Energy Release and Failure Model of Coal Samples
-Laboratory Test and Numerical Modelling

Dr. Ting Ren
Xiaohan Yang & Lihai Tan

University of Wollongong
Content

1. Introduction

2. Energy Analysis

3. Numerical Analysis

4. Current Work

5. Conclusions
Introduction

Coal Bursts in Australia

19 August 2016
Coal burst occurred on LW B2 lonwall face. Barraba Fault located on the south-west corner of longwall face.

2 February 2018
Coal burst occurred on LW B4 longwall face.

17 May 2018
Coal burst occurred on longwall face.

27 May 2018
Coal burst occurred in the roadway at the development panel.

Structural Geology of Coal Burst Sites
Energy Analysis

Static and Dynamic Load Superposition Theory
Coal burst will occur when the sum of static and dynamic load exceeds the minimum load required for coal burst formation. The energy released during coal burst is provided by static load and dynamic load.

Coal Burst Induced by Static and Dynamic Load superposition (Dou et al)
**Energy Analysis**

**Energy Sources of Coal Bursts in Australia**

Elastic energy accumulation resulted from high mining depth and complicated geological structure is the major contribution of energy sources of coal burst.

---

**Coal Burst of Coal Mine A**

**Coal Burst of Coal Mine B**
Energy Analysis

Energy Dissipation Analysis

\[ E_{\text{plastic}} + E_{\text{elastic}} = E_{\text{total}} \]

\[ E_{\text{elastic}} = E_{\text{crushing}} + E_{\text{kinetic}} + E_{\text{residual}} \]

Schematic Diagram of Energy Accumulation before Peak Strength

Stress versus Strain Curve of Coal Samples
**Energy Analysis**

**Coal Burst Propensity Index**

Coal burst propensity index method is an effective way to evaluate the burst risk of coal mines. Further tests with different coal seams are required in order to develop specific coal burst propensity classification method for Australian coal seams.

<table>
<thead>
<tr>
<th>Burst Propensity</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>DT &gt; 10000</td>
<td>1000 &lt; DT ≤ 10000</td>
<td>500 &lt; DT ≤ 10000</td>
<td>DT ≤ 500</td>
</tr>
<tr>
<td>$K_E$</td>
<td>$K_E &lt; 2$</td>
<td>$2 \leq K_E &lt; 3.5$</td>
<td>$3.5 \leq K_E &lt; 5$</td>
<td>$K_E \geq 5$</td>
</tr>
<tr>
<td>$W_{ET}$</td>
<td>$W_{ET} &lt; 2$</td>
<td>$2 \leq W_{ET} &lt; 3.5$</td>
<td>$3.5 \leq W_{ET} &lt; 5$</td>
<td>$W_{ET} \geq 5$</td>
</tr>
<tr>
<td>$R_C$/Mpa</td>
<td>$R_C &lt; 5$</td>
<td>$5 \leq R_C &lt; 10$</td>
<td>$10 \leq R_C &lt; 15$</td>
<td>$R_C \geq 15$</td>
</tr>
</tbody>
</table>

Risk Assessment

Sample Preparation

Violent Failure

Gentle Failure

Coal Burst Propensity Index Test
Energy Analysis

Coal Burst Propensity Index
Energy Analysis

Kinetic Energy Estimation

\[ E_{\text{elastic}} = \frac{V}{2E_0} \left[ \sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\mu (\sigma_1 \sigma_2 + \sigma_2 \sigma_3 + \sigma_3 \sigma_1) \right] \]

\[ E_{\text{kinetic}} \approx E_{\text{elastic}} - E_{\text{crushing}} \]

\[ F(d) = \left( \frac{d}{d_{\text{max}}} \right)^{(3-n)} \]

Coal Ejection Test

Fitting Functions of Fragment Size Distribution
Energy Analysis

Kinetic Energy Estimation

The estimated kinetic energy carried by ejected coal is between 16.24 and 20.35 MJ. Considering the total mass of ejected coal, the average initial speed of ejected coal particles ranges from 24.98 to 27.96 m/s.

<table>
<thead>
<tr>
<th>Mining Depth</th>
<th>Stress Concentration Factor</th>
<th>Vertical Stress</th>
<th>Shape Factor</th>
<th>Density</th>
<th>Volume of Ejected Coal</th>
<th>Weight of All Fragments</th>
<th>Rittinger Constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>555 m</td>
<td>1.75-2.87</td>
<td>24.28-39.82 MPa</td>
<td>1.5</td>
<td>1.37 g/cm²</td>
<td>38 m³</td>
<td>52.06 t</td>
<td>178.84 - 242.06</td>
</tr>
</tbody>
</table>

Estimated Value of Kinetic Energy of Sidewall Burst

- Elastic Energy: 32.39 MJ
- Crushing Energy: 12.04 MJ
- Kinetic Energy: 20.35 MJ
- Total Energy: 64.78 MJ

Value of Main Parameters for Crushing Energy Estimation

- Mining Depth: 555 m
- Stress Concentration Factor: 1.75-2.87
- Vertical Stress: 24.28-39.82 MPa
- Shape Factor: 1.5
- Density: 1.37 g/cm²
- Volume of Ejected Coal: 38 m³
- Weight of All Fragments: 52.06 t
- Rittinger Constant: 178.84 - 242.06
Numerical Analysis

-water effect on coal burst of pillar under geo-stress

Numerical model

The water distribution curve and numerical model (sc=0.3); the blue patterns represent water-weakened contacts and the green patterns represent normal contacts.

Sectional saturation coefficient $s_{ci}$

$$s_{ci} = m - \frac{m(1 - m)}{D_r - m} \quad m < 0 \text{ or } m \geq 1$$

Overall water saturation coefficient $s_c$

$$s_c = 2 \int_0^1 D_r \times s_{ci} \, dD_r = m + 2m(1 - m) [1 + (1 - m)\ln\left(\frac{m}{m-1}\right)]$$

Comparison between experimental results of dry specimen and saturated specimen under uniaxial compression

Nuclear magnetic resonance (NMR)-images of sandstone disk with different water contents: a saturation process; b drying process (Zhou, 2016)

NMR-images of sandstone disk in saturation condition

The relationship between saturation degree and distance ratio: (a) saturation distribution; (b) evaporation distribution
**Numerical Analysis**

**Experiment preparation**

Schematic of soaking test for cylinder coal specimens and parameters of specimens for compression tests

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Group</th>
<th>Estimated saturation coefficient</th>
<th>Actual water content (%)</th>
<th>Length /mm</th>
<th>Diameter /mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-1</td>
<td>1</td>
<td>0</td>
<td>0.0</td>
<td>108.24</td>
<td>54.02</td>
</tr>
<tr>
<td>D-2</td>
<td>1</td>
<td>0</td>
<td>0.0</td>
<td>108.03</td>
<td>53.83</td>
</tr>
<tr>
<td>D-3</td>
<td>0</td>
<td>0.0</td>
<td>108.03</td>
<td>53.74</td>
<td></td>
</tr>
<tr>
<td>M-1</td>
<td>2</td>
<td>0.3</td>
<td>0.47</td>
<td>108.15</td>
<td>53.92</td>
</tr>
<tr>
<td>M-2</td>
<td>2</td>
<td>0.3</td>
<td>0.62</td>
<td>108.18</td>
<td>53.92</td>
</tr>
<tr>
<td>M-3</td>
<td>2</td>
<td>0.3</td>
<td>0.58</td>
<td>108.32</td>
<td>53.61</td>
</tr>
<tr>
<td>H-1</td>
<td>3</td>
<td>0.5</td>
<td>1.24</td>
<td>107.87</td>
<td>53.87</td>
</tr>
<tr>
<td>H-2</td>
<td>3</td>
<td>0.5</td>
<td>1.15</td>
<td>108.26</td>
<td>53.93</td>
</tr>
<tr>
<td>H-3</td>
<td>3</td>
<td>0.5</td>
<td>1.29</td>
<td>108.07</td>
<td>53.75</td>
</tr>
<tr>
<td>S-1</td>
<td>4</td>
<td>1.0</td>
<td>1.66</td>
<td>108.13</td>
<td>53.82</td>
</tr>
<tr>
<td>S-2</td>
<td>4</td>
<td>1.0</td>
<td>1.67</td>
<td>108.19</td>
<td>53.64</td>
</tr>
<tr>
<td>S-3</td>
<td>4</td>
<td>1.0</td>
<td>1.88</td>
<td>108.24</td>
<td>53.71</td>
</tr>
</tbody>
</table>

Comparison between numerical and experimental results of dry specimen under uniaxial compression

**Mechanical properties of intact specimen in laboratory experiment and PFC numerical simulation**

<table>
<thead>
<tr>
<th>Mechanical properties</th>
<th>Experimental result</th>
<th>Numerical result</th>
<th>Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak stress /MPa</td>
<td>21.41</td>
<td>21.45</td>
<td>0.19%</td>
</tr>
<tr>
<td>Young's modulus /GPa</td>
<td>2.43</td>
<td>2.39</td>
<td>1.65%</td>
</tr>
<tr>
<td>Failure strain /10^-3</td>
<td>10.57</td>
<td>9.36</td>
<td>11.45%</td>
</tr>
</tbody>
</table>

Variation of water content and water saturation coefficient with time for coal specimens
Numerical Analysis

Parameter calibration

Comparison between two numerical models with the same saturation coefficient

Stress-strain curves for specimens with different saturation coefficients in case 2

The fitting functions between mechanical properties and water saturation coefficient for simulation results

<table>
<thead>
<tr>
<th>Mechanical properties</th>
<th>Fitting function</th>
<th>$R^2$</th>
</tr>
</thead>
</table>
| UCS $\sigma_c$                | $\sigma_c = 4.142 + 18.910e^{-1.573s_0}$ | 0.9961
| Failure strain $f_s$          | $f_s = 5.965 + 3.825e^{-2.805s_0}$ | 0.9770
| Young’s modulus $E$           | $E = 2.475 - 1.171s_0$            | 0.9982
| Absorbed energy per unit volume $e$ | $e = 0.037 + 0.067e^{-2.650s_0}$ | 0.9997

Relationships between water saturation coefficient and mechanical properties in numerical simulations: (a) UCS; (b) Failure strain; (c) Young’s modulus; (e) Strain energy per unit volume
Numerical Analysis

Numerical simulation

Sketch of the numerical experiment

Flow chart for the simulation procedure
Numerical Analysis

Stress evolution

Stress evolution with the increase of water saturation coefficient $s_r$ under different initial stress conditions

*Critical $k_s=0.65$*

**Instability mode:**
- Free-fall instability
- Step-fall instability

*Stress energy releasing rate vs:*
The decrement of axial stress when the water saturation coefficient increased 1%

*Instability water saturation coefficient for specimens in high-stress conditions*
Numerical Analysis

Energy evolution

Strain energy per unit volume \( e \)
\[
e = \frac{W}{V}
\]

\( W \) is the total work done by the testing system before the instability point of a specimen, \( V \) is the volume of the specimen

Strain energy releasing rate \( v_e \): the decrement of released strain energy per unit volume when the water saturation increased 1%

Initial stress coefficient:

65%～80% UCS: Lower instability point and higher coal burst risk.

40%～65% UCS: Water infusion is an effective approach to reduce coal burst risk as having been reported by many literatures.

≤40% UCS: Water has limited effect on releasing stress and energy for coal.
Numerical Analysis

Failure mode

- Similar failure patterns
- Splitting failure in water-rich area
- Shear-dominated failure

Final failure patterns of all damaged specimens
Current Work

Numerical Modelling of Dynamic Load

Numerical model of SHPB test system

Drop hammer test system
Current Work

Protective Structure on CM
Conclusions

**Energy Analysis**

1. The main energy source of coal burst is provided by static load.

2. Coal burst propensity index can evaluate the coal burst risk by reflecting the energy accumulation and dissipation behavior.

3. The average ejection velocity of coal particles from roadway sidewall can reach 24.98-27.96 m/s.

**Numerical modeling of pillar instability**

1. Instability
   
   Free-fall instability: stress and energy decreased linearly and stably and then overall instability appeared suddenly.
   
   Step-fall instability: several times of stress and energy drop and had been damaged obviously before the final instability.

2. The axial stress and strain energy within the specimens are more sensitive to water under a higher initial axial stress condition.

3. The stress releasing rate $v_s$ and energy releasing rate $v_e$ are suggested to be an effective index to assess the stability and of pillar.
Questions?