煤岩冲击破坏动力学物理模拟相似原理

Similarity Principle for Physical Simulation of Coal and Rock Failure Dynamics

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汇 报 提 纲

中国矿业大学
China University of Mining &Tech.

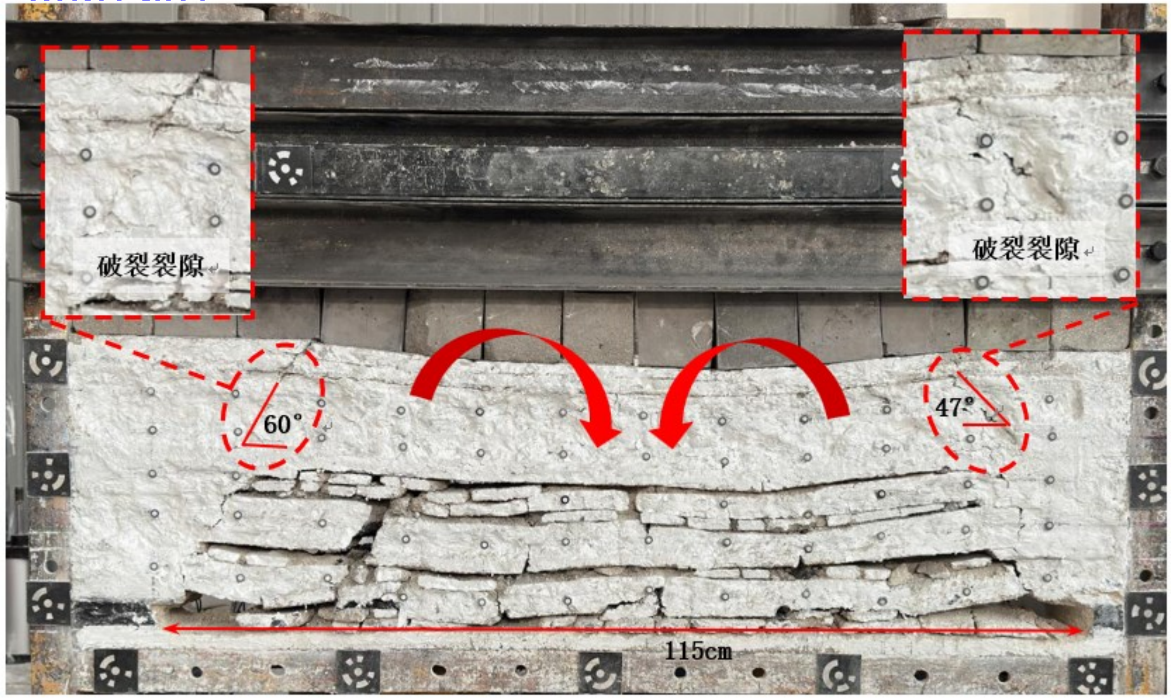
- 煤岩物理相似模拟研究现状
  Current Status of Coal-Rock Physical Similarity Research
- 煤岩破坏的动力学相似原理
  Dynamic Similarity Principle for Coal Rock Failure
- 动力学相似准数(Y-D)探讨
  Discussion on the Dynamic Similarity Criterion (Y-D)
- 煤岩动力学相似原理的验证
  Verification of Similarity Principle for Coal and Rock Dynamics

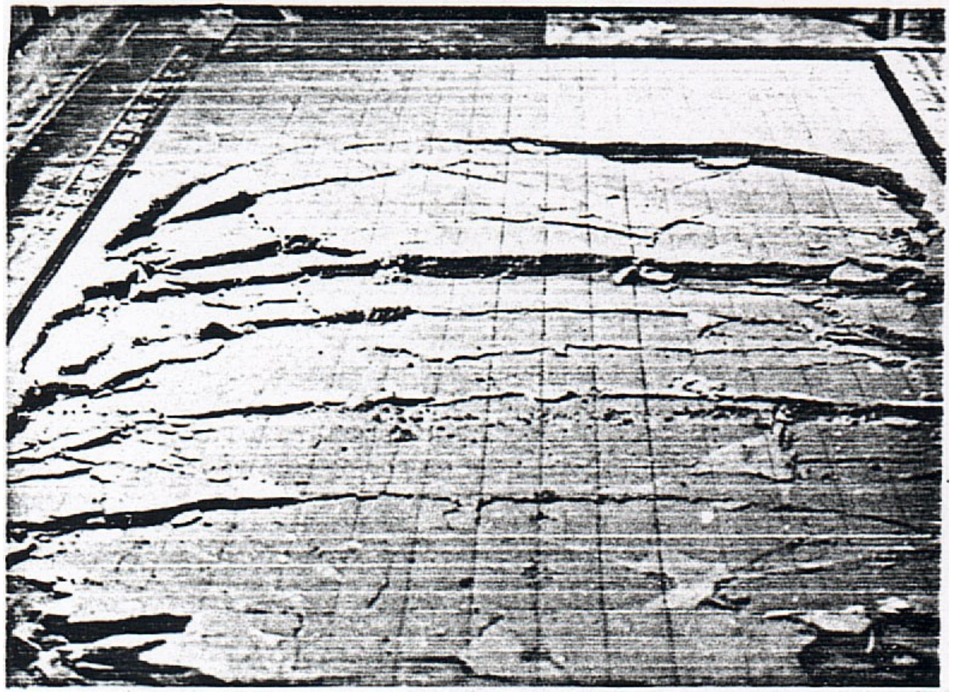
煤岩物理相似模拟研究现状

Current Status of Coal-Rock Physical Similarity Research

□ 相似模拟作用 Similar simulation functions

- **物理相似模拟是矿山开采岩层破断、运动、演化与控制等的重要研究方法之一；** Physical simulation is one of the important research methods for fracture, movement, evolution, and control of rock layers in mining operations
- **对矿山开采、岩层控制、灾害防治等作出了重大贡献。** Physical simulation has made contributions to mining operations, rock control, and disaster prevention and control





相似模拟基本原理 Fundamental principles of similarity modeling

- 相似理论：几何相似、运动相似、动力相似 Similarity theory: geometric similarity, kinematic similarity, dynamic similarity
- 静力学相似理论，满足**弗劳德准则**，$C_a=1$，The theory of static similarity satisfies the Froude criterion.

几何相似 Geometric Similarity	$C_l = l_N / l_M$
运动相似 Kinematic Similarity	$C_t = \sqrt{C_l}$
动力相似 Dynamic Similarity	$C_\sigma = C_\rho C_l$

式中：
C_l--原型与模型长度比
l_N--原型广义长度
l_M--模型广义长度
C_t--时间比
C_σ--应力比
C_ρ--密度比

重力 $F_g = mg = \rho g l^3$

惯性力 $F_i = ma = \rho V a = \rho l^3 \frac{v^2}{l} = \rho l^2 v^2$

弗劳德准数 $F_r = \frac{F_i}{F_g} = \frac{v^2}{gl}$

原型Fr=模型Fr $F_r = F_r'$ $\frac{v^2}{gl} = \frac{v'^2}{g'l'}$

速度，时间相似比 $C_v = \sqrt{C_l}$ $C_t = \sqrt{C_l}$

加速度相似比 $C_a = 1$

煤岩物理相似模拟研究现状

Current Status of Coal-Rock Physical Similarity Research

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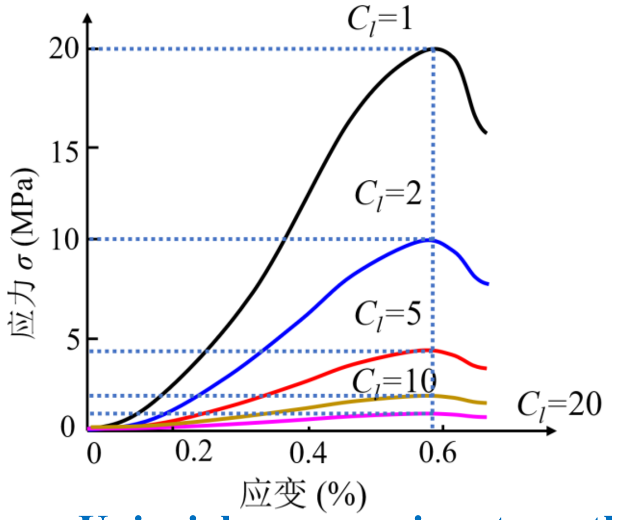
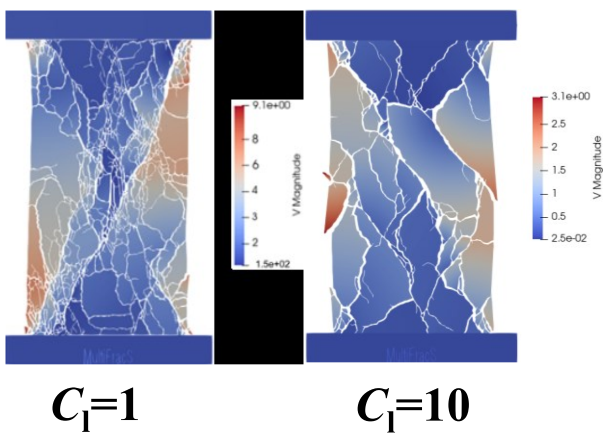
□ 相似模型材料—煤的单轴抗压强度 Uniaxial compressive strength of coal as a similar model material

- 静力学相似是弹性力学相似，冲击属于动力学，故不适用。Static similarity applies to elastic mechanics, but coal burst belongs to dynamics, so it is not applicable.
- 按静力学相似准则缩减，应力减小，应变保持不变，模型弹性模量降低，脆性减小，无法还原原型冲击现象。 Scaling by static similarity reduces stress, keeps strain unchanged, lowers the model elastic modulus, and decreases brittleness, preventing reproduction of prototype phenomenon.





Uniaxial compressive strength of coal as a similar model material

关键指标模拟值随几何比Cl变化规律

几何相似比	弹性模量 (GPa)	冲击能量指数 K_E	单轴抗压强度 Rc (MPa)	碎块最大冲击速度v (m/s)	冲击倾向性
Cl=1	4	9.30	16.26	8.9	降低
Cl=2	2	8.12	8.17	6.5	
Cl=5	0.8	7.98	3.90	4.2	
Cl=10	0.4	7.83	1.62	3.1	
Cl=20	0.2	7.90	1.10	2.5	

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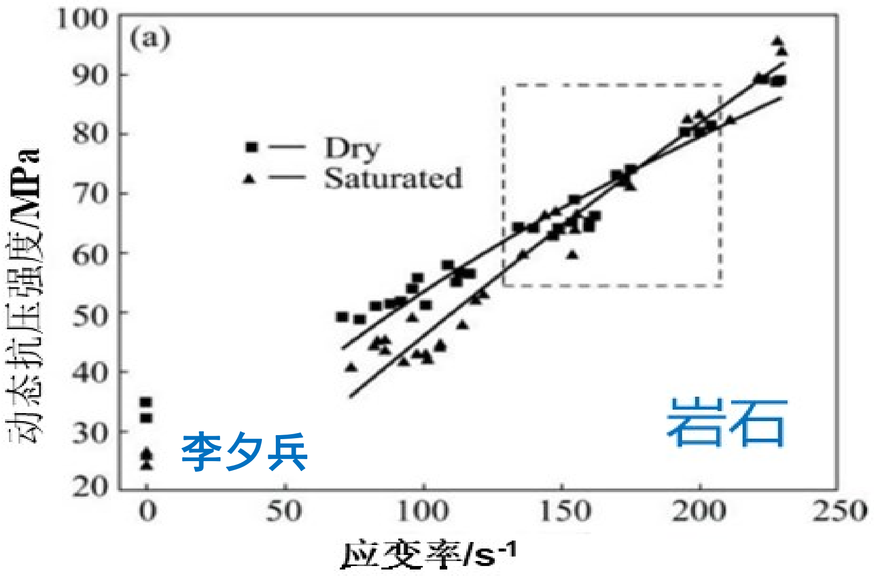
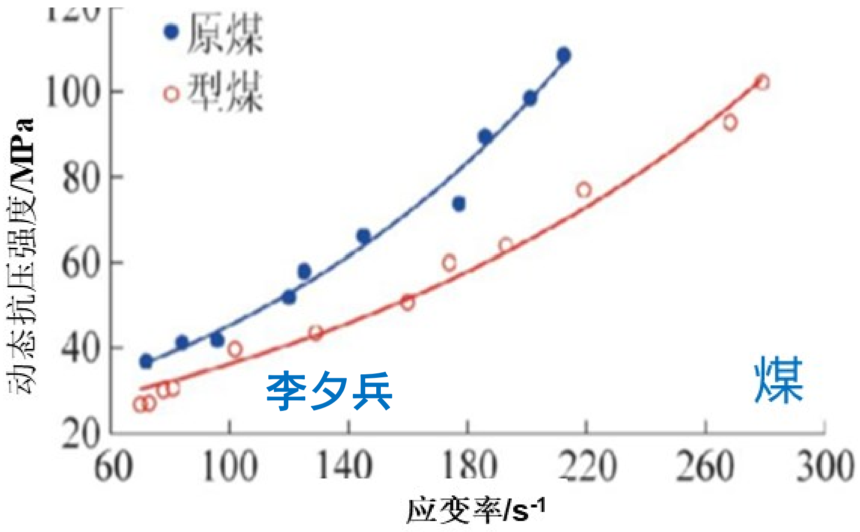
煤岩冲击破坏的动力学特征
Dynamic Characteristics of Coal Rock Impact Failure

□ 煤岩体的动静载力学特性 Dynamic and static mechanical properties of coal and rock mass

- **动载条件下煤岩体弹性模量变大，微破裂成核扩展阶段（BC）应变变小；Under dynamic loading, the elastic modulus of the coal-rock mass increases, while the strain in the microcrack nucleation and propagation stage (BC) decreases.**
- **煤岩动态抗压强度高于静态抗压强度，并随应变率增加而增加。The dynamic compressive strength of the coal and rock exceeds the static compressive strength and increases with strain rate.**





煤岩动态强度随应变率变化对比

李夕兵.岩石动力学[M].科学出版社.2014.
张文清,穆朝民,李重情.冲击荷载下煤的动态力学性质研究[J].煤炭科学技术,2019,47(10):198-204.DOI:10.13199.
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煤岩冲击破坏的动力学特征
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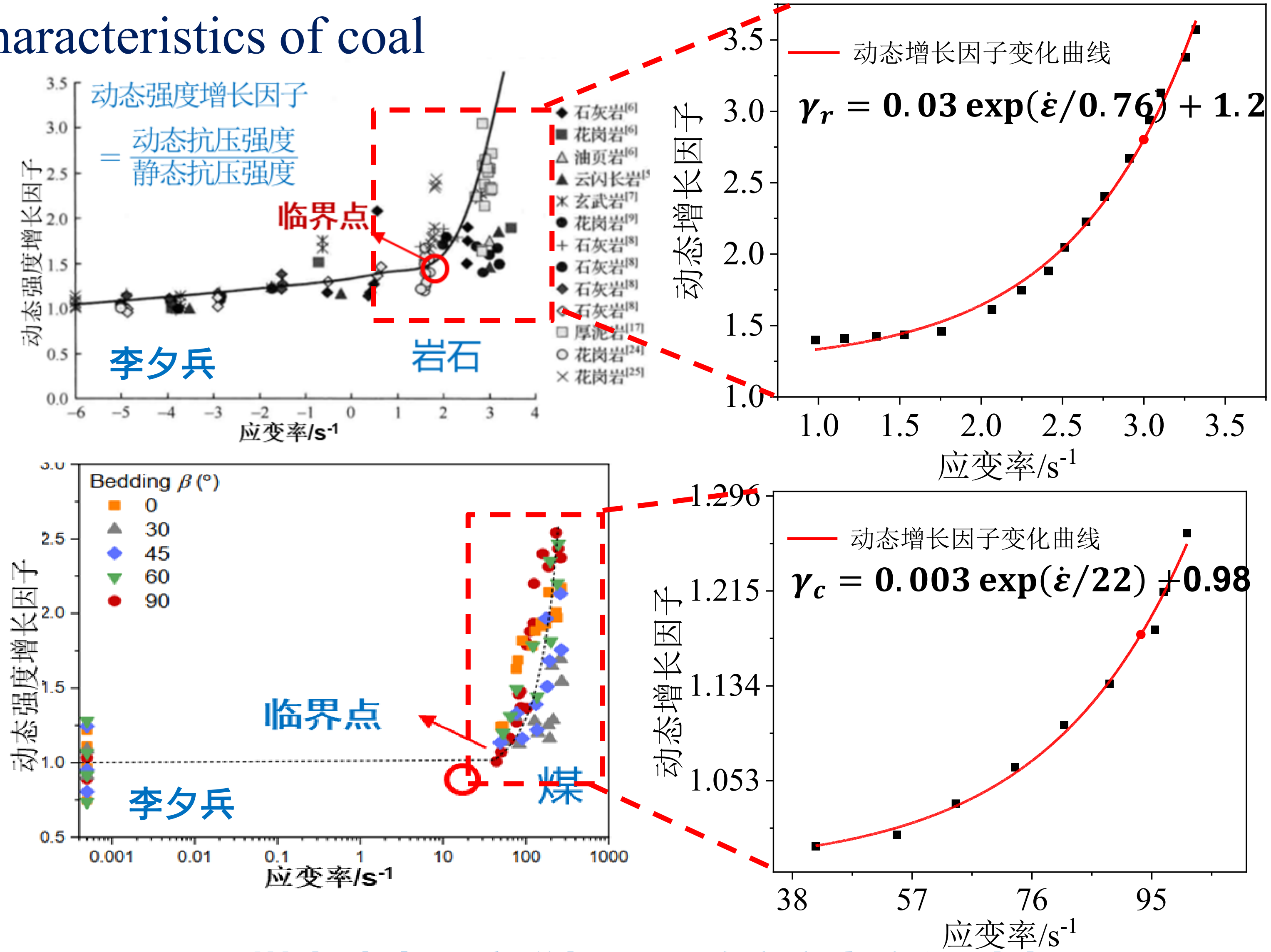
□ 煤岩体动力学特征 Dynamic characteristics of coal and rock mass

- **动态强度增长因子：动态抗压强度/静态抗压强度**
  Dynamic strength growth factor: Dynamic compressive strength / Static compressive strength

$$R_{cd} = \gamma R_{cj} = f(\dot{\varepsilon}) R_{cj}$$

$$\text{Coal:} \quad \gamma = 0.98 + 0.003e^{\left(\frac{\dot{\varepsilon}}{0.76}\right)}$$

$$\text{Rock:} \quad \gamma = 1.2 + 0.03e^{\left(\frac{\dot{\varepsilon}}{22}\right)}$$



煤岩动态强度增长因子随应变率变化对比

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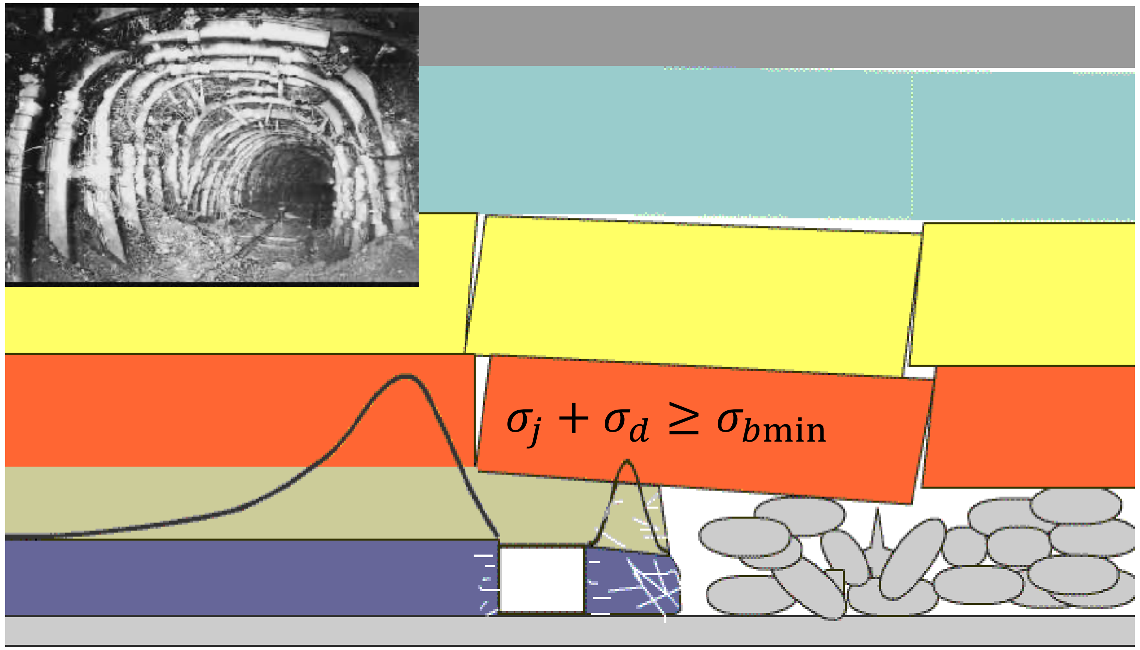
冲击地压的基本条件 Basic conditions for coal burst / rockburst

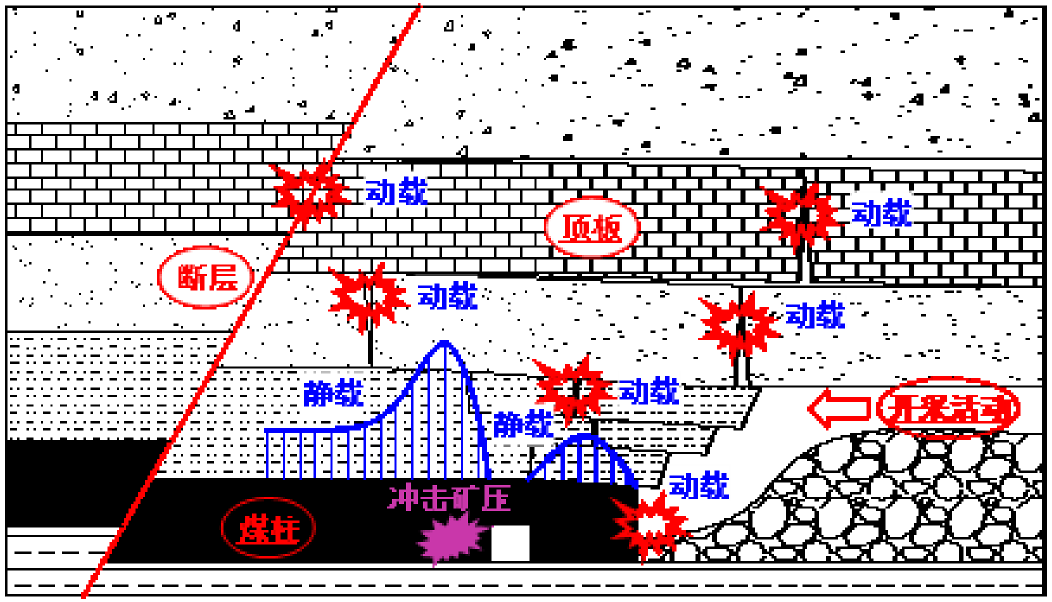
- **煤体具有冲击倾向性；** The coal mass exhibits burst proneness.
- **煤层上施加的动静载必须大于发生冲击破坏的临界应力水平；** The dynamic and static loads applied on the coal seam must exceed the critical stress level for burst failure.

- **冲击破坏临界应力与煤体性质及冲击动载相关。** The critical stress for burst failure is related to the properties of the coal mass and the dynamic load.

$$(\boldsymbol{\sigma}_j + \boldsymbol{\sigma}_d)_r \geq \sigma_{bmin}$$



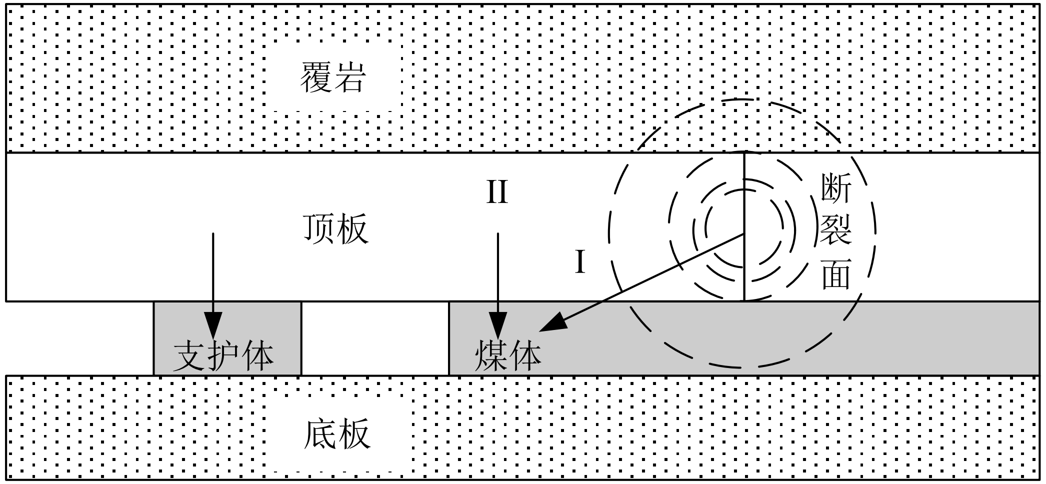
煤矿冲击动载源头 Dynamic sources inducing coal bursts in mines



- **煤矿冲击动载源主要有煤岩体对开采扰动的应力响应。The main dynamic load source inducing coal bursts is the stress response of the coal rock mass to mining disturbance.**

- **震动波传播的动载 The dynamic load propagated by the vibration wave.**

$$\begin{cases} \sigma_{dP} = \rho v_P v_{pp} \\ \tau_{dS} = \rho v_S v_{ps} \end{cases}$$



煤矿冲击动载应变率 Strain rate of dynamic loads in coal mine

- **矿震震动波以波速 v 向外传播。经时间 dt 后，震动波引起的附加应变为：**

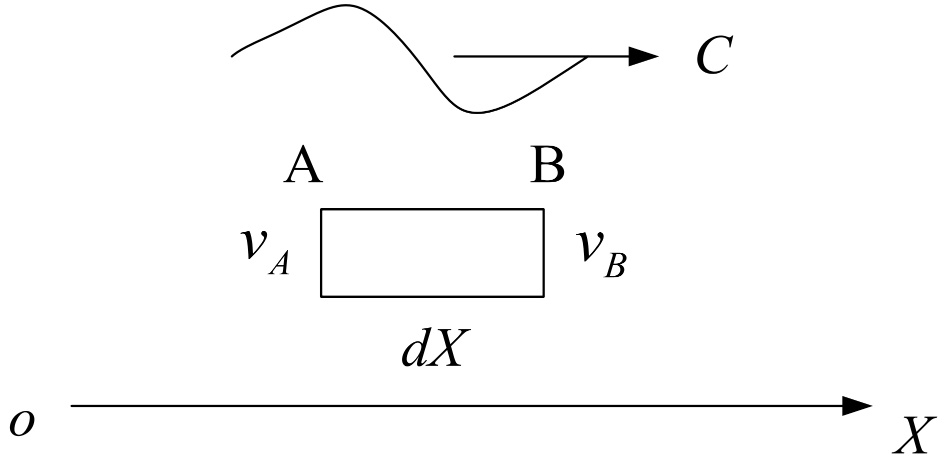
  Seismic waves from mine tremors propagate outward at a wave velocity ***v***. After a time interval ***dt***, the additional strain induced by the seismic waves is:

$$\varepsilon = \frac{(v_B dt + \frac{1}{2} v_B^{'} dt^2) - (v_A dt + \frac{1}{2} v_A^{'} dt^2)}{dX}$$

- ***dt* 时段内，应变的平均变化速率为：**

  The average rate of strain change over the time interval dt is:

$$\overline{\varepsilon_t} = \frac{(v_B dt + \frac{1}{2} v_B^{'} dt^2) - (v_A dt + \frac{1}{2} v_A^{'} dt^2)}{dXdt} = \frac{(v_A - v_B) + \frac{1}{2}(v_B^{'} - v_A^{'})dt}{dX}$$



震动传播介质应变率分析
Strain rate analysis of vibration propagation medium

- **震动波传播方向上速度的空间变化率为质点的应变率。** The spatial change rate of velocity in the direction of vibration wave propagation represents the strain rate of the particle.

$$\dot{\varepsilon}=\frac{\nu_B-\nu_A}{dX}$$

- **质点震动速度 $\nu(X,t)$ 可写为：** The particle vibration velocity ν(X,t) can be expressed as:

$$\nu(X,t)=\nu_{max}\sin[2\pi f(t-\frac{X}{C})]$$

- **震动波产生的动载应变率主要与频率和质点峰值速度相关。** The dynamic load strain rate generated by the vibration wave is mainly related to the frequency and the peak particle velocity.

$$\dot{\varepsilon}\,(X,t)=\frac{\partial[\nu(X,t)]}{\partial X}=-\frac{2\pi f\nu_{max}}{\upsilon}\cos[2\pi f(t-\frac{X}{\upsilon})]$$

$$\dot{\varepsilon}_{max}=\frac{2\pi f\nu_{max}}{\upsilon}$$

$$\sigma_d=\rho\upsilon_P\nu_{pp}=\frac{\rho\upsilon_P^2\dot{\varepsilon}_{max}}{2\pi f}$$

ν_{max} 为质点最大震动速度（峰值速度值ν_{PP} ）
$\dot{\varepsilon}_{max}$为最大应变率

煤岩破坏的动力学相似原理

Dynamic Similarity Principle for Coal Rock Failure

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□ 煤岩体动力学相似模拟原理 The principle of dynamic similarity of coal and rock failure

➢ （1）煤岩体具有冲击动力破坏特征；（2）动力学状态下煤岩单轴抗压强度大于静力学状态，动力学单轴抗压强度是加载应变率的函数；（3）动力学状态下煤岩的破坏时间小于静力学；（4）加速度相似比$C_a \neq 1$。(1) The coal rock mass exhibits characteristics of dynamic burst failure; (2) The UCS of coal rock in the dynamic state is higher than under static conditions, and the dynamic UCS is a function of the loading strain rate. (3) The failure time of coal rock in the dynamic state is less than that of statics. (4) The acceleration similarity ratio $Ca \neq 1$.

速度相似比
Speed

$$C_v = \sqrt{C_l C_a}$$

能量相似比
Energy

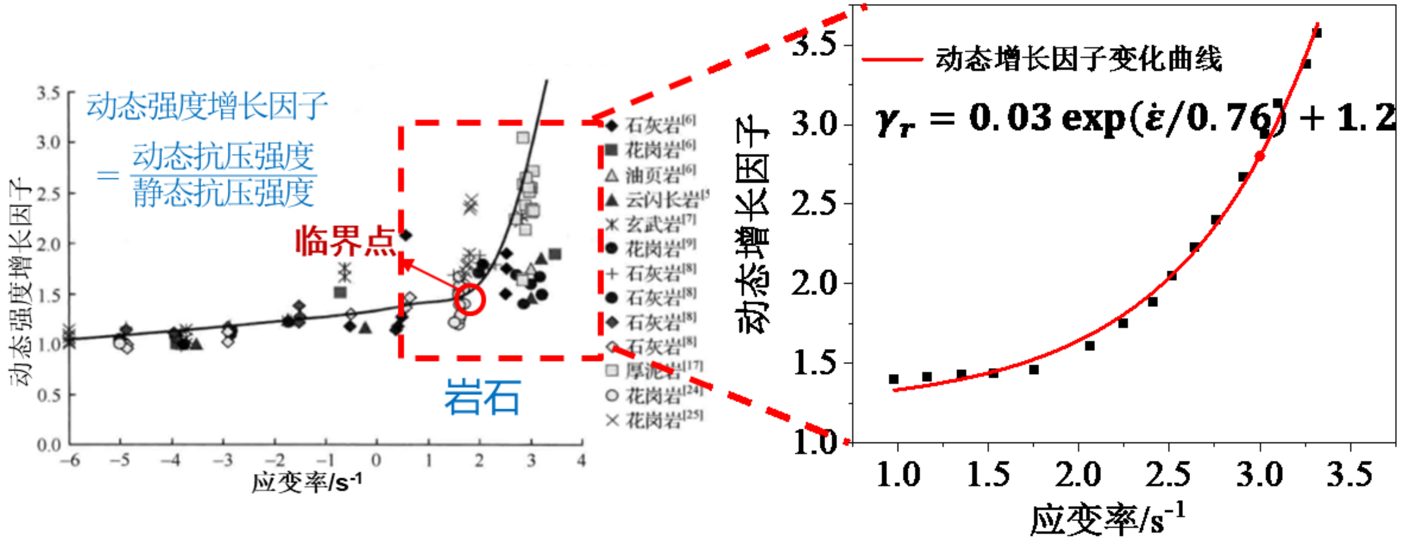
$$C_Q = C_\rho C_l^4 C_a$$

应变率相似比
Strain rate

$$C_{\dot\varepsilon} = \sqrt{\frac{C_a}{C_l}}$$

应力相似比
Stress

$$C_\sigma = C_\rho C_l C_a$$



受动载影响，试样动态强度增加

Dynamic loading enhances the strength of the specimen

煤岩破坏的动力学相似原理
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煤岩体动力学相似模拟原理 The principle of dynamic similarity of coal and rock failure

- **矿震震动波动载应力：** Dynamic stress induced by the seismic waves of tremors:

$$\sigma_d = \frac{\rho v_P^2 \dot{\varepsilon}_{max}}{2\pi f}$$

$$\sigma_d = \rho l a_d$$

- **动力学受载加速度：** Dynamic load acceleration:

$$a_d = \frac{v_P^2 \dot{\varepsilon}_{max}}{2\pi l f}$$

- **动载加速度相似比-动力学相似准则(Y-D)系数：** Dynamic load acceleration similarity ratio-dynamic similarity Principle (Y-D) coefficient

$$C_{a_d} = \frac{a_d}{a_{d'}} = C_{v_P}^2 C_{\dot{\varepsilon}} C_l^{-1} C_t = \beta$$

当煤体为静力学状态 Statics， $C_{v_P} = \sqrt{C_l}$ $C_{\dot{\varepsilon}} = \frac{1}{C_t}$， 则 $C_{a_d} = 1$，
符合静力学状态下的加速度相似比。It conforms to the acceleration similarity ratio in the static state.

其中：
a_d--动载加速度；
f —震动频率
σ_d--动载；
$\dot{\varepsilon}$ --动载应变率；
β --动力学相似准则系数

煤岩破坏的动力学相似原理

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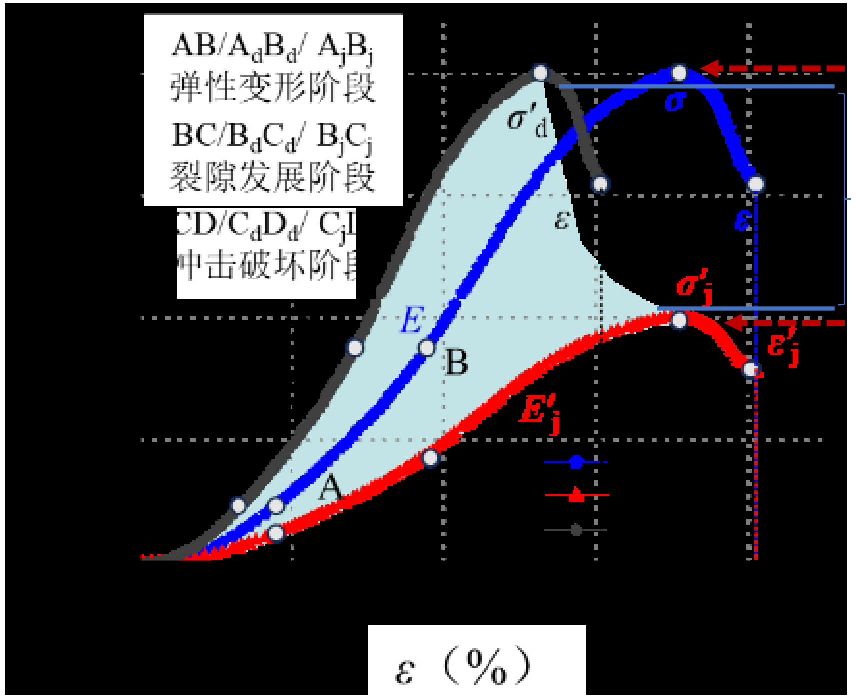
- **煤岩动力学模拟理论：几何相似、运动相似、动力相似、动力学相似。Geometric similarity, kinematic similarity, dynamic similarity，Similarity in dynamics.**

➢ **动力学相似准则系数(Y-D系数)， ratio-kinetic similarity criterion (Y-D) coefficient**

静力学相似 Static Similarity	**几何相似** $C_l = l_N / l_M$	⇨	**动力学相似** Similarity in dynamics	**几何相似** $C_l = l_N / l_M$
	运动相似 $C_t = \sqrt{C_l}$			**运动相似** $C_t = \sqrt{C_l / \beta}$
	动力相似 $C_\sigma = C_\rho \, C_l$			**动力相似** $C_\sigma = \beta C_\rho \, C_l$
				动力学相似



原型

动力学

静力学

式中： C_l --原型与模型长度；l_N--原型广义长度；l_M--模型广义长度；C_t--时间比;C_σ--应力比；C_ρ--密度比

$$C_a = \beta = C_{v_P}^2 C_{\dot{\varepsilon}} C_l^{-1} C_t$$

β <1 动力学相似系数（Y-D数）

β =1 静力学相似系数（弗劳德）

⇨ 静力学状态时 $C_{v_P} = \sqrt{C_l}$

$C_{\dot{\varepsilon}} = \frac{1}{C_t}$，则 $\beta = C_{a_d} = 1$，

煤岩破坏的动力学相似原理
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量纲分析 Dimensional analysis

- **取应力、时间、应变率和弹性模量等作为基础相似准则参数。对煤岩动力学的参数进行量纲分析，并取质量(M)、长度(L)和时间(T)作为特征值。Stress, time, strain rate and elastic modulus are taken as the basic similarity criterion parameters. The parameters of coal and rock dynamics were analyzed dimensionally, and mass (M), length (L) and time (T) were taken as eigenvalues.**

$$f(t,\sigma,E,\dot{\varepsilon} \quad\quad = 0$$

$$\pi = t^{\alpha}\sigma^{\chi}E^{\gamma}\dot{\varepsilon} \quad\quad ,$$

动力学相似准则 Dynamic similarity criterion

$$\pi = \begin{array}{c} \\ \pi_1 \\ \pi_2 \\ \pi_3 \\ \pi_4 \end{array} \left[\begin{array}{ccccccc} M & L & T & t & \sigma & E & \dot{\varepsilon} \\ 0 & 0 & -1 & 1 & 0 & 0 & 0 \\ -1 & 1 & 2 & 0 & 1 & 0 & 0 \\ -1 & 1 & 2 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 \end{array}\right]$$

基础相似准数 Basic similarity parameters

时间 $\pi_1 = \frac{t}{T}$

应力 $\pi_2 = \frac{\sigma}{\rho L^2 T^{-2}}$

刚度 $\pi_3 = \frac{E}{\rho L^2 T^{-2}}$

动力学相似准数 Dynamic similarity parameters

应变率相似准数 $\pi_{\dot{\varepsilon}} = \dot{\varepsilon} T$

动力学相似准数 $\pi_d = \frac{\beta L}{v_P^2 \dot{\varepsilon} T}$

（Y-D数）

煤岩破坏的动力学相似原理
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- **以动力学相似系数(Y-D数) β 为基础，建立了无量纲的动力学相似准数（Y-D数）π_d 和应变率准数 $\pi_{\dot{\varepsilon}}$** Based on the dynamic similarity coefficient (Y-D number) β, the dimensionless dynamic similarity standard (Y-D number) π_d and the strain rate quasi-number $\pi_{\dot{\varepsilon}}$ are established

量纲分析

$$f(t,\sigma,E,\dot{\varepsilon}) = 0$$

$$\pi = t^{\alpha}\sigma^{\chi}E^{\gamma}\dot{\varepsilon}$$

构建π矩阵

$$\pi = \begin{array}{c} \\ \pi_1 \\ \pi_2 \\ \pi_3 \\ \pi_4 \end{array} \begin{bmatrix} M & L & T & t & \sigma & E & \dot{\varepsilon} \\ 0 & 0 & -1 & 1 & 0 & 0 & 0 \\ -1 & 1 & 2 & 0 & 1 & 0 & 0 \\ -1 & 1 & 2 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 \end{bmatrix}$$

基础相似准数

时间 $\pi_1 = \frac{t}{T}$　应力 $\pi_2 = \frac{\sigma}{\rho L^2 T^{-2}}$

刚度 $\pi_3 = \frac{E}{\rho L^2 T^{-2}}$

动力学相似准数

应变率相似准数 $\pi_{\dot{\varepsilon}} = \dot{\varepsilon}T$

$\pi_{\dot{\varepsilon}}$ 表示模型与原型的变形速率保持相似。在动态问题中尤为重要，因为应变率直接影响煤岩体的强度、断裂模式与能量释放行为；

动力学相似准数 $\pi_d = \frac{\beta L}{v_P^2 \dot{\varepsilon} T}$（Y-D数）

π_d 表示，加速度相似性由几何尺度、时间尺度、速度尺度和应变率尺度共同控制，是动力学相似准则区别于传统静力学相似准则的重要特征。

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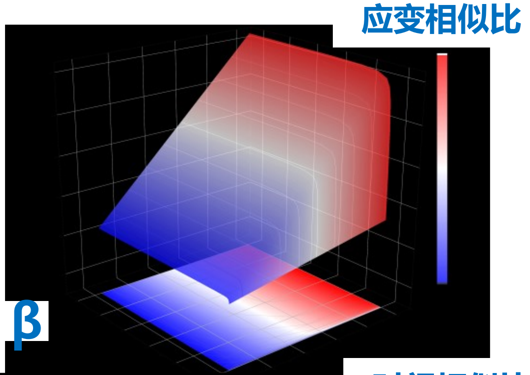
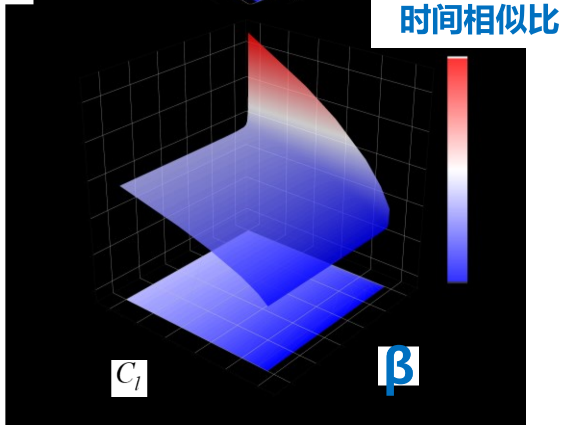
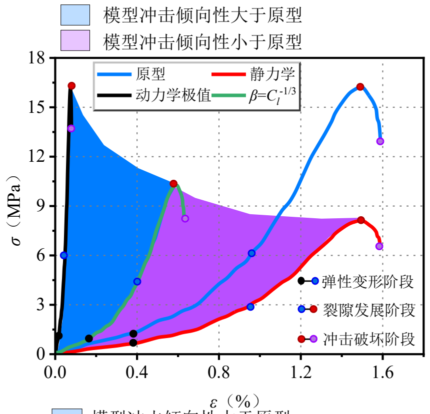
- 动力学相似系数(Y-D系数) *β* 是非线性的；The dynamic similarity coefficient (Y-D coefficient) β is nonlinear $\beta = C_{v_P}^2 C_{\dot{\varepsilon}} C_l^{-1} C_t$
- 与几何比呈负相关，与时间比、应变率比、波速平方比成正相关 It is negatively correlated with the geometric ratio and positively correlated with the time ratio, strain rate ratio, and square wave-velocity ratio.

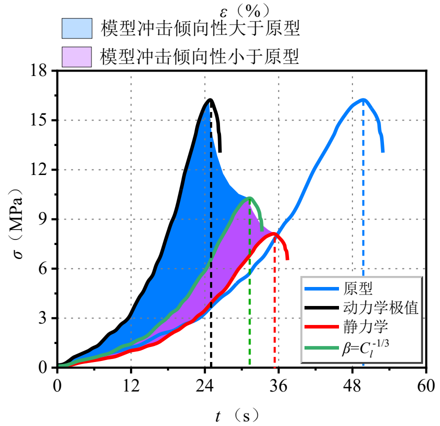




σ-ε



σ-t



动力学曲线介于原型与静力学曲线之间

B 的科学意义

- *B* 突破了传统静力学相似准则体系，可用于定量表征不同动载加载速率、不同输入能量等级下模型与原型的相似程度；
- 通过调节*β*，可以在实验室尺度下实现与原型不同动态强度水平的等效再现，从而为冲击地压等问题的相似模拟提供理论基础

动力学相似准数(Y-D)探讨

Discussion on the Dynamic Similarity Criterion (Y-D)

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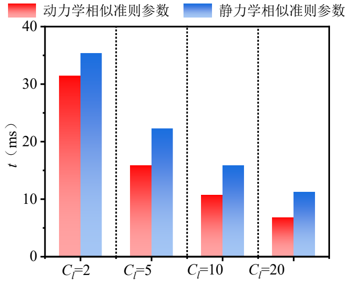
hina University of Mining &Tech

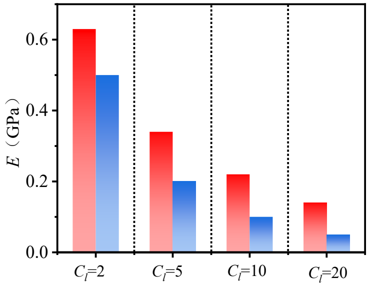
■ **动力学相似准则下模型的应力、弹性模量大于静力学；时间相似比小于静力学。**

Under the dynamic similarity criterion, the stress and elastic modulus of the model are greater than those under static similarity, while the time similarity ratio is smaller.

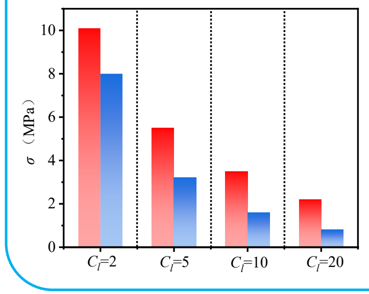
动态破坏时间，ΔT



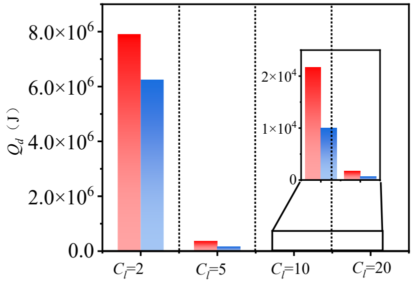
弹性模量，E



单轴抗压强度，Rc



冲击能量，Ke



模型的应力、弹性模量大于静力学；时间相似比小于静力学； The stress and elastic modulus of the model are greater than those of static, but the time similarity ratio is less than that of the statics. **反映出更快的响应过程** Reflects a faster response process.

以C_l=10为例

判别指标	公式	倾向性		
		无	弱	强
弹性能量指数	$W_{ET}=\frac{\Phi_{SE}}{\Phi_{SP}}$	<2	2~5	>5
冲击能量指数	$K_E=\frac{A_s}{A_x}$	<1.5	1.5~5	>5
动态破坏时间	$t'=t\sqrt{C_{a_d}/C_l}$	>105	10.5~105	<10.5
单轴抗压强度	$\sigma'=\frac{\sigma}{C_l C_\rho C_{a_d}}$	< 1.52	1.52 ~ 3.04	> 3.04

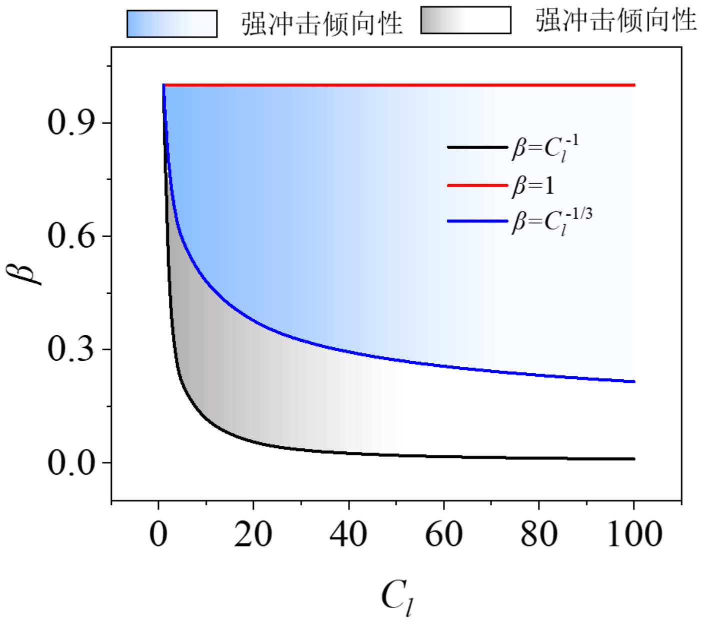
动力学相似准数(Y-D)探讨

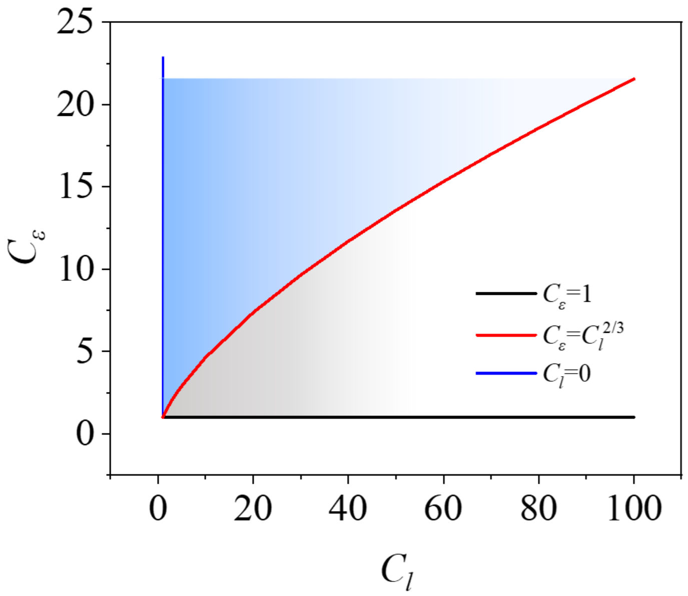
Discussion on the Dynamic Similarity Criterion (Y-D)

□ 动力学相似准则(Y-D)系数与应变相似比范围 The dynamic similarity criterion (Y-D) coefficient and strain similarity ratio range

➢ **图为在不同几何相似比时，动力学状态下的动力学相似准则(Y-D)系数取值范围，应变相似比取值范围。 The figure shows the value range of the dynamic similarity criterion (Y-D) coefficient and the strain similarity ratio under different geometric similarity ratios.**

动力学相似准则系数

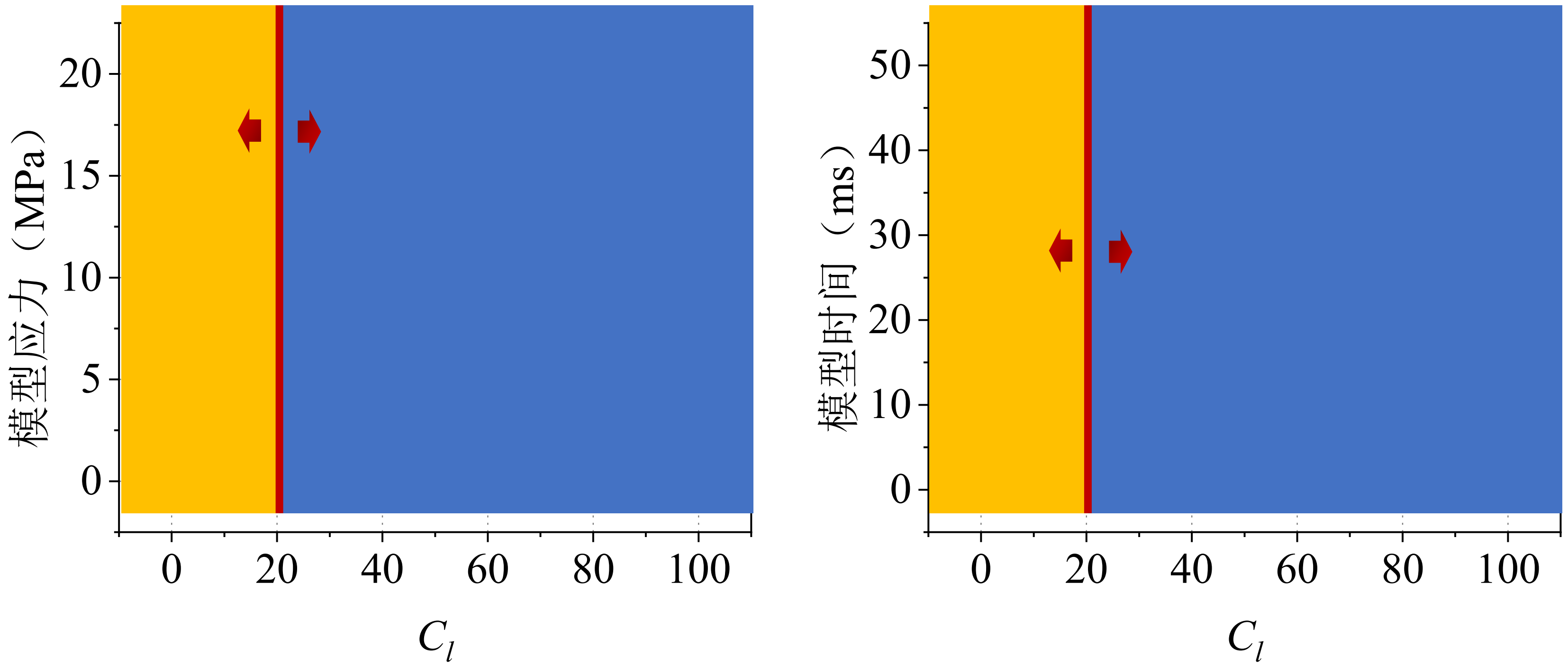




应变相似比

最优几何比的确定 Determination of the optimal geometric ratio

- 对模型曲线求一阶二阶导，得 C_l在20为最优几何相似比 By taking the first and second order derivatives of the model curve, it is determined that C_l at 20 is the optimal geometric similarity ratio.
- 当C_l<20时，模型各参数较大；当C_l >20时，模型参数变化趋势不明显。When C_l < 20, the model parameters are relatively large, when C_l > 20, the trend of change in the model parameters is not significant.

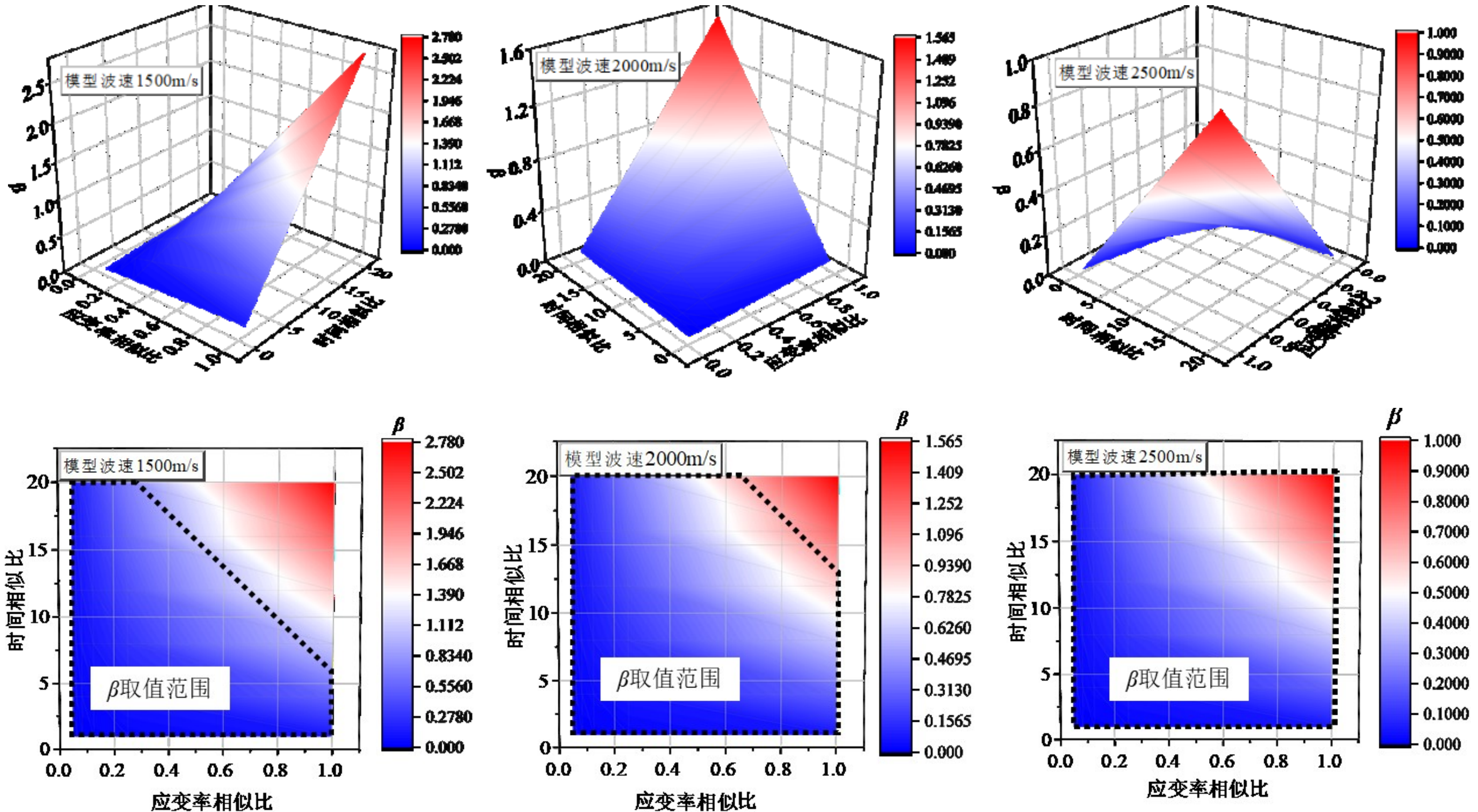


动力学相似准数(Y-D)探讨
Discussion on the Dynamic Similarity Criterion (Y-D)

□ 模型波速的确定 Determination of the model wave velocity

➢ **模型波速1500–2500 m/s，既接近原型波速，又保留一定的参数调节空间。** The model wave velocity of 1500–2500 m/s is close to the prototype wave velocity while retaining a certain degree of parameter adjustment space.

• **模型波速不能超过2500 m/s，在该区间范围内，模型波速越大，β可取值范围越大** The model wave velocity cannot exceed 2500 m/s. Within this range, the larger the model wave velocity, the wider the range of values that β can take.

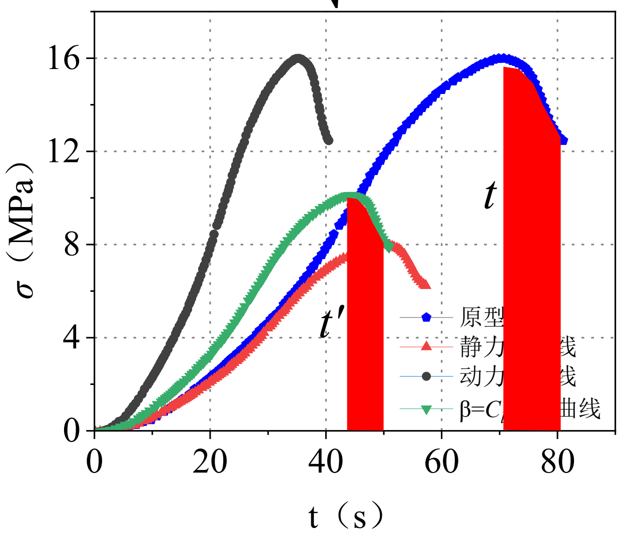


动力学相似准数(Y-D)探讨
Discussion on the Dynamic Similarity Criterion (Y-D)

- **模型的冲击倾向性指标完全符合相似原理下的指标特征 The burst proneness indicators of the model fully conform to the indicator characteristics under the similarity principle.**

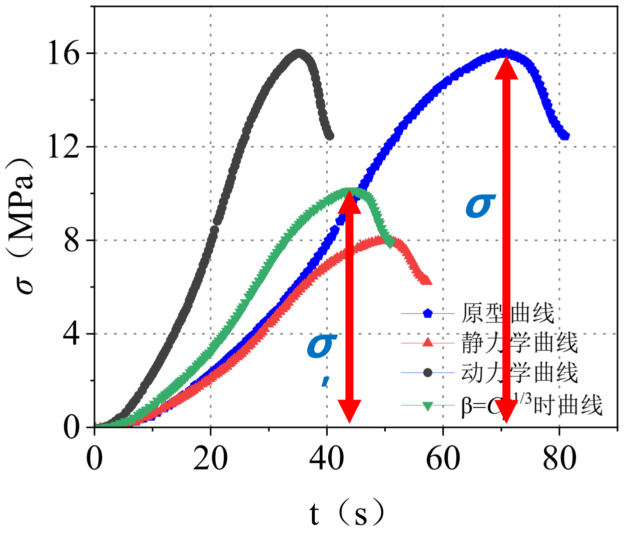
动态破坏时间，ΔT

$$t' = t\sqrt{\frac{C_{a_d}}{C_l}}$$



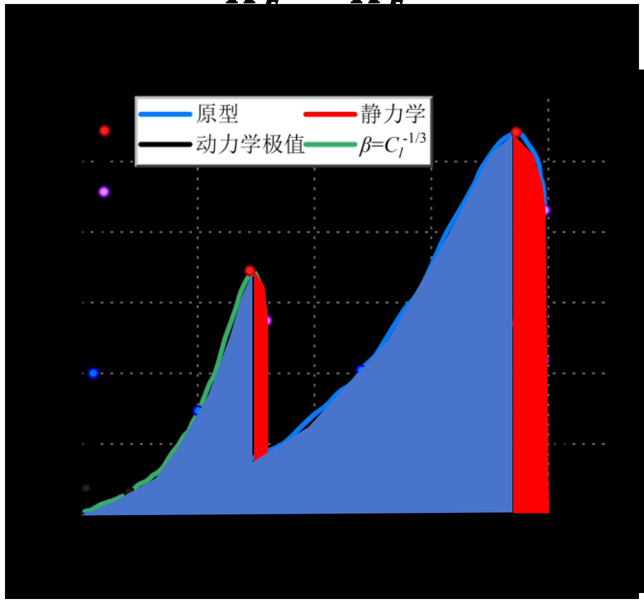
单轴抗压强度、Rc

$$\sigma' = \frac{\sigma}{C_{a_d}C_lC_\rho}$$



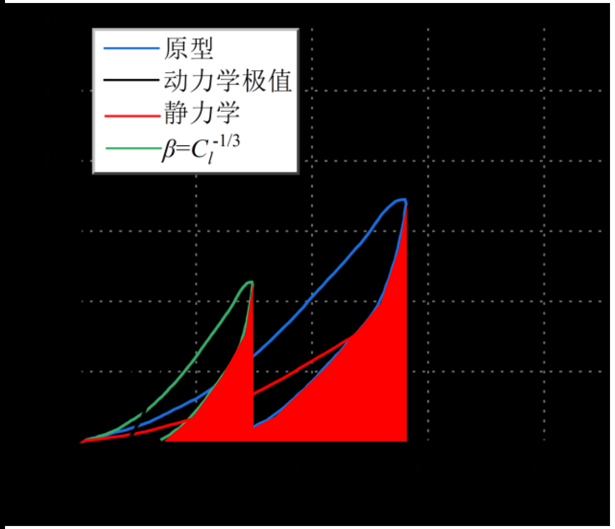
冲击能指数，Ke

$$K_E = K_E'$$



弹性能指数，Wet

$$W_{ET} = W_{ET}'$$



汇 报 提 纲

- 煤岩物理相似模拟研究现状
  Current Status of Coal-Rock Physical Similarity Research
- 煤岩破坏的动力学相似原理
  Dynamic Similarity Principle for Coal Rock Failure
- 动力学相似准数(Y-D)探讨
  Discussion on the Dynamic Similarity Criterion (Y-D)
- 煤岩动力学相似原理的验证
  Verification of Similarity Principle for Coal and Rock Dynamics

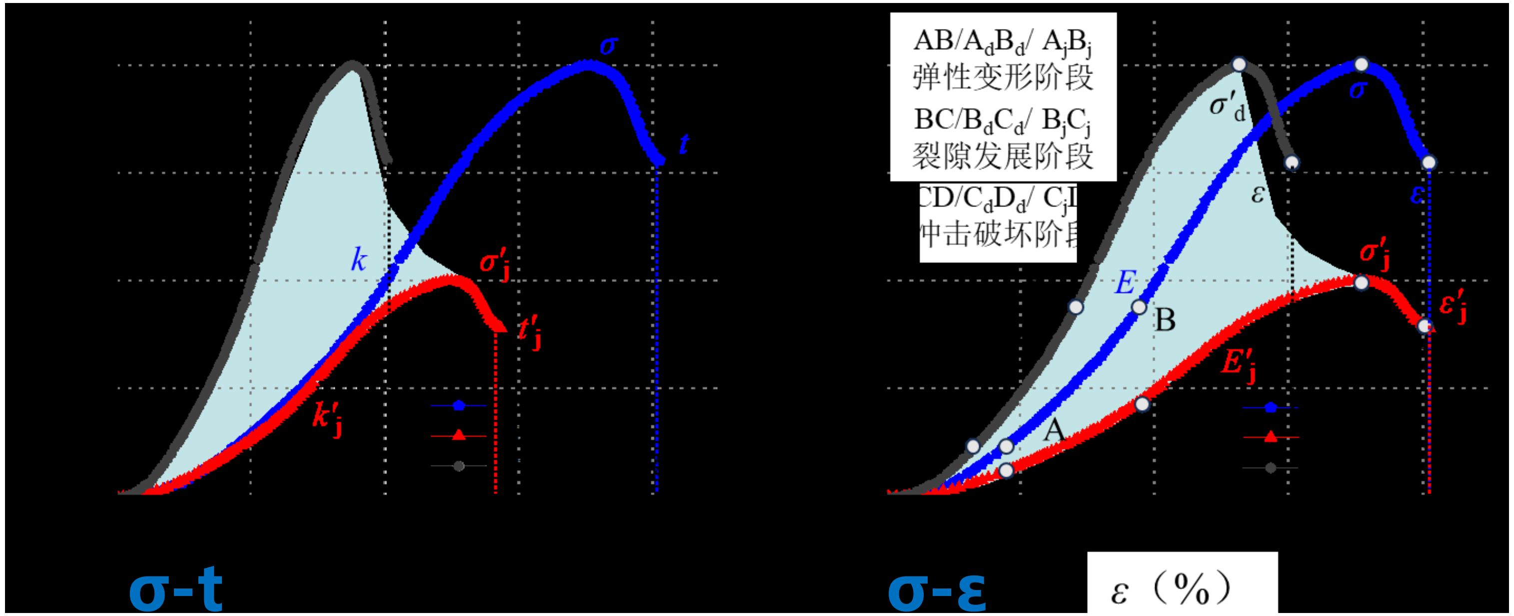
煤岩动力学相似原理的验证

Verification of Similarity Principle for Coal Rock Dynamics

中国矿业大学
hina University of Mining &Tech

地层相似材料的要求 Requirements for similar materials of geological strata

- **材料强度大于静力学要求，小于原型。** The material strength is greater than the static requirement and less than the prototype.
- **材料动态破坏时间小于静力学要求。** The dynamic failure time of the material is less than the static requirements.
- **材料弹性模量大于静力学要求。** The elastic modulus of the material is greater than the static requirement.



$$
\begin{cases}
① & \sigma_j < \sigma_d \le \sigma_y \\
② & t_d < t_j \\
③ & E_j < E_d
\end{cases}
$$

式中：σ_j为静力学强度

σ_d为动力学强度

t_j为静力学时间

t_d为动力学时间

E_j为静力学弹性模量

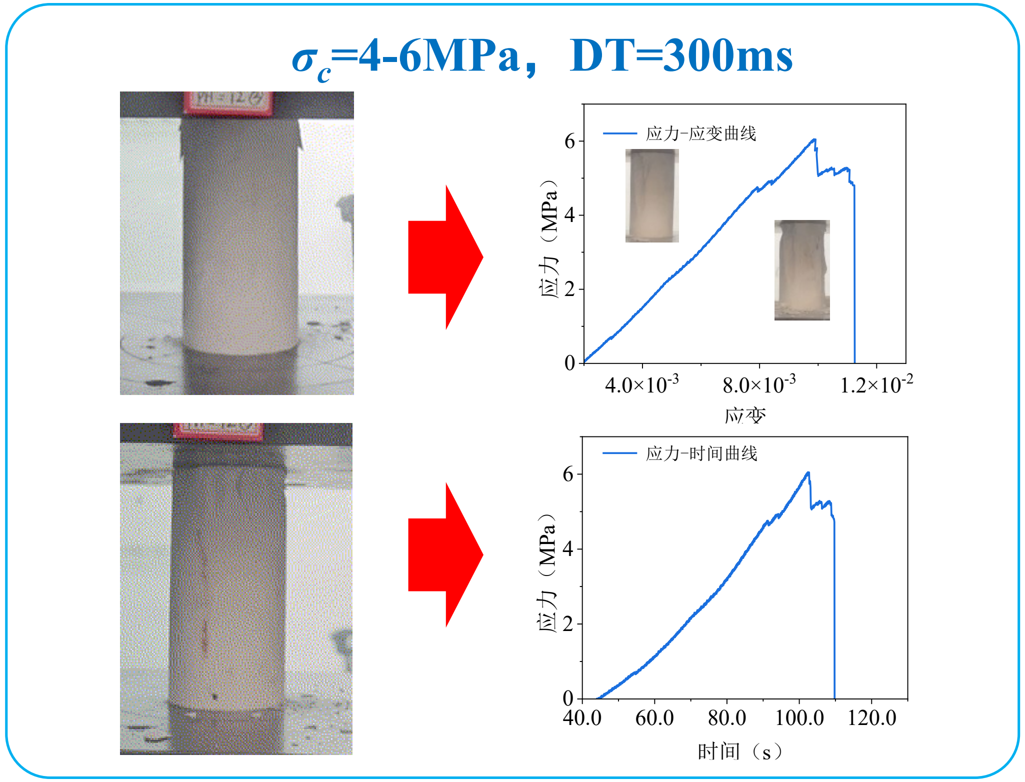
E_d为动力学弹性模量

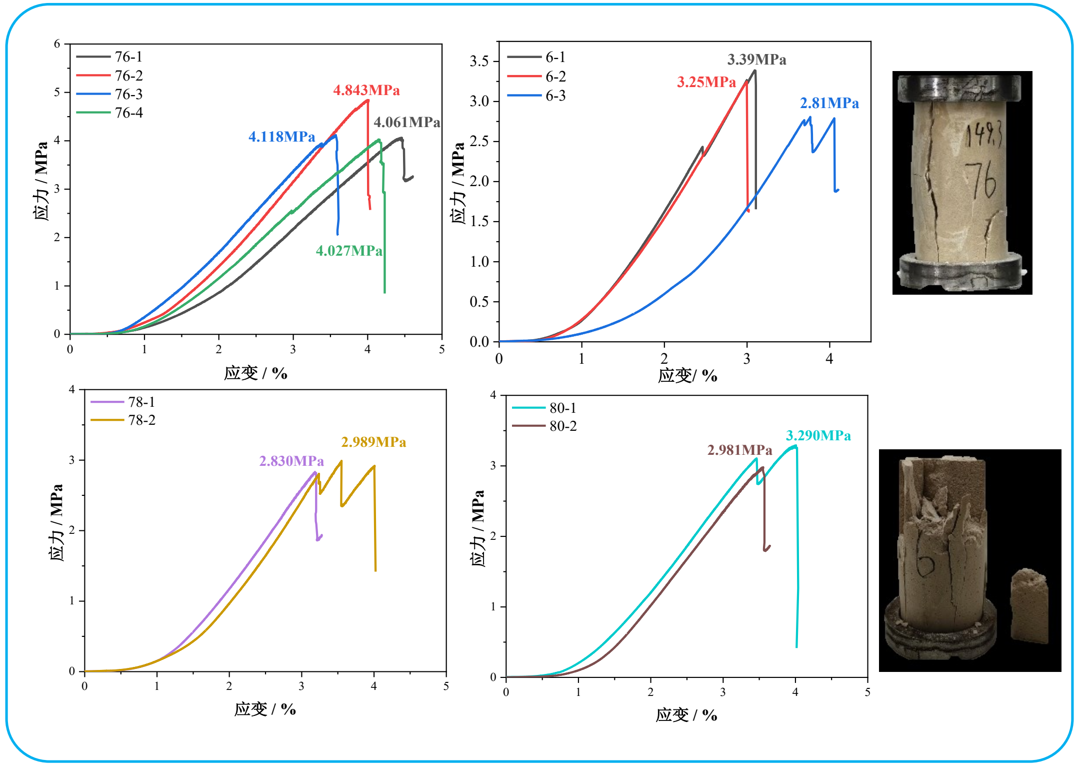
煤岩动力学相似原理的验证

Verification of Similarity Principle for Coal Rock Dynamics

■ 冲击煤岩相似材料 Similar materials for coal burts

- 低强高脆材料，强度、弹性模量等匹配。Low strength and high brittleness materials, matching strength, elastic modulus, etc.
- C_l=20，Rc=3-5MPa，ΔT=200-300ms





煤岩动力学相似原理的验证
Verification of Similarity Principle for Coal Rock Dynamics

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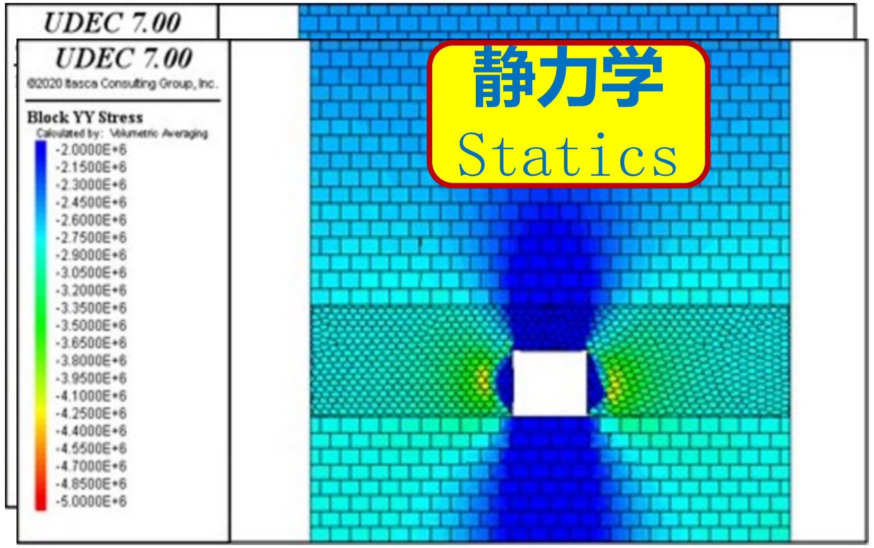
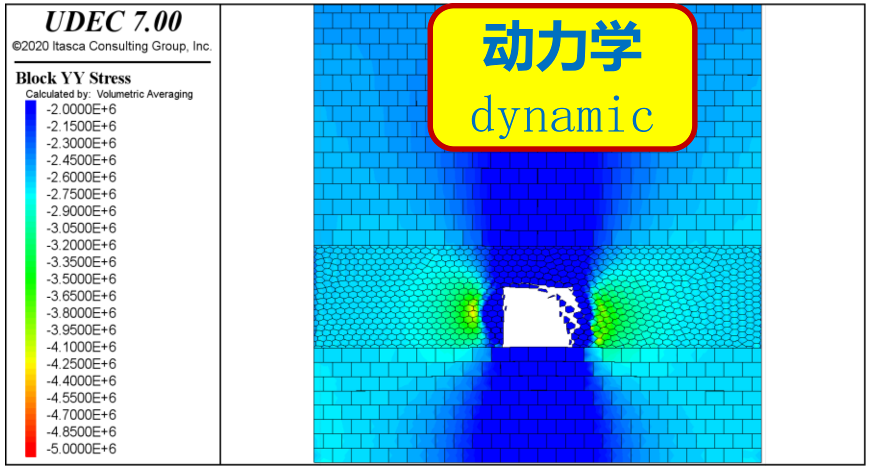
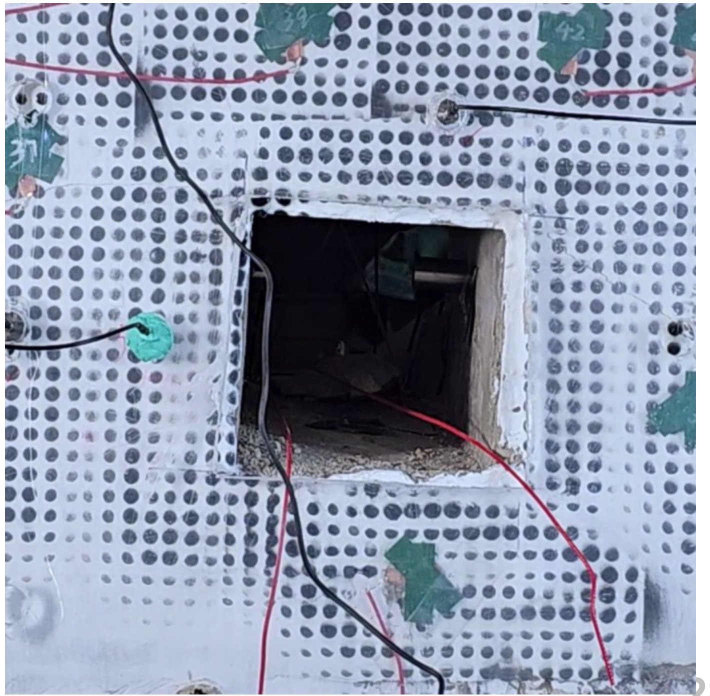
■ 冲击地压的模拟验证 Simulation and verification of coal burst

- **煤柱型和构造型冲击地压数值模拟，验证动力学相似理。**
  Numerical simulation of coal pillar-type and tectonic-type coal bursts to verify the dynamic similarity theory.
- **冲击物理模型试验。**
  Physical model test.





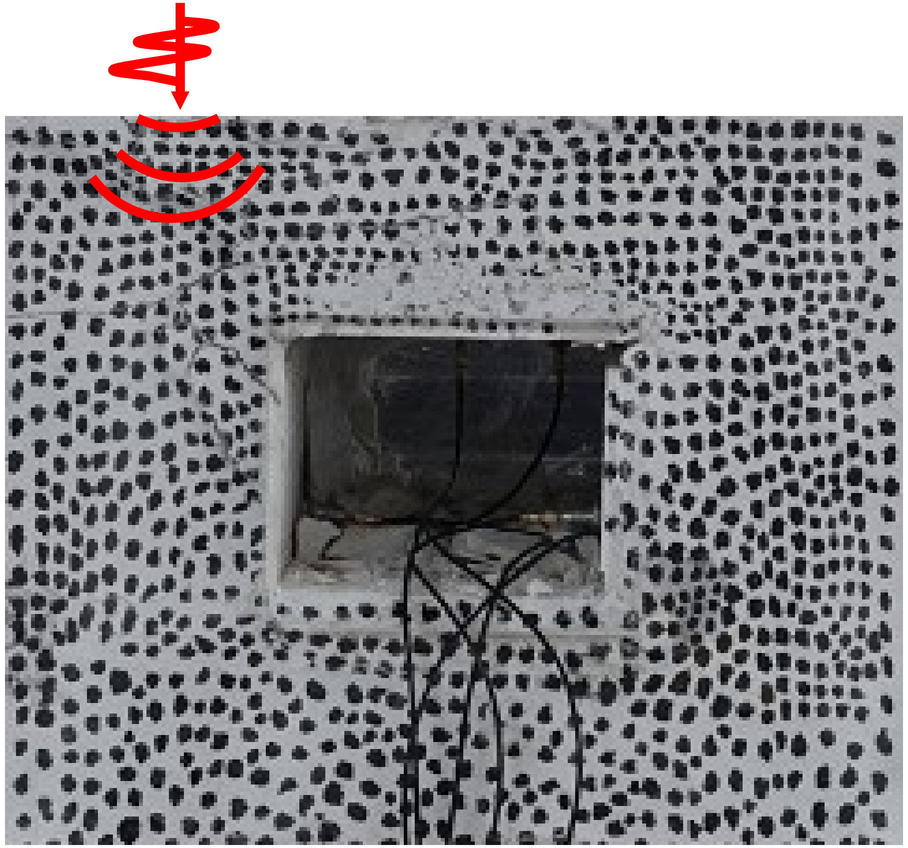
巷道顶板　巷道冲击破坏主视图　巷道底板

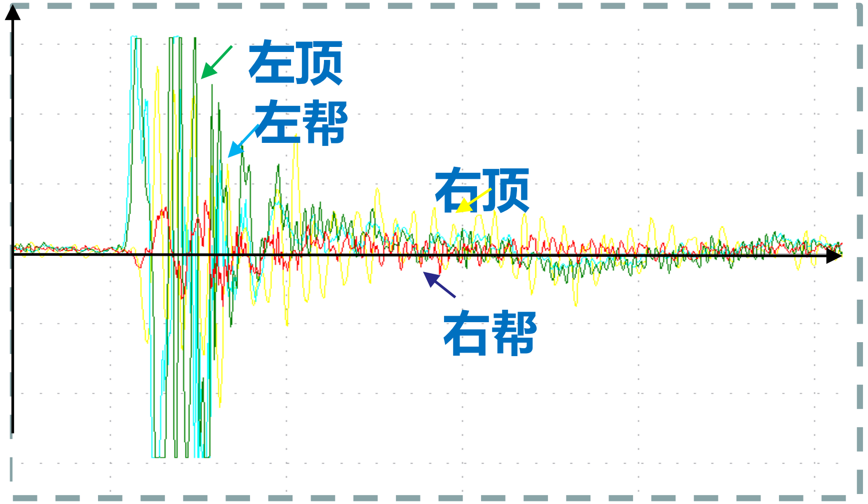


煤岩动力学相似原理的验证
Verification of Similarity Principle for Coal Rock Dynamics

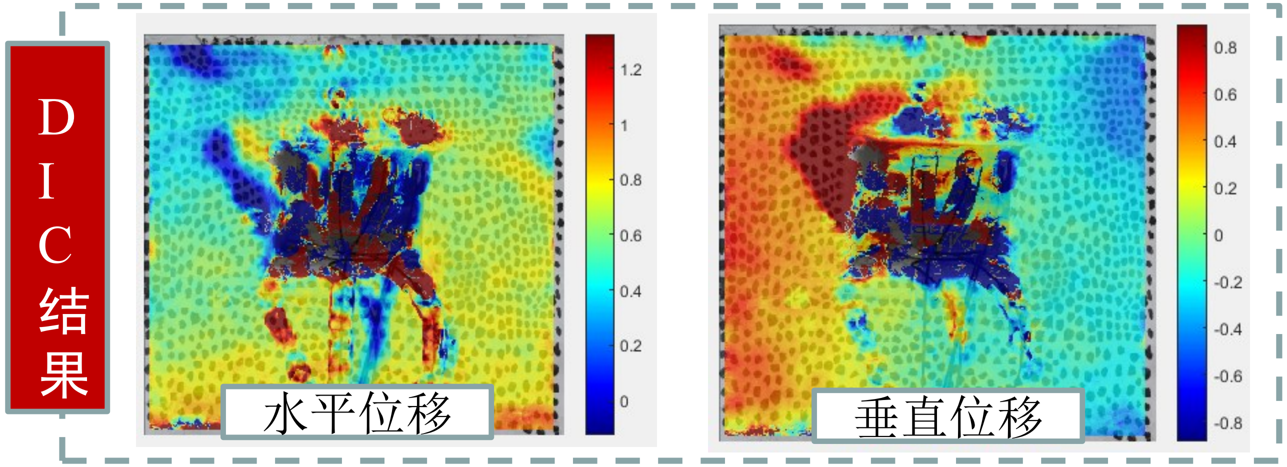
冲击地压特征 Characteristics of coal burst

➢ **左右帮动力显现差异 Differences in dynamic response between the left and right ribs.**





加速度峰值：左顶＞左帮＞右顶＞右帮



水平位移在两帮，垂直位在左帮 **Horizontal displacement occurs at both ribs, while vertical displacement occurs at the left rib**

煤岩动力学相似原理的验证

Verification of Similarity Principle for Coal Rock Dynamics

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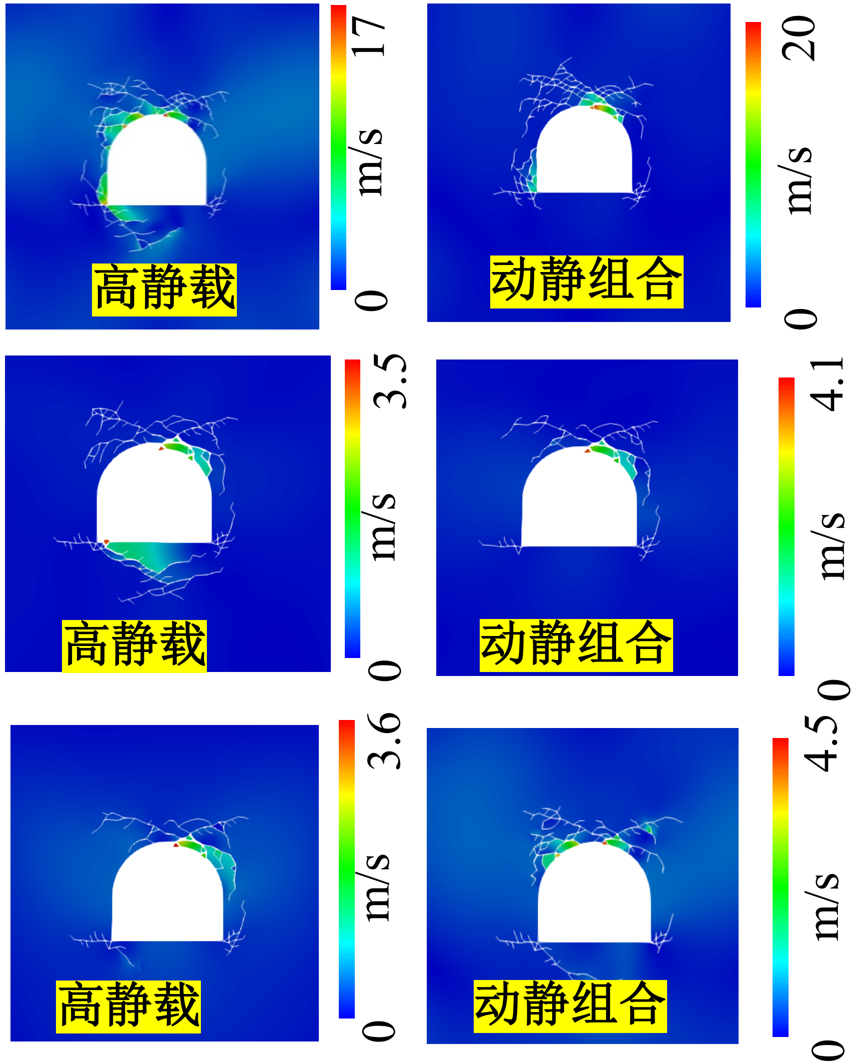
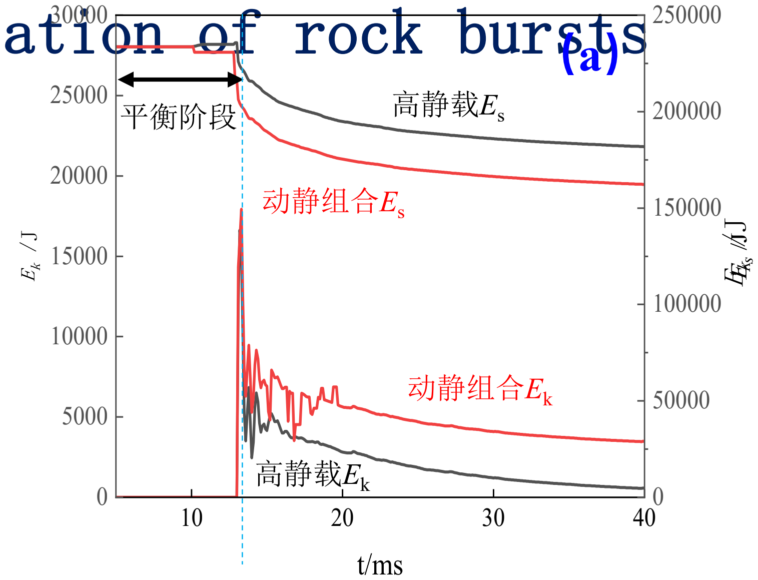
岩爆数值模拟 Numerical simulation of rock bursts

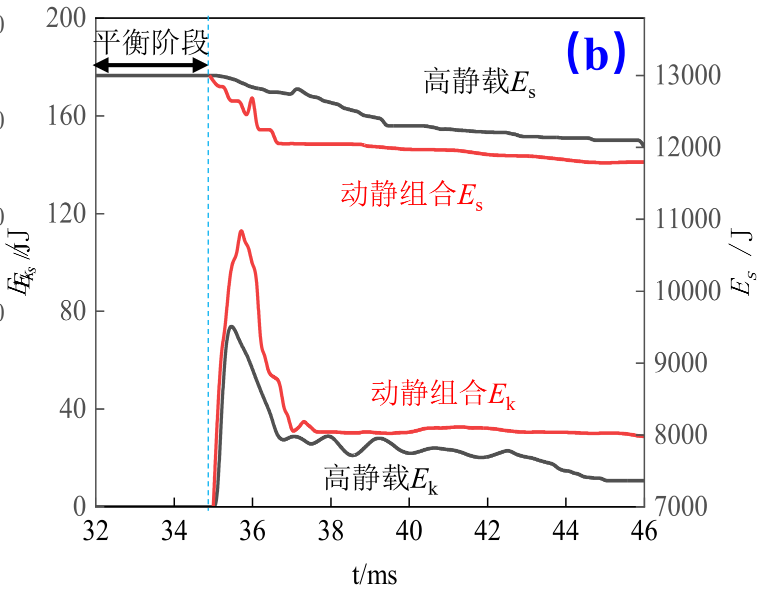
原型

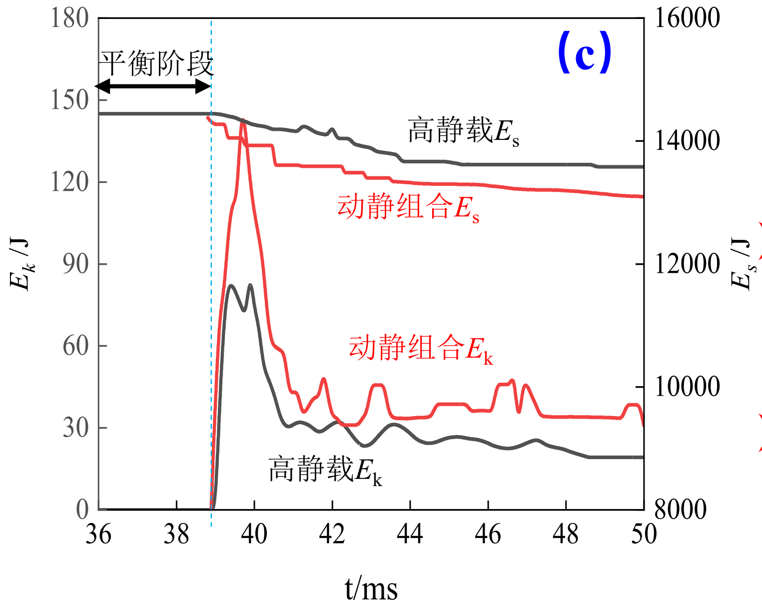
模型 静力学

模型 动力学









应变能和动能曲线：原型（a），静力学（b），动力学（β=0.9）（c）

- 动静载组合作用能量释放大于静载，破碎程度也更高
- 动静载叠加作用下，动力学参数的模拟更准确

煤岩动力学相似原理的验证

Verification of Similarity Principle for Coal Rock Dynamics

最大碎块抛射速度 Maximum fragment ejection velocity

- 根据原型碎块速度计算碎块在静力学相似理论和动力学相似理论下碎块速度，并与模拟值进行比较。The fragment velocities under the static similarity theory and dynamic similarity theory were calculated based on the prototype fragment velocity and then compared with the simulated values.

	碎屑最大速度理论值(m/s)	碎屑最大速度模拟值(m/s)	偏离率λ
原型(高静载)	/	17	
原型（动静叠加）	/	20	
静力学相似（高静载）	3.8	3.5	7.9%
静力学相似（动静叠加）	4.47	4.1	8.3%
动力学相似（高静载）	4.01	3.6	10.2%
动力学相似（动静叠加）	4.71	4.5	4.5%

总 结
Summary

- 煤岩动力学物理模拟相似原理，解决了传统静力学相似准则无法真实模拟冲击地压等动力灾害的局限。
- 以几何、运动、动力和动力学四大相似基础，建立的动力学相似准则与几何比成反比，与应变率、时间和波速比的平方成正比。
- 全面覆盖了模型与原型在空间、运动、受力及动态响应过程的相似性。突破了静力学框架，实现了动力学与静力学相似准则统一。

敬请各位专家批评指正！
Thanks！