Three-Dimensional Numerical Modelling of Longwall Mining from Final Highwall at Mae Moh Lignite Mine, Thailand

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1. Introduction
   – Abstract of Mae Moh lignite mine
   – Background and purpose of research

2. Numerical Analysis
   – Numerical modeling; $FLAC^{3D}$
   – Modeling procedure, results and discussion

3. Conclusion
Abstract of Mae Moh lignite mine

**Mine**: Mae Moh

**Location**: Thailand

**Type**: Lignite

**Heat value (kcal/kg)**
- Mae Moh: 2,810
- Envirocoal: 5,200
- Newcastle: 6,420

**Ash content (%)**
- Mae Moh: 20.1
- Envirocoal: 1.2
- Newcastle: 14.0

**Moisture content (%)**
- Mae Moh: 30.7
- Envirocoal: 26.0
- Newcastle: 9.0

**Volatile matter (%)**
- Mae Moh: 25.5
- Envirocoal: 43.0
- Newcastle: 32.0

**Fixed carbon (%)**
- Mae Moh: 21.5
- Envirocoal: 40.5
- Newcastle: 51.5

**Sulfur (%)**
- Mae Moh: 2.77
- Envirocoal: 0.10
- Newcastle: 0.50

**Waste Removal**: 80–100 Mil. BCM/year (5:1)

**Dumping Area**: 7 km

**Mining Area**: 4 km

**FGD (Flue Gas Desulphurization)**

Installed

Generate 18,000 Mil. unit of electricity/year

Unit 1-3 = 225 MW. *Removed*

(Courtesy of EGAT)
Mine map: plan view at the end of operation

- Dump height: 275 m
- Pit depth: 480 – 500 m
- Remained coal: ~ 160 Mt
Residual coal is abundant beneath highwall.

Underground mining is able to enhance coal recovery.
Underground mining methods

- Pillar supported
  - Room-and-pillar
    - Sublevel and longhole open stoping
- Artificially supported
  - Bench-and-fill stoping
  - Cut-and-fill stoping
  - Shrink Stoping
  - VCR stoping
- Unsupported
  - Longwall mining
  - Sublevel caving
  - Block caving

Magnitudes of displacements in country rock

Strain energy storage in near-field rock

Rock mass response to mining

(Brady and Brown, 1993)
Longwall mining method

A coalbed is blocked out into a panel averaging nearly 100-200m in width by excavating gateways around its perimeter.

Advantage
- High productivity
- Continuous operation
- Fewer workers are required
- Working under roof supports

Disadvantage
- High capital costs
- Complex system
- Dust controls
- Surface subsidence
Development of underground mine is considered before the open-pit operation comes to the end.

- Adverse conditions (weak strength of coal, slope failures, etc.)
- No experience of longwall mining in Thailand

However,

The purpose of this study is to examine applicability of longwall mining at Mae Moh mine by predicting the ground behavior using three-dimensional explicit finite difference program; *FLAC*³."
Numerical modeling - \textit{FLAC}^{3D}

**Bench:**
- Height = 10m, Width = 10m
- Angle = 45°

**Berm:**
- Width = 20m

**Thickness:**
- Interburden = 20m
- K_seam = 25m
- Q_seam = 20m
- Underburden = 500m

**Overall slope angle:**
\[ \text{angle} = 18.4^\circ \]
**FLAC$^3$D** – Mining scenario

Longwall panel length

= 300 m

Side barrier-pillar mining direction

Barrier-pillar

Improve slope stability by **rib-pillar**!!
FLAC$^{3D}$ – Pillars for safer operation

Side barrier-pillar

Rib-pillar

Barrier-pillar

5m

4m

10m
Material properties used in simulations
(Courtesy of EGAT)

<table>
<thead>
<tr>
<th>Materials</th>
<th>Clay stone</th>
<th>Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>1,950</td>
<td>1,430</td>
</tr>
<tr>
<td>Young’s modulus (MPa)</td>
<td>10,000</td>
<td>100</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.25</td>
<td>0.4</td>
</tr>
<tr>
<td>Internal frictional angle (deg)</td>
<td>25</td>
<td>22.3</td>
</tr>
<tr>
<td>Cohesion (MPa)</td>
<td>1.75</td>
<td>0.16</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>
Goaf compaction

Coefficients for average height of caving zone

<table>
<thead>
<tr>
<th>Strata Type</th>
<th>$C_1$</th>
<th>$C_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong and hard</td>
<td>2.1</td>
<td>16</td>
</tr>
<tr>
<td>Medium strong</td>
<td>4.7</td>
<td>19</td>
</tr>
<tr>
<td>Soft and weak</td>
<td>6.2</td>
<td>32</td>
</tr>
</tbody>
</table>

Modulus Updating Method
(Badr et al., 2003)

$$K = \frac{1.75}{0.5 - \varepsilon_v}$$

$K = $ Bulk modulus, $\varepsilon_v = $ Vertical strain

$$G = 3K(1-2\nu)/2(1+\nu)$$

Caving Height
(Whittles et al., 2005)

$$H_c = \frac{100h}{C_1h + C_2}$$

$H_c = $ Caving height (m)
$h = $ Mining height (m)
$C_1, C_2 = $ Coefficients

Coal Seam
Direction of mining
Layer
Assessment of stability

Assessment by monitoring surface subsidence.

3 panels

Surface subsidence (m)

Horizontal distance from pit center (m)

(Unit: m)
Results ① - Subsidence

Horizontal distance from pit center (m) vs. Surface subsidence (m)

- 1panel-300m-rib100m
- 1panel-300m-rib200m
- 1panel-400m-rib100m
- 1panel-400m-rib200m
- 1panel-500m-rib100m
- 2panels-300m-rib100m
- 2panels-300m-rib200m
- 2panels-400m-rib100m
- 2panels-400m-rib200m
- 2panels-500m-rib100m
- 3panels-300m-rib100m
- 3panels-300m-rib200m
- 3panels-400m-rib100m
- 3panels-400m-rib200m
- 3panels-500m-rib100m

Plane of symmetry
Results ① - Subsidence (1 panel)

Horizontal distance from pit center (m)

Surface subsidence (m)

Plane of symmetry

300m-rib100m
300m-rib200m
400m-rib100m
400m-rib200m
500m-rib100m
Results ① - Subsidence (2 panels)

**Graph:**
- **Horizontal distance from pit center (m):** 0, 100, 200, 300, 400, 500
- **Surface subsidence (m):** 0, 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4

**Legend:**
- 300m-rib100m
- 300m-rib200m
- 400m-rib100m
- 400m-rib200m
- 500m-rib100m

**Notes:**
- Plane of symmetry
- Subsidence (2 panels)

**Inset:**
- FLAC3D 5.00 by Itasca Consulting Group Inc.
Results - Subsidence (3 panels)

Horizontal distance from pit center (m)

Surface subsidence (m)

- 300m-rib100m
- 300m-rib200m
- 400m-rib100m
- 400m-rib200m
- 500m-rib100m

Plane of symmetry
### Results ① - Subsidence (3 panels)

**Rib-pillar length**

<table>
<thead>
<tr>
<th>100m</th>
<th>200m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longwall panel length</td>
<td></td>
</tr>
<tr>
<td>300m</td>
<td>300m</td>
</tr>
<tr>
<td>400m</td>
<td>400m</td>
</tr>
</tbody>
</table>

(Unit: m)
Results and discussion ① - Subsidence

<table>
<thead>
<tr>
<th>Subsidence reduction rate (%)</th>
<th>Number of longwall panels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Longwall panel length (m)</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>9.9</td>
</tr>
<tr>
<td>400</td>
<td>7.2</td>
</tr>
</tbody>
</table>

(※In the case that the rib-pillar length is extended from 100m to 200m)

✔ The more longwall panels, the more effectiveness of longer rib-pillar appears on the surface subsidence.

✔ Shorter longwall panel length, more effectiveness of longer rib-pillar can be expected.
Assessment of stability

Assessment by contours of strength factor based on the Mohr-Coulomb failure criteria.

Strength factor

\[\text{Strength factor} = c \cos \phi + \frac{\sigma_1 + \sigma_3}{2} \sin \phi \div \frac{\sigma_1 - \sigma_3}{2}\]
Results ② - Strength factor (1 panel)

Rib-pillar length

Longwall panel length

300m

100m

200m

400m
Results ② - Strength factor (3 panels)

Longwall panel length

- 300m
- 400m

Rib-pillar length

- 100m
- 200m
Results② - Strength factor

- **No stress influence over adjacent longwall panels**
  (Single panel, or wide enough barrier-pillar)
  The slope stability improves with extending the length of rib-pillar as well as the behavior of subsidence.

- **Stress influence over adjacent longwall panels**
  (With influence of stress superposition)
  The slope stability deteriorates with extending the length of rib-pillar since the overburden gets high and shear stress around rib-pillar becomes excessively large.
For further research

- The spatial relationship between the width of barrier-pillar and that of longwall panel needs to be taken into account.
  - Wider barrier-pillars to decrease the stress superposition.
  - Shortwall mining method.

- Backfilling methods should be considered to enhance the stability.
  - Using industrial wastes from the adjacent power plant, such as flue-gas desulfurization gypsum and fly ash.
Conclusions

- Surface subsidence can be reduced by extending the length of rib-pillar.

- In the case that stress superposition occurs, shear stress on the slope surface becomes large regardless of whether rib-pillar is extended to 200m.

- In this pillar conditions, extracting several longwall panels is not accepted. Further research is needed to develop the planning of longwall mining method.
Thank you for your attention.
1. An “explicit” solution scheme is used. Explicit schemes can follow arbitrary nonlinearity in stress/strain laws in almost the same computer time as linear laws, whereas implicit solutions can take significantly longer to solve nonlinear problems.

2. FLAC\(^3D\) is robust in the sense that it can handle any constitutive model with no adjustment to the solution algorithm; many finite element codes need different solution techniques for different constitutive models.
## FLAC\(^3\)D – Material properties

### Material properties of rocks

<table>
<thead>
<tr>
<th>Materials</th>
<th>Density (kg/m(^3))</th>
<th>Young's modulus (MPa)</th>
<th>Poisson’s ratio</th>
<th>Internal frictional angle (°)</th>
<th>Cohesion (MPa)</th>
<th>Tensile strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay stone</td>
<td>1,950</td>
<td>10,000</td>
<td>0.25</td>
<td>20</td>
<td>1.75</td>
<td>1.0</td>
</tr>
<tr>
<td>Coal</td>
<td>1,430</td>
<td>500</td>
<td>0.28</td>
<td>22.3</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

(Courtesy of EGAT)

### Coal properties used in simulations

<table>
<thead>
<tr>
<th>Location</th>
<th>Density (kg/m(^3))</th>
<th>Young's modulus (MPa)</th>
<th>Poisson’s ratio</th>
<th>Internal frictional angle (°)</th>
<th>Tensile strength (MPa)</th>
<th>UCS (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>1,400</td>
<td>2,000</td>
<td>-</td>
<td>25</td>
<td>0.6</td>
<td>7.6</td>
</tr>
<tr>
<td>U.S.A</td>
<td>1,350</td>
<td>3,000</td>
<td>0.25</td>
<td>-</td>
<td>-</td>
<td>7.6</td>
</tr>
</tbody>
</table>
Remedy - Backfilling

Backfilling can enhance slope stability.

ex) 3 panels,

Longwall panel length = 400m, rib-pillar length = 200m
Backfill properties used in numerical simulations (cemented material)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m$^3$)</td>
<td>2,000</td>
</tr>
<tr>
<td>Young’s modulus (MPa)</td>
<td>200</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.20</td>
</tr>
<tr>
<td>Internal frictional angle (deg)</td>
<td>35</td>
</tr>
<tr>
<td>Cohesion (MPa)</td>
<td>0.5</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>0</td>
</tr>
</tbody>
</table>
Results of backfilling - Subsidence

Horizontal distance from pit center (m) vs. Surface subsidence (m)

- Improvement by 17% compared to 400m-rib200m

- 3 panels: Backfilled

- H' and H represent different measurement points.
Results② - Strength factor (3 panels)
Results ② - Strength factor (6 panels)

- Rib-pillar length
  - 100m
  - 200m

- Longwall panel length
  - 300m
  - 400m
Results② - X-displacement (3 panels)

Not backfilled

Backfilled
## Coal properties

<table>
<thead>
<tr>
<th>Mine</th>
<th>Mae Moh</th>
<th>Envirocoal</th>
<th>Newcastle Weak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Thailand</td>
<td>Indonesia</td>
<td>QLD, Australia</td>
</tr>
<tr>
<td>Type</td>
<td>Lignite</td>
<td>Sub-bituminous</td>
<td>Bituminous</td>
</tr>
<tr>
<td>Heat value (kcal/kg)</td>
<td>2,810</td>
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<td>6,420</td>
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<tr>
<td>Sulfur (%)</td>
<td>2.77</td>
<td>0.10</td>
<td>0.50</td>
</tr>
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</table>
**Mark-Bieniawski empirical strength formula:**

\[
\sigma_p = \left(17.4\ (\text{MPa})\right)
\]

\[
\sigma_1 = \left[0.64 + 0.54\left(\frac{w}{h}\right) - 0.18\left(\frac{w^2}{lh}\right)\right]
\]

\[
\sigma_1 = 4.11\ (\text{MPa})\quad (\text{Courtesy of EGAT})
\]

\[
\sigma_p = \text{Pillar average strength}
\]

\[
\sigma_1 = \text{In-situ strength}
\]

\[
w = \text{Narrowest pillar width}
\]

\[
h = \text{Pillar height}
\]

\[
l = \text{Pillar length}
\]
Shift to underground mining

(Courtesy of EGAT)
Assessment of stability ②

Assessment by contours of strength factor based on the Mohr-Coulomb failure criteria.

Strength factor

\[ = \frac{L}{r} \]