VISUALIZATION METHODS FOR THE DISCONTINUOUS STRUCTURES AND STRESS FIELDS OF DEEP COAL MASSES

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HONG KONG, DEC 14-17, 2016

Coal is one of the non-renewable energy resources. Safe, environmental friendly, and sustainable excavation of coal would not only relieve energy shortage but also reduce risks of coal mine disasters.

Huge energy demand for industrial and economic developments in China causes the enormous use of coal. As a result, many Chinese coal mines have launched deep underground excavation with a depth more than 1,000 meters.

Intensive, large-scale mining technology is extensively employed in deep coal mines, which brings serious disturbances to rock strata.

Animation of large-scale mining and collapse of surrounding rocks

Severe dynamic disasters such as rockburst, coal gas outburst, water inrush, etc., **emerge frequently**, resulting in huge losses of human life and property.

Lack of full knowledge about the properties and governing mechanisms of devastating failure of discontinuous rocks is one of the crucial factors that lead to difficulties of effectively controlling, monitoring, and early warning the disasters.

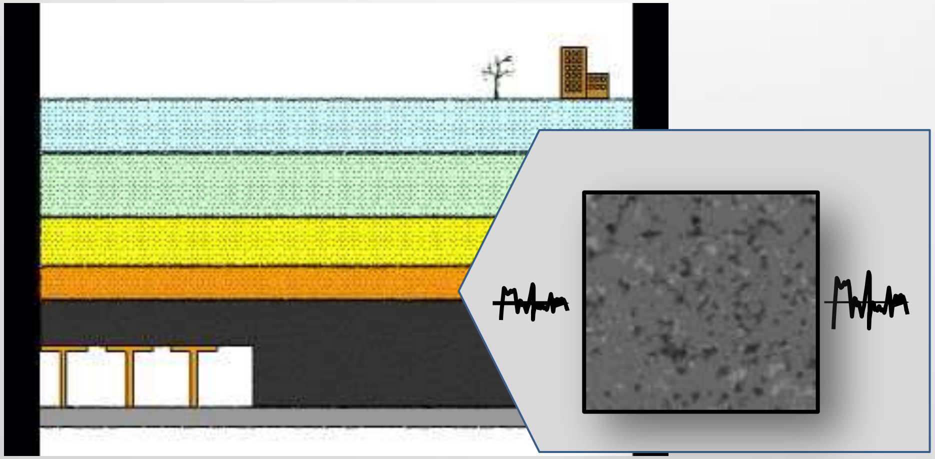


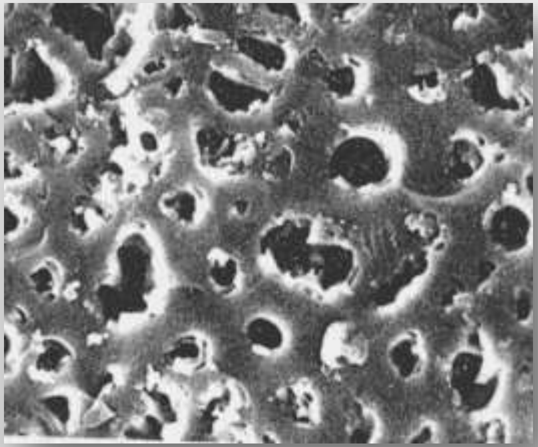
Illustration of stress wave propagation in porous rocks

Animation of a rockburst in a roadway

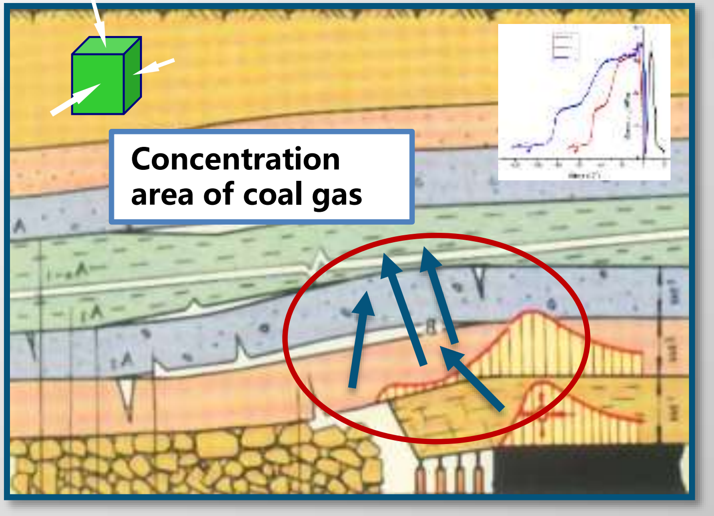
BACKGROUND MOTIVATION

Coal gas outburst is a fatal disaster in coal mines. It occurs accompanied by rapid dynamic failure of rocks, releasing huge amount of elastic energy.

Knowledge of the discontinuous porous structure and nature of gas transport and concentration motivated by excavation is essential for understanding the mechanism and prediction of coal gas outbursts.

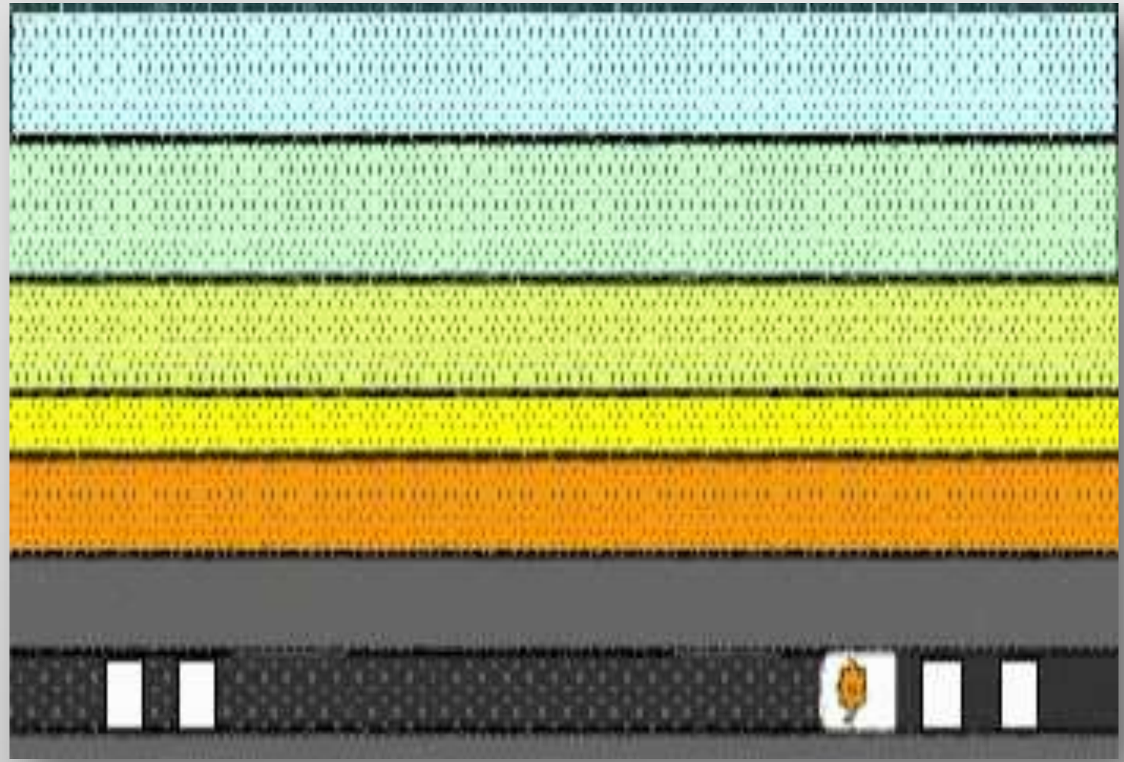


SEM image of the pore structure of the coal rock (magnified 500 times)



Transport and gathering of coal gas induced by excavation

Motivation problems



Complex lithology

Complicated, intractable-to-identify discontinuous structures

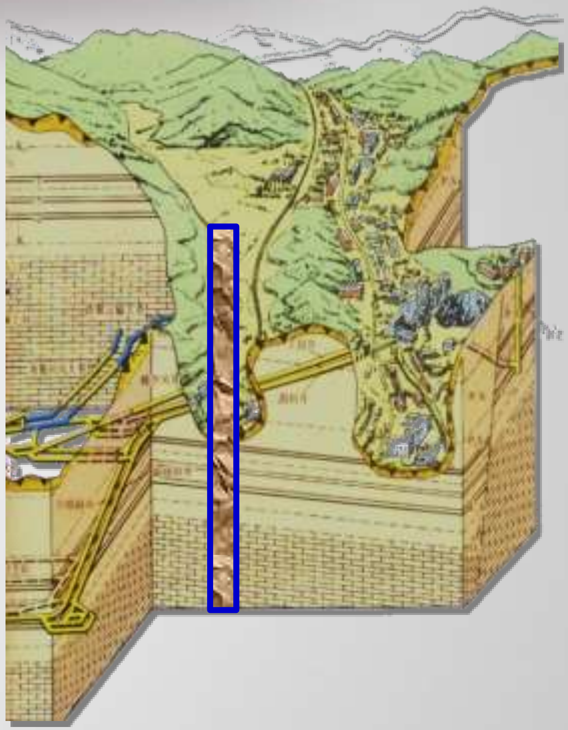
Invisible and difficult-to-identify stress distribution and energy accumulation

Motivation problems

Rock is buried underground with a depth more than hundreds or even thousands of meters and complicated geoenvironmental conditions, which requires advanced technology and massive influx of money to accomplish drilling and sampling for understanding and specifying its physical or mechanical properties.

It is technically difficult and costly for current approaches to attain sufficient number of rock cores.

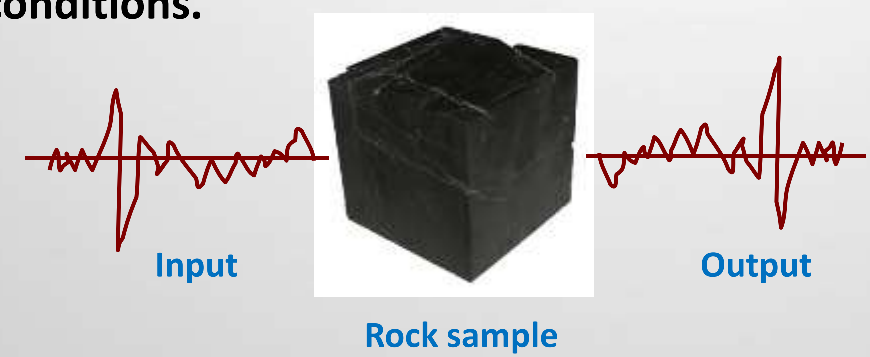
People have to use very limited amount of borehole data to specify rock, which has caused significant discrepancy in specification of rock behavior when compared each other.



Drilling and sampling

Motivation problems (Cont'd)

Rock involves plenty of disorderly distributed discontinuities, such as fractures, joints, pores, that essentially govern the apparent behavior of rock . The popular method people used to determine rock behavior is to conduct a series of tests on core samples, measure properties and their influencing factors, and formulate the relationships between the responses and ambient conditions.



What happened inside is unclear

Few accurate descriptions of the 3D interior discontinuities are available. Specifying rock behavior is more like solving a blackbox problem, i.e. one can hardly access to the interior governing mechanisms but the external responses.

Motivation problems (Cont'd)

IDEA:

Is it possible to develop a visualization method to visually and quantitatively reveal and characterize the interior discontinuous structures and the physical processes including stress concentration, energy release, fracturing, mechanical failure, fluid flow, etc., which essentially governs the external macroscopic responses of reservoir rocks?

Based on the quantitative and physical visualization of the dynamic failure of coal masses, people can understand and predict where, why, when the coal disasters take place before doing excavation design.

Natural reservoir core

Visualization of the interior structure

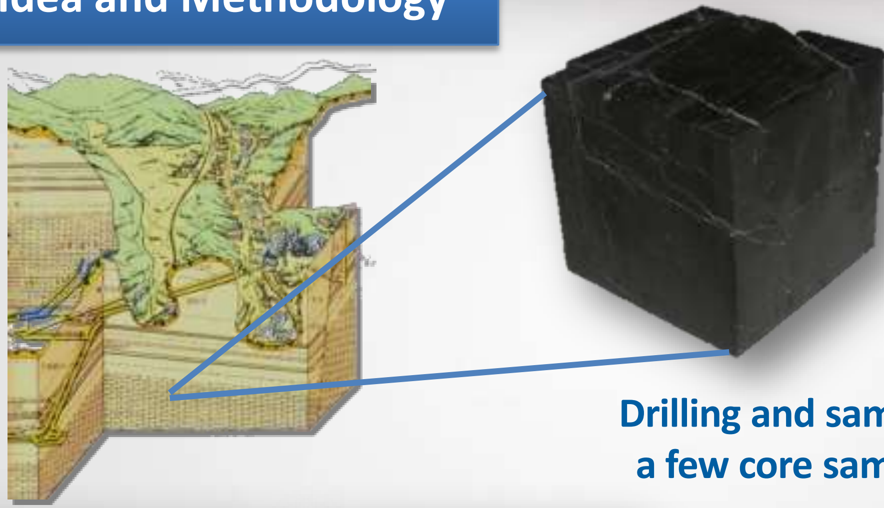
Background & Motivation

Materials and Methods

Results and Analysis

Conclusions

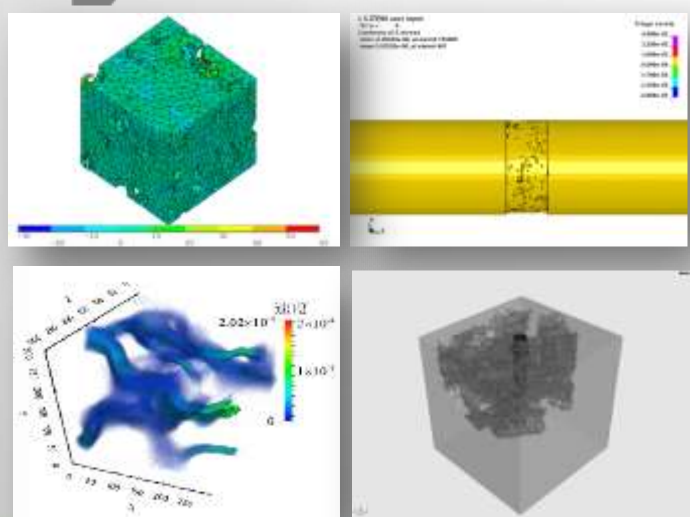
Idea and Methodology

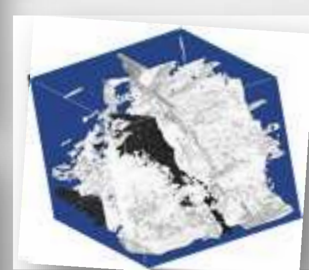


Drilling and sampling a few core samples

Complete mechanical and CT tests to identify the correlation characteristics and functions that govern external physical and mechanical performance

Developing 3D reconstruction algorithms and models for representing the real structure of fractured coal rocks on a computer





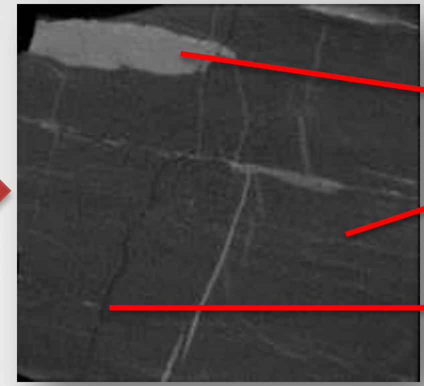
Disclosing interior structure of rock

Ju et al, Comput Meth Appl Mech Engg, 2014, 279, 212-226

3D Reconstruction of natural fractured coal mass

Natural fractured coal

CT Identification



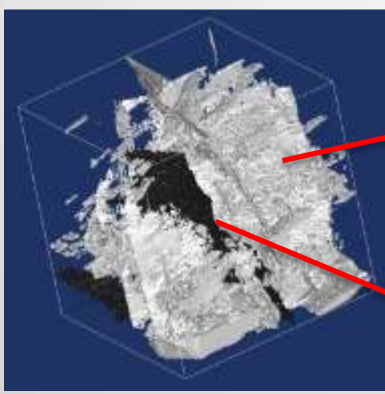
2D cross-section

Image processing

$$S=\frac{n(r_1,r_2,r_3)}{N(r_1,r_2,r_3)}$$

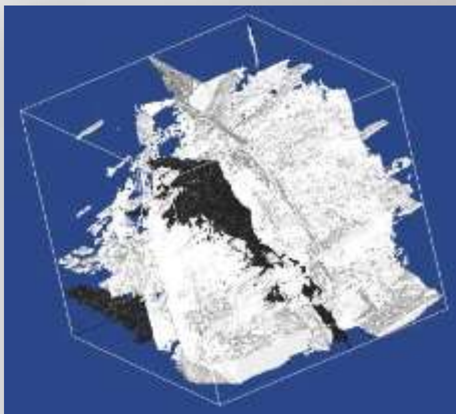
$$L=\frac{n(\overrightarrow{r_1,r_2,r_3})}{N(\overrightarrow{r_1,r_2,r_3})}$$

$$D=-\lim_{\delta\to 0}\frac{\log N_\delta}{\log \delta}$$



3D representations of fractured coal mass

MATERIALS & METHODS



Reconstructed fractured rock

Reconstructed porous rock

Physical models produced by 3D printing technology

3D Printing

Ju et al, Chin Science Bulletin, 2014, 36, 1-16. DOI 10.1007/s11434-014-0579-9

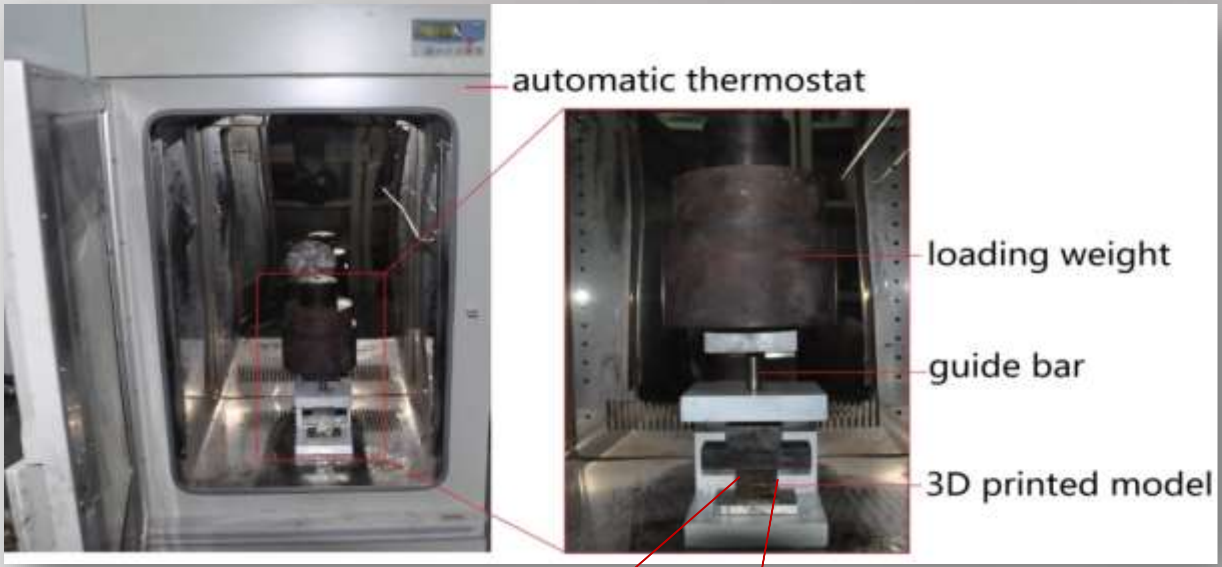
Printed transparent model of fractured and porous rock

State Key Laboratory
Coal Resources & Safe Mining

China University
Mining Technology

State Key Laboratory Geomechanics
Deep Underground Engineering

MATERIALS & METHODS

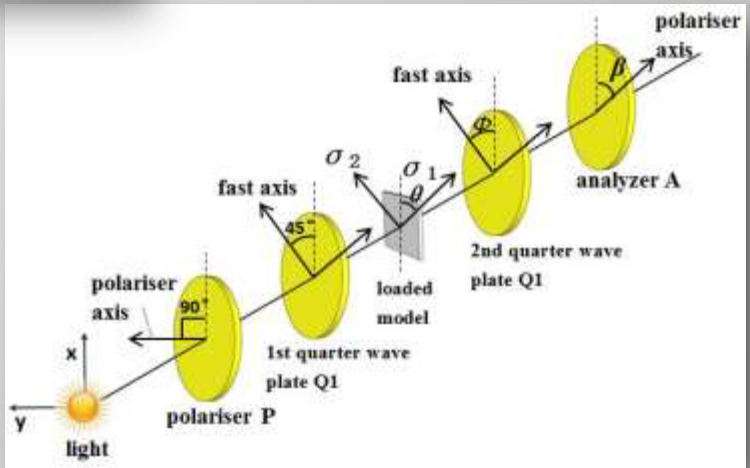


Adopted 3D photo-elastic measure and frozen stress techniques to freeze and memorize the interior stresses at various loading stages

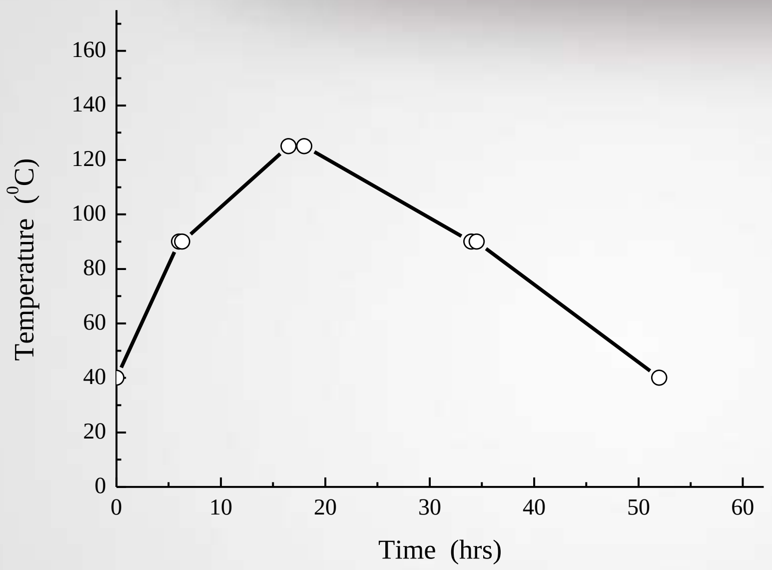
Applied photopolymers and frozen stress techniques

Printed model

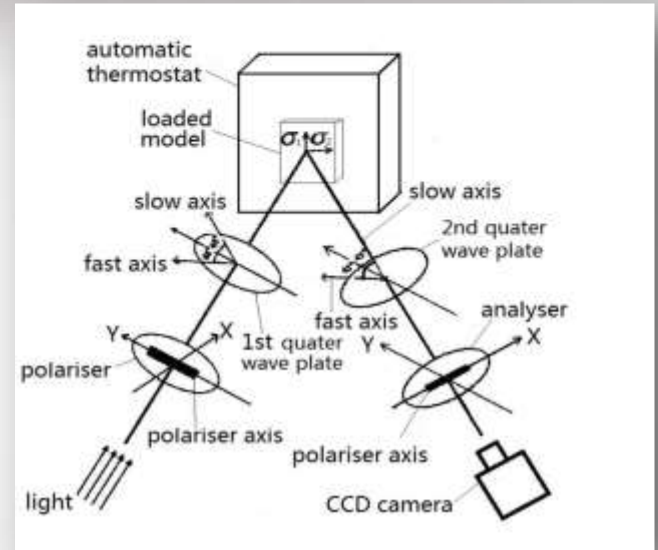
Slicing



MATERIALS & METHODS



Temperatures for freezing models



Setup of the reflection-type polariscope path system

Cut model into slices to identify the 3D internal stress distribution. The determinant factors of the slice thickness:

1. It should meet the minimum requirement to assure the necessary optical-path difference for light travelling;
2. It should keep an enough thickness to ensure a quality manufacture with less impact on the original fractures;
3. There are enough slices in order to get a complete picture of 3D stress distribution over the body.

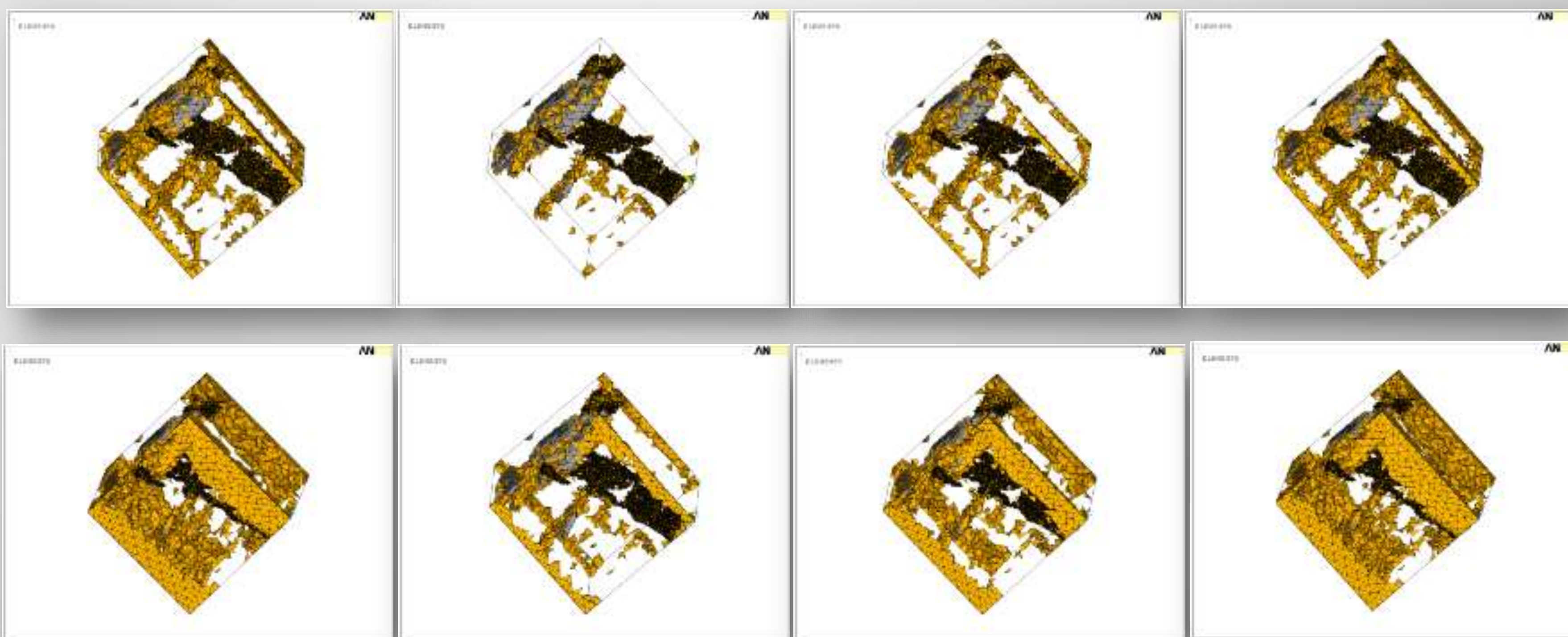
Background & Motivation

Materials and Methods

Results and Analysis

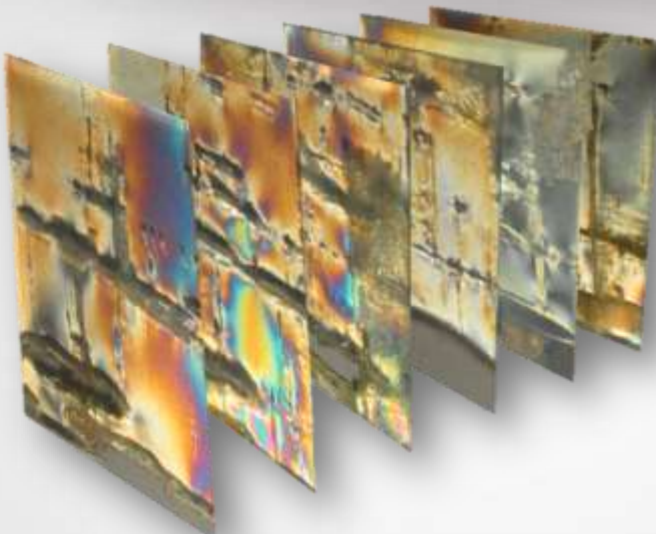
Conclusions

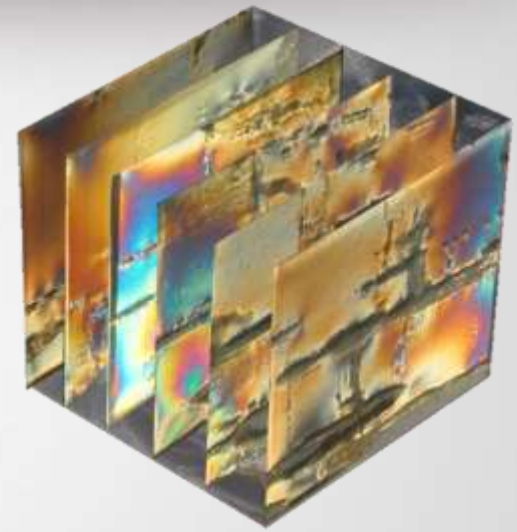
Numerical results of the stress distribution and energy accumulation of fractured coal based on the reconstruction models



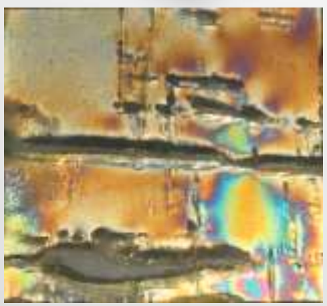
3D distribution of the failure zones of fractured coal during excavation with various unloading paths

RESULTS & ANALYSIS

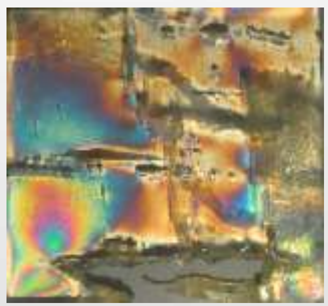




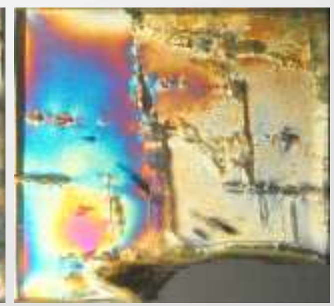
slice at *x*=4 mm



slice at *x*=12 mm

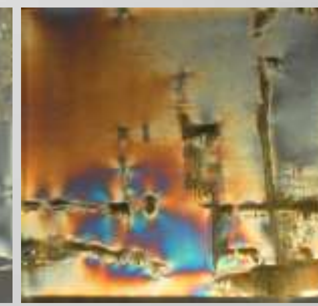


slice at *x*=20 mm



slice at *x*=28 mm

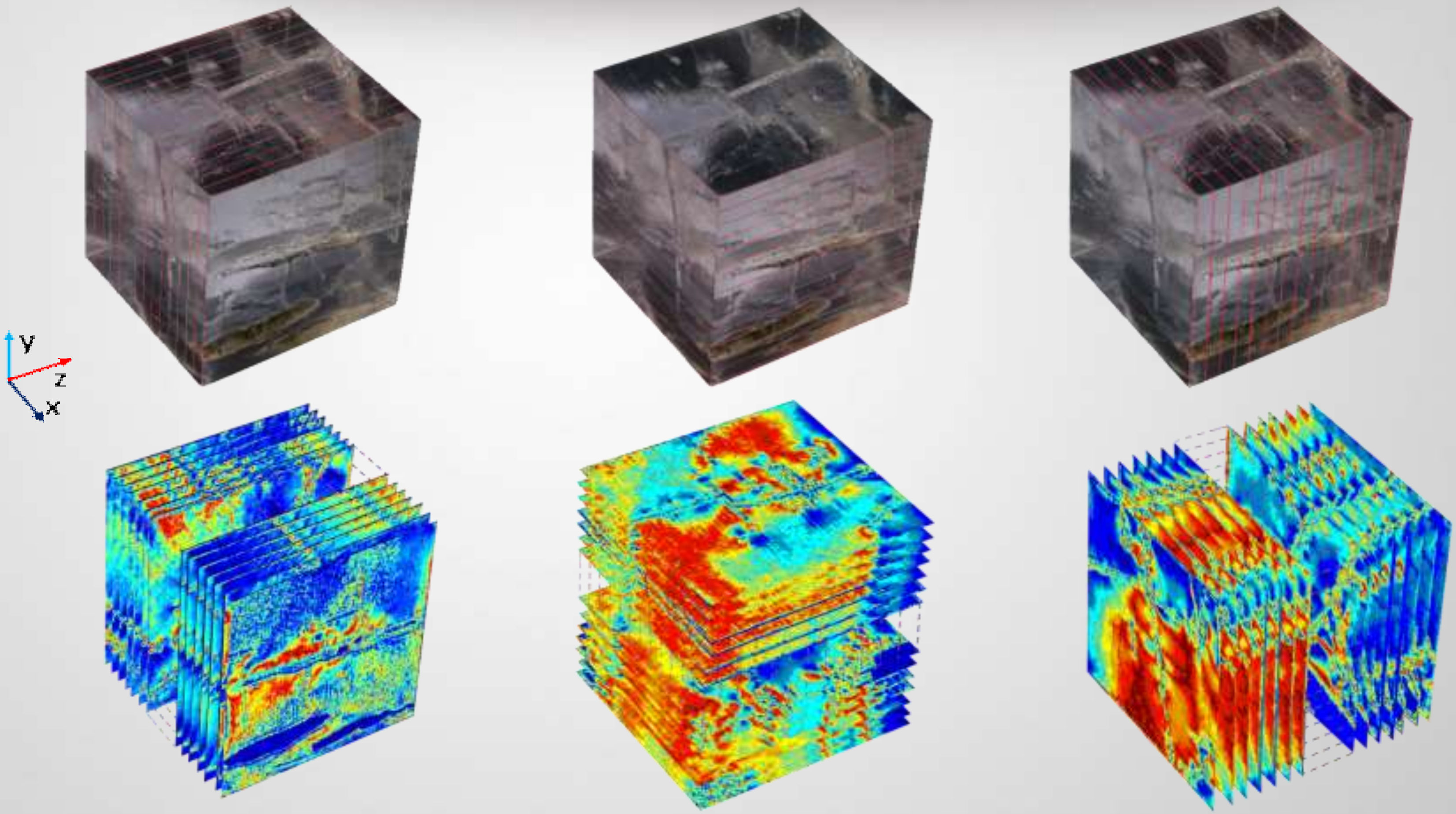
slice at *x*=36 mm



slice at *x*=44 mm

Distribution of the stress fringes on the slices at different heights in the fractured rock model under uniaxial compressions by using frozen stress techniques and 3D photoelastic methods

RESULTS & ANALYSIS

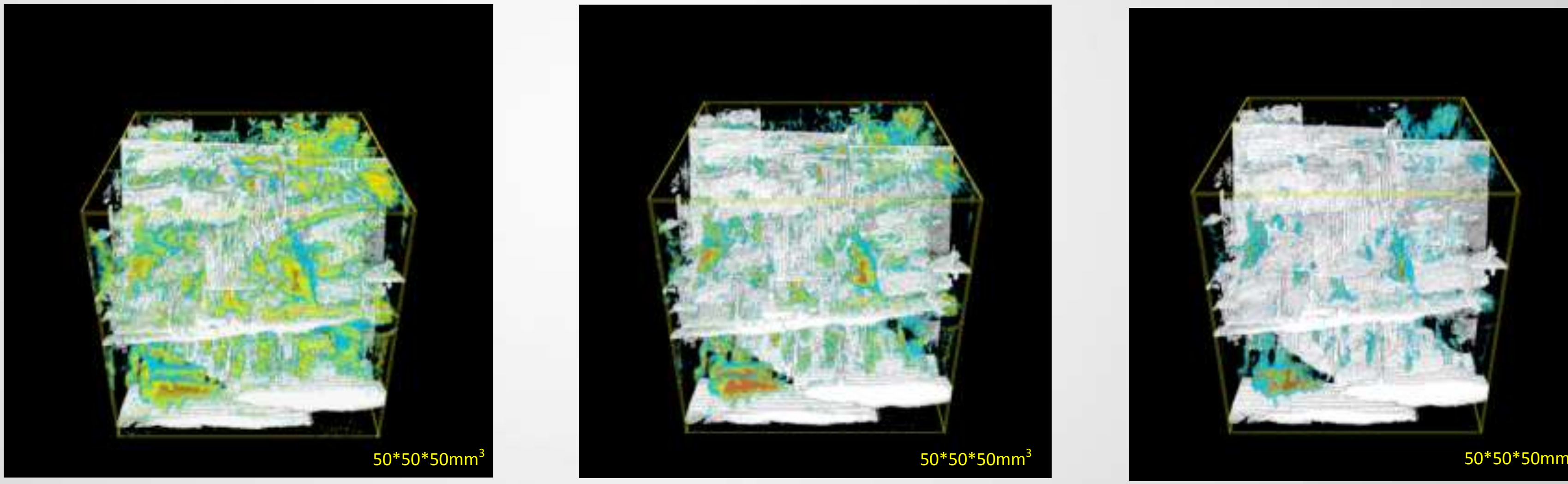


Stress component along X abscissa

Stress component along Y abscissa

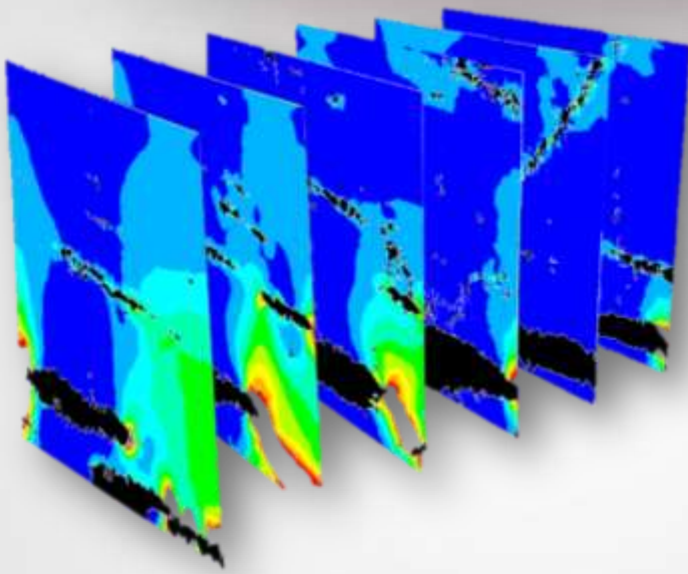
Stress component along z abscissa

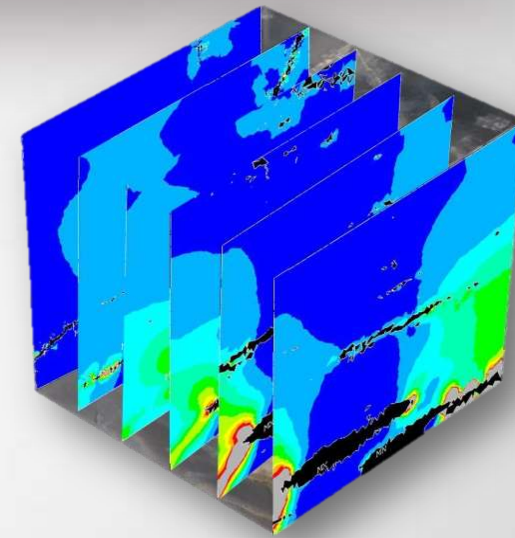
Results of the frozen stress test

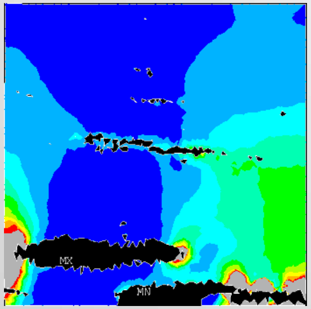


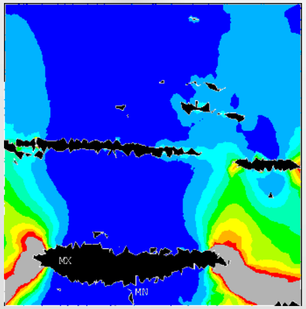
Physical visualization of the principal stress difference distribution in three-dimensions of a fractured coal subjected to uniaxial compressive loads at different loading stages utilizing frozen stress and 3D printing techniques.

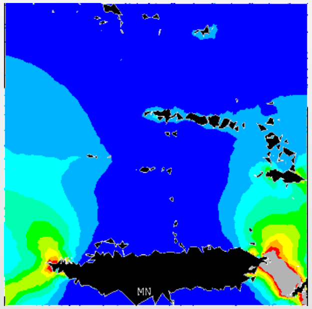
RESULTS & ANALYSIS

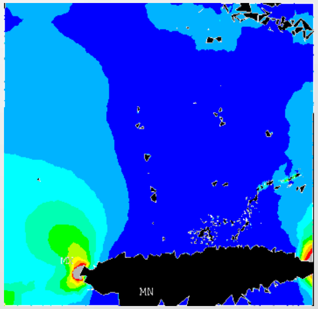


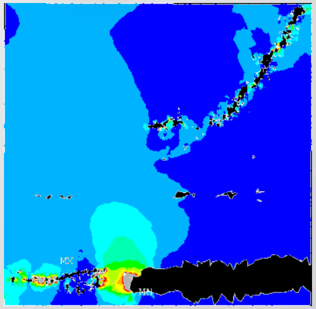


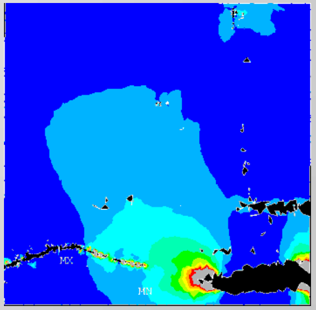

slice at *x*=4 mm


slice at *x*=12 mm


slice at *x*=20 mm

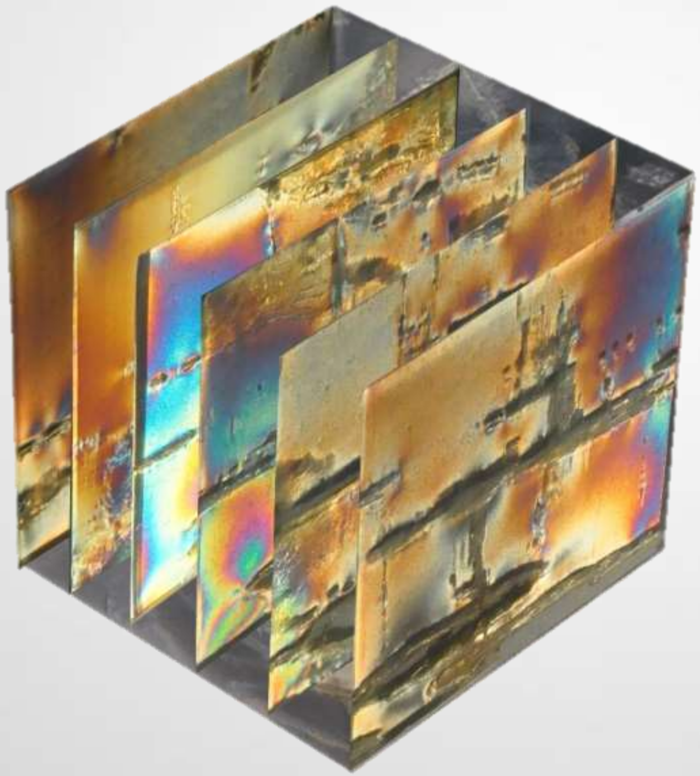

slice at *x*=28 mm


slice at *x*=36 mm

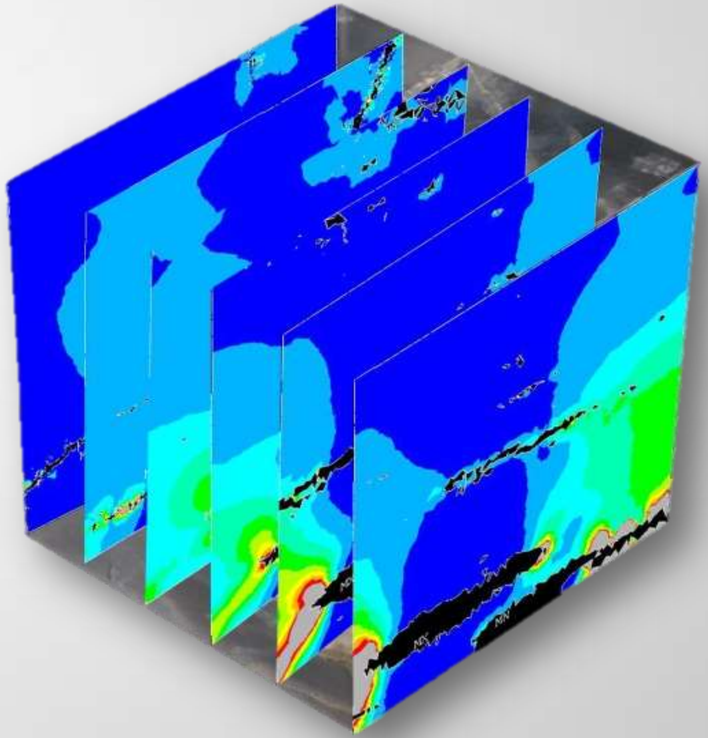

slice at *x*=44 mm

Numerical results of stress distribution on the slices at different heights in fractured rock model under uniaxial compressions

Comparison and verification



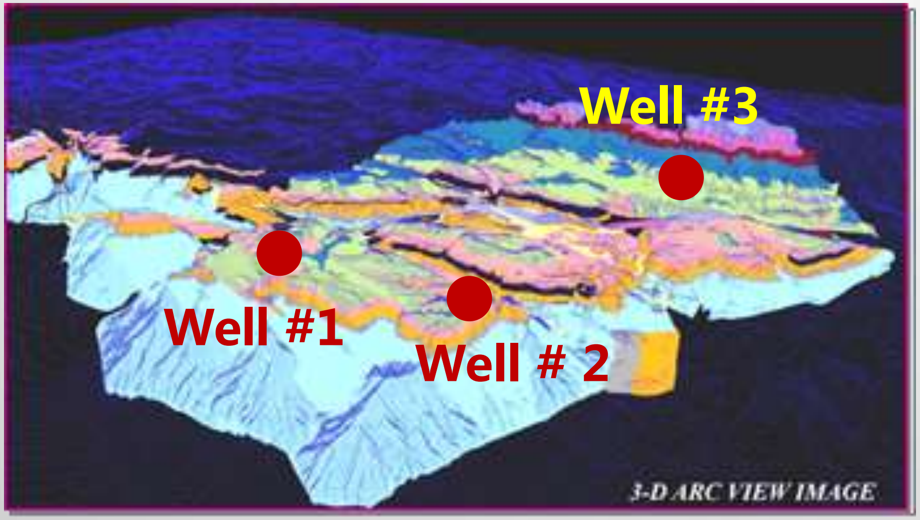
Experimental results of 3D stress field in fractured coal rock

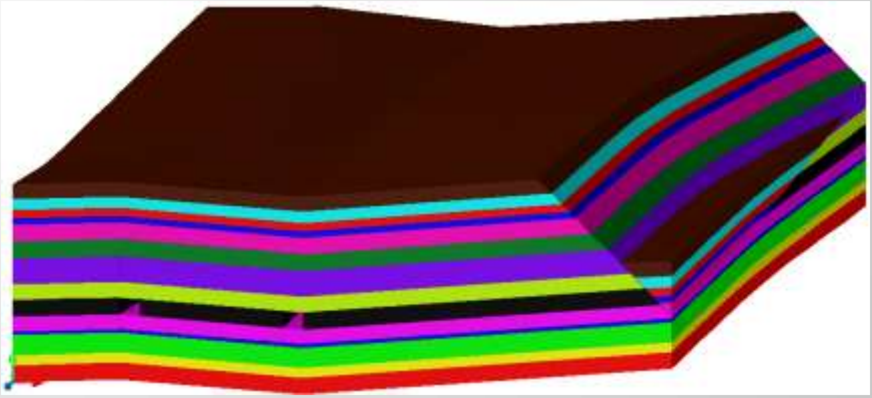


Numerical results of 3D stress field in fractured coal rock

3D Reconstruction model for tunnels or roadways of coal mines

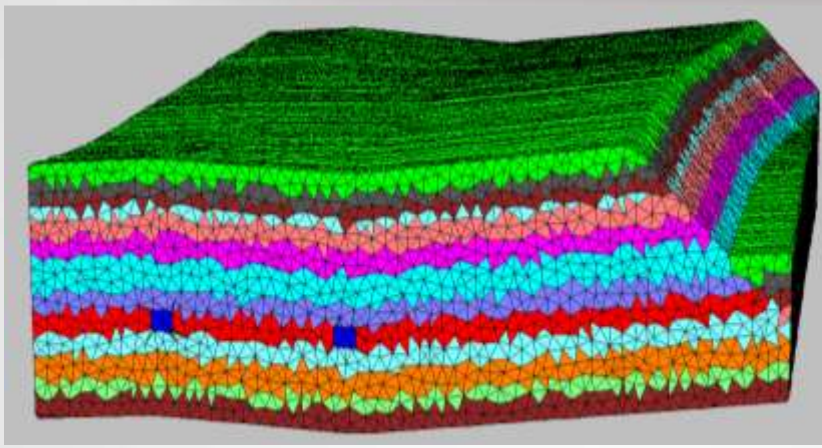
We have reconstructed the 3D model of the mining area including coal seams, geological faults, roadways, roof and bottom layers, etc.
The locations where the stress concentrated, energy accumulated and transmitted can be identified.



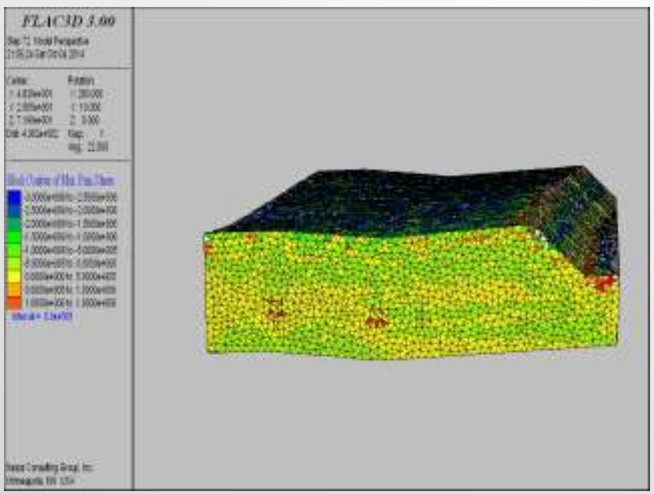


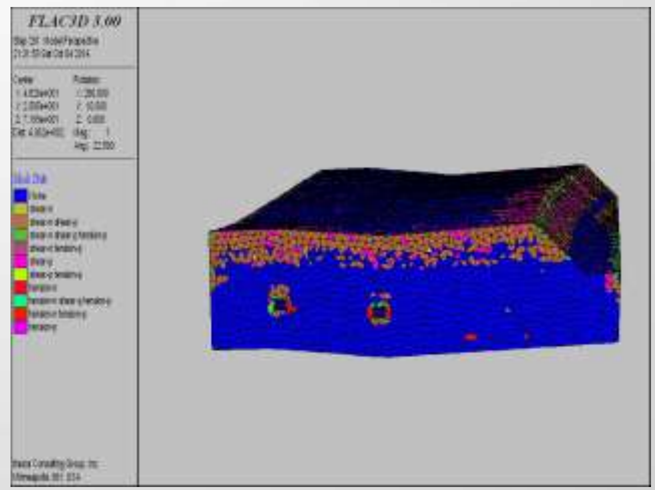
3D reconstruction model

RESULTS & ANALYSIS

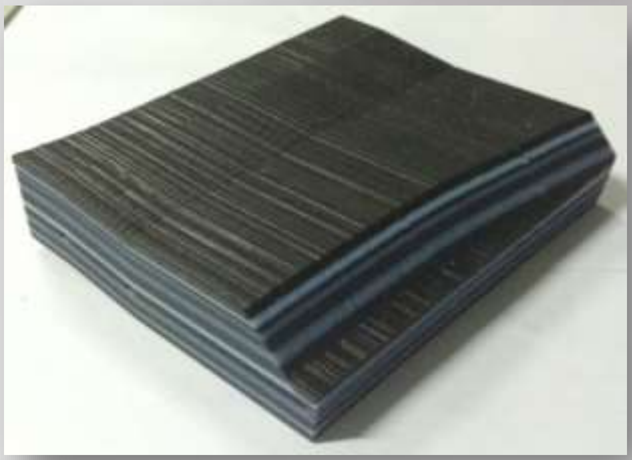


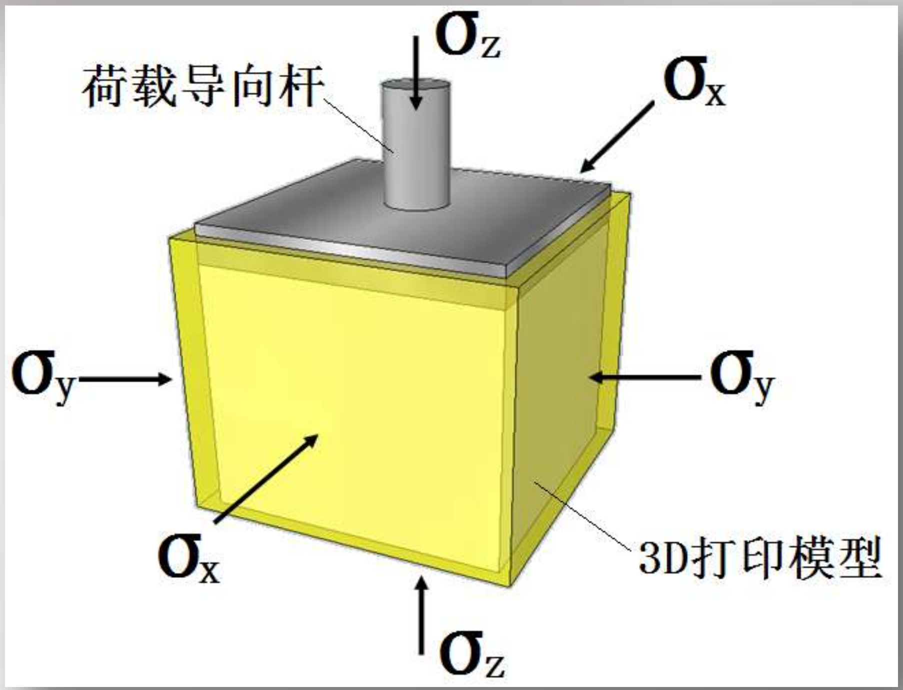
**Elements and meshes
(900, 000 elements)**

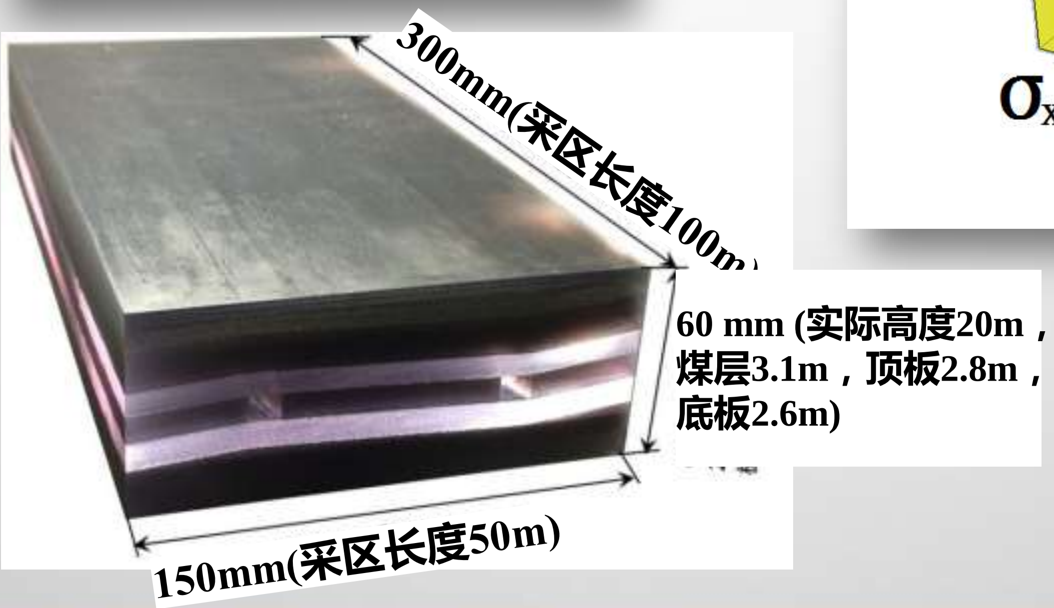




Numerical simulation of the stress concentration and element failure during roadway excavation based on FLAC3D, ANSYS and MIMICS codes.

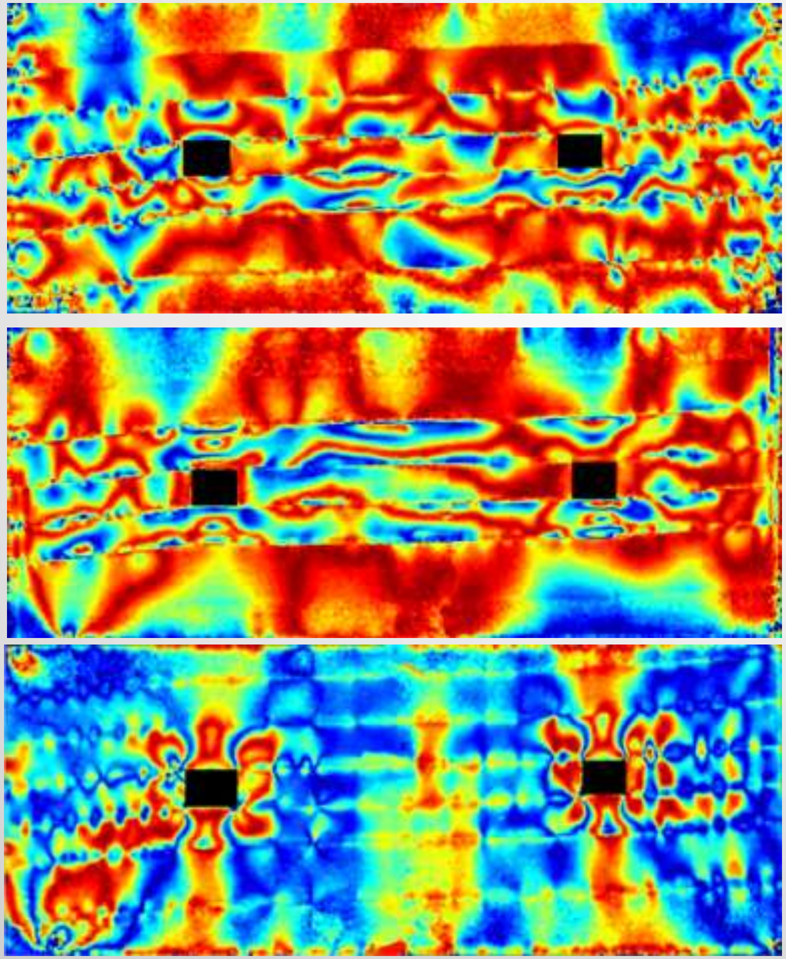


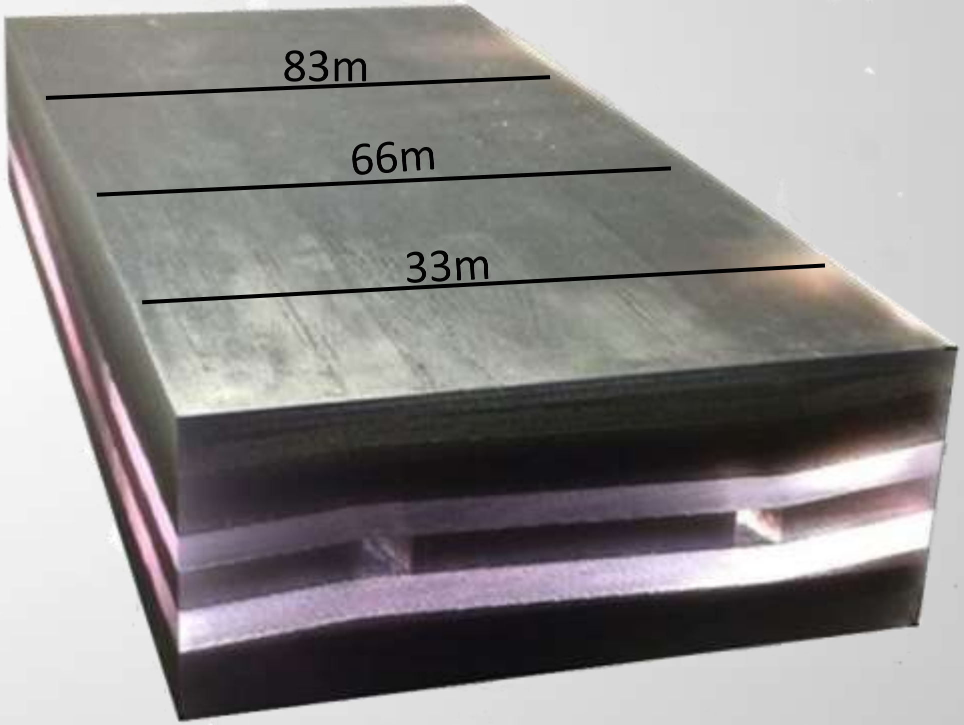




The printed 3D model of the mining area containing roadways and coal seams

Experimental results of stress distribution

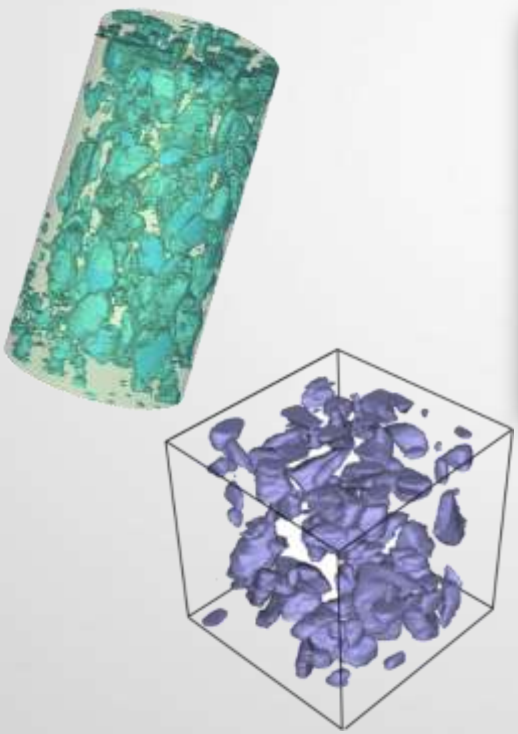




Slicing at different places corresponding to different mining stages, showing the stress distribution around tunnels

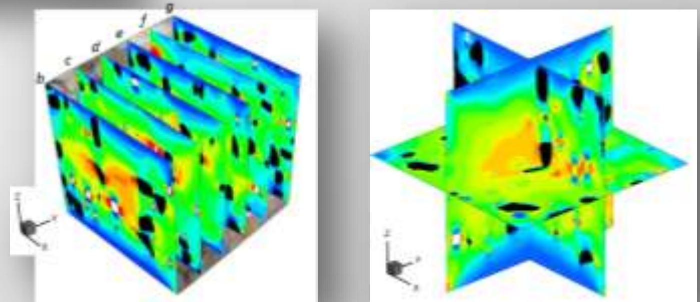
Similar methods were applied to print the heterogeneous glutenite rock containing randomly distributed particles for triaxial hydrofracturing tests. Through the methods, the internal complex aggregated structure, hydrofracturing cracks distribution and even stress distribution can be directly observed and quantitatively characterized。

Experimental visualization of the Hydrofracturing crack inside the model



Numerically reconstructed models of heterogeneous glutenite

3D printed models



Experimental results of stress distribution and concentration

Background & Motivation

Materials and Methods

Results and Analysis

Conclusions

CONCLUSIONS & DISCUSSIONS

- The 3D printed model with matrix made from Vero Clear and the fractures filled by Fullcure 705 presents the consistent characteristics of the fracture structures.
- The mechanical properties of the printed model, such as uniaxial compressive strength, elastic modulus, and Poisson's ratio, are close to those of the prototype rock.
- The experimental tests and the numerical results show good consistency in terms of the distribution area of high stresses and the stress gradients in the vicinity of discontinuous fractures.
- The materials used for the printed models show good photoelastic properties. The method of incorporating 3D printing and frozen stress technique can quantify and visualize the complex fracture structures

CONCLUSIONS & DISCUSSIONS

- The method incorporating the 3D printing, frozen stress and photoelastic technologies is able to visualize and quantify the stress distribution around complex fractures inside coal samples.
- The photoelastic test results of stress concentration and the stress gradient show a good agreement with the numerical predictions of the real coal sample.
- The photoelastic results of the stress amplitude and distribution range from the frozen stress method present a certain amount of margin from the numerical predictions.

THANK YOU VERY MUCH !