Downhole Geophysical Logging Applications for Mining – Industry Experience

Prepared for: Ninth Annual PE Seminar – Virginia Coal & Energy Alliance - Lebanon, VA
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March 29, 2018
Outline

> Introduction
> Mining Applications
> Downhole Geophysical Methods
  > Fracture Orientations - Acoustic Televiewer
  > Density Logging
  > Sonic Logging
> Case Studies
> Summary
> Questions
Introduction - Geophysical Logging Applications

Mineral Exploration:
   Coal, Limestone, Aggregates, Uranium, Metal Ores, Other Minerals, and Oil and Gas. (Two general types of logging probes, Oil and Gas and “Mineral Logging” probes – higher resolution, smaller diameters, etc. Used for mineral investigations)

Groundwater - Environmental Site Investigations- Hydrogeology: Contaminant Site Investigations; Mining Industry;
Water Supply - Municipal Wells - Residential Wells

Geotechnical:
   Surface Mining Highwall Design, Underground Mining or Tunneling - Rock Mass Evaluation, Foundation Studies, DOT- Road cuts, Undermining, Deep Soil Moisture-Density Studies,

Miscellaneous Applications:
   If a boring or well is drilled in rock for any reason, geophysical logging data can enhance the understanding of the geology, mineralogy, hydrogeology, geotechnical or other aspects of the site.
Mining Applications

> Downhole geophysical logging tools have been used for geological and geotechnical characterization associated with mining applications for many decades.

> **Examples:** mining – coal and ore delineation - reserves, mining engineering parameters, groundwater hydrology, fractured rock aquifer flow assessment, geotechnical applications for tunneling, rock mechanics applications, etc.

> Downhole geophysical methods are faster, more accurate, more versatile, and significantly less expensive than more traditional methods of oriented core drilling.

> Downhole geophysical data does not provide all the answers, but is a very cost effective method to gather a lot of good data. (Another good tool to have in your toolbox.)
Downhole Geophysical Methods for Fracture Orientations

> **Tools Used**: Acoustic Televiewer (ATV) or Optical Televiewer (OTV).

> ATV = very-high resolution, oriented, sonic image of the borehole wall revealing fractures, bedding planes and the orientation of those features.

> Discontinuity orientation, aperture width, fracture frequency, and relative estimate of rock competency collected.

> ATV data collection from a hole 500 feet deep will take approximately three hours.
Downhole Geophysical Methods for Pit Slope Stability Assessment – Basic Process
RQD from Core logging versus RQD from Acoustic Televiewer Log

- Matching ATV data to discontinuities in core can be difficult
- Rock Quality Designation (RQD) derived via ATV data can be significantly overestimated
- Resolution of ATV data decreases with an increase in hole diameter
- Resolution of ATV data can be significantly affected by mud and cuttings clogging fractures in borehole sidewalls. Care must be taken to maintain hole for good quality data.

<table>
<thead>
<tr>
<th>RQD Unit</th>
<th>RQD from ATV (%)</th>
<th>RQD from Core Logging (%)</th>
<th>Difference</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>87</td>
<td>13</td>
<td>15%</td>
</tr>
<tr>
<td>2</td>
<td>99</td>
<td>73</td>
<td>26</td>
<td>36%</td>
</tr>
<tr>
<td>3</td>
<td>96</td>
<td>91</td>
<td>5</td>
<td>5%</td>
</tr>
<tr>
<td>4</td>
<td>99</td>
<td>92</td>
<td>7</td>
<td>8%</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>92</td>
<td>8</td>
<td>9%</td>
</tr>
<tr>
<td>6</td>
<td>99</td>
<td>93</td>
<td>6</td>
<td>6%</td>
</tr>
<tr>
<td>7</td>
<td>100</td>
<td>100</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>8</td>
<td>99</td>
<td>93</td>
<td>6</td>
<td>6%</td>
</tr>
<tr>
<td>9</td>
<td>98</td>
<td>91</td>
<td>7</td>
<td>8%</td>
</tr>
<tr>
<td>10</td>
<td>98</td>
<td>84</td>
<td>14</td>
<td>17%</td>
</tr>
</tbody>
</table>
Density Logging for Aggregate – Crushed Stone Industry

- Density logging data is useful for crushed stone/aggregate companies to be inserted into geologic models for mine planning and geologic modeling.

- Data is provided in spreadsheet or .LAS or similar format for import into modeling software as a variable for the model, as well as various graphic presentations.

- Incorporation of rock density information for formations allows mine planners to more accurately predict product parameters.

- More detailed, site-specific correlations of density data with other quality parameters is also possible, given sufficient data.

- Compositing strategies for density data in geologic models: by lithologic unit, by mining unit, by mine bench, etc.

- Contouring of data in stratified deposits versus more massive deposits.
Typical Density Logging Probe

9033 Logging Tool

**Background Information**
The 9033 tool contains a single detector, focused density system using a Cesium 137 source, to record apparent bulk density of the formation. Additionally, the tool also records natural gamma, caliper, and a medium guard resistivity.

**Features**

<table>
<thead>
<tr>
<th>Properties Measured (see diagram)</th>
<th>Tool Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. 3-Element Guard Resistivity:</td>
<td>Length: 307.3 cm (121 in.)</td>
</tr>
<tr>
<td>38.1 cm (15 in.) center electrode.</td>
<td>Temperature: 75 C (167 F)</td>
</tr>
<tr>
<td>139.7 cm (55.5 in.) Offset: 71.1 cm (28.5 in.)</td>
<td>Diameter: 56 mm (2.2 in.)</td>
</tr>
<tr>
<td>2. Natural Gamma: 3.175 x 11.43 cm (1.25 x 4.5 in.) NAI Scintillation</td>
<td>Pressure: 175 kg/cm² (2500 PSI)</td>
</tr>
<tr>
<td>Offset: 45.7 cm (18 in.)</td>
<td>Weight: 28.1 kg (62 lb.)</td>
</tr>
<tr>
<td>3. Caliper: Motorized, uphole actuated Collimator</td>
<td>Logging Speed: 9 m/min. (30 ft/min.)</td>
</tr>
<tr>
<td>Offset: 259 cm (102 in.)</td>
<td>Tool Voltage Required: 50 VDC</td>
</tr>
<tr>
<td>4. Density: 1.27 x 3.81 cm (0.5 x 1.5 in.)</td>
<td>radioactive source: 200 mCi Cesium 137 in bullplug</td>
</tr>
<tr>
<td>NAI focused scintillation Offset: 283.5 cm (111.6 in.) Source-to-detector spacing selectable between 19.1 cm (7.5 in) or 95 cm (3.75 in.)</td>
<td></td>
</tr>
<tr>
<td>5. Radioactive source: 200 mCi Cesium 137 in bullplug</td>
<td></td>
</tr>
</tbody>
</table>

**Sensor Response Ranges**

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Response Limits</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Gamma</td>
<td>0 - 10,000 API units</td>
<td>± 5%</td>
</tr>
<tr>
<td>Short Arm Caliper</td>
<td>0 to 20.3 cm (8 in.)</td>
<td>± 0.635 cm (0.25 in)</td>
</tr>
<tr>
<td>Long Arm Caliper</td>
<td>0 to 30.5 cm (12 in.)</td>
<td>± 0.635 cm (0.25 in)</td>
</tr>
<tr>
<td>High Resolution Density</td>
<td>0.5 to 3.5 g/cc (0.126 lbs./ct)</td>
<td>± 0.05 g/cc (0.001 lbs./ct)</td>
</tr>
<tr>
<td>Resistivity</td>
<td>0 to 60,000 ohm meters</td>
<td>± 5%</td>
</tr>
</tbody>
</table>
Density Log – Principle of Operation

Source and Detector Configuration on Typical Density Logging Probe

Bassiouni, 1994

Depth of Reading – Halfway Between Source and Detector

(From Tittman and Wahl, Geophysics, April 1965)
Calibration of Density Logging Probes (Standard Procedure)

Water Barrel Calibration for low end = 1.0 g/cc
   (Typical 25,000 CPS)

Limestone Test Hole Calibration for High
   end = 2.65 g/cc  (Typical 3300 CPS)

Steel Sleeve Calibration Jig for Field
   Check on site in Water Barrel
   (Typical = 2.2 g/cc / 9400 CPS)
Examples of Potential Sources of Density Data Deviations

- Pad-type tool separated from the formation by mudcake.
- Pad-type tool trapping drilling-mud pockets in a rough borehole.
Density Logging Limestone Aggregate Quarry

- Limestone Quarry Density Logging of HQ coreholes
- Log Density compared to selected Lab Density Data - Half foot intervals
- Limitations of this Data: No depth comparison of core to density log depths was done

<table>
<thead>
<tr>
<th>Lab Data</th>
<th>Log Data</th>
<th>Actual Difference</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.59</td>
<td>2.62</td>
<td>0.03</td>
<td>1.2%</td>
</tr>
<tr>
<td>2.42</td>
<td>2.68</td>
<td>0.26</td>
<td>9.5%</td>
</tr>
<tr>
<td>2.44</td>
<td>2.62</td>
<td>0.18</td>
<td>6.7%</td>
</tr>
<tr>
<td>2.63</td>
<td>2.67</td>
<td>0.04</td>
<td>1.4%</td>
</tr>
<tr>
<td>2.56</td>
<td>2.42</td>
<td>-0.14</td>
<td>-5.8%</td>
</tr>
<tr>
<td>2.39</td>
<td>2.55</td>
<td>0.16</td>
<td>6.3%</td>
</tr>
<tr>
<td>2.04</td>
<td>2.31</td>
<td>0.27</td>
<td>11.8%</td>
</tr>
<tr>
<td>2.71</td>
<td>2.7</td>
<td>-0.01</td>
<td>-0.5%</td>
</tr>
<tr>
<td>2.70</td>
<td>2.59</td>
<td>-0.11</td>
<td>-4.4%</td>
</tr>
<tr>
<td>2.27</td>
<td>2.42</td>
<td>0.15</td>
<td>6.3%</td>
</tr>
<tr>
<td>2.33</td>
<td>2.64</td>
<td>0.31</td>
<td>11.8%</td>
</tr>
<tr>
<td>2.56</td>
<td>2.74</td>
<td>0.18</td>
<td>6.4%</td>
</tr>
<tr>
<td>2.63</td>
<td>2.76</td>
<td>0.13</td>
<td>4.6%</td>
</tr>
<tr>
<td>2.70</td>
<td>2.67</td>
<td>-0.03</td>
<td>-1.0%</td>
</tr>
<tr>
<td>2.50</td>
<td>2.73</td>
<td>0.23</td>
<td>8.3%</td>
</tr>
<tr>
<td>2.19</td>
<td>2.51</td>
<td>0.32</td>
<td>12.8%</td>
</tr>
<tr>
<td>2.54</td>
<td>2.77</td>
<td>0.23</td>
<td>8.5%</td>
</tr>
<tr>
<td>2.48</td>
<td>2.64</td>
<td>0.16</td>
<td>6.2%</td>
</tr>
</tbody>
</table>

0.10 3.9% Average
Density Log Thru Drill Rods Corrected with Lab Data

Example of Apparent Density Log Data to Lab Data Correlation to Determine Correction Factor

<table>
<thead>
<tr>
<th>Lab Specific Gravity</th>
<th>Log Specific Gravity</th>
<th>Percent Difference</th>
<th>Lab-Log Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.652</td>
<td>2.584</td>
<td>2.6%</td>
<td>0.068</td>
</tr>
<tr>
<td>2.691</td>
<td>2.601</td>
<td>3.3%</td>
<td>0.080</td>
</tr>
<tr>
<td>2.655</td>
<td>2.558</td>
<td>3.6%</td>
<td>0.097</td>
</tr>
<tr>
<td>2.727</td>
<td>2.650</td>
<td>2.8%</td>
<td>0.077</td>
</tr>
<tr>
<td>2.742</td>
<td>2.623</td>
<td>4.3%</td>
<td>0.119</td>
</tr>
<tr>
<td>2.744</td>
<td>2.681</td>
<td>2.3%</td>
<td>0.063</td>
</tr>
<tr>
<td>2.728</td>
<td>2.675</td>
<td>2.0%</td>
<td>0.053</td>
</tr>
<tr>
<td>2.720</td>
<td>2.607</td>
<td>4.1%</td>
<td>0.113</td>
</tr>
</tbody>
</table>

\[ y = 0.9847x - 0.0435 \]

\[ R^2 = 0.7048 \]
Gamma radiation is not constant over short periods of time since it is a factor of radioactive decay.

Since the logging probes are moving up hole at a constant rate, “time constants” or (now with digital data) “filter points” are used to average the raw counts per second data that generate the natural gamma curves and gamma-gamma density curves, sometimes referred to as “smoothing”.

An appropriate number of filter points are used to average the raw data over specific hole intervals, depending on tool configuration, purpose of logging (bulk density or thin bed definition) etc.
Density Logs for Coal Exploration

> Natural Gamma – Density logging regularly performed for coal exploration holes to define Lithology of strata and coal thickness

> These logs are highly useful to correlate complex stratigraphy across properties.

> High Resolution density logs can be used to define thin partings down the quarter inch thickness in some coal deposits.
Sonic Logging

> Sonic Data used for a variety of applications for mining:
> Rock strength characteristics
> Elastic Moduli Calculations
> Compression and Shear wave velocities determination for blasting optimization.
> Porosity Determination
A Typical Sonic Log Presentation

A Sonic Log presentation: Green is P wave travel time VDL of waveform
Correlation of Sonic Log Data with Laboratory Uniaxial Compression Testing

Regional correlations have been established by others (Oyler, et al*).

Correlation of UCS with sonic signal allows for efficient and thorough geotechnical data acquisition throughout large areas.

Data collection can be integrated into normal exploration activities without requiring cost and labor associated with laboratory testing.

Increases understanding of geotechnical conditions and enhances ability to identify changes in conditions that may affect mining operations.

Example: Data from Coal Mine in Eastern United States

Study focused on massive sandstones in overburden that may affect caving.

Possible correlation suggesting that sandstone units are weaker at top and stronger near base (possible function of depositional or post-depositional environment).

Moderate correlation of sandstone units, but may be improved with more detailed analysis; poor correlation of shale units.

Sonic vs. UCS - Outliers Removed, By General Lithology

*Oyler, D. C., Mark, C., and Molinda, G.M., “In Situ Estimation of Roof Rock Strength Using Geophysics”, NIOSH-Pittsburgh Research Laboratory.

Oyler, D.C., Mark, C., and Molinda, G.M., “Correlation of Sonic Travel Time to the Uniaxial Compressive Strength of U.S. Coal Measure Rocks”, NIOSH-Pittsburgh Research Laboratory.
### Elastic Moduli of Rock from Sonic and Density Logs

<table>
<thead>
<tr>
<th>Depth</th>
<th>Density</th>
<th>Sonic</th>
<th>TTe</th>
<th>TTf</th>
<th>Poissons</th>
<th>Youngs</th>
<th>Shear</th>
<th>Bulk</th>
<th>Vc</th>
<th>Va</th>
<th>Vc/Va</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0</td>
<td>1.1</td>
<td>2.2</td>
<td>3.3</td>
<td>4.4</td>
<td>5.5</td>
<td>6.6</td>
<td>7.7</td>
<td>8.8</td>
<td>9.9</td>
<td>10.0</td>
</tr>
<tr>
<td>1</td>
<td>0.1</td>
<td>1.1</td>
<td>2.2</td>
<td>3.3</td>
<td>4.4</td>
<td>5.5</td>
<td>6.6</td>
<td>7.7</td>
<td>8.8</td>
<td>9.9</td>
<td>10.0</td>
</tr>
<tr>
<td>2</td>
<td>0.2</td>
<td>1.1</td>
<td>2.2</td>
<td>3.3</td>
<td>4.4</td>
<td>5.5</td>
<td>6.6</td>
<td>7.7</td>
<td>8.8</td>
<td>9.9</td>
<td>10.0</td>
</tr>
<tr>
<td>3</td>
<td>0.3</td>
<td>1.1</td>
<td>2.2</td>
<td>3.3</td>
<td>4.4</td>
<td>5.5</td>
<td>6.6</td>
<td>7.7</td>
<td>8.8</td>
<td>9.9</td>
<td>10.0</td>
</tr>
</tbody>
</table>

**Notes:**
- Depth values range from 0 to 3.
- Sonic, TTe, TTf, Poissons, Youngs, Shear, Bulk, Vc, Va, and Vc/Va are properties measured under varying conditions.
- The table includes a range of values for each property, indicating variability in the measured data.

**Source:**
- Marshall Miller & Associates

**Graph:**
- A graph illustrates the relationship between depth and the properties listed above, with different colors representing various types of elastic moduli.
Case Study - Neutron and Density Log for Bridge Settlement Investigation

Moisture/Density of Soils and Fill

> The Pennsylvania Department of Transportation (PennDOT) along with MM&A designed a drilling and logging program to investigate subsurface conditions at several locations where bridge abutment settlement was taking place.

> MM&A was contracted to perform geophysical logging of steel cased borings with both density and neutron logging probes in the fill material and natural soils in the vicinity of several bridges.

> The goal was to derive the moisture - density relationship for the fill and soil materials at each location from near surface down to the bedrock horizon.

> Steel casings were installed using a casing advancer by the drilling contractor, and split spoon samples were collected for moisture content analysis at various intervals within each boring.

> Each cased boring was logged by MM&A for natural gamma, neutron and density inside the steel casing as it was completed.

> Other applications for this method would be for soft clay zones in coal mining or other mining applications. Specifically coal mines in the Illinois Basin and other basins.
Neutron and Density Log for Bridge Settlement Investigation

Moisture/Density of Soils and Fill

> The density curve was calibrated using two calibration jigs constructed with known density material outside pieces of the actual steel casing used.

> Calibration curves to convert the raw neutron data to moisture content were developed by linear regression analysis of the raw neutron counts and the reported moisture contents of the laboratory analysis of samples.

> The resulting formulas were used to create an Apparent Moisture Content curve by applying each calibration curve to the raw Neutron counts.
Log plots were developed for each boring showing the natural gamma curve, apparent density curve, raw neutron counts, and apparent moisture content curves. Density and moisture content curves are labeled as apparent density or apparent moisture content, as these were logged through the steel casing and are not compensated for any conditions, such as washouts, that may occur outside the casing.
Composite Log for Deep Rock Tunnel Project in Atlanta, GA

Borehole Geophysical Logging Example
Downhole Video Cameras
Missed Pilot Hole when Enlarging Bedrock Well
Summary

- Many companies do not include geophysical logging as part of regular exploration activities.
- Many mines lack geological and geotechnical data required for a good model of reserves and geotechnical conditions.
- Downhole geophysical logging techniques provide a fast and cost effective means for collecting large amounts of quality data.
- Data collection can accommodate ongoing operations and can be integrated into already planned exploration drilling.
- Faster and less expensive data acquisition allows for better spatial coverage, which results in a better understanding of complex geological and geotechnical conditions.
- Overall, more efficient data acquisition techniques have the potential to enhance safety, mineral recovery, and mine life.
Assessment of Sequenced Room and Pillar Retreat Coal Mine Subsidence Using the Surface Deformation Prediction System (SDPS)

To be presented at 2018 ARMA, American Rock Mechanics Association

Andrews, K., Marshall Miller & Associates, Blacksburg, Virginia, USA
Agioutantis, Z., University of Kentucky, Lexington, Kentucky, USA
Surface Deformation Prediction System (SDPS)

- Subsidence modeling program for prediction of both static and dynamic longwall mine subsidence, and static prediction for almost any mining scenario (including multi-seam mining)
- Influence function method for calculating mine subsidence and subsidence-related deformations
- Initially developed in 1987 at Virginia Polytechnic Institute and State University (Virginia Tech)
- Continuously updated and expanded since its creation

Longwall Mining – Dynamic Subsidence

- Includes a time factor - rate of advance
- Can predict end of main phase of subsidence in days
Long-Term Landscape Stability

- Risk-based approach
- Evaluate the results of various “worst case” scenarios very efficiently
- Compare model results to relevant threshold values
- Establish “high-risk” zones

Map showing combination of threshold strain values and boundary of planned surface development. High-risk zones are those where overlap occurs.
Retreat Mining Subsidence

- Variable speed
- Irregular pattern
Modeling Sequenced Pillar Extraction

- Use Long-Term Landscape Stability module of SDPS
- Produce sequenced, final, static results for each step of mining
- DOES NOT ACCOUNT FOR TIME, but does provide expected subsidence effects at a surface point in terms of mining position.
Power Pole 1 Results

Subsidence Development

Ground Strain Development

Mining Sequence

Power Pole 1

Power Pole 2

Mining Sequence
Power Pole 2 Results

Subsidence Development

Ground Strain Development

Power Pole 1

Power Pole 2

28 25 22 19 16 13 10 7 4 3
29 26 23 20 17 14 11 8 5
30 27 24 21 18 15 12 9 6
77 72 67 62 57 52 47 42 37 32
78 73 68 63 58 53 48 43 38 33
79 74 69 64 59 54 49 44 39 34
80 75 70 65 60 55 50 45 40 35
81 76 71 66 61 56 51 46 41 36
82

0 remnant 23.1 remnant

0 remnant 23.1 remnant
Other Calculated Subsidence Effects

Maximum Total Slope Development

Direction of Maximum Total Slope (Down-Slope Direction)

Direction of Maximum Displacement (Horizontal and 3D)