effective mitigation techniques

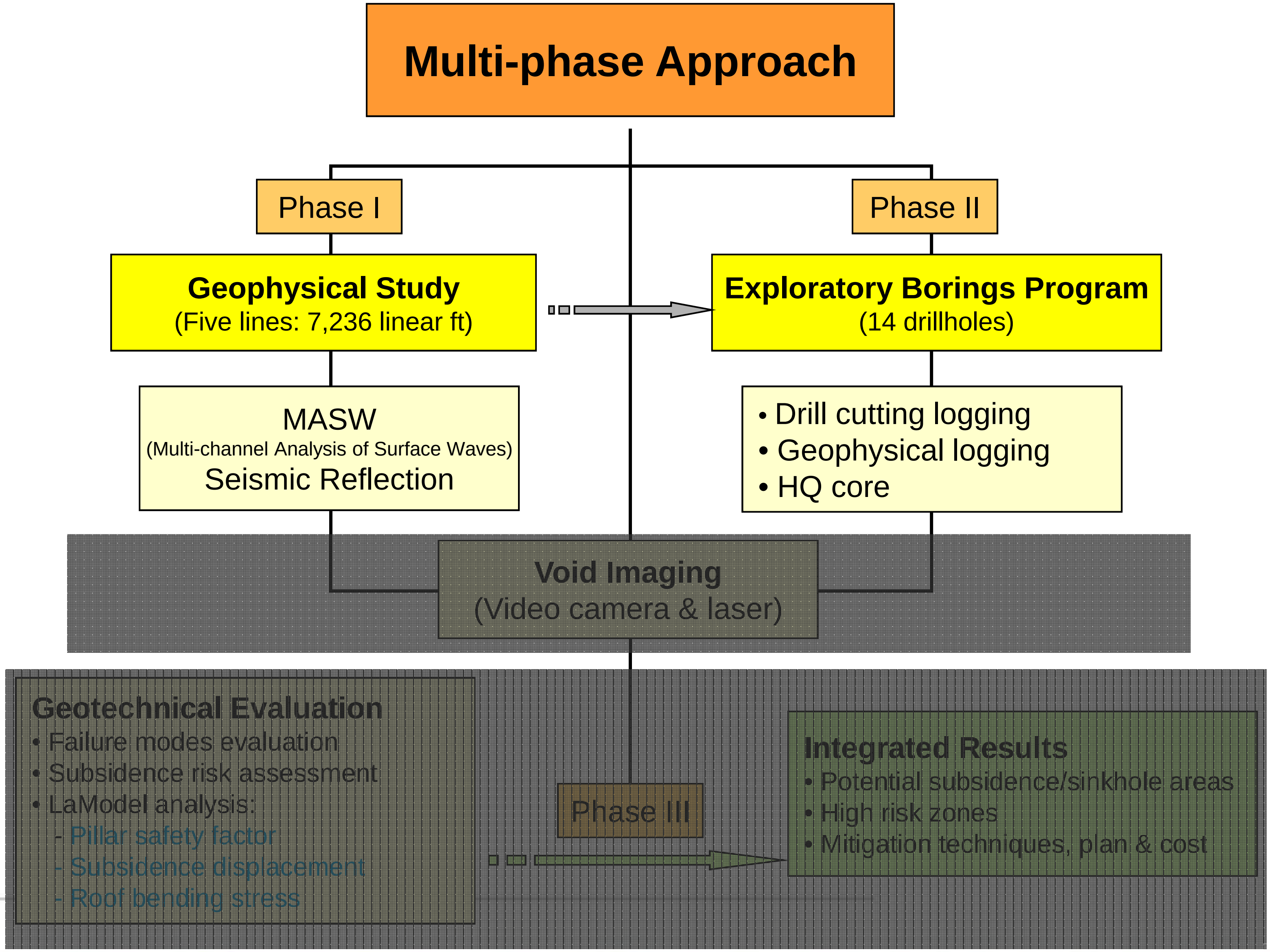
but what will be the acceptable subsidence risk level…..

Extreme to high?

High to low?

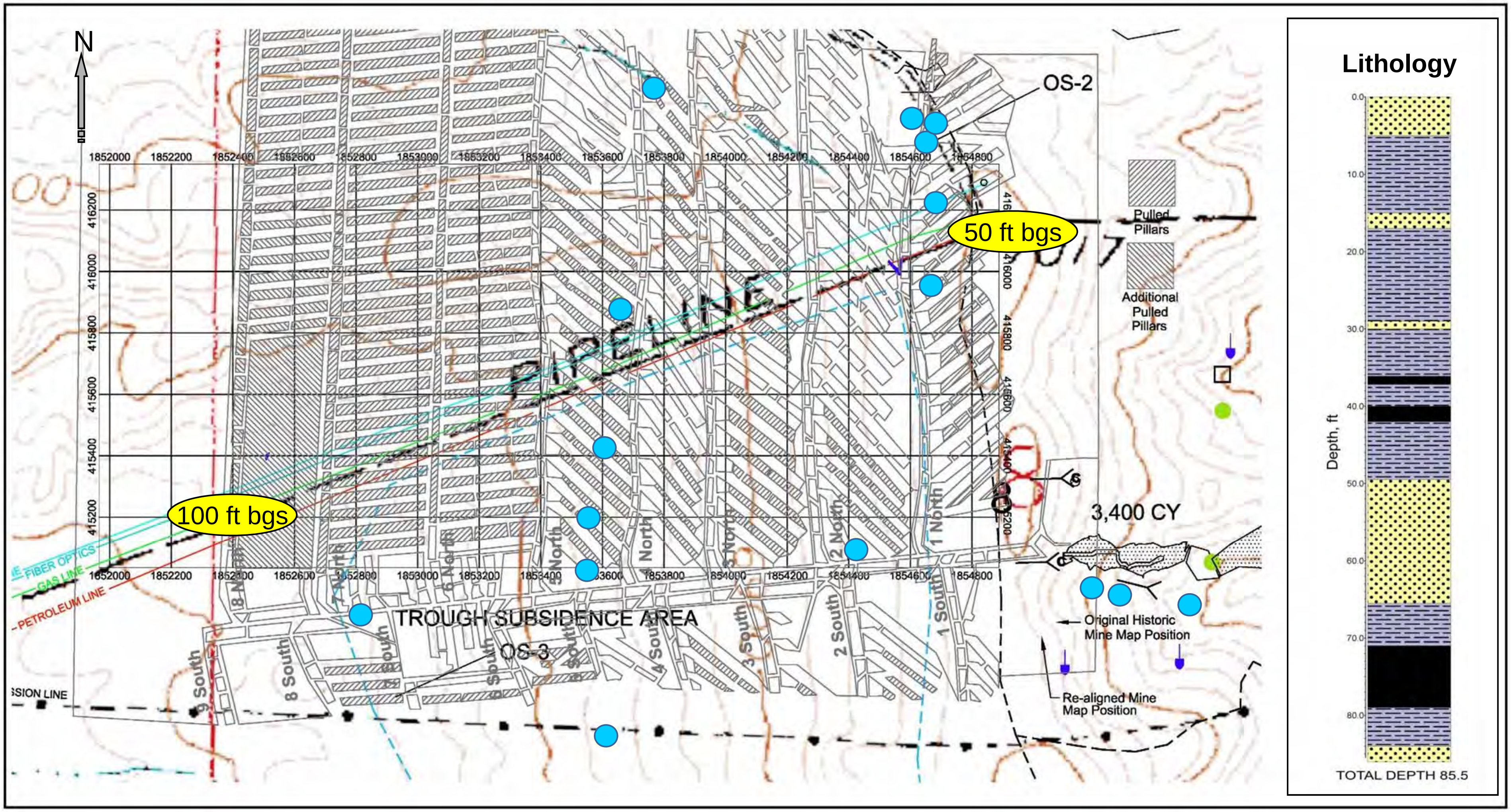
Low to negligible?

➢Engineering Geophysical Investigation



Mine Layout – Typical Geologic Setting

- Mining method: Room-and-pillar • Operation: 1919-1922 • Coal seam thickness: ~ 8ft
- Seam strike and dip: N 23º W, 7º 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

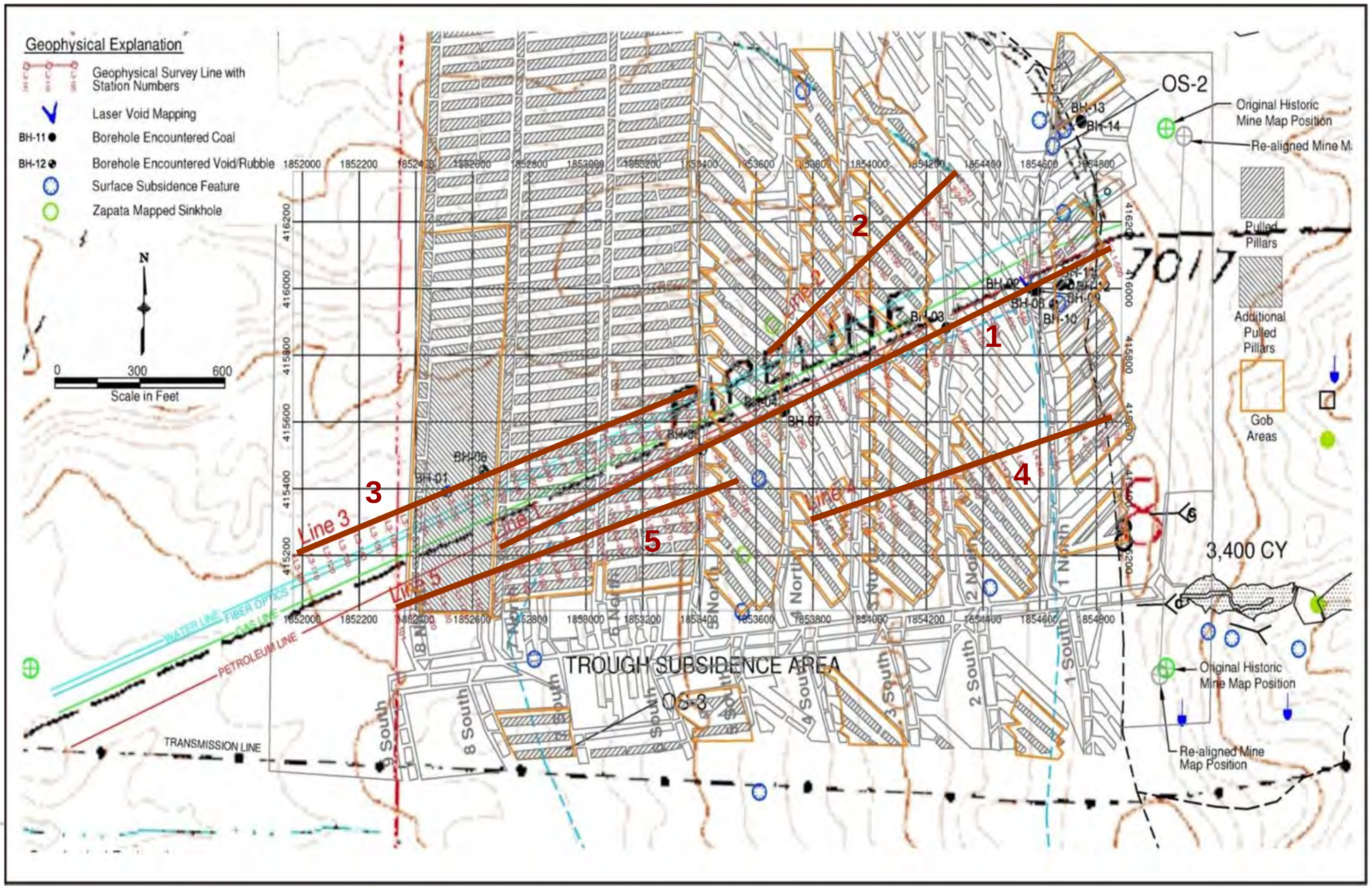
Recording vehicle:
- Geometric Geodes, 24 bid A/D
- 72 active channels
- 0.5 ms sample rate

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.



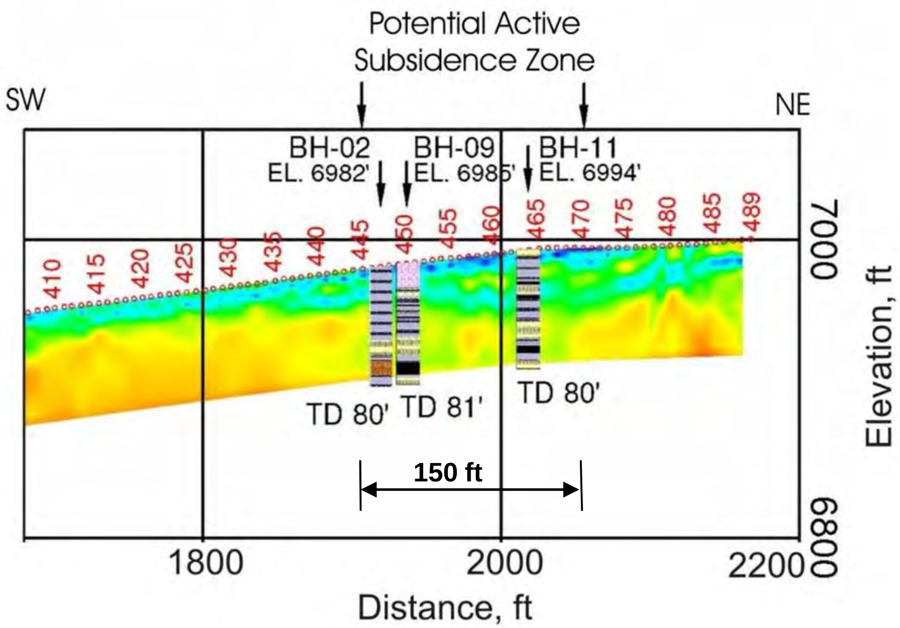
Portion of MASW Profiles for Lines 1 & 3

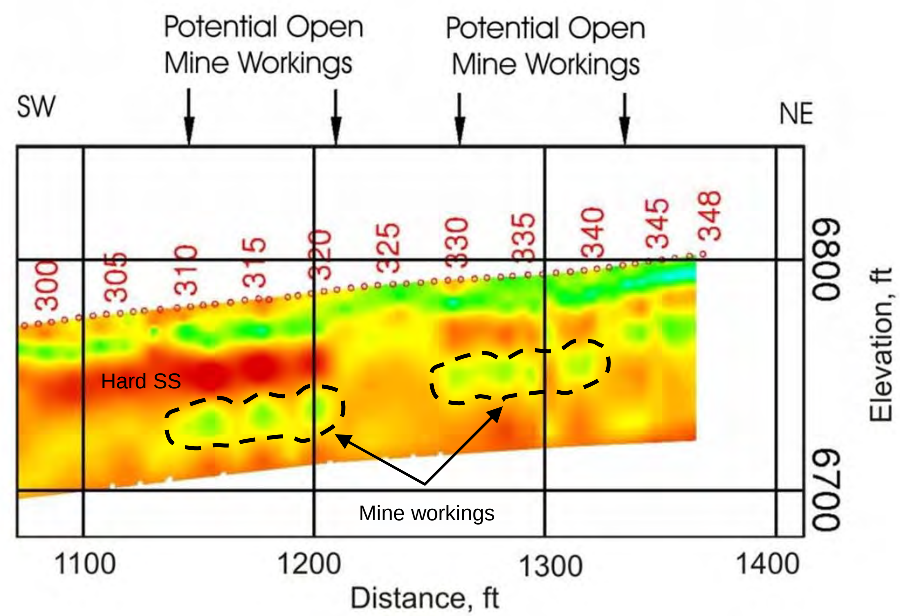
Line 1

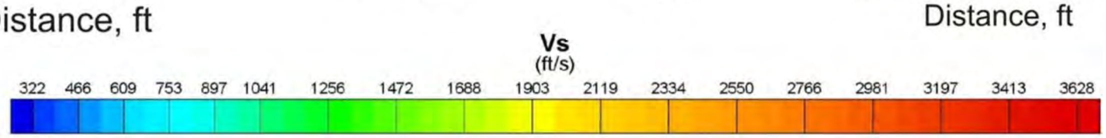
Low velocity anomaly between ST's 445 – 470 (150')
BH-01 & BH-11show disturbed / rubblized mine roof, reducing rock shear strength & decreasing its Vs (weak rock).

Line 2

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







Low Vs / weaker rock (strata)

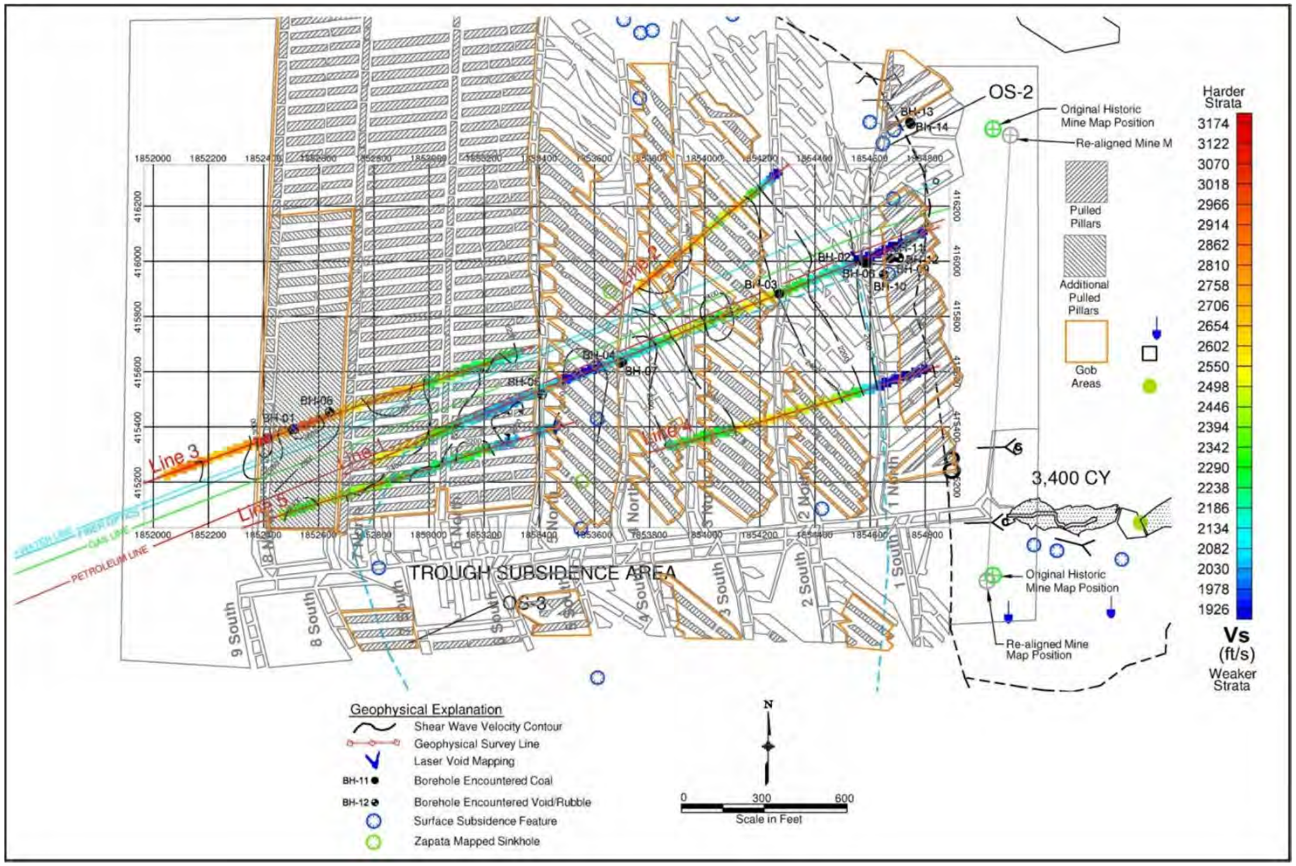
High Vs / harder rock (strata)

Average Shear Wave Velocity (Vs) Isopach Map

(Interval from 45 to 65 ft bgs approximates the immediate mine roof over the eastern two-third of the site)

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

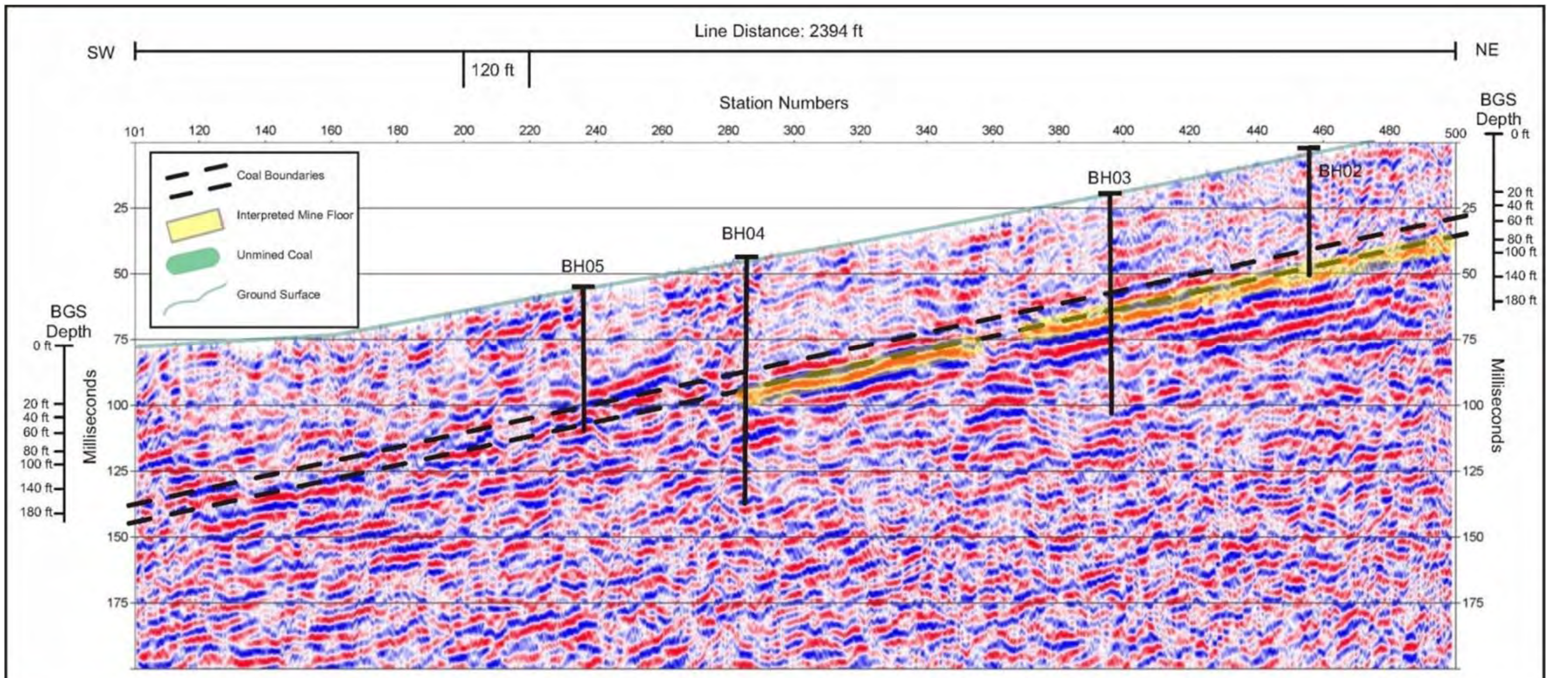


Seismic Reflection Data Interpretation

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)



Absence of mine floor reflector
Rubble / collapsed mine workings

Presence of mine floor reflector
Open mine workings

➢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

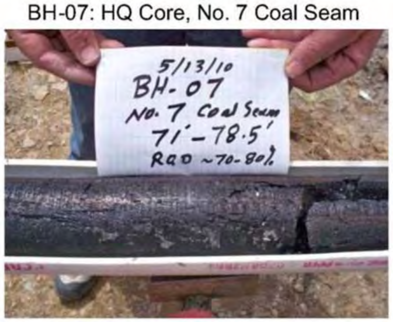
Drilling

Laser Scanning

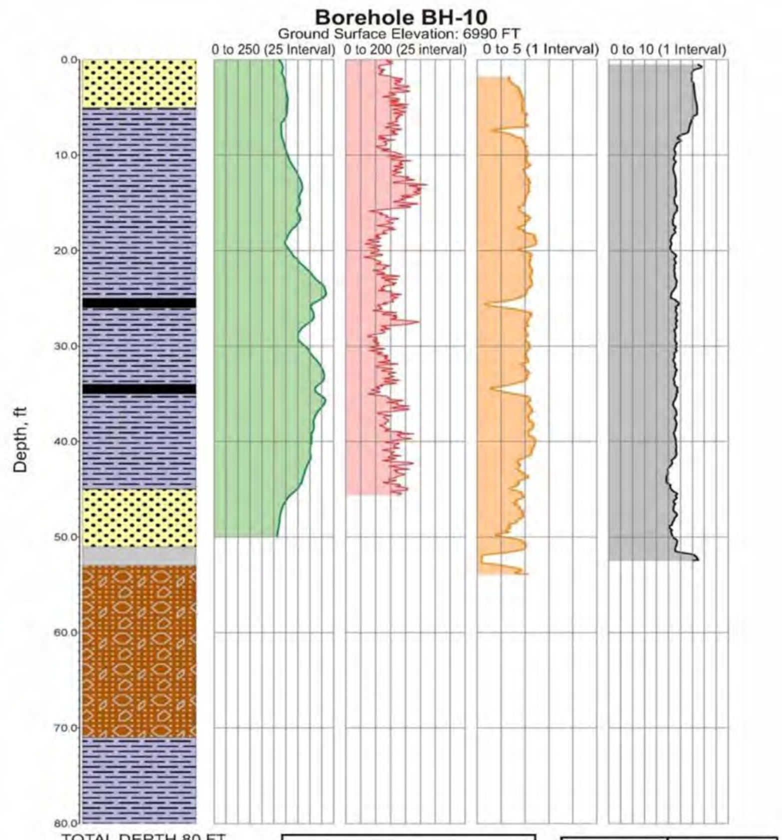
BH-07: HQ Core, Sandstone (100%RQD)

Video Imaging

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



Checkshot Survey



Geophysical Logs
Conductivity (Ms/m)
Natural Gamma (CPS)
Density (g/cc)
1-Arm Caliper (in)

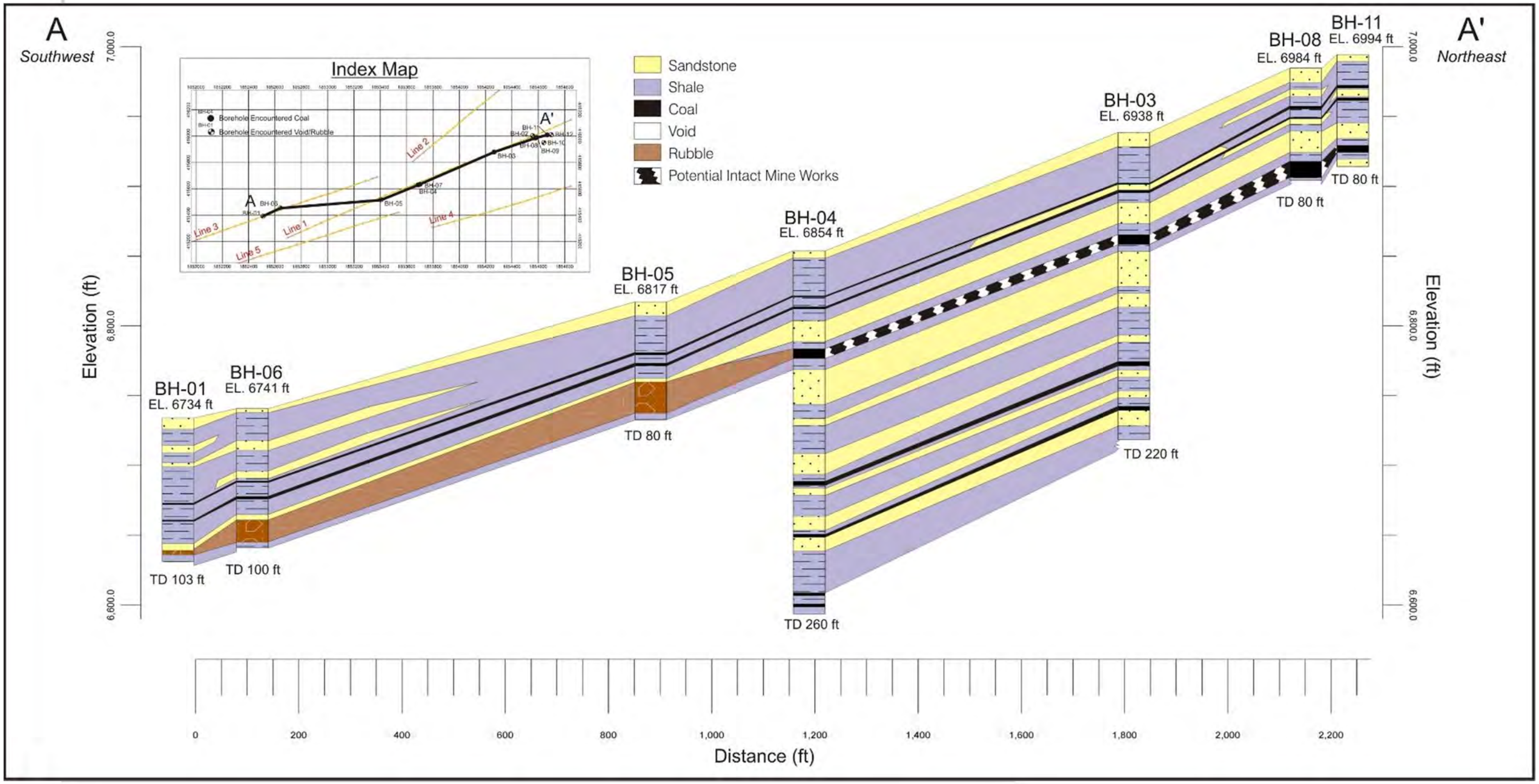
Lithology
Coal
Not Specified
Rubble
Sandstone
Shale
Void

Depth (FT)	Lithology
0.0 - 05.0	Sandstone
05.0 - 25.0	Shale
25.0 - 26.0	Coal
26.0 - 34.0	Shale
34.0 - 35.0	Coal
35.0 - 45.0	Shale
45.0 - 51.0	Sandstone
51.0 - 53.0	Void
53.0 - 71.0	Rubble
71.0 - 80.0	Shale

➢Geotechnical Evaluation of Subsurface Conditions

Geologic Cross Sections

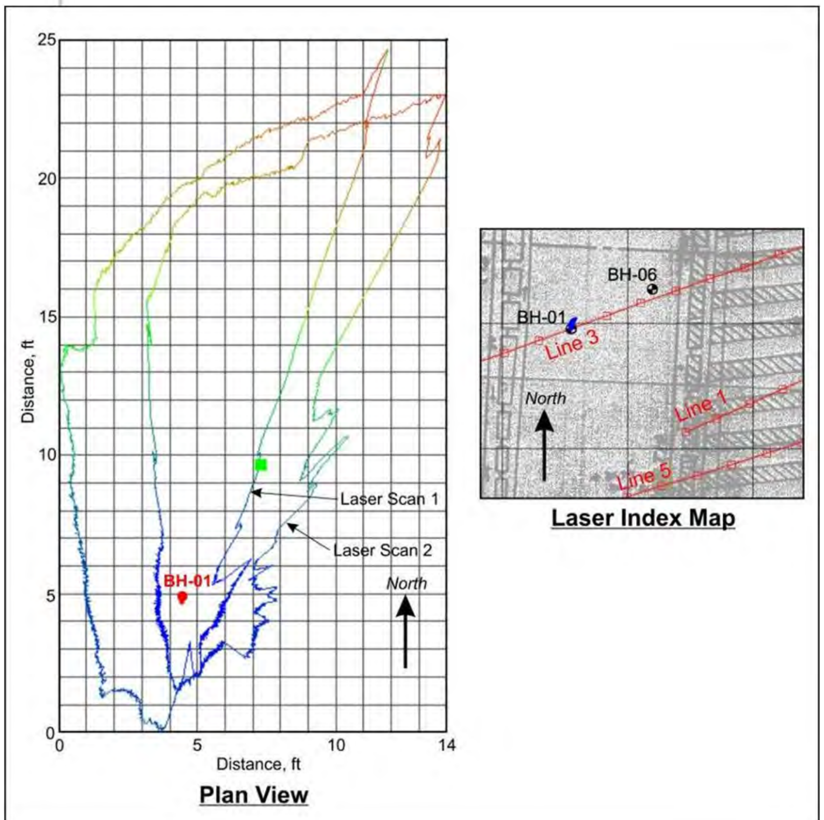
No. 7 seam strike ~ N 23º W, dipping 7º to the west



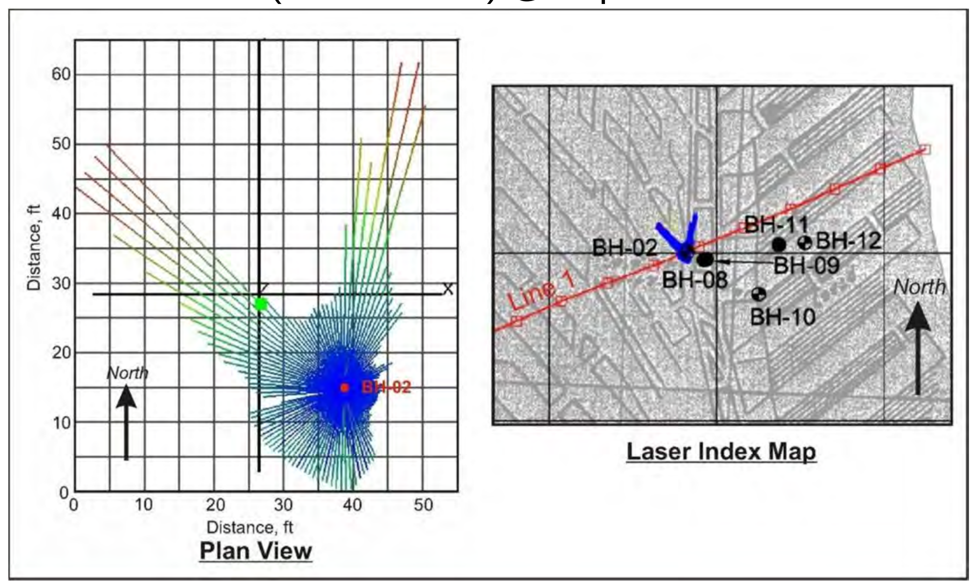
➢Geotechnical Evaluation of Subsurface Conditions

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

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



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



Mine workings (18 in high):

- Void extensions: 25’ N-S direction
  14’ E-W direction

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)

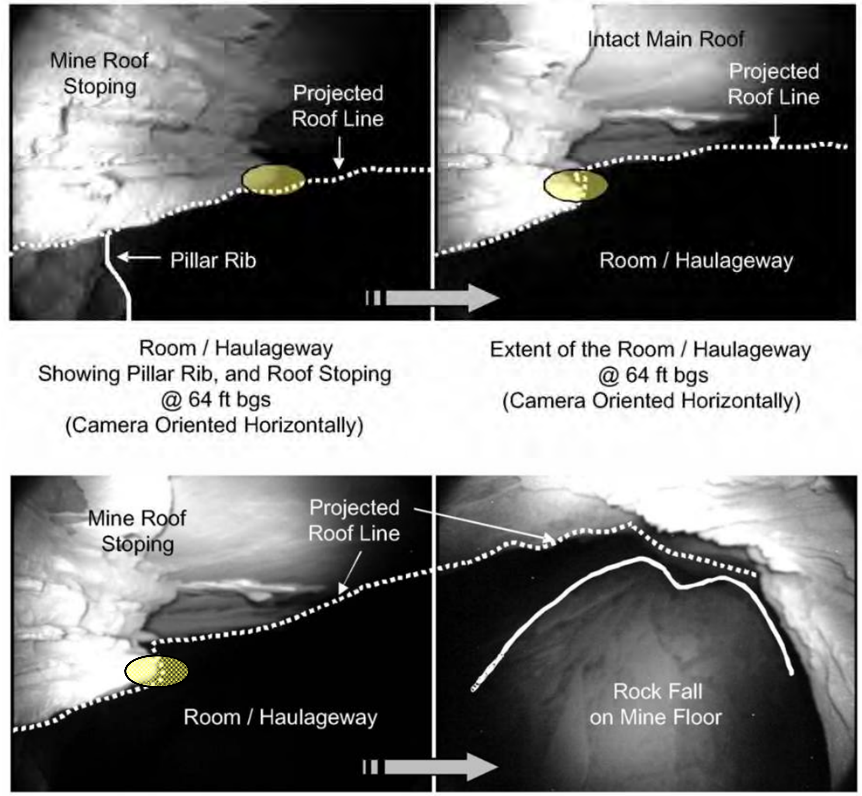
➢Geotechnical Evaluation of Subsurface Conditions

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'

Video Images in Borehole BH-02
Mine Void from 61 – 73 ft bgs. Total Depth @ 80 ft



Room / Haulageway
Showing Pillar Rib, and Roof Stoping
@ 64 ft bgs
(Camera Oriented Horizontally)

Extent of the Room / Haulageway
@ 64 ft bgs
(Camera Oriented Horizontally)

Room / Haulageway
Showing Roof Stoping, and
Projected Roof Line into Adjacent Picture
@ 64 ft bgs
(Camera Oriented Horizontally)

Extent of the Room / Haulageway
with Rock Fall on Mine Floor
@ 63 ft bgs
(Camera Oriented Horizontally)

NOTE: Opening height (including pillar and roof fall) is estimated at approximately 15 ft.

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

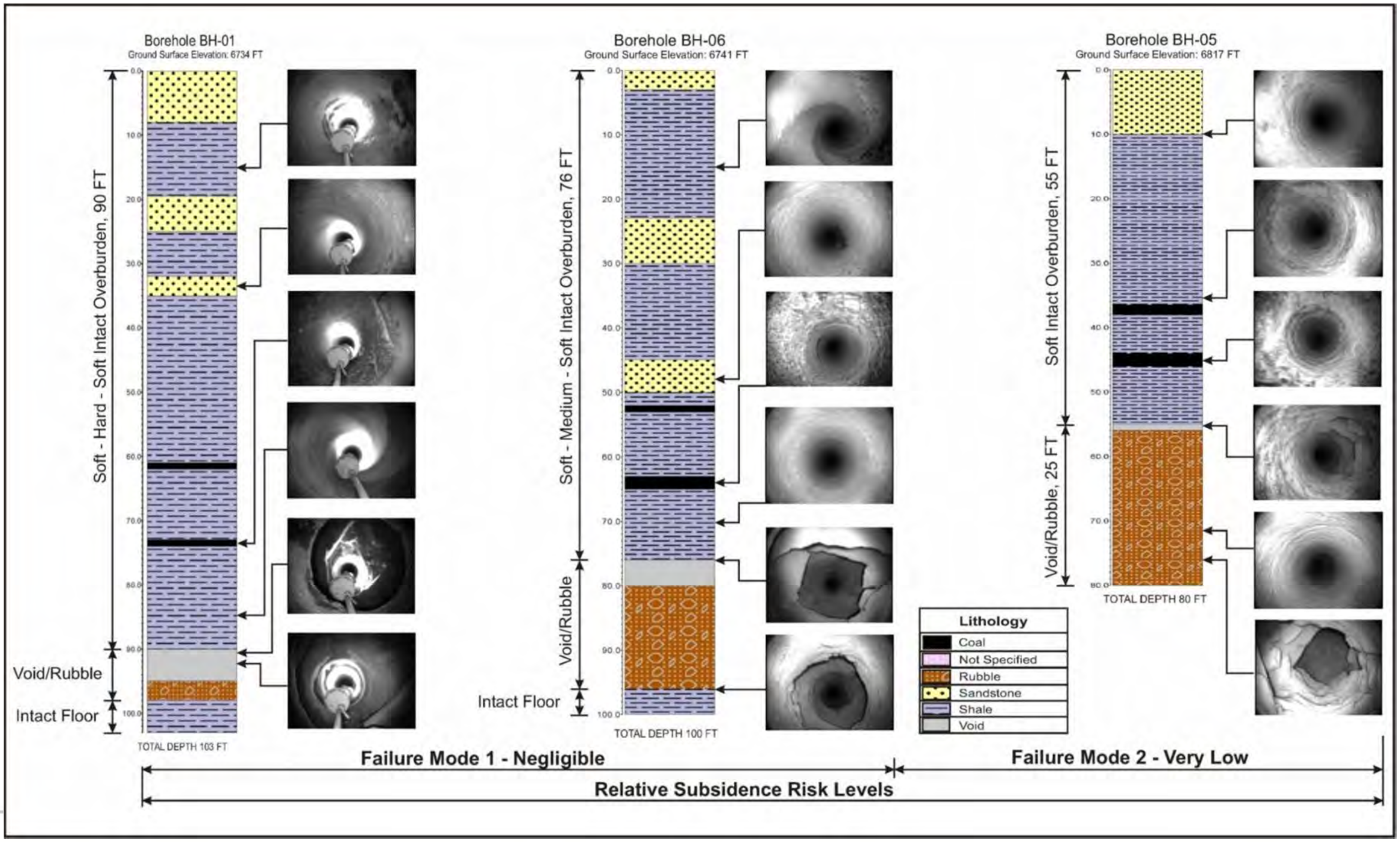
❖ Failure Modes and Associated Relative Risk Levels:

- 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

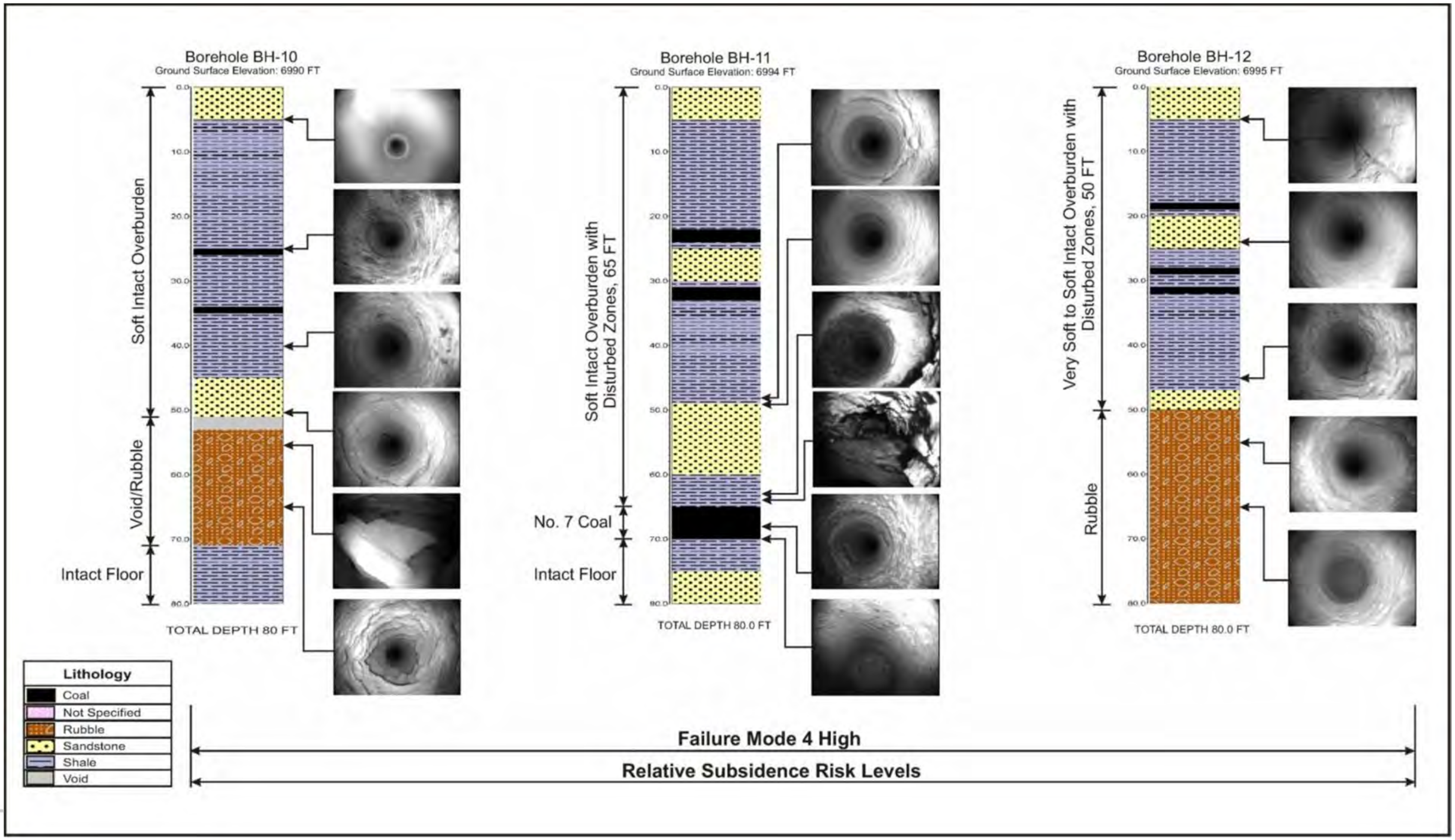
Relative Subsidence Risk Levels

Failure Mode 1 – Negligible *to* Failure Mode 2 – Very Low



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

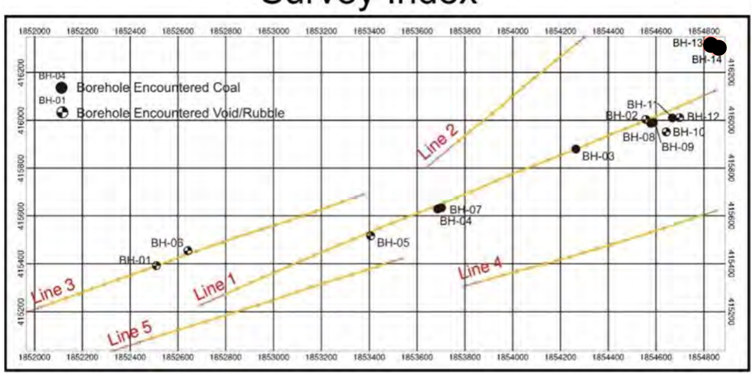
Assuming:

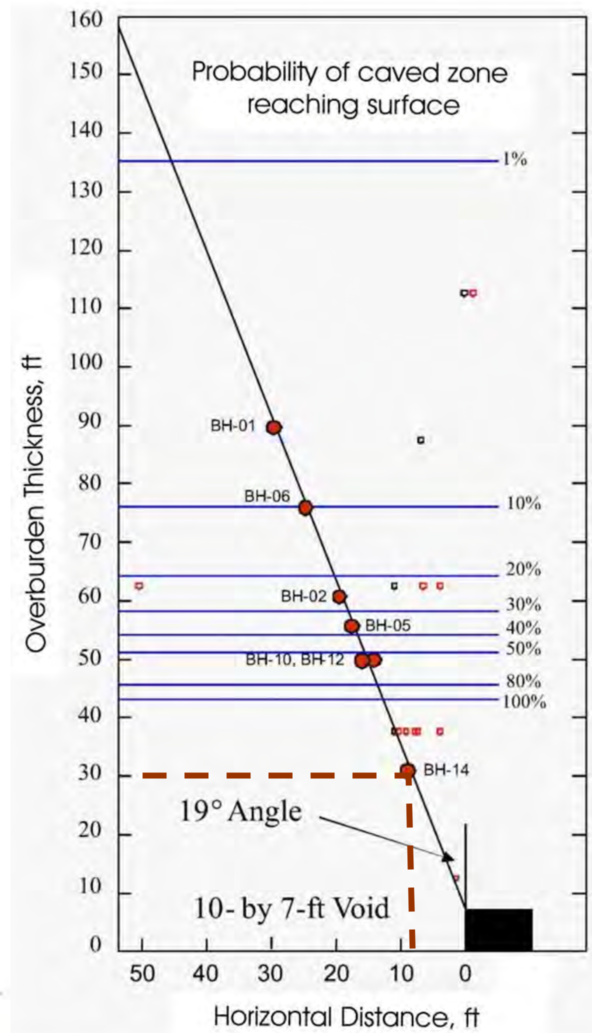
- Angle of draw: 19º (margin of safety in sinkhole size estimation, American West ranges from 12º to 16º (Peng, 1978)
- Void size: 7 ft H x 10 ft W

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





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

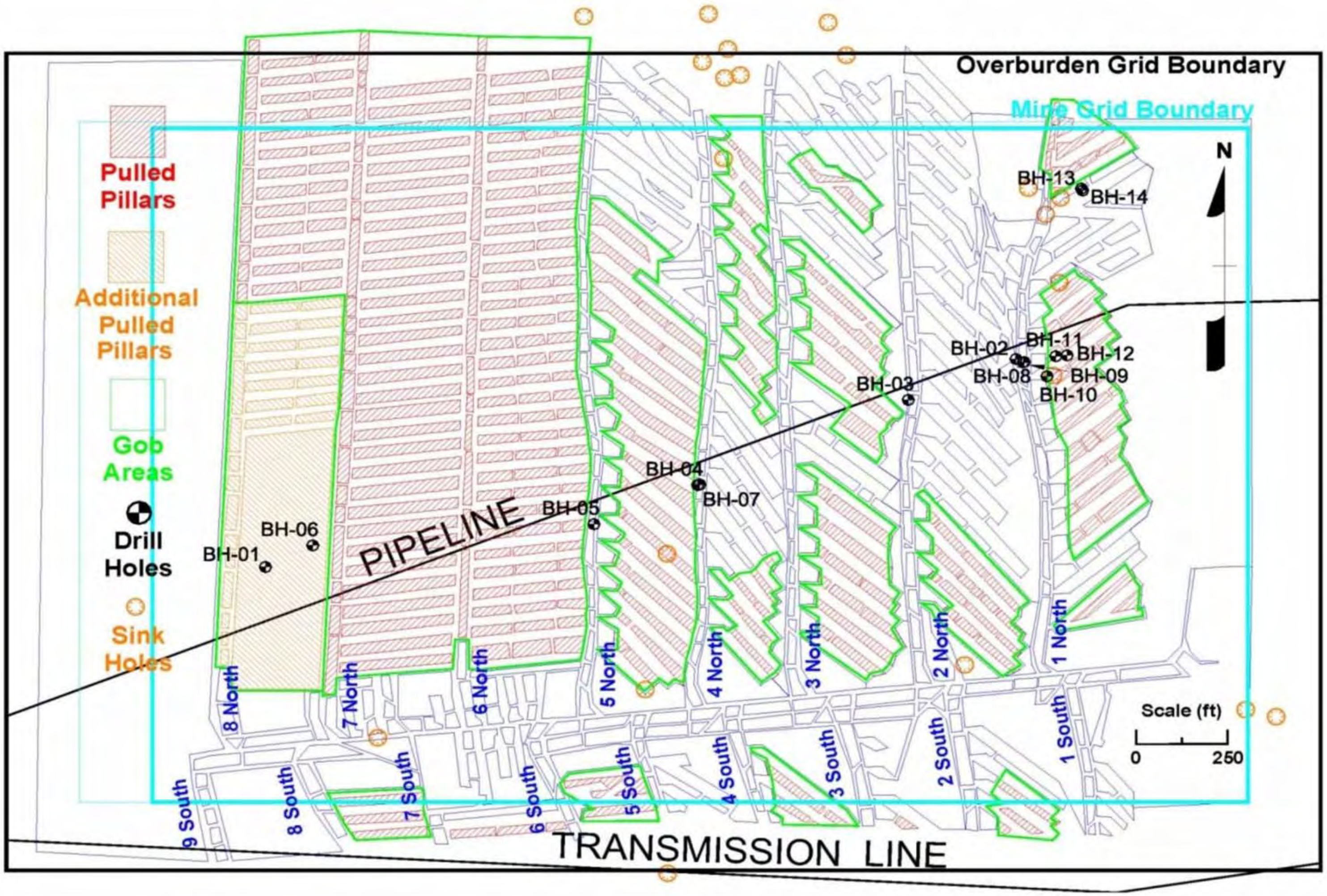
Parameters/Material Properties	Value
Overburden thickness or depth of cover (ft)	0 to 300
Mining seam height (ft)	7.75
In-situ coal strength @ various stages of deterioration (psi)	900, 775, 650, 525, & 400
Elastic modulus (E) for coal (psi)	300,000
Poisson's ratio (ν) for coal	0.33
E for overburden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

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

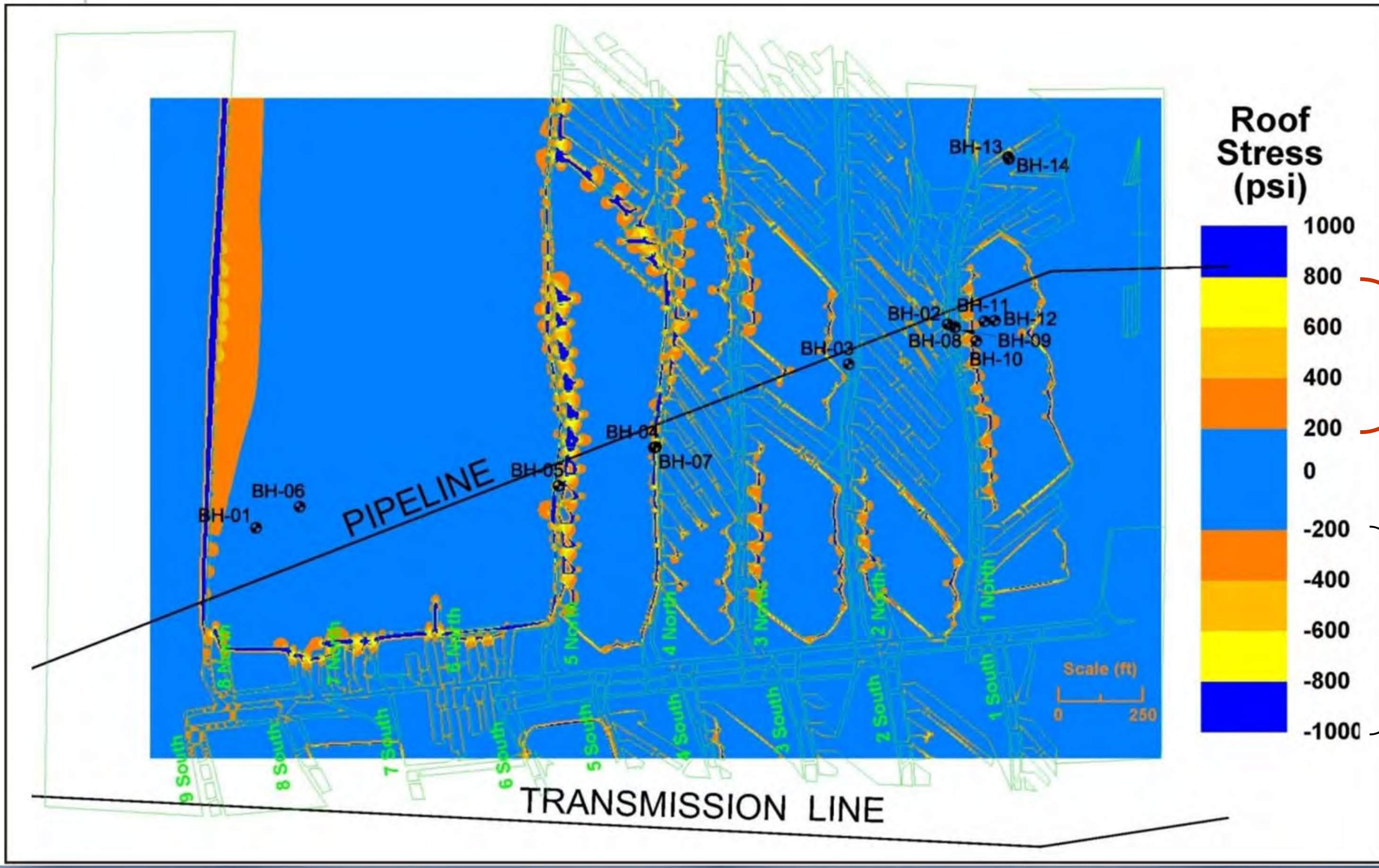
Digitized Mine Map and Topography

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

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

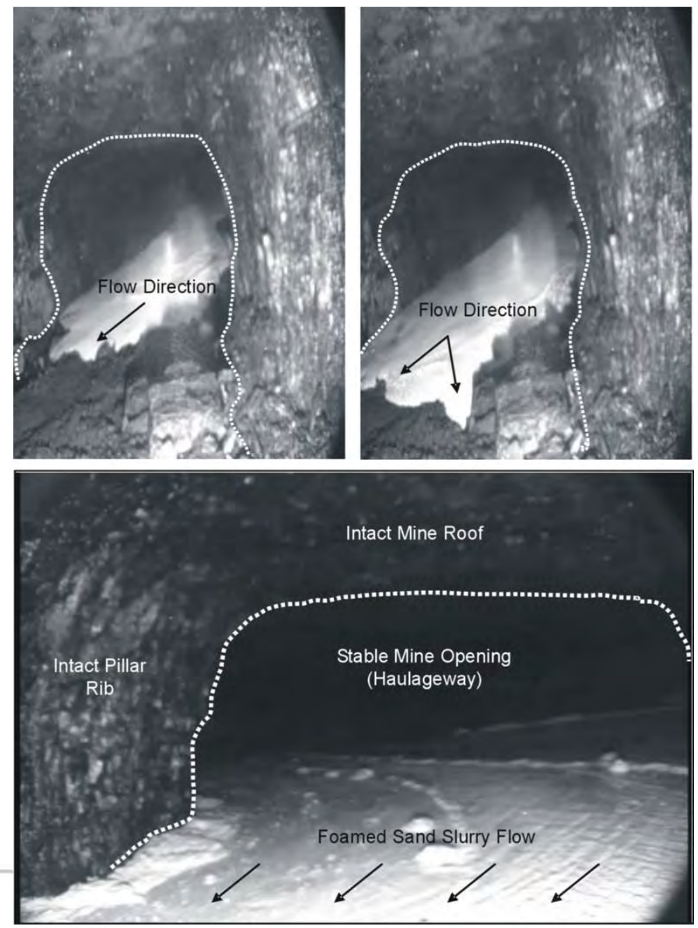
Recommended Mitigation Technique

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

<u>Project Example</u>

Abandoned Coal Mine beneath Residential Area, Colorado Springs, CO

Video snapshot images during the foamed-sand backfilling



Thank You!