U O W

Energy Release and Failure Characteristics of Coal Samples: Laboratory Test and Numerical Modelling

Ting Ren, Xiaohan Yang and Lihai Tan

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Coal Burst in Australian U/G Coal Mines

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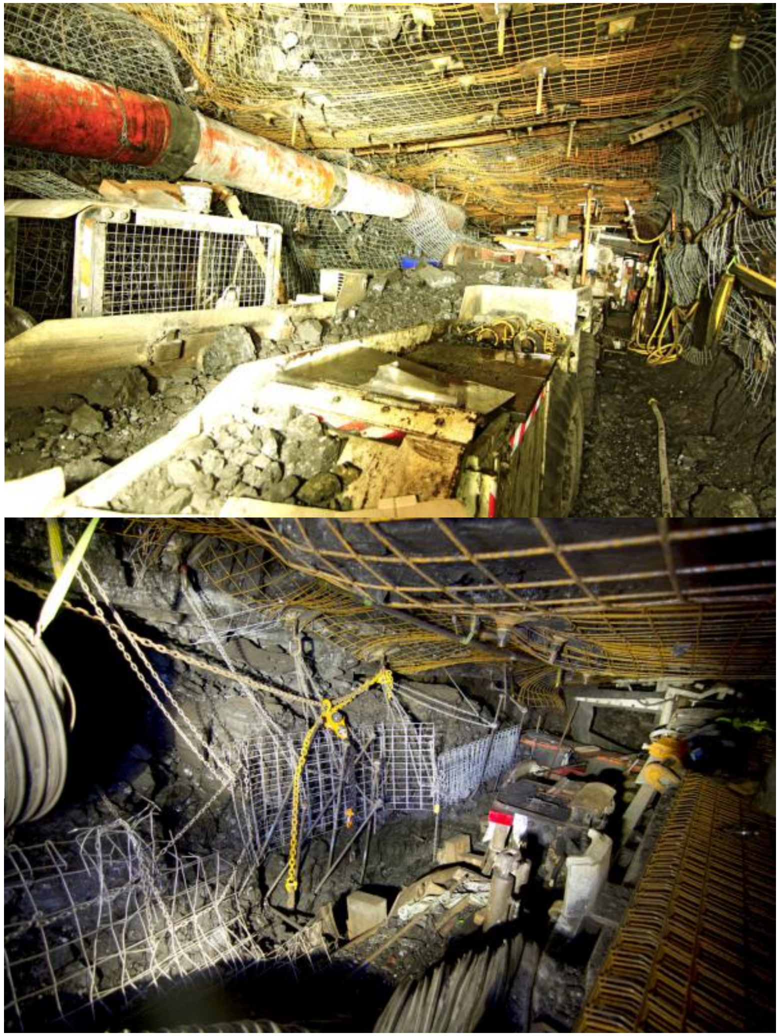
MINE SAFETY INVESTIGATION UNIT

INFORMATION RELEASE

Double fatality

Incident date	15 April 2014
Event	Major rib burst in an underground coal mine



Coal Burst in Australian U/G Coal Mines

Department of Industry
Resources Regulator
NSW GOVERNMENT
Mine Safety

MINE SAFETY
INSPECTORATE

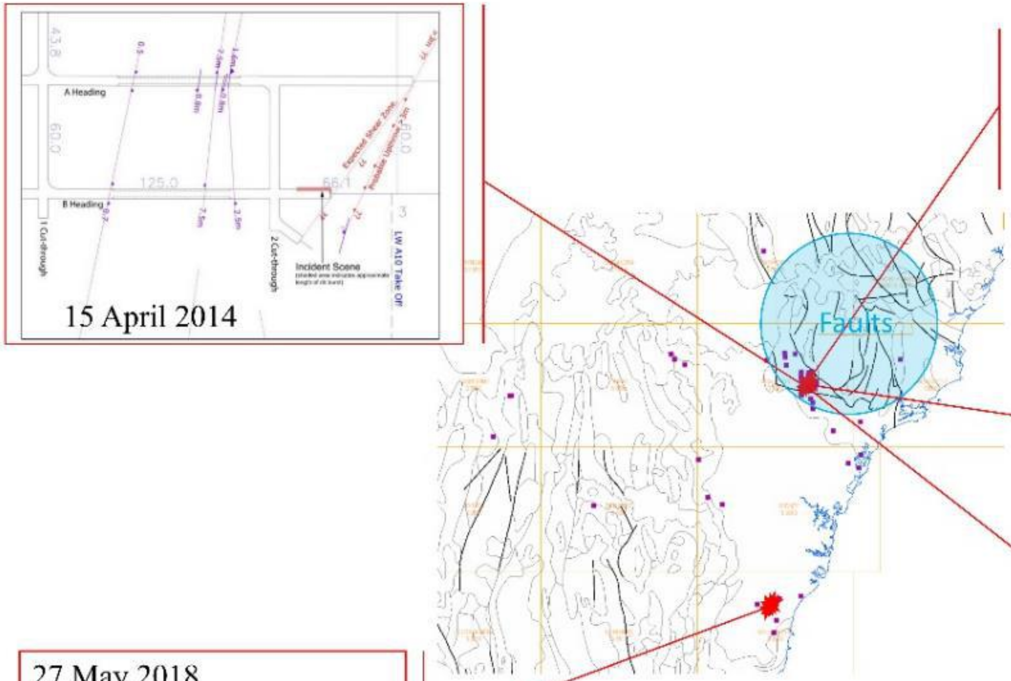
INVESTIGATION INFORMATION RELEASE

High potential incident

Incident date 19 August 2016
Event Coalburst on longwall face

- Coal 'BUMPS' have also been reported by other mines in NSW
- Awareness of potential Burst hazards in QLD

Coal Burst in Australian U/G Coal Mines



15 April 2014

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

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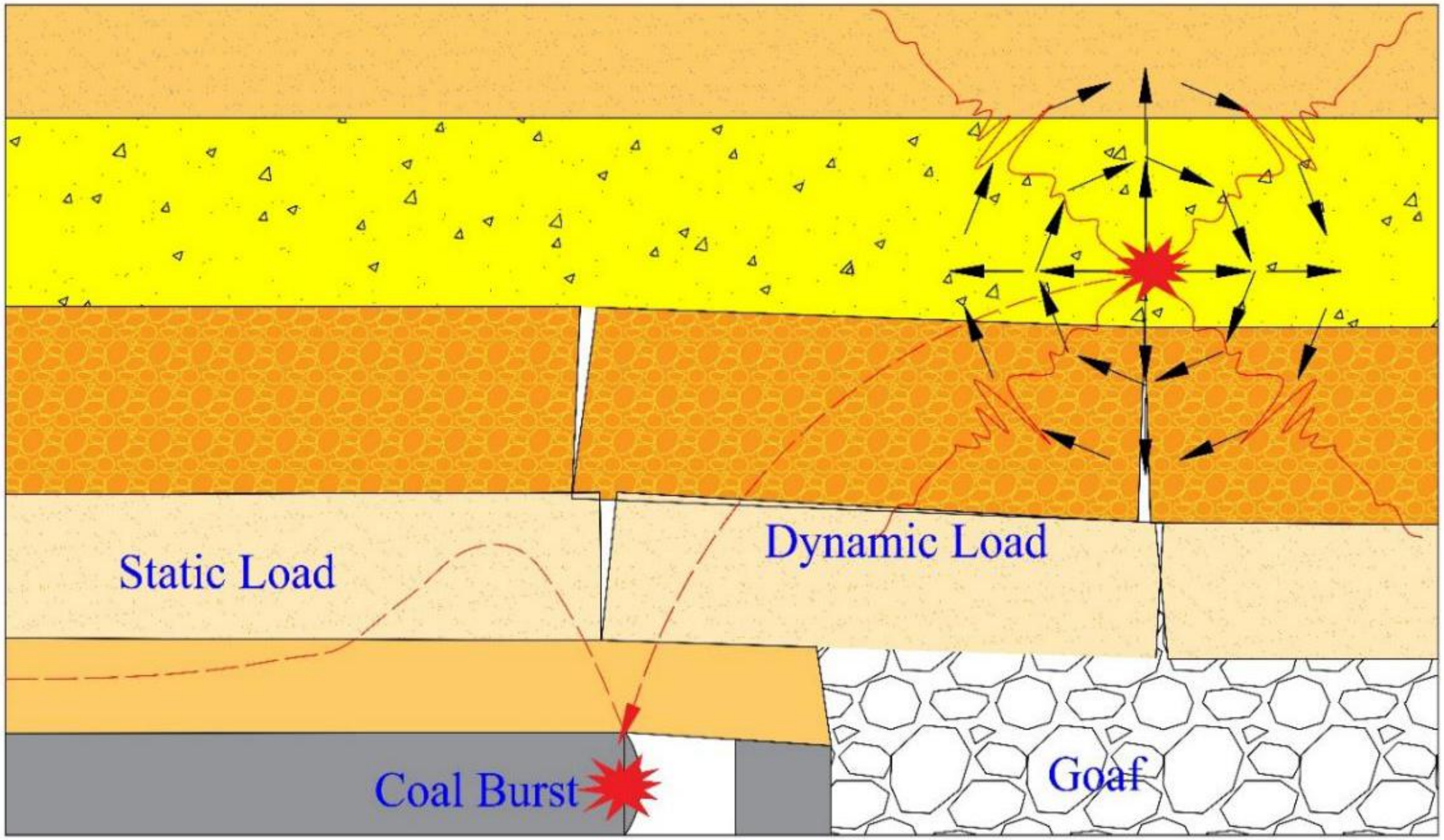
Energy Analysis

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.

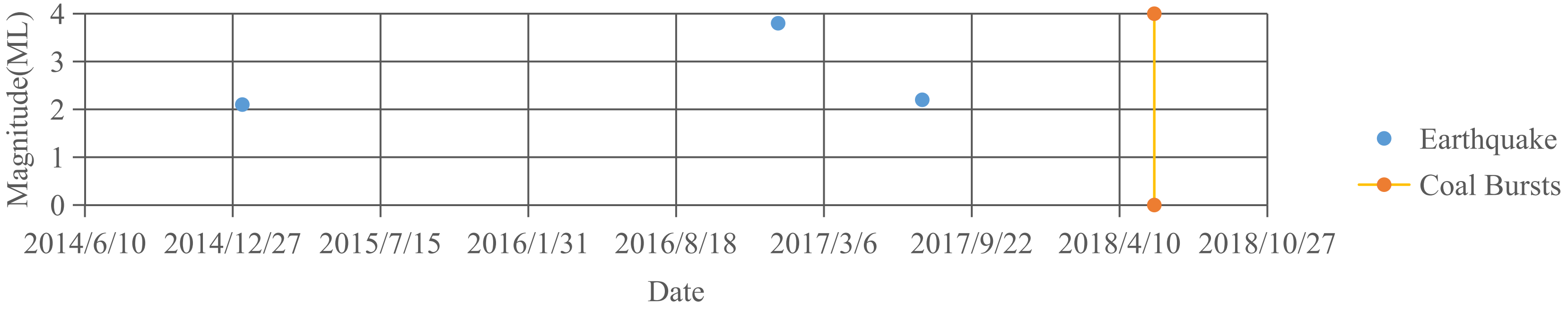


Coal Burst Induced by Static and Dynamic Load superposition (Dou et al)

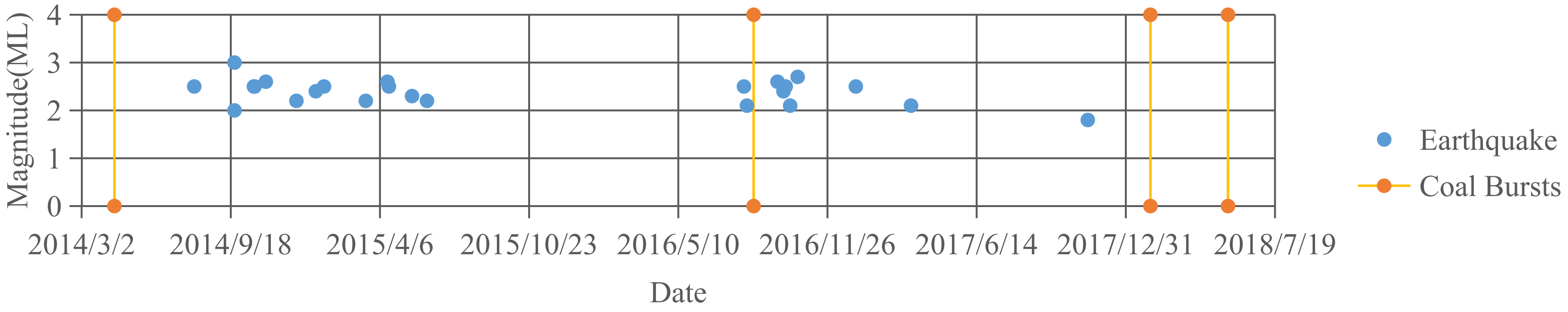
Energy Analysis

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

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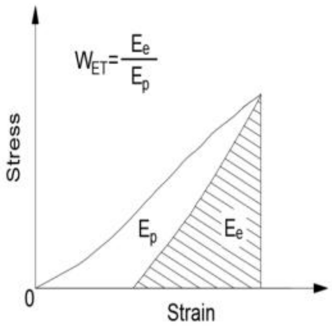
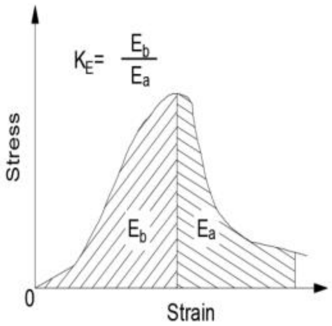
Coal Burst Propensity Index



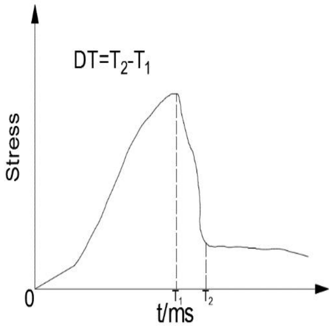
Elastic strain energy index (W_{ET})

W_{ET} is the indicator of the proportion of elastic energy storage of coal when coal is near critical stress.



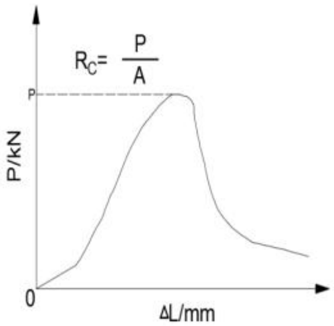
Bursting energy index (K_E)

Coal samples with low K_E value will fail gentler as more energy is dissipated by deformation.



Dynamic failure time (DT)

The violence of coal burst reflects in the instantaneous of energy releasing as well (WB Zhang et. al, 1986).



Uniaxial compressive strength (R_C)

According to our analysis, elastic energy storage of coal samples increases with uniaxial compressive strength (UCS) ranges from 0 to 50.

Coal Burst Propensity Index

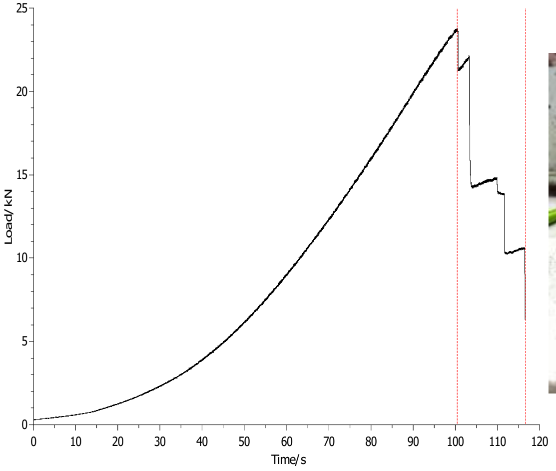
Radial Coring Drill Machine

Loading Machine and Control System

Coal Sample with Strain Gauges

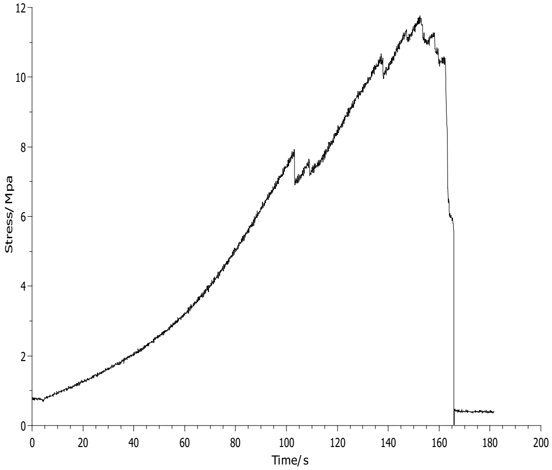
1. Sample Preparation
2. Sample Measuring
3. R_C and K_E Test
4. Calculation
5. W_{ET} Test
6. DT Test
7. Risk Classification

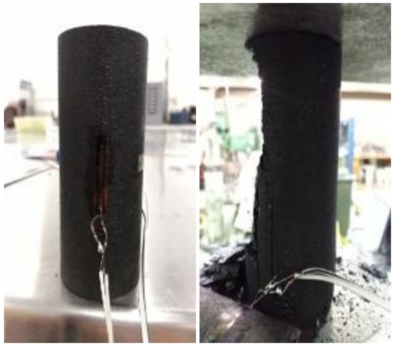
Coal Burst Propensity Index



Intact Sample **Failed Sample**

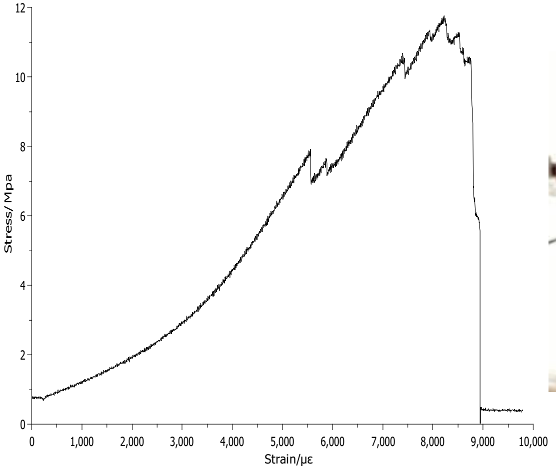
DT Test Curve





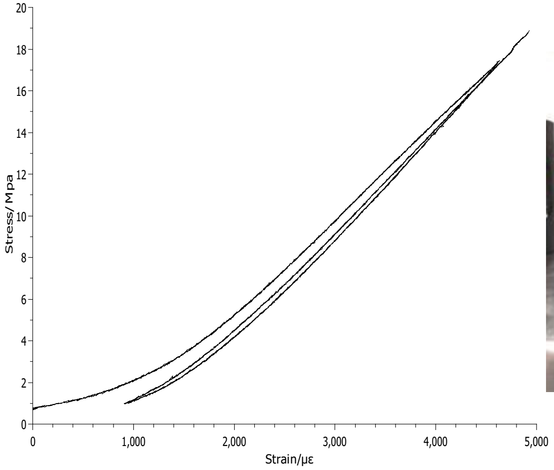
Intact Sample **Failed Sample**

R_C Test Curve



Intact Sample **Failed Sample**

K_E Test Curve



Intact Sample **Failed Sample**

W_{ET} Test Curve

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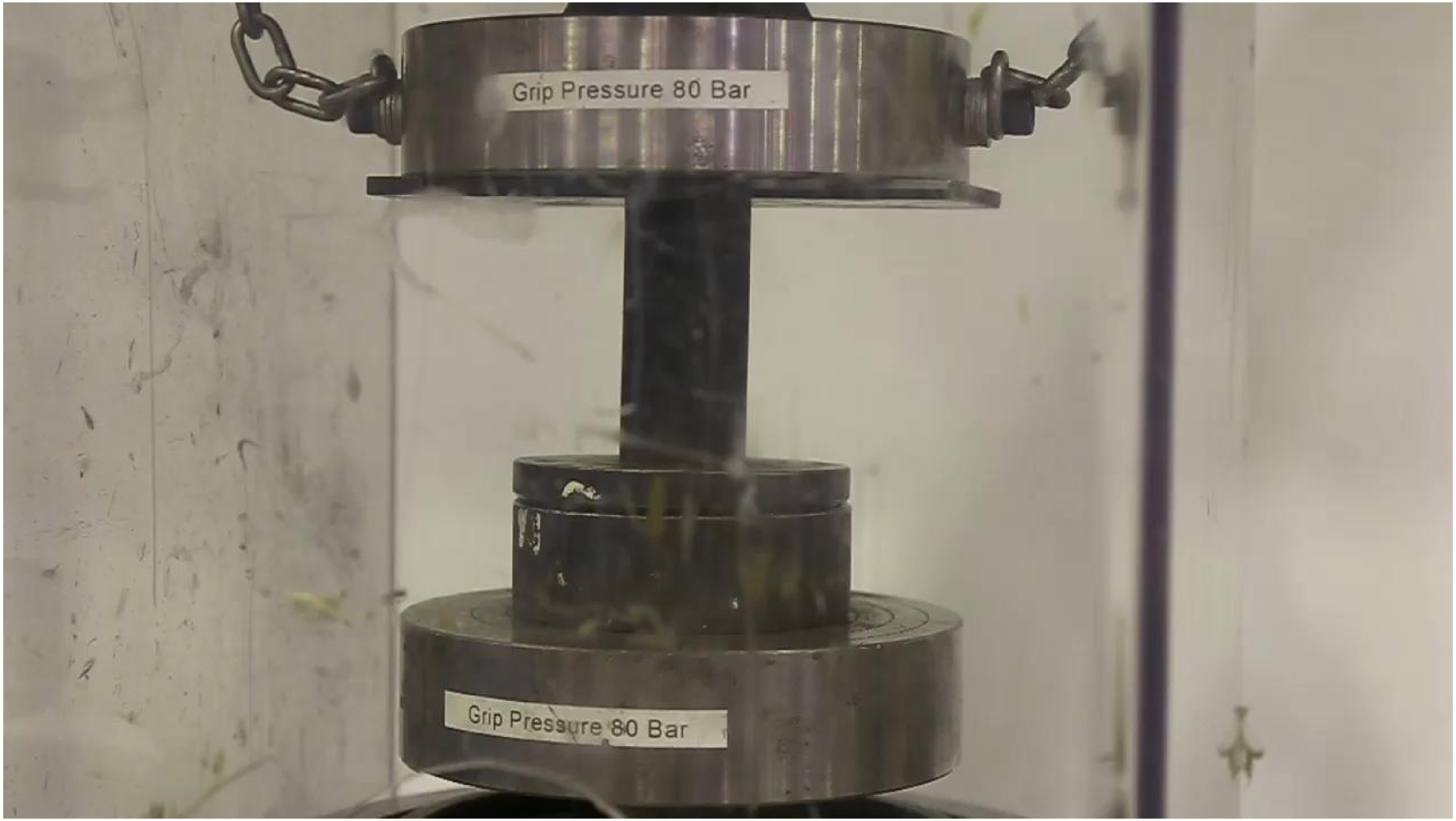
Coal Burst Propensity Index



Coal Burst Propensity Index

Risk Classification Method in Original Reference (Kidybiński A, 1981; WB Zhang et. al, 1986; LP Jin & XF Xian, 1993; QX Qi et. al, 2011)

Burst Propensity		None	Moderate	High
Index	DT/ms	$DT > 500$	$50 < DT \leq 500$	$DT \leq 50$
	K_E	$K_E < 2$	$2 \leq K_E < 5$	$K_E \geq 5$
Burst Propensity		None	Low	High
Index	W_{ET}	$W_{ET} < 2$	$2 \leq W_{ET} < 5$	$W_{ET} \geq 5$
	R_C/Mpa	$R_C < 7$	$7 \leq R_C < 14$	$R_C \geq 14$

Risk Classification of Chinese Standard (National Standards of the People's Republic of China 2010)

Type		I	II	III
Burst Propensity		None	Low	High
Index	DT/ms	$DT > 500$	$50 < DT \leq 500$	$DT \leq 50$
	K_E	$K_E < 1.5$	$1.5 \leq K_E < 5$	$K_E \geq 5$
	W_{ET}	$W_{ET} < 2$	$2 \leq W_{ET} < 5$	$W_{ET} \geq 5$
	R_C/Mpa	$R_C < 7$	$7 \leq R_C < 14$	$R_C \geq 14$

Recommended Risk Classification Method for Australia Coal Mines

Type		I	II	III	IV
Burst Propensity		None	Low	Moderate	High
Index	DT/ms	$DT > 10000$	$1000 < DT \leq 10000$	$500 < DT \leq 1000$	$DT \leq 500$
	K_E	$K_E < 2$	$2 \leq K_E < 3.5$	$3.5 \leq K_E < 5$	$K_E \geq 5$
	W_{ET}	$W_{ET} < 2$	$2 \leq W_{ET} < 3.5$	$3.5 \leq W_{ET} < 5$	$W_{ET} \geq 5$
	R_C/Mpa	$R_C < 5$	$5 \leq R_C < 10$	$10 \leq R_C < 15$	$R_C \geq 15$

Note: Fuzzy evaluation method can be adopted if the value of W_{ET}, K_E, R_C and DT are in conflict with each other. The weighting factors of four indices are equal.

Quantitative Study of Coal Burst Energy

Energy Accumulation and Releasing of Coal Burst

$$W_E + W_P = W_B + W_F + W_R + W_T$$

Where W_E is elastic energy of coal, W_P is plastic energy of coal, W_B is coal burst energy, W_F is energy consumed by deformation and fracture, W_R is residual energy of coal after burst and W_T is energy transferred into other form, such as heat, acoustic energy and electromagnetic energy

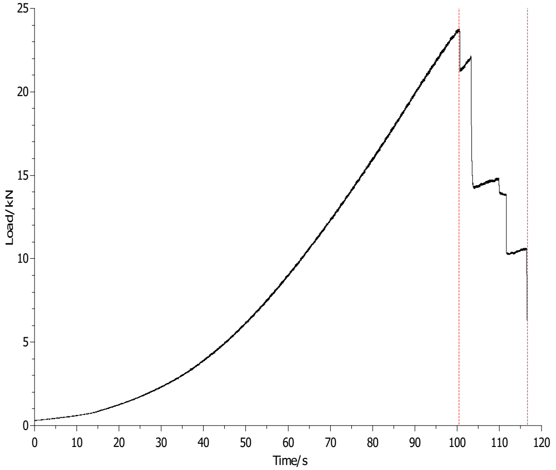
Coal burst energy is the cause of personal injury and equipment damage.

Quantitative Study of Coal Burst Energy

$$f(W_E) = W_B ? \, or \; f(W_T) = W_B ? \, \text{or other?}$$

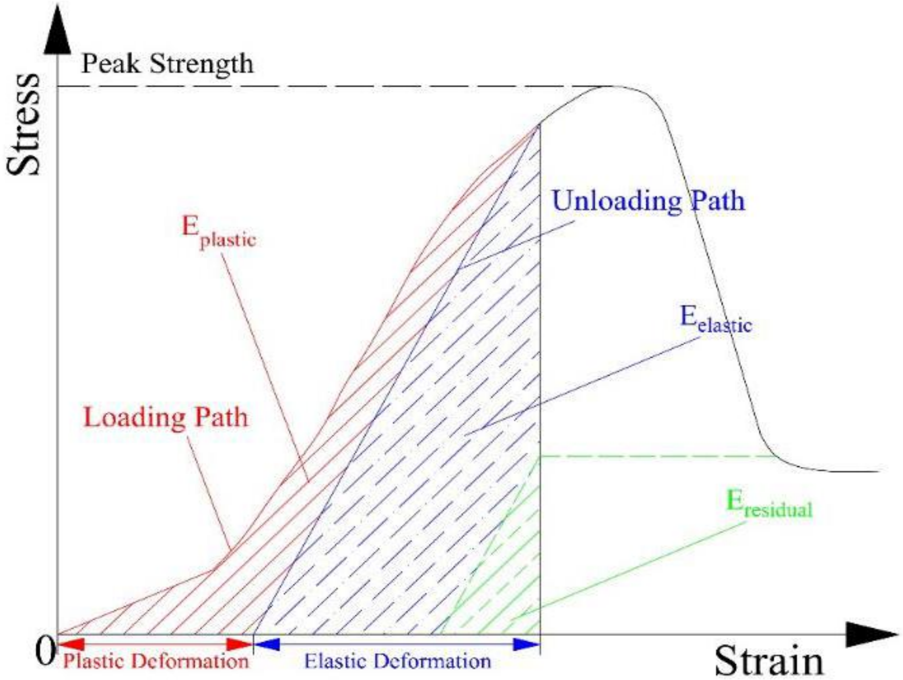
The relationship between elastic energy and plastic energy of coal samples can be measured by coal burst propensity index. The relationship between the various energy forms of coal samples, in particular the relationship between elastic energy and burst energy, acoustic emission energy and burst energy will need future research.

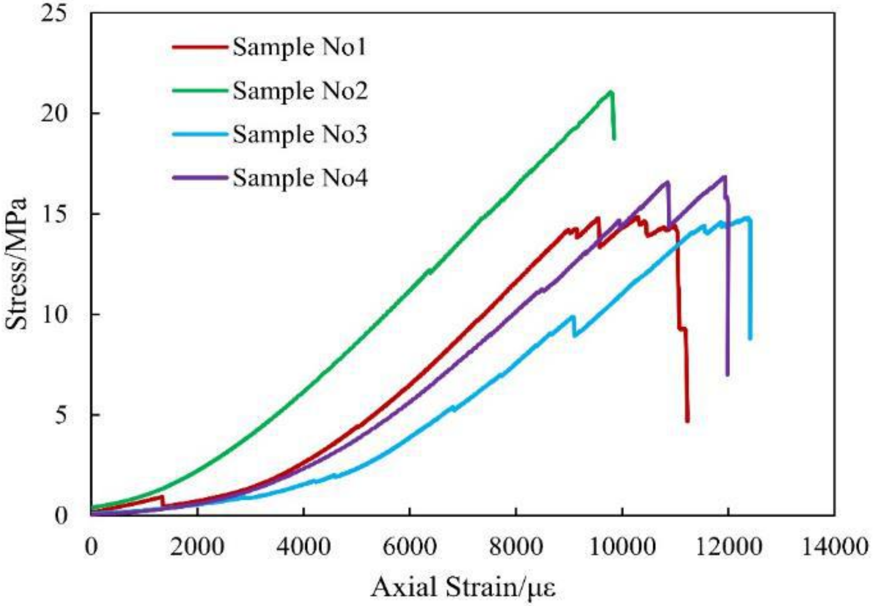
Energy Analysis



$$E_{total} = E_{plastic} + E_{elastic}$$

$$E_{elastic} = E_{crushing} + E_{kinetic} + E_{residual}$$





Stress versus Strain Curve of Coal Samples

Schematic Diagram of Energy Accumulation before Peak Strength

Energy Analysis

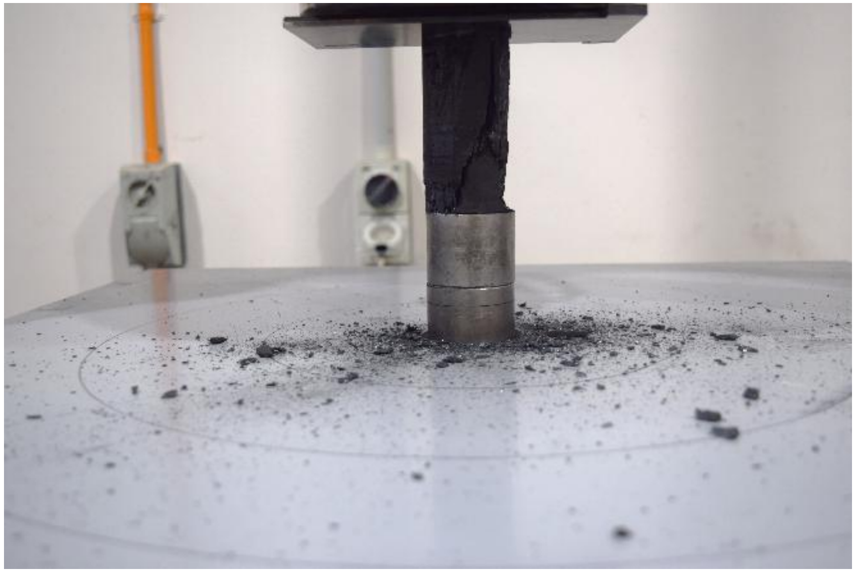
Kinetic Energy Estimation

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

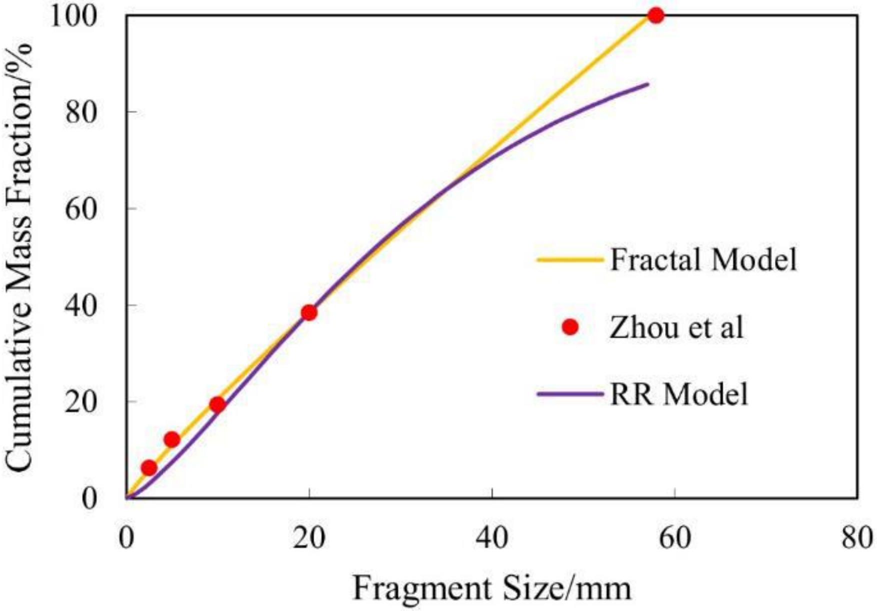
$$E_{kinetic} \cong E_{elastic} - E_{crushing}$$

$$F(d) = (\frac{d}{d_{max}})^{(3-n)}$$

Where E_0 is the unloading elasticity modules, V is the volume of the sample, σ is the principal stress and μ is the Poisson's ratio; F(d) is the cumulative mass fraction of the fragments '



Coal Ejection Test



Fitting Functions of Fragment Size Distribution

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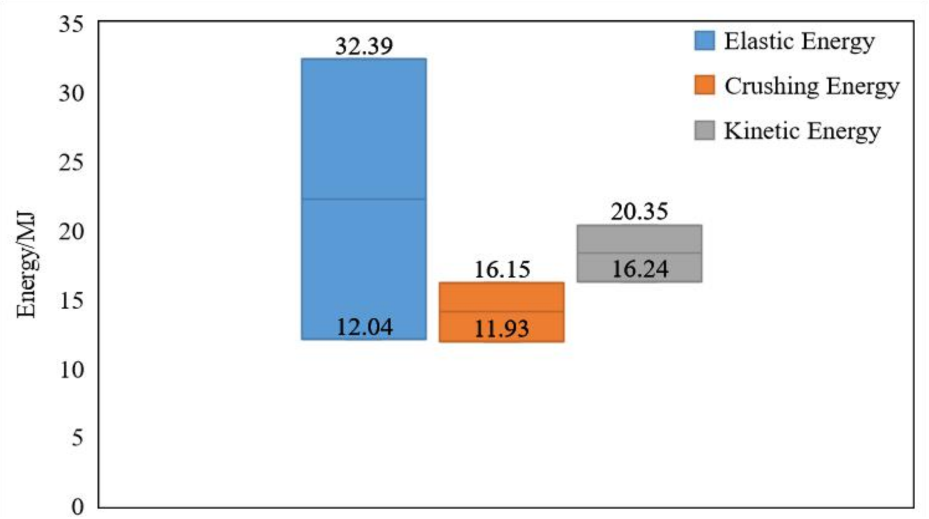
Energy Analysis

Kinetic Energy Estimation

The estimated kinetic energy 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.

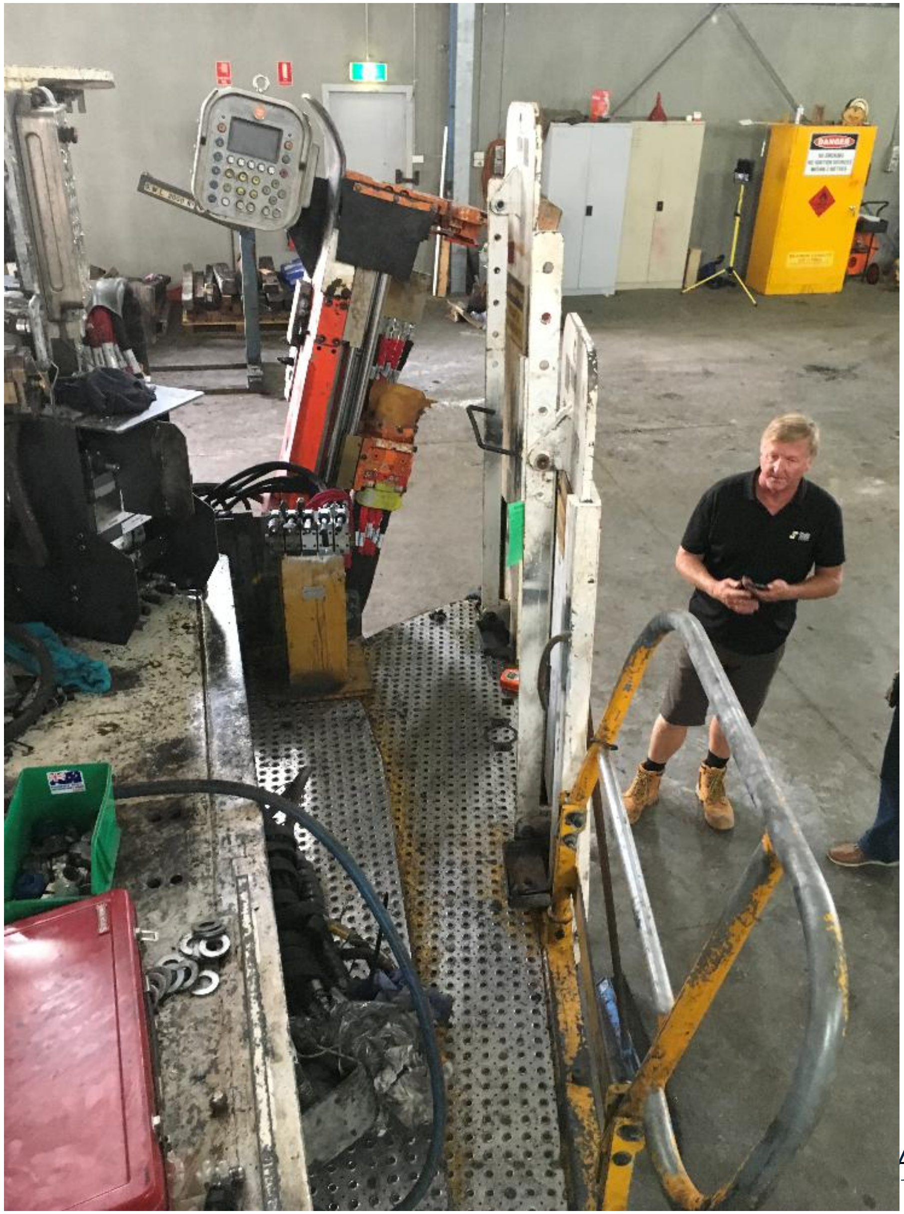
Value of Main Parameters for Crushing Energy Estimation

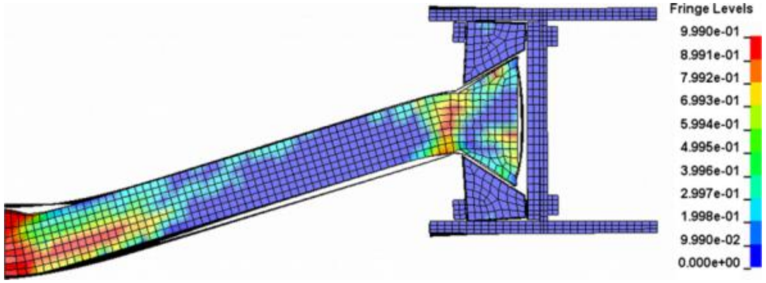
Mining Depth	Stress Concentration Factor	Vertical Stress	Shape Factor	Density	Volume of Ejected Coal	Weight of All Fragments	Rittinger Constant
555 m	1.75-2.87	24.28-39.82 MPa	1.5	1.37 g/cm2	38 m^3	52.06 t	178.84 - 242.06

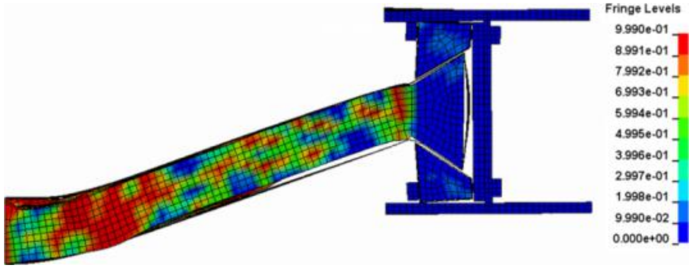


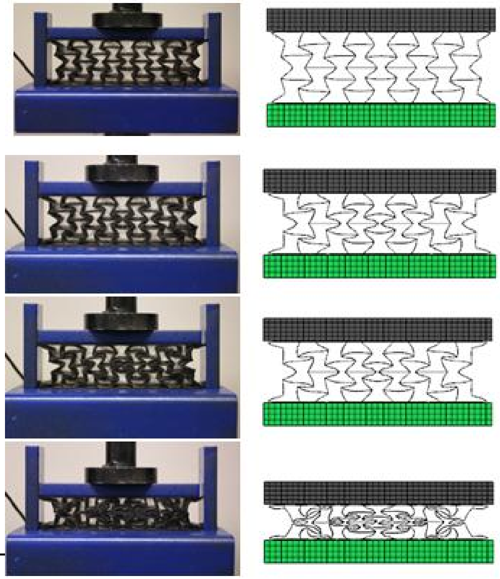
Estimated Value of Kinetic Energy of Rib Burst

Energy Analysis – A Protective Structure for CM



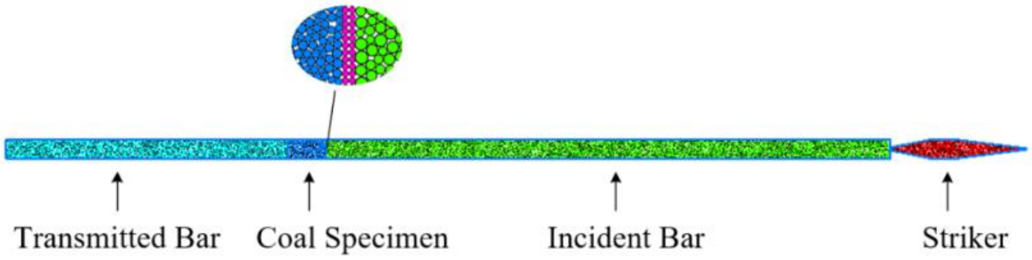




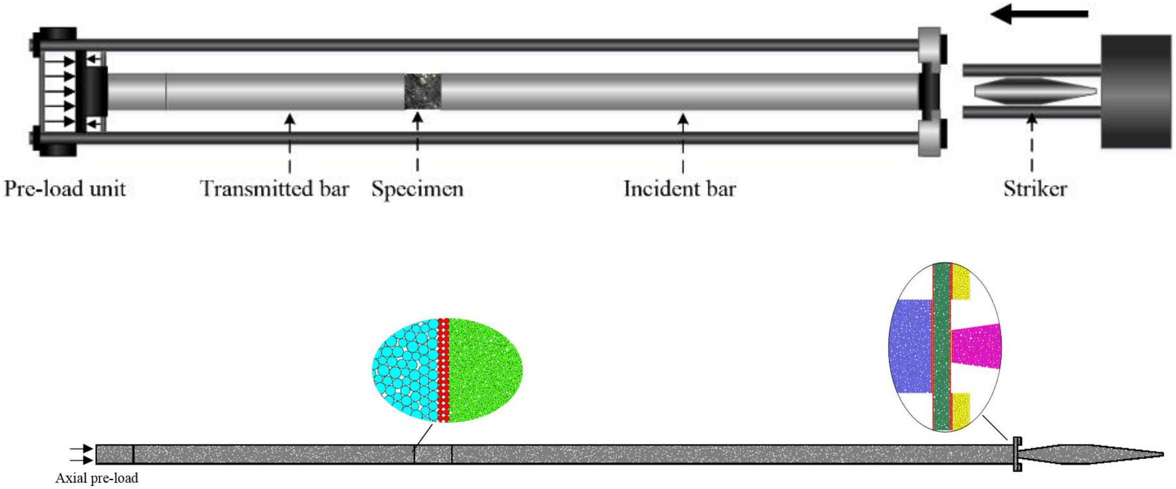


Numerical modelling

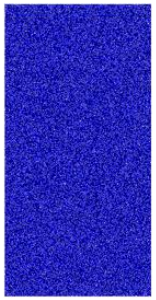
Numerical Modelling of Dynamic Load



Numerical model of SHPB test system



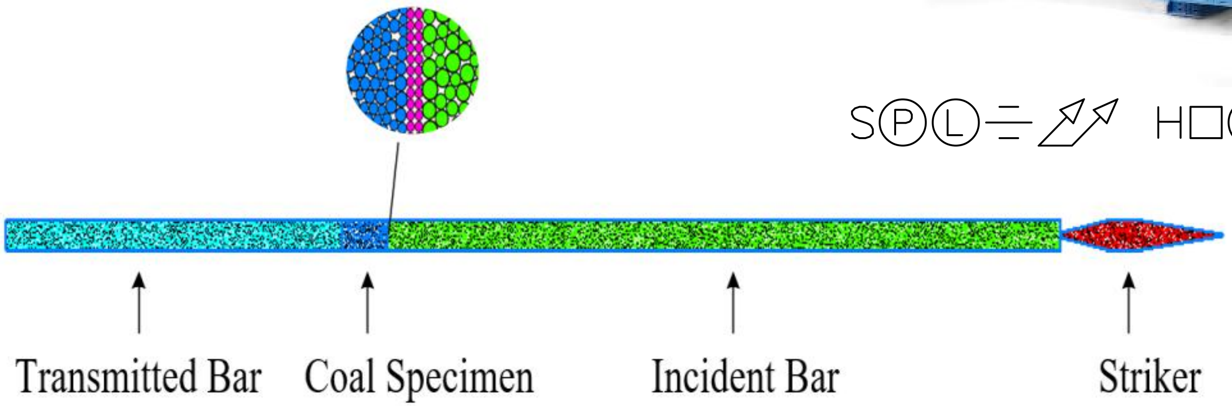
Numerical model of Pre-load SHPB test system



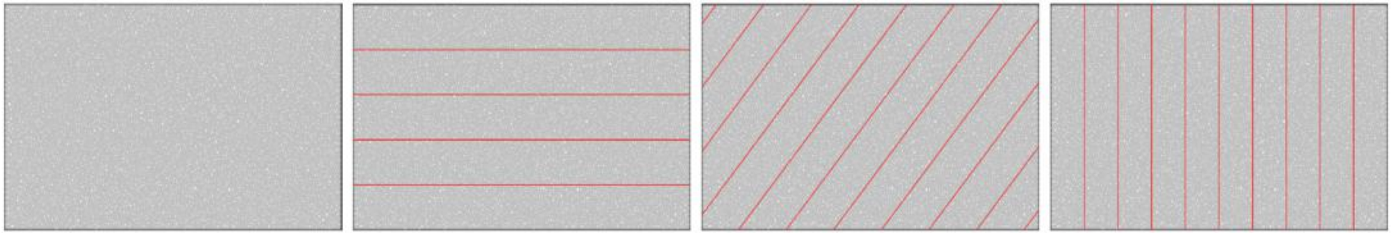
Drop hammer test system

Influence of beddings on dynamic behaviour of coal

- Numerical Simulation of SHPB Test with particle flow code (PFC)



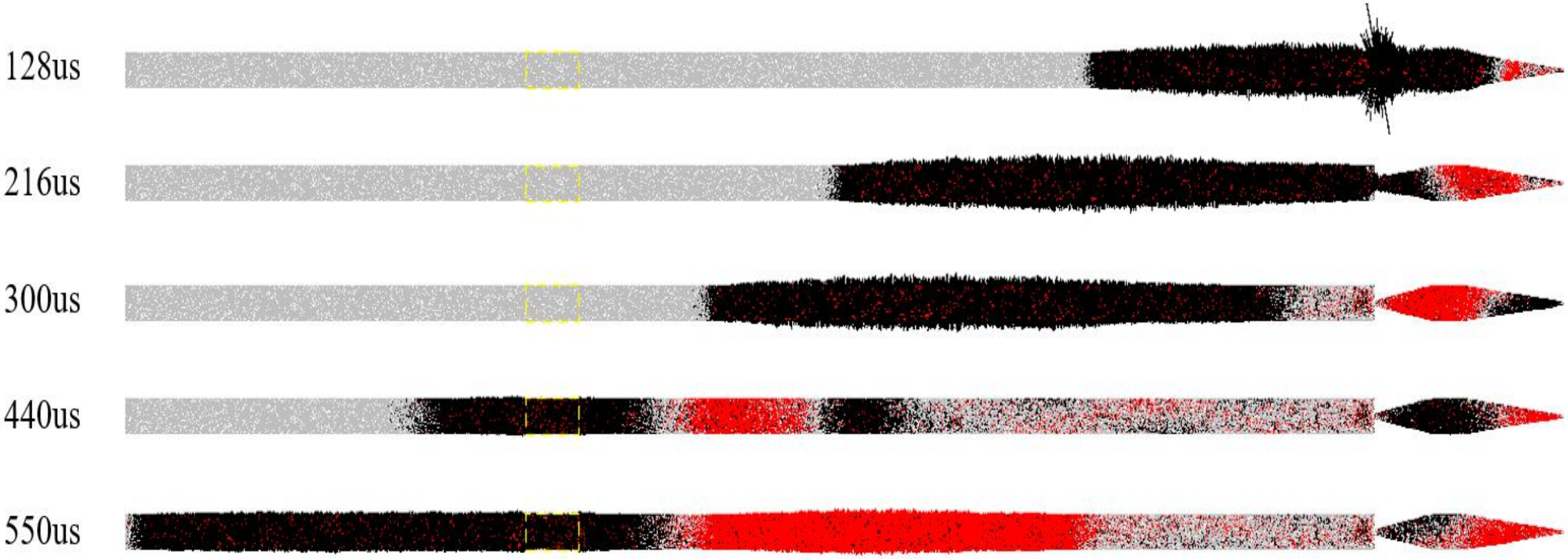
Numerical model of SHPB test system



(a) S1 (b) S2 (c) S3 (d) S4

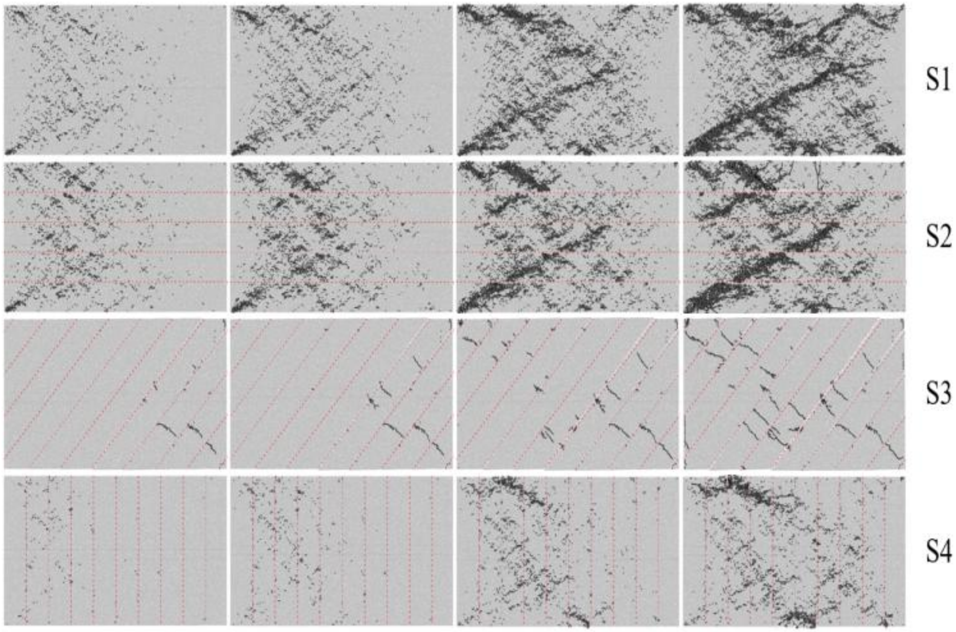
Numerical models of specimen (red represents beddings in coal specimen)

Stress Wave Propagation (resulting from dynamic load)



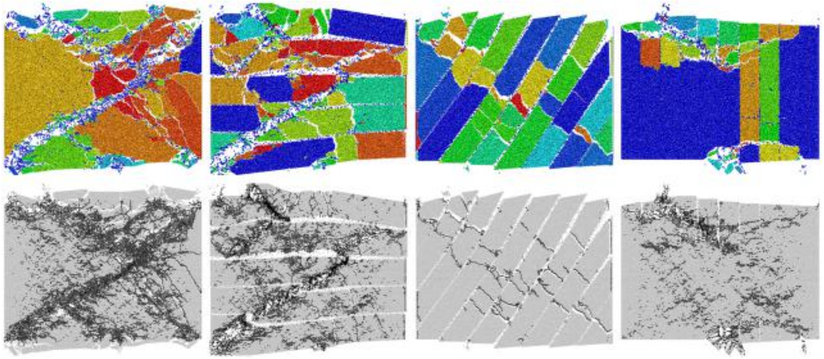
Stress wave propagation in bars with specimen S1 (no beddings): the red denotes tensile wave and the black denotes compressive wave

Failure Mode of Specimen



(a) 410us (b) 460us (c) 510us (d) 560us

Failure evolution of different specimens



(a) S1 (b) S2 (c) S3
(d) S4

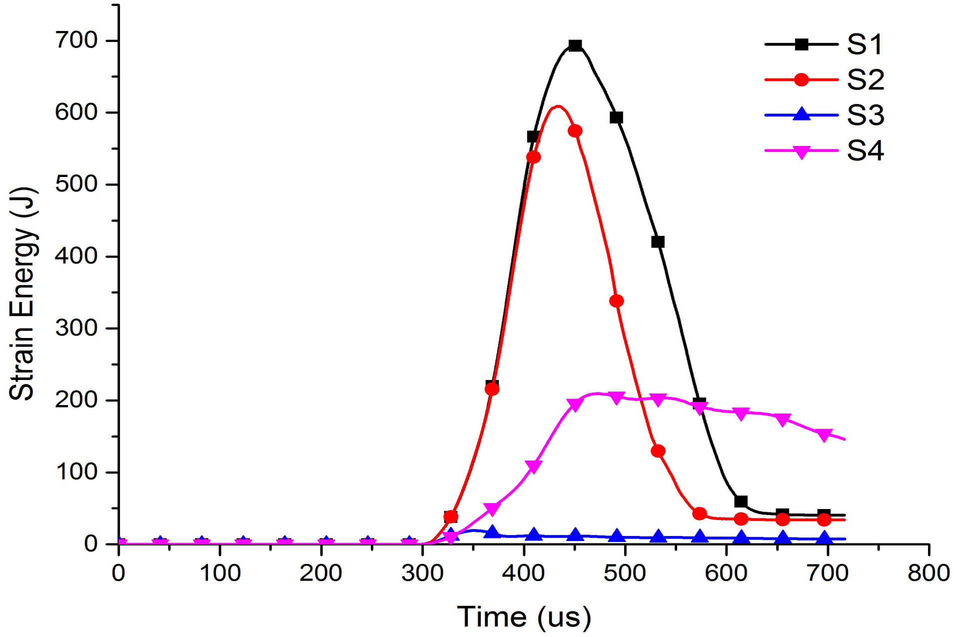
Fragment (fracture) pattern and failure mode of each specimen at 1000us

- [illegible] S1 [illegible] S2 [illegible]

- ~~[illegible] S3 [illegible]~~ [illegible]

Strain Energy

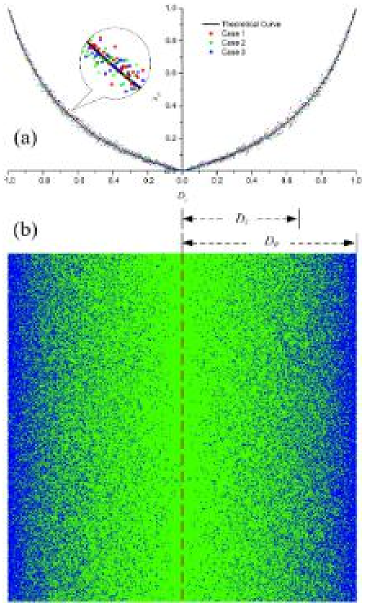
- **Beddings in a coal specimen lead to the degradation of its dynamic mechanical properties.** This influence is closely associated with the angle between bedding and loads direction. When dynamic loads are inclined to beddings, specimen is most vulnerable with bedding breaking and sliding.
- **Strain energy and failure are effected by beddings.** For specimen containing inclining beddings, coal bump and burst are not likely to appear in such coal as its instability is gradual and its storage capacity of strain energy is limited. Coal specimens with beddings parallel to dynamic loads is more vulnerable to burst.



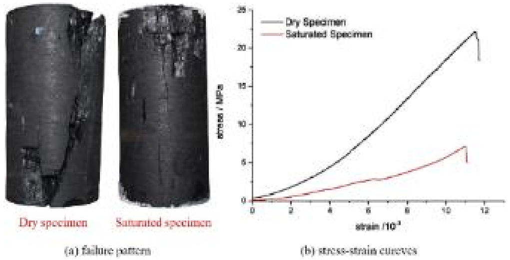
Strain energy changes vs time for different specimens

Modelling of Water (moisture) influence

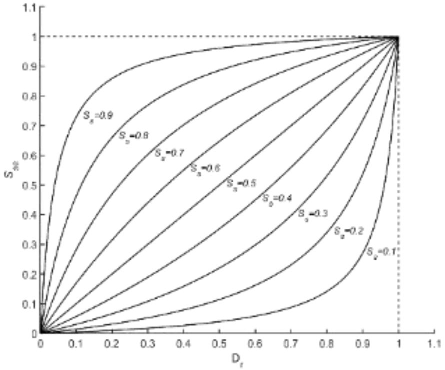
Numerical model



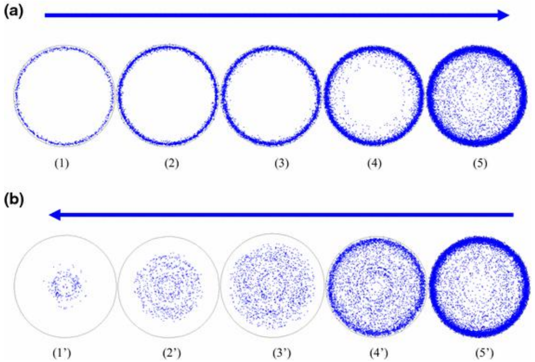
The water distribution curve and numerical model (sc=0.3); the blue patterns represent water-weakened contacts and the green patterns represent normal contacts.



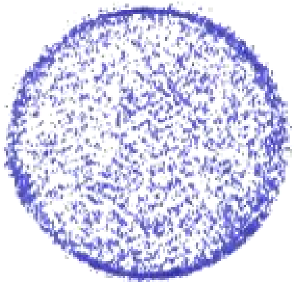
Comparison between experimental results of dry specimen and saturated specimen under uniaxial compression



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



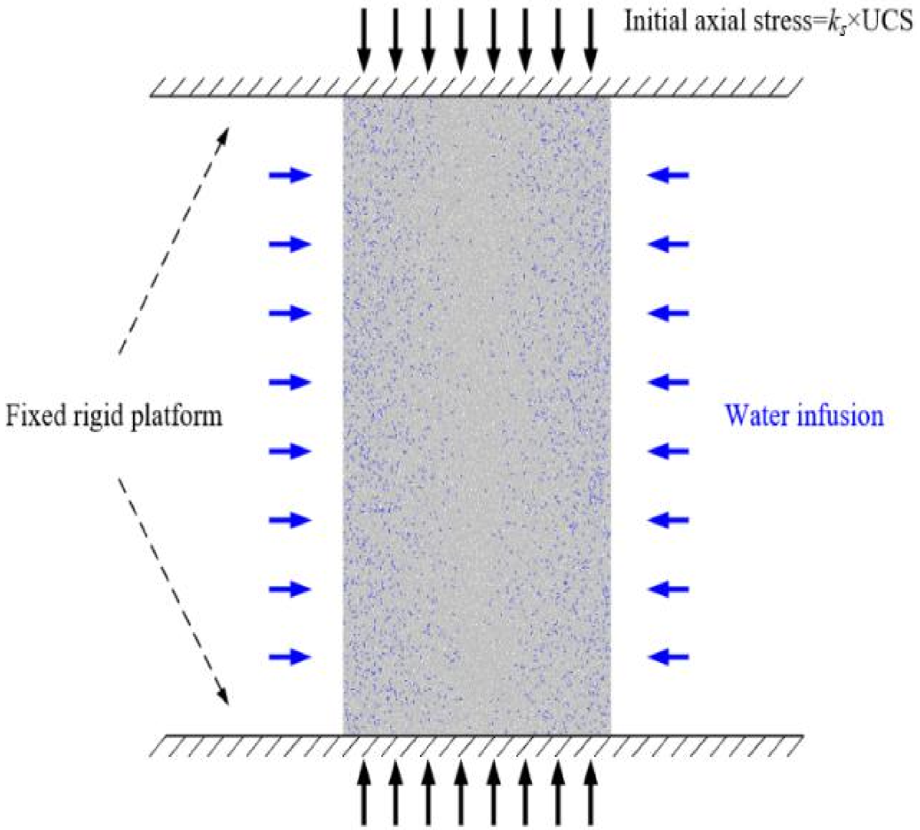
Nuclear magnetic resonance (NMR)-images of sandstone disk with different water contents: a saturation process; b drying process (Zhou, 2016)



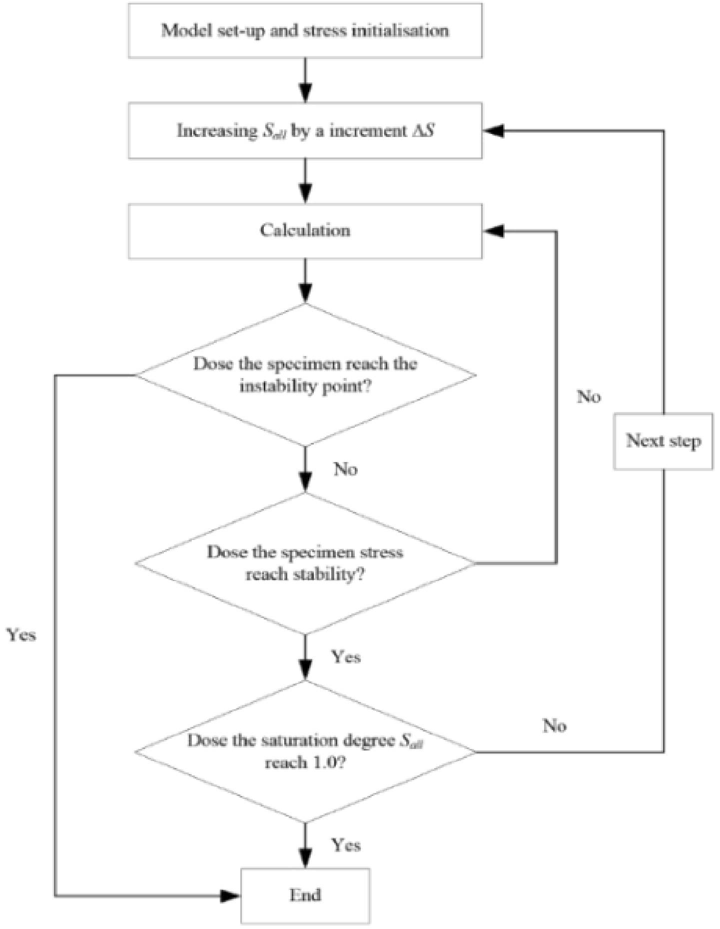
NMR-images of sandstone disk in saturation condition

Modelling of Water (moisture) influence

Numerical simulation



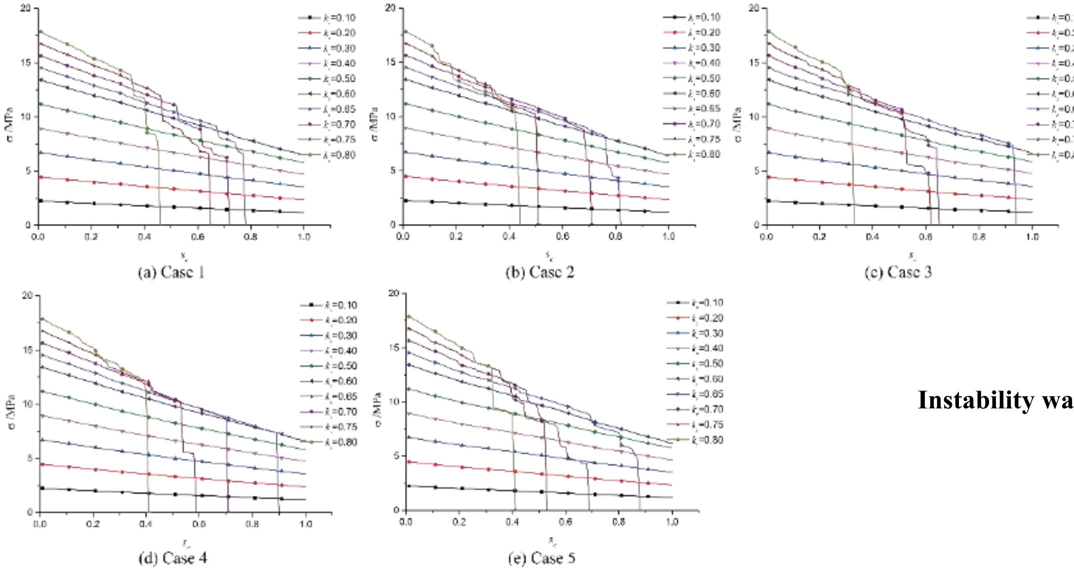
Sketch of the numerical experiment



Flow chart for the simulation procedure

Modelling of Water (moisture) influence

Numerical simulation



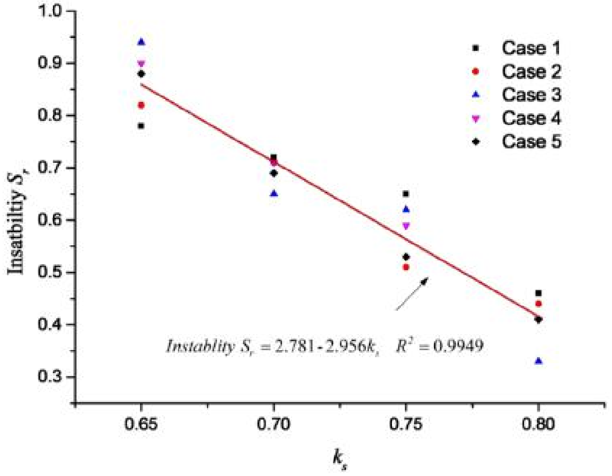
Stress evolution versus ks in different cases

Initial stress coefficient:

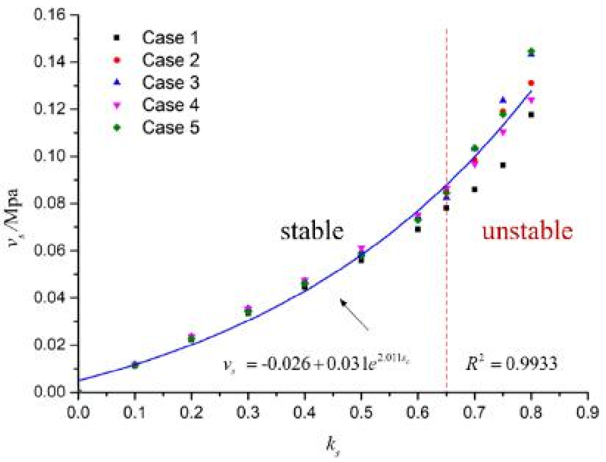
65%~80% UCS: Lower instability point and higher coal burst risk.

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

≤40% UCS: Water has limited effect on releasing stress and energy for coal at such a low stress level.



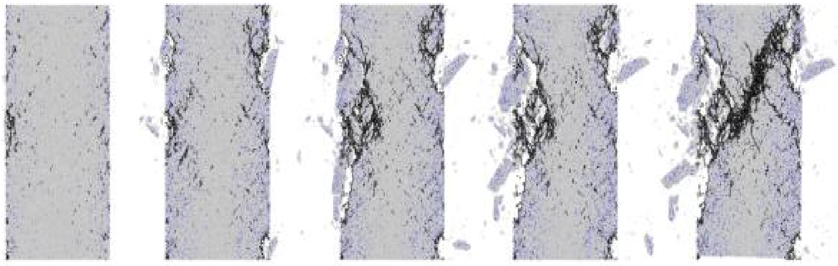
Instability water saturation coefficient for specimens in high-stress conditions



vs evolution curves with ks increasing

Modelling of Water (moisture) influence

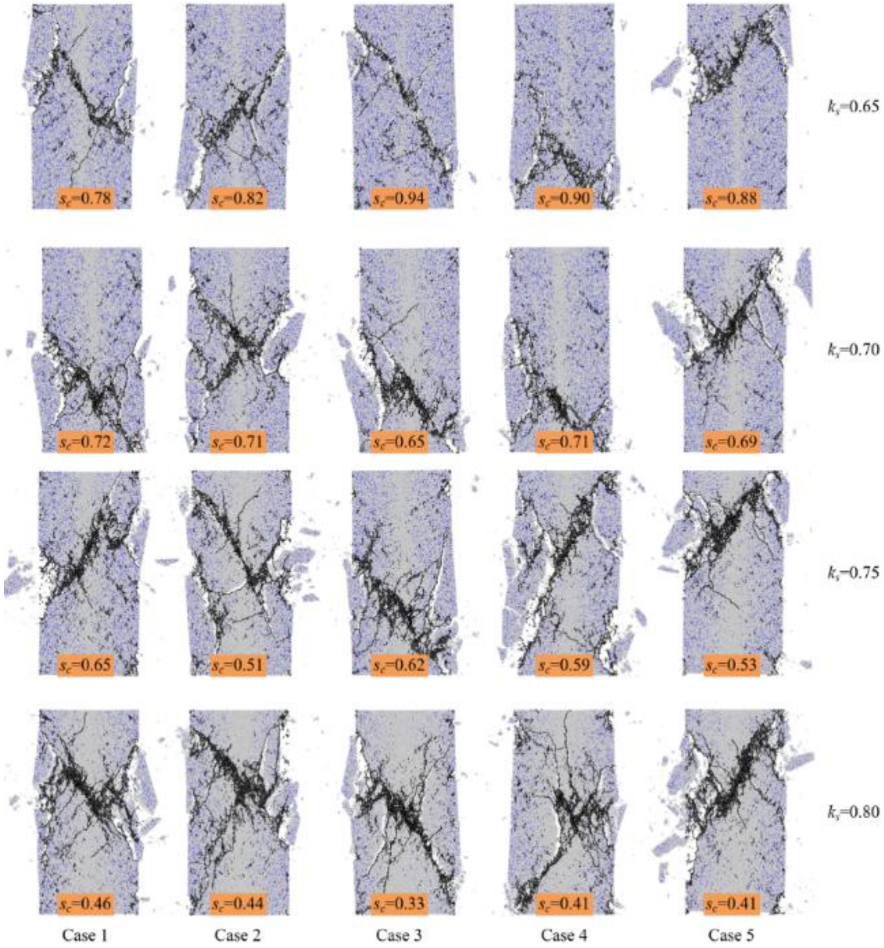
Numerical simulation



(a) s_c=0.10 (b) s_c=0.20 (c) s_c=0.30 (d) s_c=0.35 (e) s_c=0.41

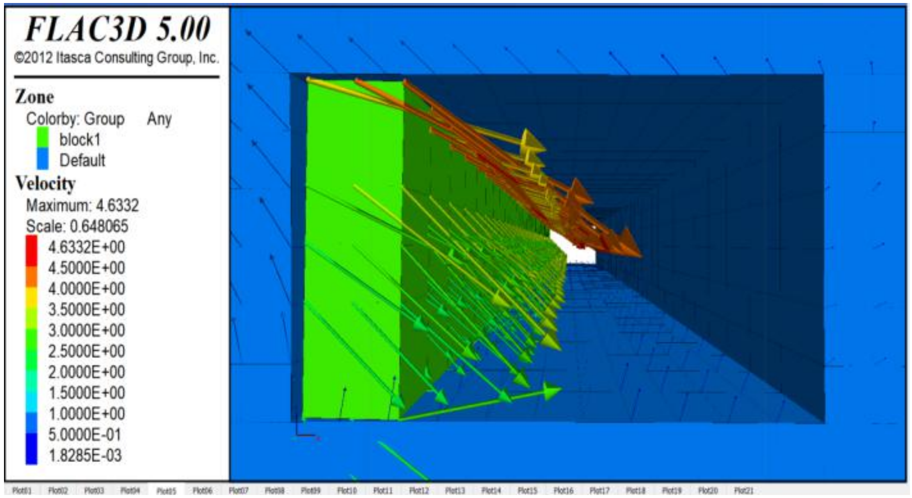
Failure evolution of specimen in Case 5, ks=0.8

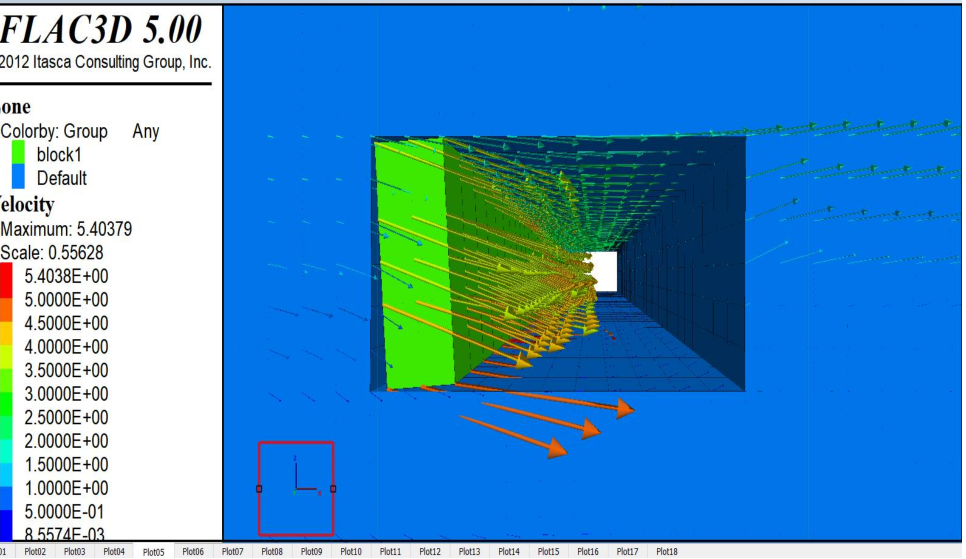
- Failure patterns were dominated by shear failure through the specimens.
- Higher initial axial stress indicates more severely with more cracks and fragments.
- Failure intensity highly depends on the release of strain energy.



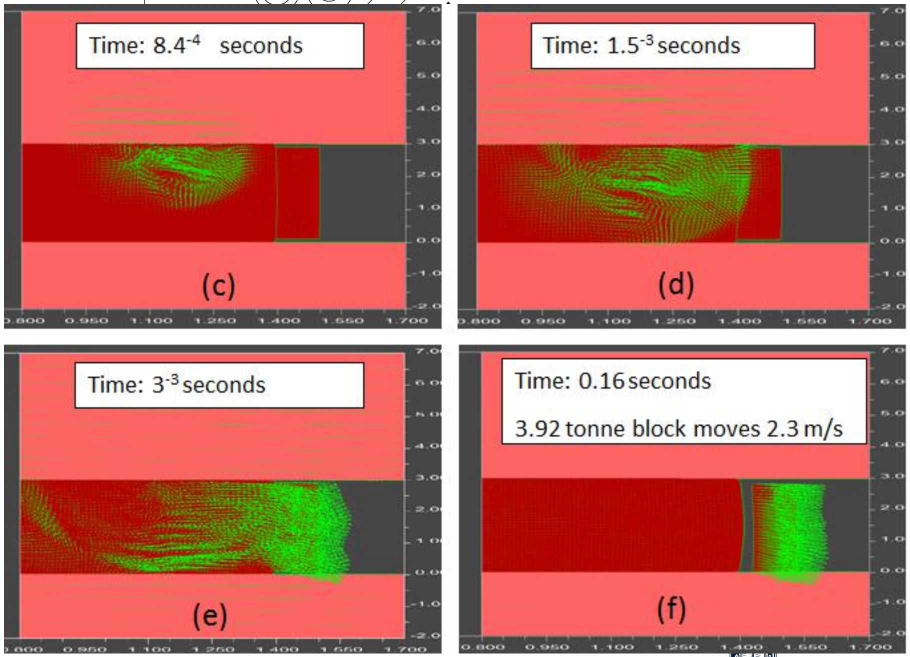
Final failure patterns of all damaged specimens

Numerical Modelling:





- Fundamental studies of mechanisms
- A new risk assessment methodology for coal/rock burst:



Thank you!

Questions?

Contact

Ting Ren

tren@uow.edu.au

Questions?