Ground Control Studies for Mining Through a Fault Using Retreat Longwall Mining: Field and Analytical Observations

Y. P. Chugh, Harrold Gurley, Behrooz Abbasi
Mining and Minerals Resources Engineering
Southern Illinois University Carbondale
In cooperation with
American Coal Company
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Acknowledgements

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• Dr. Joseph Hirschi for his technical guidance and oversight.

• Sincere thanks to Mark Mormino, Gary Vancil and their staff members of American Coal Company for their technical support and cooperation.

• Additional thanks are due to Itasca Consultants, Inc. for allowing the use of Version 5 FLAC3D software.
Goals of the Cooperative Study

• Develop better understanding of longwall mining operations around geologic anomalies.
• Quantify the movements that can occur in development areas while mining around faults.
• Assess if these movements can be projected with some confidence using numerical models even with large number of uncertainties.
• Develop a better understanding of the mechanisms of movements as the face advances.
• Have made progress in all these areas and will be working more over the next 1-2 years.
Ground movements can be significantly affected around a fault in longwall mining areas due to varying support provided to the fault plane and adjoining rock mass by gob, pillars in development entries, and longwall face itself.

Ground movements depend upon face location in relation to fault, spatial geometry of the fault, engineering properties of fault interfaces, gob, and coal measure rocks and interaction between them.

Ground movements impacts can significantly affect production, productivity, and safety in the face area.

Therefore, it is critical to understand these movements assess impacts of fault in advance of mining- even if there are large number of unknowns.
Impacts of fault on ground control in headgate entries and face area
Impacts of fault on ground control around tail gate entries and face

- Fault
- Solid Coal
- Gob
- Gate Entries
- Set-up Rooms
Impact of fault on head gate, tail gate entries, and face areas.
Research Summary

• Research performed in two adjacent panels with very complex faulting.
• Studies involved field measurements in development entries as the face advanced toward the fault.
• Developed a 3-D structural behavior model for the mine using FLAC3D, and estimated ground movements.
• The results show that development of a macro-level structural model is the key to success.
• Agreement between projected ground movements and field observations is reasonable for mine planning purposes.
Field Geotechnical Studies
Location of Major Faults and Monitoring Locations in Headgate Entries (Areas 1, 2)

Area 1

Area 2
Smaller Faults in Area 2 Near Set-up Rooms
Faulted Area Geology
Area 1 Studies
The Major fault had down-throw displacement of 7 ft.

Fault down-thrown east with strike of N30°W and dip of 60-63°.

A smaller fault was located 300 ft. inby (east) and was down-thrown to the west.
Ground Movement Monitoring

- Roof-to-floor convergence using rod extensometer
- Roof and rib rosettes.
- Each data point was measured 3-4 times and the average was used for inference development.
Four crosscuts were monitored for roof-to-floor convergence as longwall began production.
Convergence as Longwall Face Approached Fault Area

Face 7/18
Face 7/16
Face 7/13
Face 7/09
Face 7/06
Face 7/05
Area 1 Convergence in Belt Entry as Longwall Face Approaches

Convergence (mm)

Date

7/05 7/06 7/08 7/09 7/10 7/11 7/12 7/16 7/13 7/18

Pt 1  Pt 2  Pt 3  Pt 4

Pt 4  Pt 3  Pt 2  Pt 1

Longwall face advance

Fault

Pt 4
Pt 3
Pt 2
Pt 1

Area 1 Convergence in Belt Entry as Longwall Face Approaches
Area 1- Roof Rosette Indicated Movements

RR3 E1 @ 88+00

RR3 E1 @ 63+64
Summary In-Mine Studies: Area 1

- Around the fault area 25-30 mm of roof-floor convergence observed.
- Significant distortions of the roof in entries when the longwall face is within 100 ft of the fault.
- Away from the fault roof to floor convergence is only on the order of 4-5 mm.
- Even divergence was observed in some areas.
- Divergence was attributed to beam action with fault as the rotation point (by authors).
Area 2 Studies
Area 2 Studies – Small Fault Area Near Set-up Rooms

Face had advanced about 150 feet on December 20 to within 625 feet from first point – Pt 14. Points 11 and 12 show most convergence.
Area 2 - Convergence Major Fault Area

Longwall production began
Area 2 Convergence/divergence as Longwall Face Approaches Points on Up-thrown Side of Fault

Production begins

Period during development of set-up rooms and installation of longwall equipment

Convergence (inch)

Date


Pt 1 Pt 2

Pts 8-9-10 Face by 01/29 Face by 01/24 Face advance by 01/03

Production begins
Area 2 Convergence/divergence as Longwall Face Approaches Points on Down-thrown Side of Fault

- Production begins
- Period during development of set-up rooms and installation of longwall equipment

Date:
- 1/25/2013
- 1/21/2013
- 12/20/2012
- 12/8/2012
- 12/26/2012
- 12/14/2012
- 10/21/2012
- 10/9/2012
- 9/27/2012
- 9/15/2012
- 9/3/2012
- 8/22/2012
- 8/10/2012

Convergence (inch):
- Pt 8
- Pt 9
- Pt 10

Notes:
- Pt 1
- Pt 2
- Pts 8-9-10
- Face by 01/29
- Face by 01/24
- Face advance by 01/03
Bent Supplemental Supports While Crossing the Fault
Summary In-Mine Studies: Area 2

• Fault dip in this area was only 20-30 degrees as compared to 55-60 degrees in Area 1.
• Around the fault area 20-25 mm of roof-floor convergence observed.
• Distortions of the roof in entries toward mined out areas but it was not very severe.
• Away from the fault roof to floor convergence is only on the order of 5-7 mm.
• As in Area 1, divergence was observed in some areas.
Model Development and Analysis Techniques (Area 2)
Numerical modeling: Some major points

• Fault geometry in Area 2 was modeled as a single fault. Fault was modeled as a joint (UJRM) with Mohr-Coulomb properties.

• Engineering properties on cores from the mine were transformed to rock mass properties using Hoek-Brown models.

• GSI was used for estimating rock mass properties.

• Gob load carrying behavior was estimated as non-linear based on field observations.

• Both linear and non-linear analyses were performed.
Model Development and Analysis Techniques: Gob Behavior

VSCF vs. cross section AA’ after 500 ft. face advance

VSCF vs. cross section BB’ after 500 ft. face advance

Gob load behaviour along longwall panel Implemented in the numerical model

Gob load behaviour along longwall panel (predicted by Field Observation)

Gob load behaviour across longwall panel Implemented in the numerical model
Location of Cross-sections AA’, BB’, and CC’ Used for Displacement Analysis
Vertical Displacement Along Cross-section AA’ for Models 1 and 2
Vertical Displacement Along Cross-section BB’ for Models 1 and 2
Vertical Displacement Along Cross-section CC’ for Models 1 and 2
### Results: Field Measurements in Gate Entries Related to Fault Zone

<table>
<thead>
<tr>
<th>Lateral Wall Face Distance</th>
<th>Side</th>
<th>Field Data</th>
<th>Numerical Analysis</th>
<th>Percent Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>70 m away from fault</td>
<td>Up-Thrown</td>
<td>1.47</td>
<td>1.70</td>
<td>+13.43</td>
</tr>
<tr>
<td></td>
<td>Down-Thrown</td>
<td>0.30</td>
<td>0.44</td>
<td>+13.64</td>
</tr>
<tr>
<td>39.6 m away from fault</td>
<td>Up-Thrown</td>
<td>2.06</td>
<td>2.39</td>
<td>+16.36</td>
</tr>
<tr>
<td></td>
<td>Down-Thrown</td>
<td>0.53</td>
<td>0.66</td>
<td>+10.23</td>
</tr>
</tbody>
</table>
Numerical Modeling Predicted Values of Peak Displacements for Models 1 and 2

<table>
<thead>
<tr>
<th>Cross-section</th>
<th>LF 70-m away from fault</th>
<th>LF 39.6-m away from fault</th>
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<tbody>
<tr>
<td></td>
<td>Model 1</td>
<td>Model 2</td>
</tr>
<tr>
<td>Vertical Displacement</td>
<td></td>
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</tr>
<tr>
<td>AA'</td>
<td>1.74</td>
<td>2.01</td>
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<tr>
<td>BB'</td>
<td>2.23</td>
<td>2.44</td>
</tr>
<tr>
<td>CC'</td>
<td>3.66</td>
<td>3.66</td>
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<tr>
<td>X-Horizontal Displacement</td>
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<td></td>
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<tr>
<td>AA'</td>
<td>0.06</td>
<td>0.27</td>
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<tr>
<td>BB'</td>
<td>0.3</td>
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<td>CC'</td>
<td>0.64</td>
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<tr>
<td>Y-Horizontal Displacement</td>
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<tr>
<td>AA'</td>
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<td>0.76</td>
</tr>
<tr>
<td>BB'</td>
<td>0.16</td>
<td>0.67</td>
</tr>
<tr>
<td>CC'</td>
<td>0.46</td>
<td>0.64</td>
</tr>
</tbody>
</table>
Concluding Remarks

- There were large number of unknowns in this study.
- In spite of all the simplifications, field convergence while crossing faults in reasonable agreement with models.
- It can be used to plan ahead of mining to improve safety and productivity in mining.
- Guided the coal company through faults without unsafe incident and significant loss in production or productivity.
- Key to success: development of the structural model.
- Model used to redesign more efficient and stable setup rooms geometries (size of pillars and entries), and behavior of the fault.
- Over the years, Chugh has advocated a combination of analytical modeling-field studies to improve productivity and safety in coal mines. This study represents a success story in that regard.
- Authors urge companies to develop simplified structural models of their mine to assess effects of mining through geologic anomalies.
Questions??
Hoek-Brown Rock Mass Properties Used for Analytical Modeling

<table>
<thead>
<tr>
<th>Parameters</th>
<th>GSI</th>
<th>mi</th>
<th>$\sigma_c$ MPa</th>
<th>$m_r$</th>
<th>$s_r$</th>
<th>$a_r$</th>
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<td>20</td>
<td>100</td>
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<tr>
<td>Black Shale</td>
<td>45</td>
<td>10</td>
<td>37</td>
<td>0.8118</td>
<td>0.001188</td>
<td>1</td>
</tr>
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<td>Weak Limestone</td>
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<td>60</td>
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<td>10</td>
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<tr>
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<td>Friction Angle (deg.)</td>
<td>Joint Cohesion MPa</td>
<td>Joint Friction Angle (deg.)</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Strong Limestone</td>
<td>12</td>
<td>30</td>
<td>6</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Black Shale</td>
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<td>22</td>
<td>2.7</td>
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<td></td>
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<tr>
<td>Weak Limestone</td>
<td>8</td>
<td>30</td>
<td>4</td>
<td>17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lawson Shale</td>
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<td>22</td>
<td>1.3</td>
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<td>Grey Shale</td>
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<tr>
<td>Coal</td>
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<td>26</td>
<td>2.2</td>
<td>15</td>
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</tr>
<tr>
<td>Weak Claystone</td>
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<td>20</td>
<td>0.4</td>
<td>15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
X-Displacement (D to D')

- Displacement (mm)
  - Solid Coal
  - Setup Rooms
  - Solid Coal
  - Development Entries
  - Solid Coal

- Distance D to D' (m)
  - D₁
  - D₂

(Development Only)
Y-Displacement (D to D')

Distance D to D' (m)

Displacement (mm)

(6m face advance from Setup Rooms)

D1

D2

Solid Coal
Setup Rooms
Solid Coal
Development Entries
Solid Coal
# Analytical Studies: Model Development and Analysis Techniques

<table>
<thead>
<tr>
<th>Model</th>
<th>Type of Analysis</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Longwall panel without fault zone</td>
<td>Longwall face 230-ft away from intersection of fault and gate entries. Longwall face 130-ft away from intersection of fault and gate entries.</td>
</tr>
<tr>
<td>2</td>
<td>Longwall panel with fault zone</td>
<td>Longwall face 230-ft away from intersection of fault and gate entries. Longwall face 130-ft away from intersection of fault and gate entries.</td>
</tr>
</tbody>
</table>
Fault Modeling

- Ubiquitous Joint Rock Mass (UJRM) is a technique for introducing rock mass anisotropy (weak planes such as discontinuity and lamination) in a continuum numerical modeling.
- UJRM is a weak plane with a user defined cohesion, friction angle, dip direction and dip orientation.
- UJRM does not consider:
  - Joint spacing, stiffness and length.
  - UJRM can’t consider more than one weak plane (anisotropic direction).

$$\tau = c + \sigma_n \tan \varphi$$

Mohr-Coulomb failure criteria
A combined Discrete/DFN modelling approach can be used to derive equivalent continuum properties.

Limitations of 2D approach. Ideally the analysis should be carried out in 3D.

! Structurally Controlled Response !
Area 2 - Roof Rosette Indicated Movements

RR2 - XC 53 E3

RR3 - XC 54 - E3

RR4 - XC 54 E2
Rock Mass Properties

Idealized Discrete Model

Simulation of step-path and intact rock bridge failure

Larger Problem Discretization / Less Details

Simplified Discrete Model

Smaller Problem Discretization / More Details

Continuum Model

Randomly oriented ubiquitous joint planes could be distributed in the model to account for the effects of jointing
Vertical Displacement Along Cross-section AA' and BB'

Cross-section AA'

Cross-section BB'

0.013 in

0.04 in

0.01 in

0.03 in
## Results: Field Measurements in Gate Entries Related to Fault Zone

<table>
<thead>
<tr>
<th>LW face 70-m away from fault</th>
<th>Side</th>
<th>Field data</th>
<th>Numerical analysis</th>
<th>Percent (%) difference</th>
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<tr>
<th>LW face 39.6-m away from fault</th>
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<td>+10.23</td>
</tr>
</tbody>
</table>
## Comparison of Model Data to Field Data

<table>
<thead>
<tr>
<th>Distance to face to fault – Model - Field</th>
<th>Model Predicted Convergence</th>
<th>Field Measured Convergence</th>
</tr>
</thead>
<tbody>
<tr>
<td>70 m (230 ft.) – 84 m (275 ft.)</td>
<td>24.4 mm</td>
<td>13 mm</td>
</tr>
<tr>
<td>39 m (130 ft.) – 43 m (140 ft.)</td>
<td>33.5 mm</td>
<td>2.6 mm</td>
</tr>
</tbody>
</table>

Differences: Field points were installed after openings were created. Model predicted values include movements of excavations. Model data did not account for additional supports. Entries had supplemental crib supports in each intersection, T-channels and cable bolts, and intermittent installation of “Super Props”.