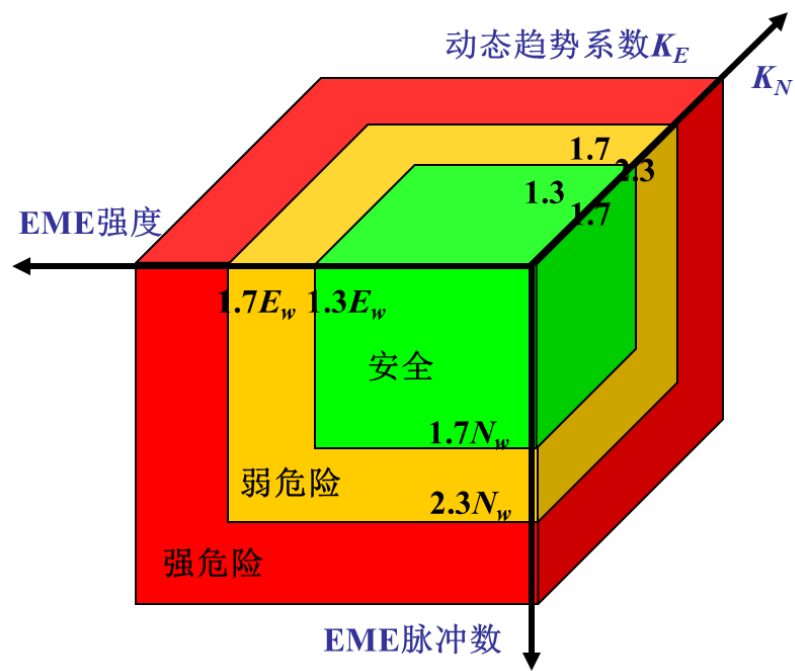


4



- 1) 冲击危险性预测与评价技术
- 2) 冲击危险的电磁辐射监测技术
- 3) 冲击危险监测的地音技术
- 4) 冲击变形能时空监测预警技术
- 5) 区域应力场CT 探测技术
- 6) 冲击危险多参量监测预警技术
- 7) 顺层钻孔高压射流卸压技术
- 8) 顶板高压定向水力致裂技术



1) 冲击危险性预测与评价技术

- 综合指数法
- 多因素耦合分析法
- 应力分析法

1.1) 综合指数法



□ 冲击矿压危险评价的综合指数法（2003）

- 地质因素确定冲击危险：主要考虑了冲击矿压发生的情况、开采深度、地质构造、坚硬顶板、顶板厚度特征参数、煤的冲击倾向性、煤的强度等7个因素。
- 开采因素确定冲击危险：主要考虑了开采技术条件、开采历史、煤柱、停采线、采空区、煤层的变化带、断层皱曲等12个开采因素对冲击矿压发生的影响

$$W_{t1} = \frac{\sum_{i=1}^7 X_i}{\sum_{i=1}^7 X_{i \max}}$$

$$W_{t2} = \frac{\sum_{i=1}^{12} X_i}{\sum_{i=1}^{12} X_{i \max}}$$

1.2) 多因素耦合分析法

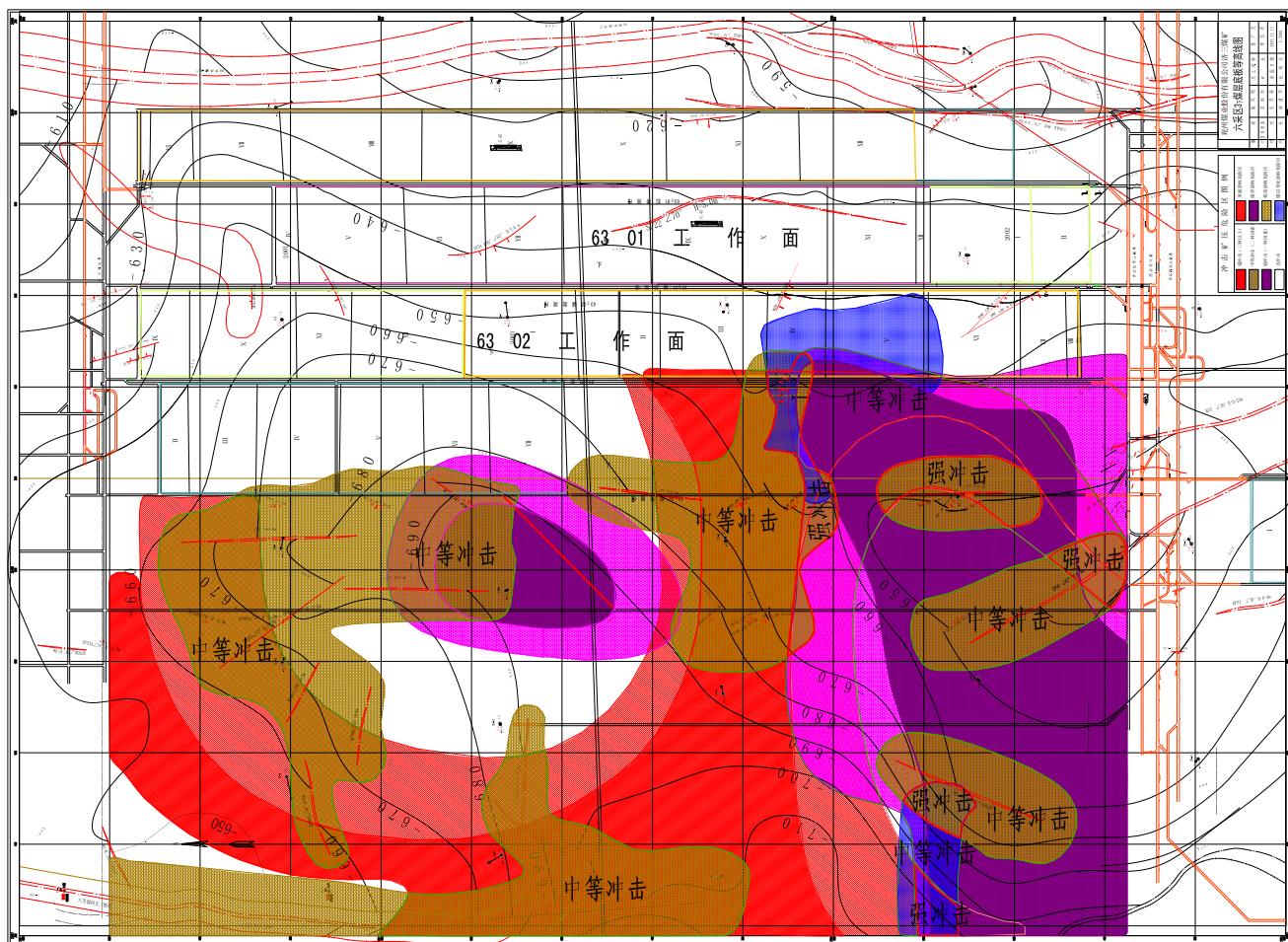


State Key Laboratory
of Coal Resources and Safe M



□ 多因素耦合分析法

济三煤矿六采区冲击矿压危险区域分布



编号	影响因素
W_1	落差大于3m、小于10m的断层区域
W_2	倾角变化($>15^\circ$)褶曲区域
W_3	煤层侵蚀、合层或厚度变化区域
W_4	顶底板岩性变化区域
W_5	上保护层开采遗留的煤柱下方区域
W_6	落差大于10m的断层或断层群区域
W_7	向采空区推进的工作面
W_8	不规则采面或多个采面开切眼、停采线不齐区域
W_9	巷道交叉区域
W_{10}	沿空巷道煤柱
W_{11}	工作面超前支承压力区
W_{12}	老顶初次来压
W_{13}	工作面采空区“见方”区域
W_{14}	留底煤区域
W_{15}	采掘扰动区域

1.3) 应力分析法



State Key Laboratory
of Coal Resources and Safe M



□ 相对应力集中系数叠加法

影响冲击矿压发生的某因素引起的最大主应力与自重应力的比值，称为相对应力集中系数分量，用 δ_{ij} 表示。各分量的乘积为该区域的相对应力集中系数，记为 δ_i

危险等级	Rc<16MPa 判据	Rc<20MPa 判据
无冲击危险	$\delta_i < \frac{R_c}{\sigma_0}$	$\delta_i < \frac{R_c}{\sigma_0}$
弱冲击危险	$\frac{R_c}{\sigma_0} < \delta_i < \frac{70}{\sigma_0}$	$\frac{R_c}{\sigma_0} < \delta_i < \frac{50}{\sigma_0}$
中等冲击危险	$\frac{70}{\sigma_0} < \delta_i < \frac{90}{\sigma_0}$	$\frac{50}{\sigma_0} < \delta_i < \frac{70}{\sigma_0}$
强冲击危险	$\delta_i > \frac{90}{\sigma_0}$	$\delta_i > \frac{70}{\sigma_0}$

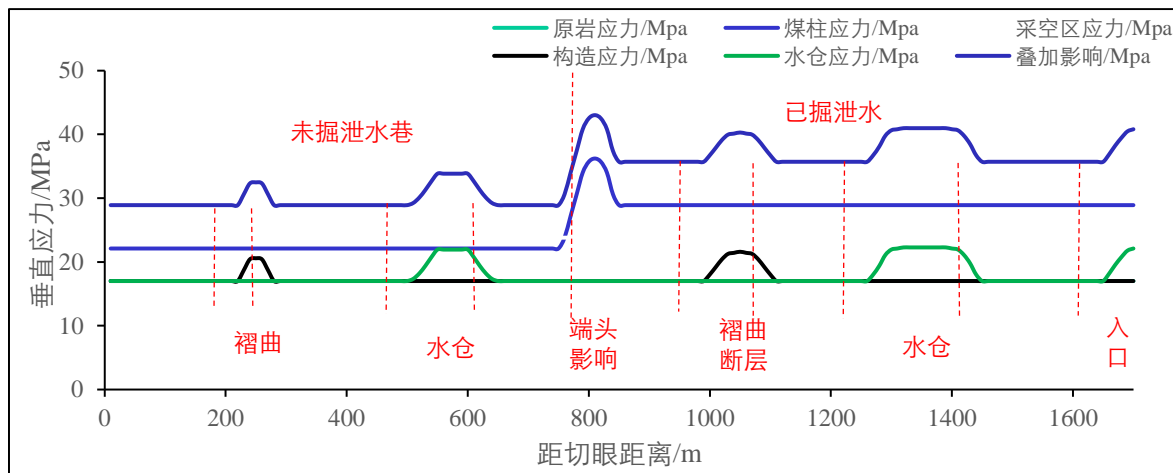
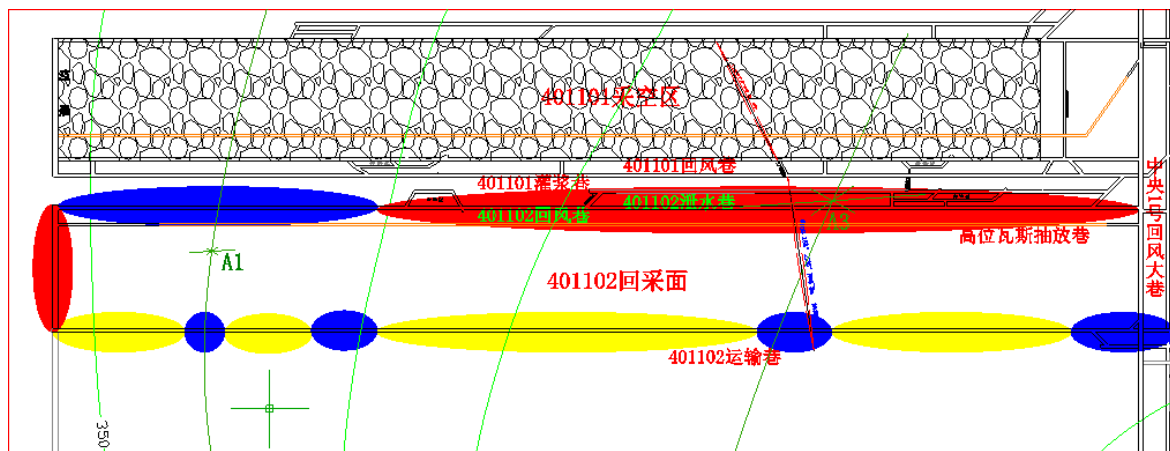
1.3) 应力分析法



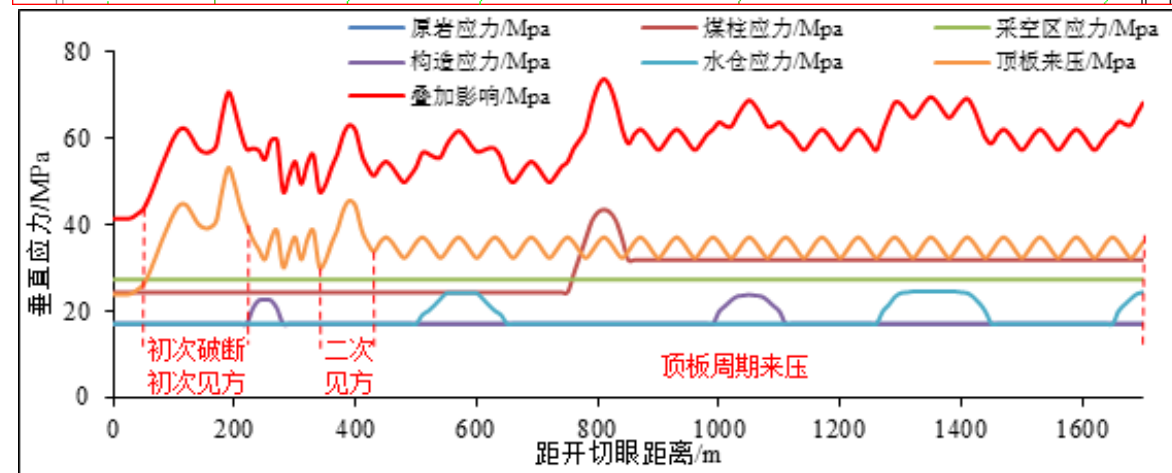
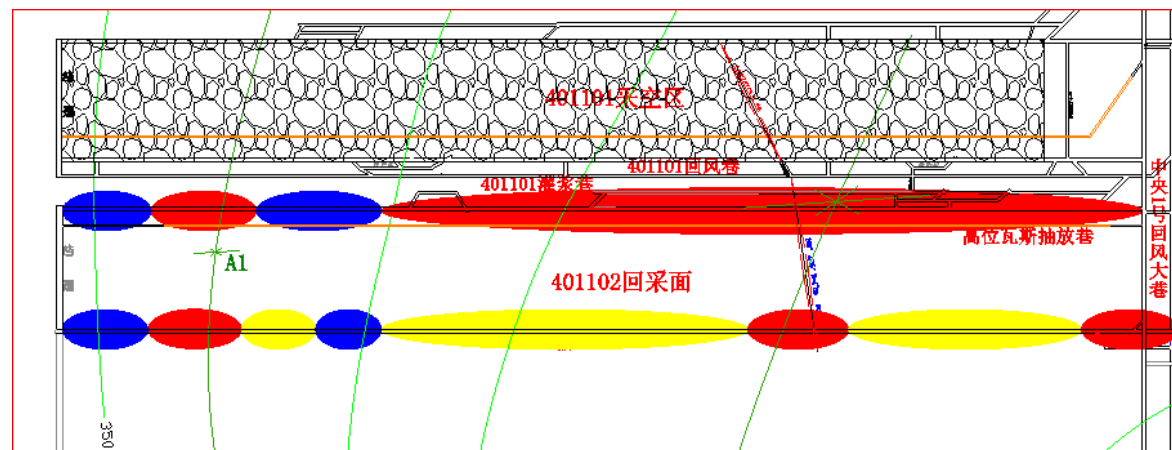
State Key Laboratory of Coal Resources and Safe M



□ 应力分析法 (2011)



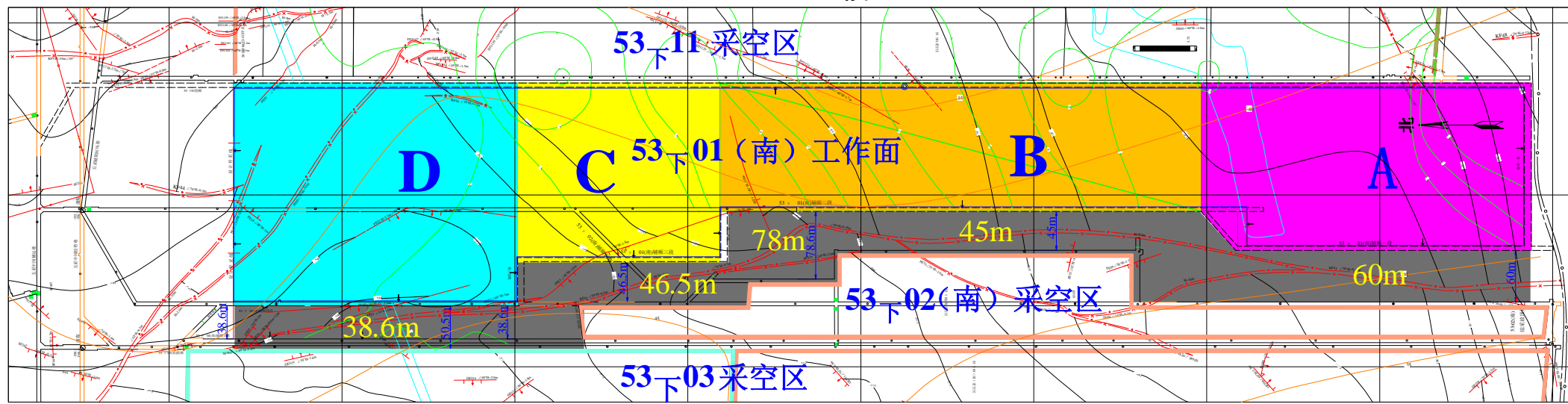
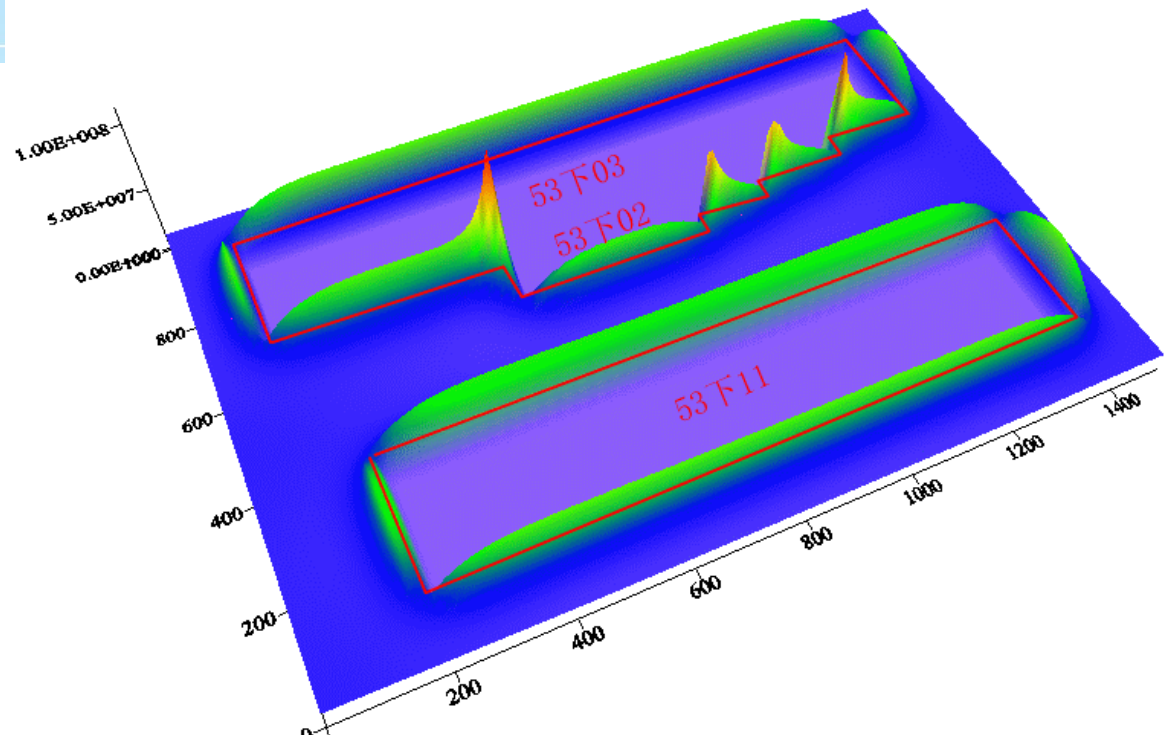
掘进期间主控因素及应力叠加法



回采期间主控因素及应力叠加法

1.3) 应力分析法

□ 应力分析法





2) 冲击危险的电磁辐射监测技术

- 力-电磁辐射耦合模型
- 冲击危险预警准则
- 电磁辐射监测预警技术

2.1) 力-电耦合模型

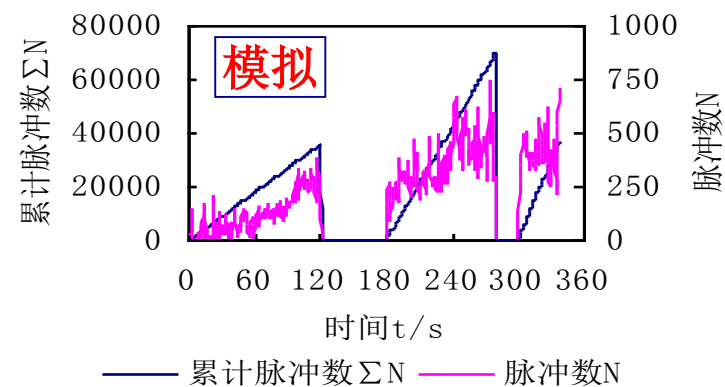
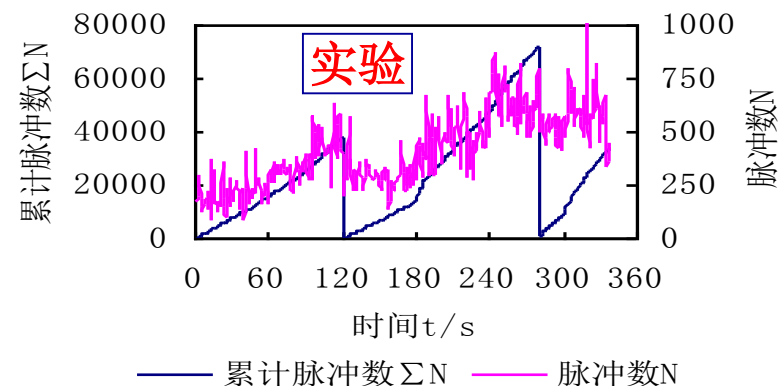
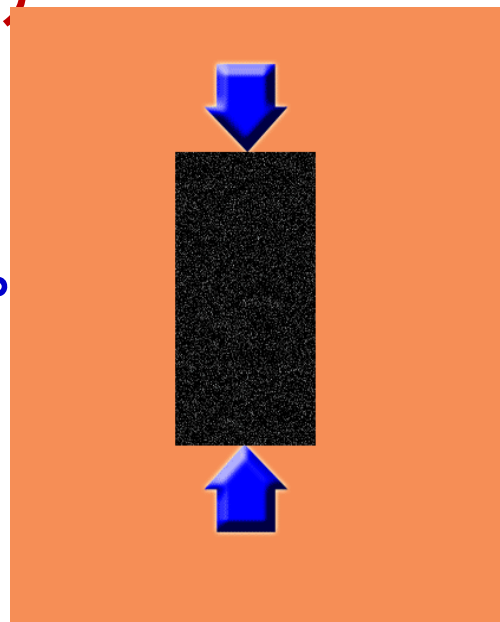


State Key Laboratory
of Coal Resources and Safe M



电磁辐射监测预警技术 (2000)

- 煤岩流变-突变过程产生电磁辐射，是能量耗散的一种形式。
- 煤岩体的变形破裂是电磁辐射产生的根本原因。



$$\Delta N = N_m \cdot \frac{m}{\sigma_0} \left(\frac{\sigma_1 - \sigma_3}{2} \right)^{m-1} \exp \left[- \left(\frac{\sigma_1 - \sigma_3}{2} \right)^m \right] \cdot \Delta \sigma$$

$$\frac{\sum N}{N_m} = 1 - \exp \left(- \left(\frac{\varepsilon}{\varepsilon_0} \right)^m \right)$$

式中， ε —应变； σ_1, σ_3 —轴向应力和环向应力； m, ε_0 —Weibull分布的分布标度和以应变形式表征的形态参数； $\Delta N, \sum N$ —电磁辐射脉冲数增量和累计脉冲数； N_m —完全破坏的电磁辐射累计脉冲数。

2.2) 冲击危险预警准则



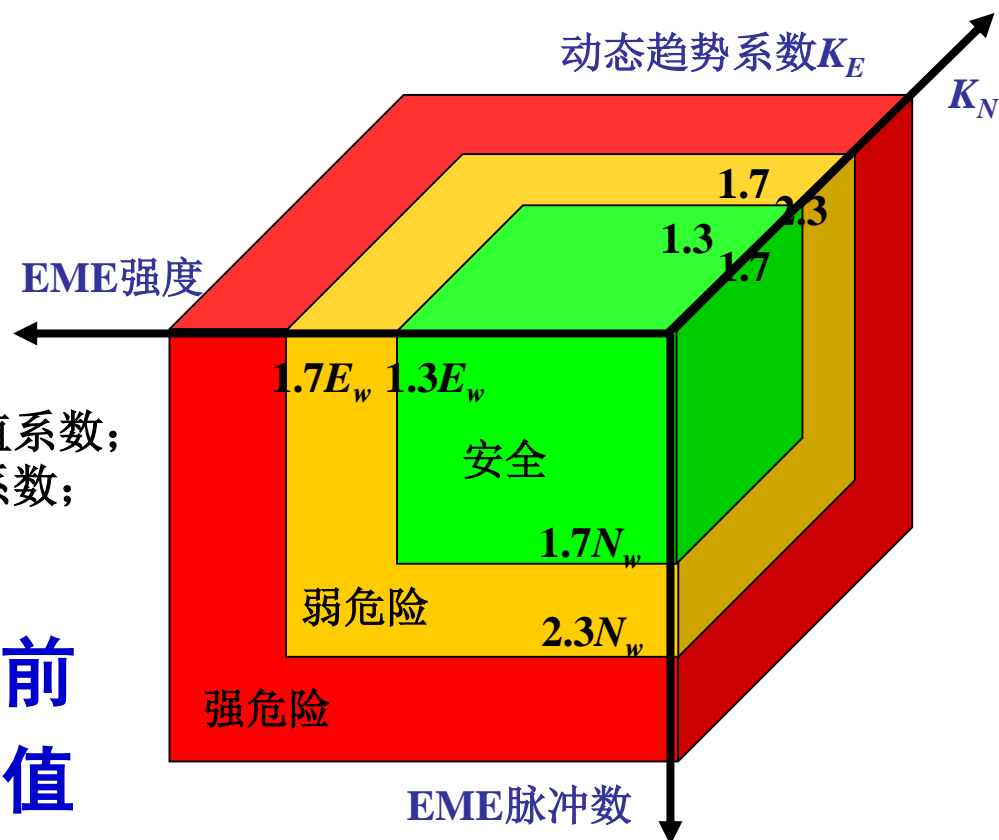
- 由煤岩动力灾害过程的电磁辐射规律建立了煤岩动力灾害危险性的电磁辐射预测准则：

$$K_{Nr} = \frac{\Delta N_r / \Delta \sigma_r}{\Delta N_w / \Delta \sigma_w} = \left(\frac{\sigma_r}{\sigma_w} \right)^{m-1} \exp \left[\left(\frac{\sigma_w}{\sigma_0} \right)^m - \left(\frac{\sigma_r}{\sigma_0} \right)^m \right]$$

$$K_{Nq} = \frac{\Delta N_q / \Delta \sigma_q}{\Delta N_w / \Delta \sigma_w} = \left(\frac{\sigma_q}{\sigma_w} \right)^{m-1} \exp \left[\left(\frac{\sigma_w}{\sigma_0} \right)^m - \left(\frac{\sigma_q}{\sigma_0} \right)^m \right]$$

式中， K_{Nr} 和 K_{Nq} 分别为有弱危险和强危险时电磁辐射脉冲数的临界值系数；
 K_{Er} 和 K_{Eq} 分别为有弱危险和强危险时的电磁辐射强度临界值系数；
 E 为电磁辐射强度； N 为电磁辐射脉冲数； σ 为应力。

- 电磁辐射的强度、脉冲数是煤岩动力灾害前兆的敏感指标，其大小和变化率超过临界值就有煤岩动力灾害危险。



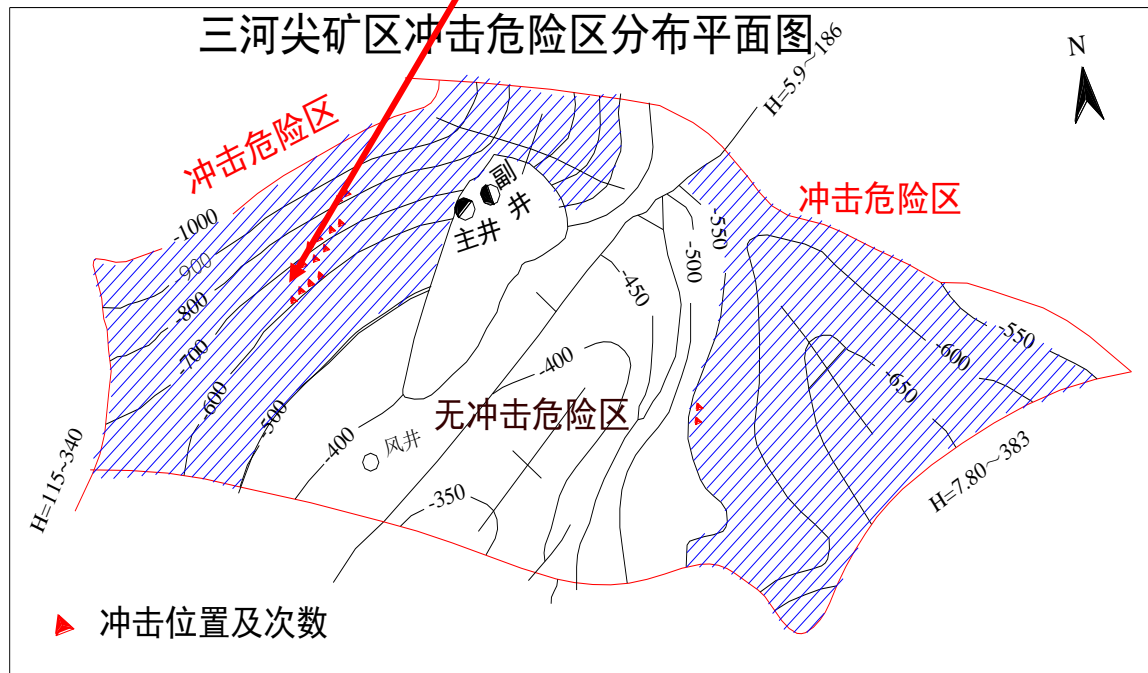
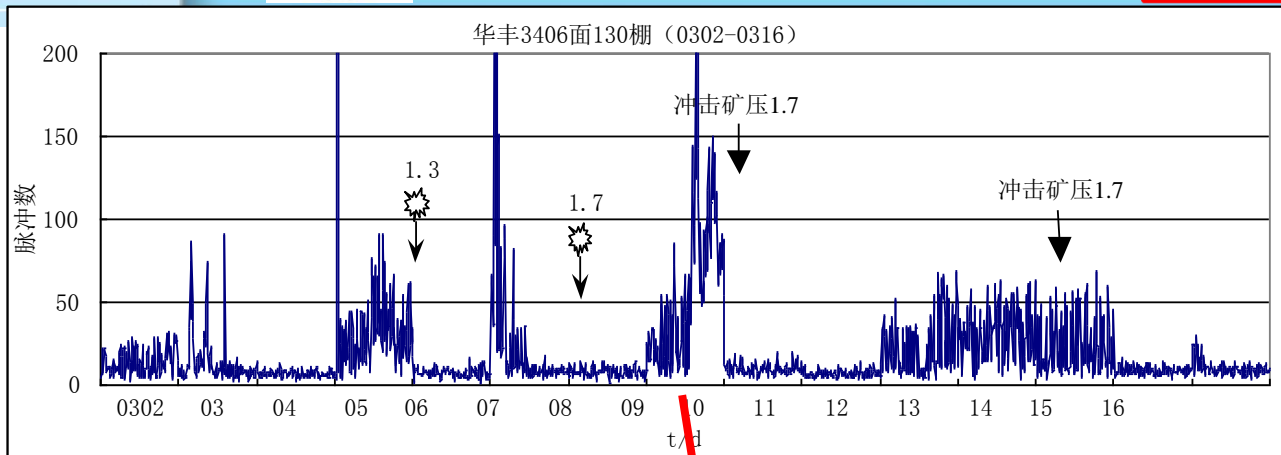
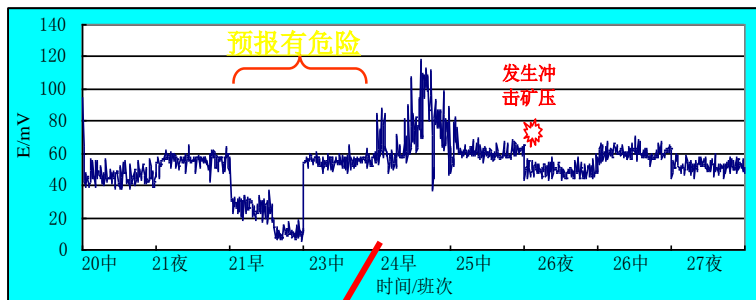
2.3) 电磁辐射监测预警技术



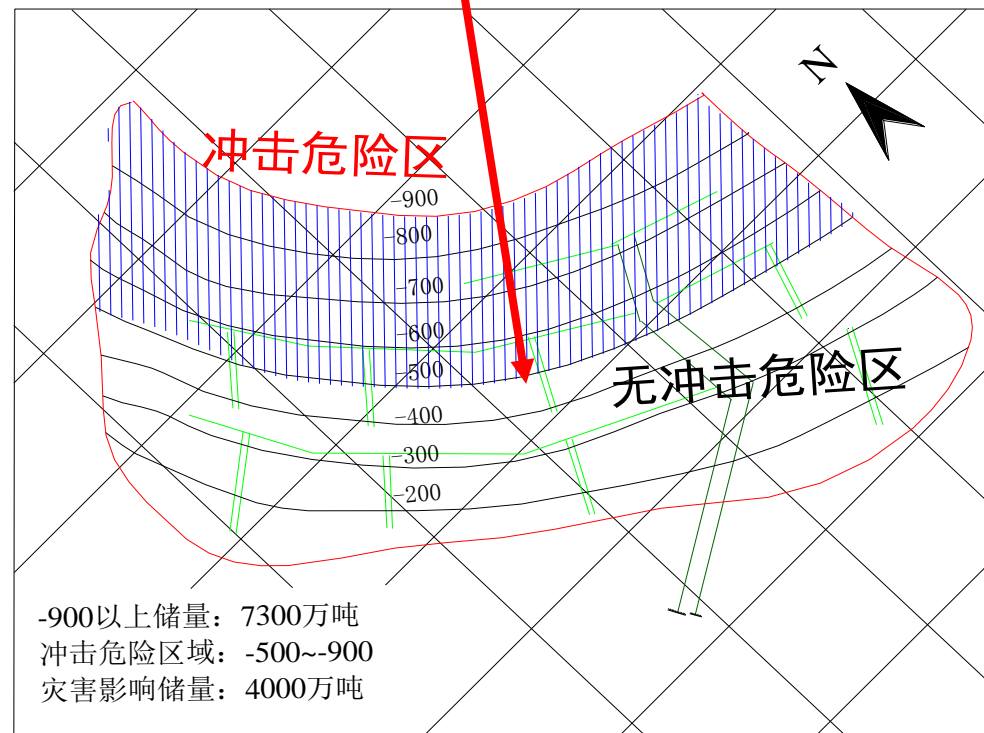
State Key Laboratory of Coal Resources and Safe M



电磁辐射监测预警技术 (2000)



华丰矿区冲击危险区分布平面图

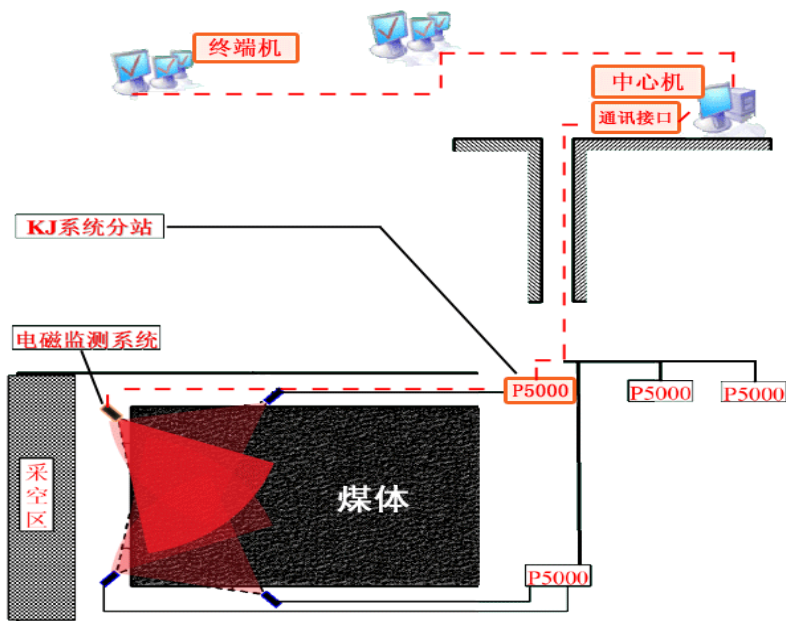
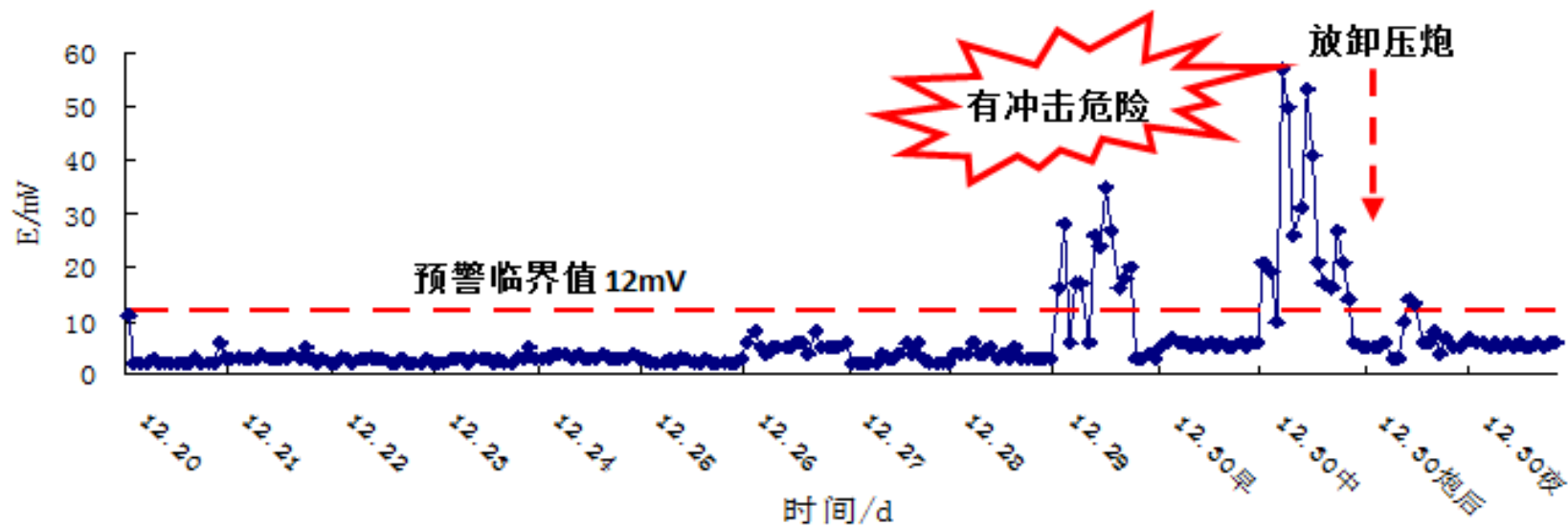
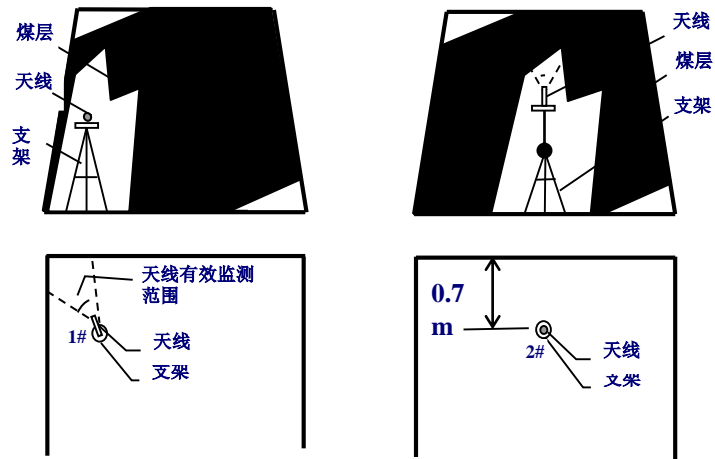


国家科技进步二等奖 (2006)

2.3) 电磁辐射监测预警技术



State Key Laboratory of Coal Resources and Safe M





3) 冲击危险监测的地音技术

- 地音监测原理
- 冲击危险地音监测指标
- 地音监测预警技术

3.1) 地音监测原理



□ 煤岩变形与声发射的关系

$$\varepsilon(t) = \varepsilon_0 + C_a W(t)$$

$W(t)$ 为与岩石微破坏有关的地音事件总能量

地音变化率 $-1 \leq d = \frac{E - \bar{E}}{\bar{E}}$

冲击危险性 $\bar{Z}(t) = \bar{Z}_0 + \sum F_1(\bar{d}(t))$

- 正常情况下，采掘面匀速推进，则煤体破坏的顶板运动产生的地音（声发射）值是一个稳定值；
- 地音小的变化，说明煤岩体破裂的程度有个小的变化；
- 地音的较大变化和较长的持续时间，说明煤岩体破裂的急剧变化，预示着冲击危险性的变化。这就是连续声发射监测法的基础。

3.2) 地音监测指标



CISM

State Key Laboratory
of Coal Resources and Safe M



□ 冲击危险地音监测指标——八个指标

- 采煤班的班平均事件数
- 非采煤班的班平均事件数
- 采煤时间的每小时平均事件数
- 非采煤时间的每小时平均事件数
- 采煤班的班平均地音强度
- 非采煤班的班平均地音强度
- 采煤时间的每小时平均地音强度
- 非采煤时间的每小时平均地音强度

变化率

$$d = \frac{N - \bar{N}_{wt}}{\bar{N}_{wt}} \times 100\%$$

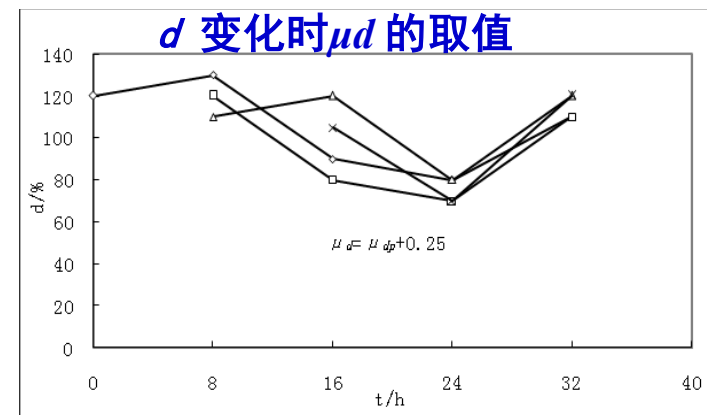
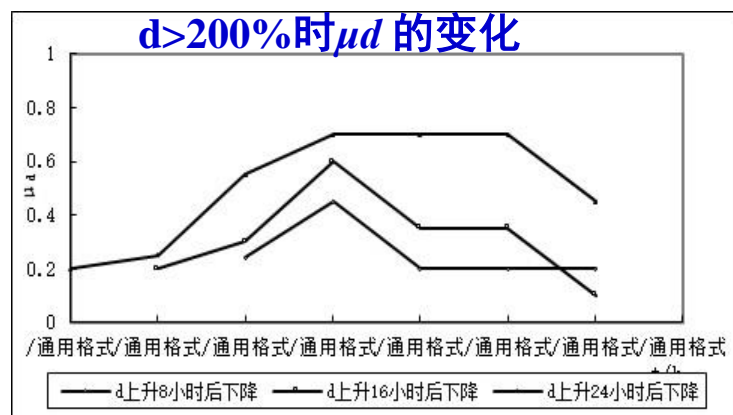
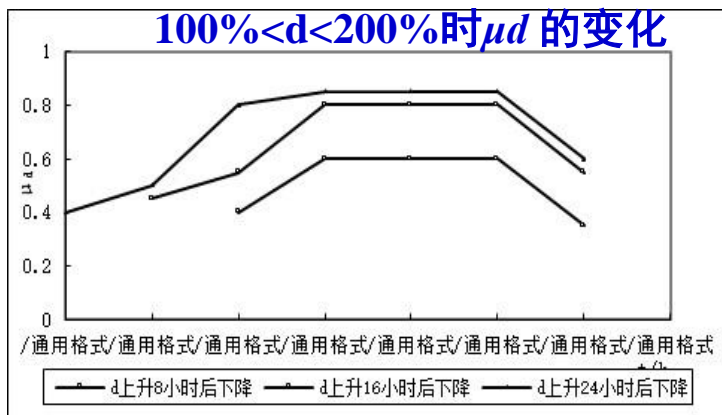
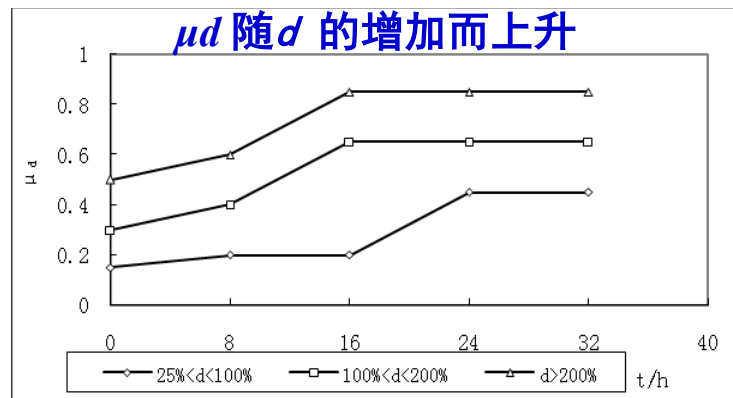
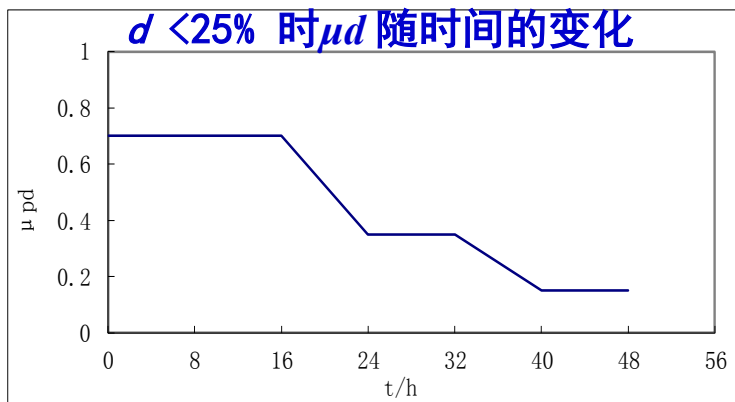
3.3) 地音监测预警技术



以班来判别准则

$$\mu_{d0} = \begin{cases} 0 & d < 0 \\ 0.25d & 0 \leq d < 400\% \\ 1 & d \geq 400\% \end{cases}$$

- μ_{d0} 为以本班数据为基础确定的危险状态;
- d 为地音事件数或地音强度的变化率。



3.3) 地音监测预警技术



State Key Laboratory of Coal Resources and Safe M



以小时判别准则—— $d > 100\%$

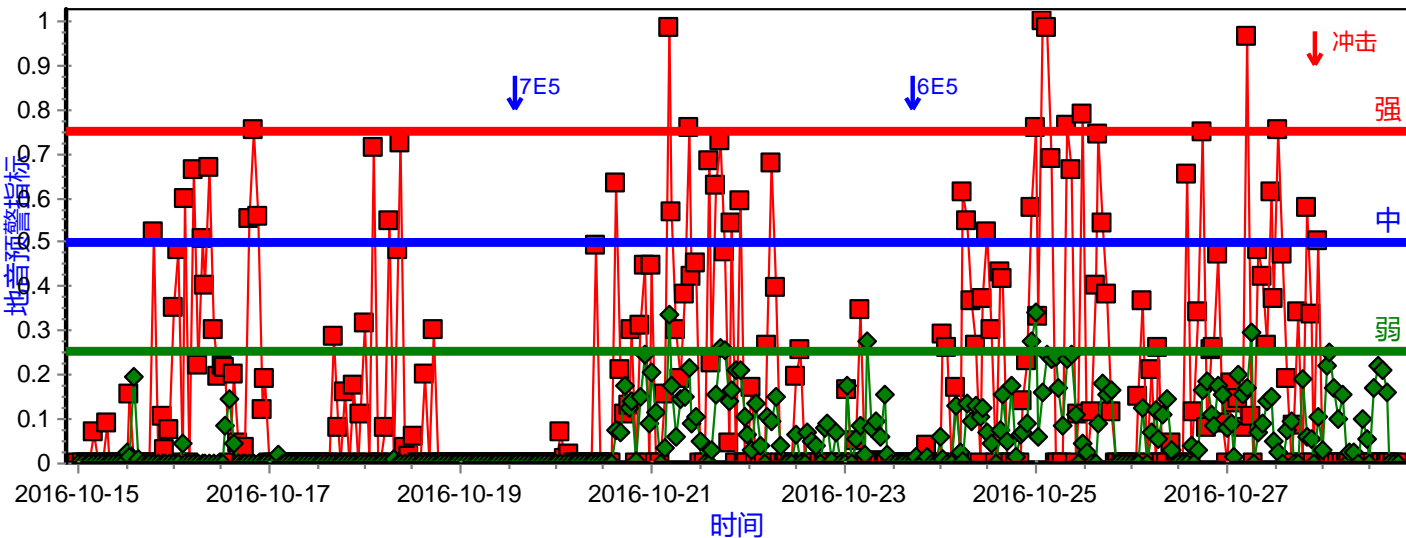
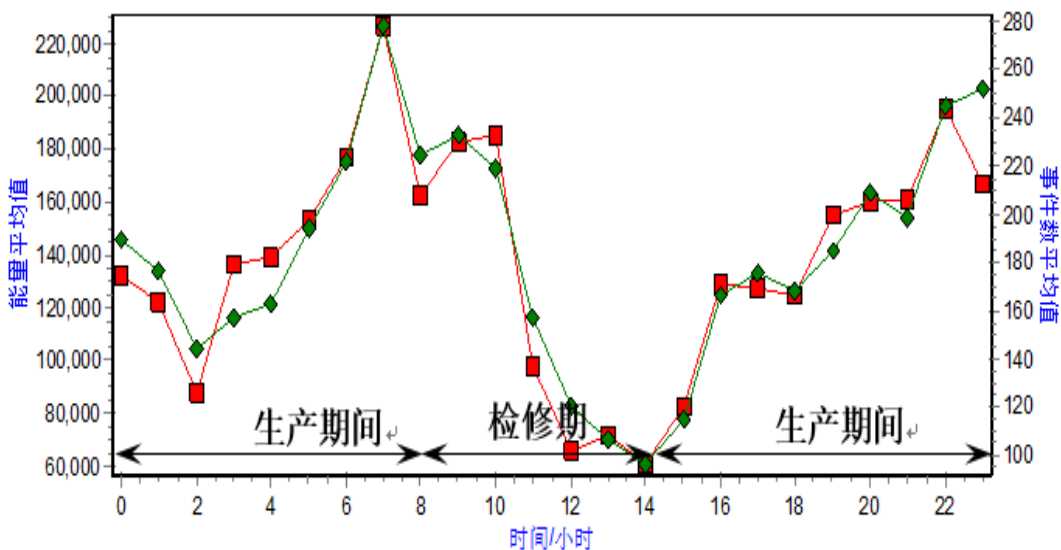
$$\mu_d = \begin{cases} \max\{\mu_{d0}(d) - 0.15(4-t), 0\} & t < 4h \\ \mu_{d0}(d) & t \geq 4h \end{cases}$$

$$\mu_{d1} = \begin{cases} \mu_{dp} + 0.125 \left(1 - \sqrt{1 - \frac{d}{\sqrt{8}}} \right) & \text{当 } d \leq \sqrt{8} \\ \mu_{dp} + 0.125 \sqrt{\frac{d}{\sqrt{8}}} & \text{当 } d > \sqrt{8} \end{cases}$$

持续时间, h	μ_d			
	$d < 100\%$	$d = 100\% \sim 200\%$	$d = 200\% \sim 300\%$	$d > 300\%$
1	0	0~0.05	0.05~0.30	>0.30
2	0	0~0.20	0.20~0.45	>0.45
3	<0.10	0.10~0.35	0.35~0.60	>0.60
4	<0.25	0.25~0.50	0.5~0.75	>0.75
5	<0.25	0.25~0.50	0.5~0.75	>0.75
6	<0.25	0.25~0.50	0.5~0.75	>0.75
7	<0.25	0.25~0.50	0.5~0.75	>0.75
8	<0.25	0.25~0.50	0.5~0.75	>0.75

■ 能量平均值 ◆ 事件数平均值

■ 地音能量危险系数 ◆ 地音事件数危险系数





4) 冲击变形能时空监测预警技术

- 冲击变形能预测模型
- 冲击变形能时空监测预警
- 冲击变形能监测预警技术

4.1) 冲击变形能监测模型



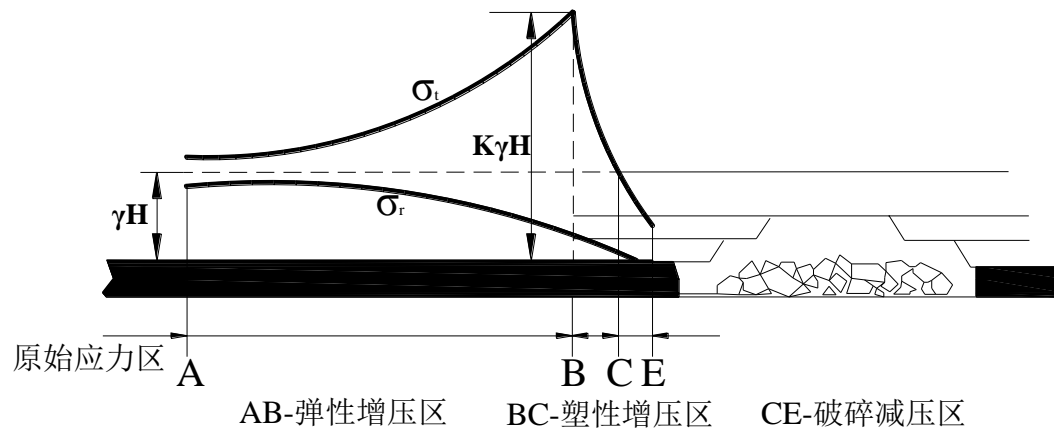
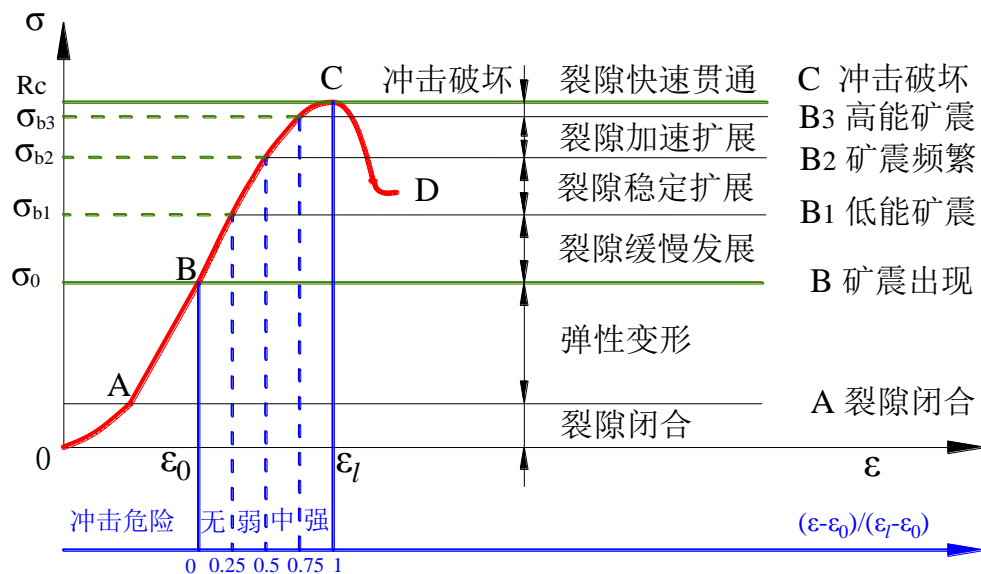
State Key Laboratory of Coal Resources and Safe Mining



冲击变性能监测预警指数指数 (2013)

$$\varepsilon_t = \sum_{i=1}^N \sqrt{E_i}$$

$$W_\varepsilon = \frac{\varepsilon_t - \varepsilon_0}{\varepsilon_l - \varepsilon_0}$$



E_i - 第*i*次矿震能量
 N - 上次宏观破裂后的矿震次数
 ε_t - 在*t*时刻的应变
 ε_l - 宏观破裂时应变
 ε_0 - 初始应变

冲击危险指标	异常对应的危险性特征	W_ε
A	无	<0.25
B	弱	0.25-0.5
C	中等	0.5-0.75
D	强	>0.75

4.2) 冲击变形能时空监测



State Key Laboratory of Coal Resources and Safe M

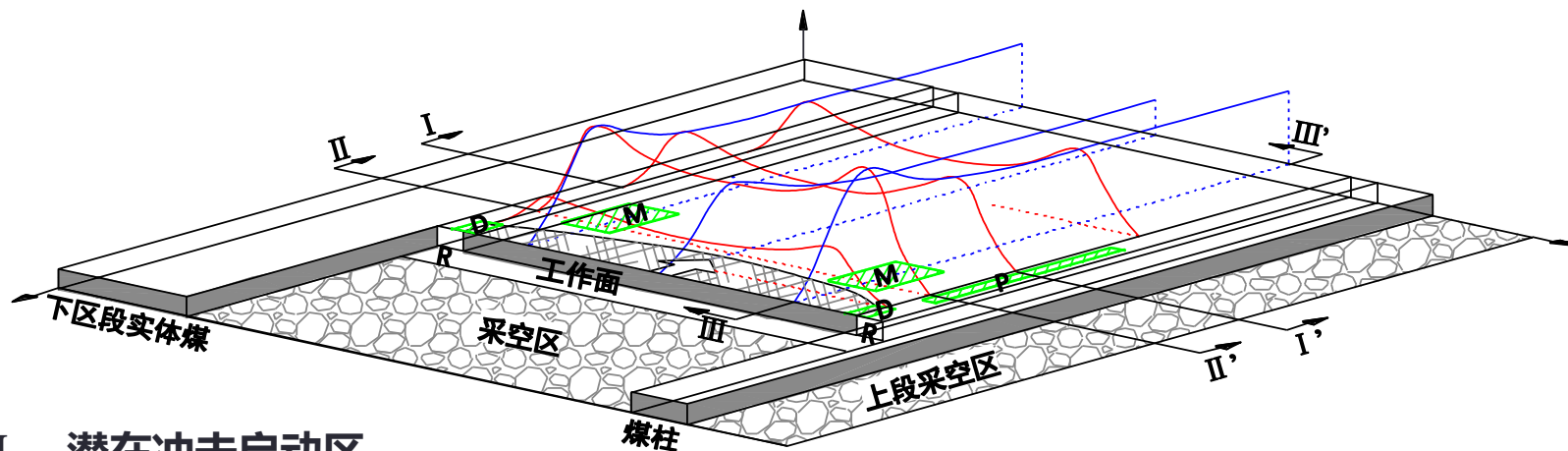


冲击变形能监测预警——时序与空间

$$W_{\varepsilon\text{-temporal}} = \frac{(\varepsilon - \varepsilon_{Nt-1}) + (\varepsilon_{Nt-1} - \varepsilon_{Nt-2}) + \dots + (\varepsilon_1 - \varepsilon_0)}{(\varepsilon_l - \varepsilon_{Nl-1}) + (\varepsilon_{Nl-1} - \varepsilon_{Nl-2}) + \dots + (\varepsilon_1 - \varepsilon_0)} = \frac{\varepsilon - \varepsilon_0}{\varepsilon_l - \varepsilon_0} = \frac{\sum_{i=1}^{Nt} \sqrt{U_{AE-i}}}{\sum_{i=1}^{Nl} \sqrt{U_{AE-i}}}$$

$$W_{\varepsilon\text{-spatial}} = \frac{e - e^{1-\beta(t)}}{e - 1}$$

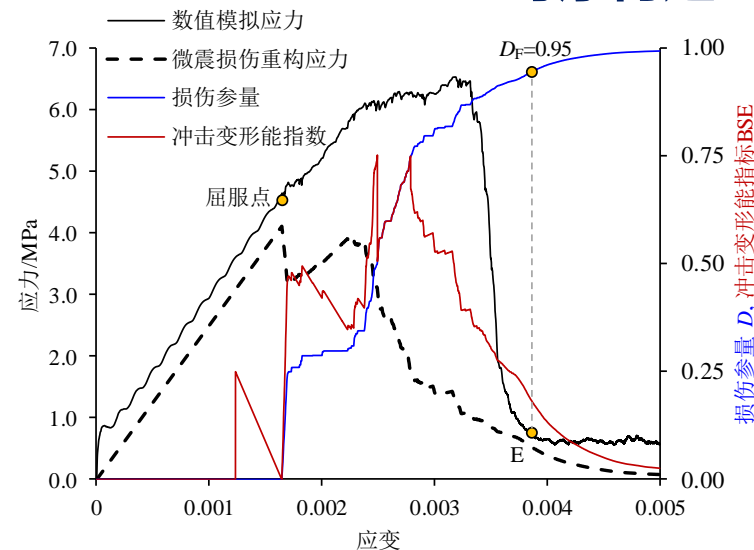
$$\beta(t) = (U_{\varepsilon} - U_{\varepsilon\text{-min}}) / (U_{\varepsilon\text{-max}} - U_{\varepsilon\text{-min}})$$



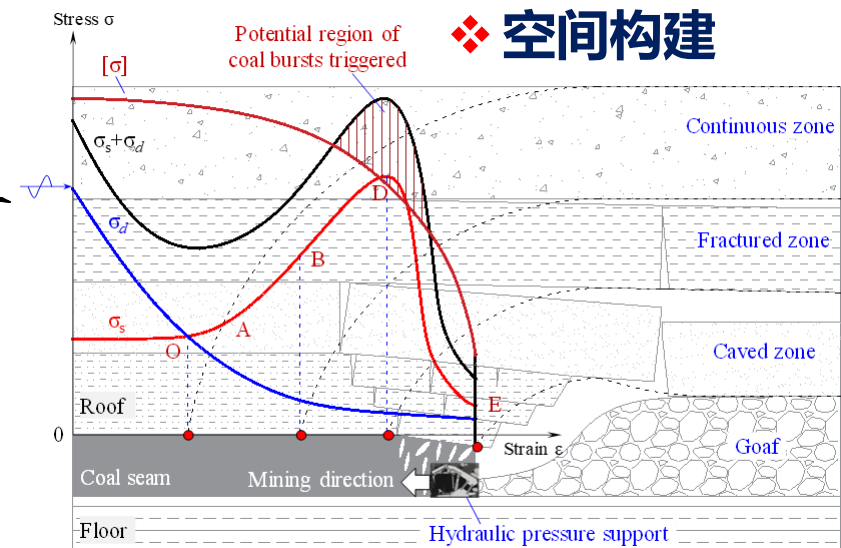
M — 潜在冲击启动区

P — 潜在冲击危险区

时序构建



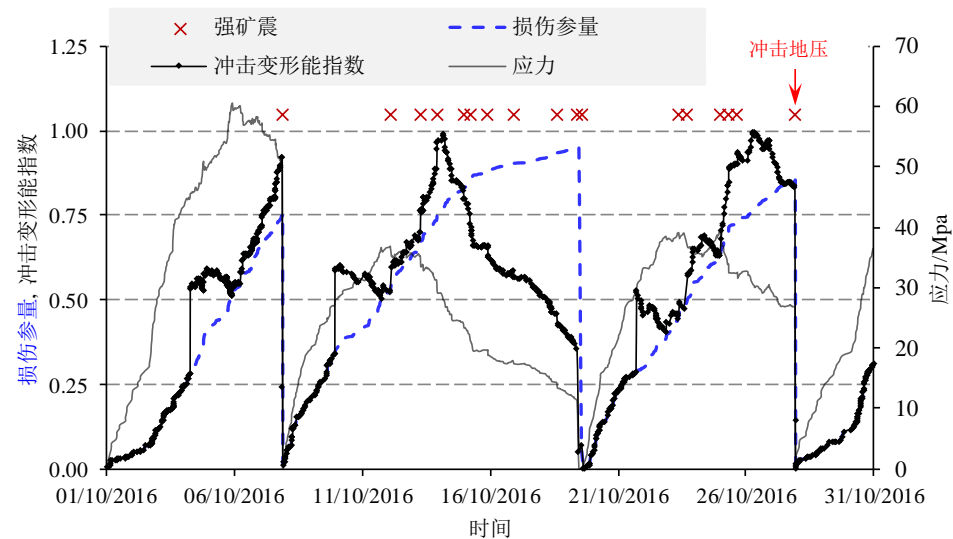
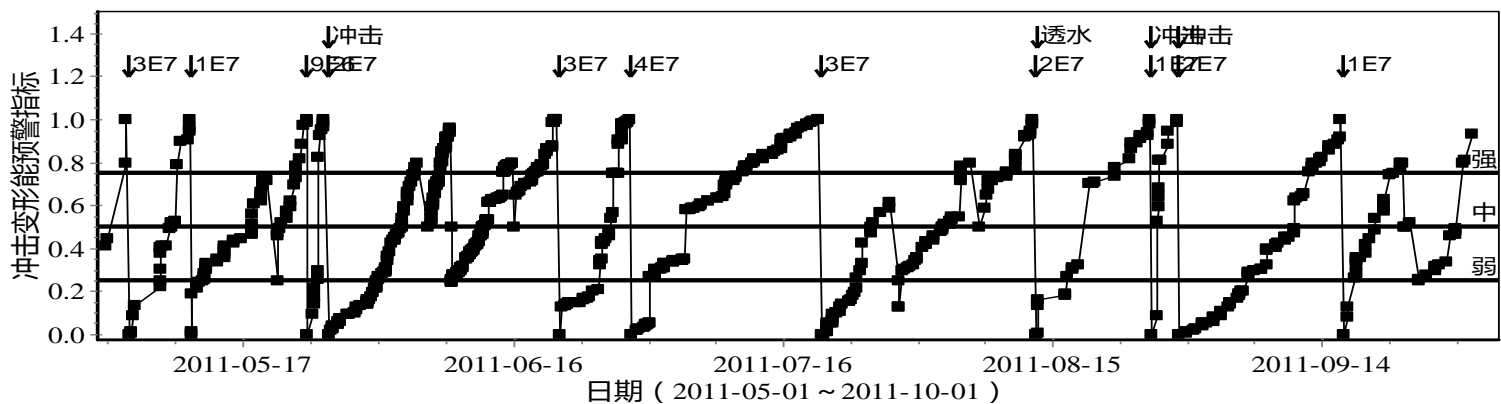
空间构建



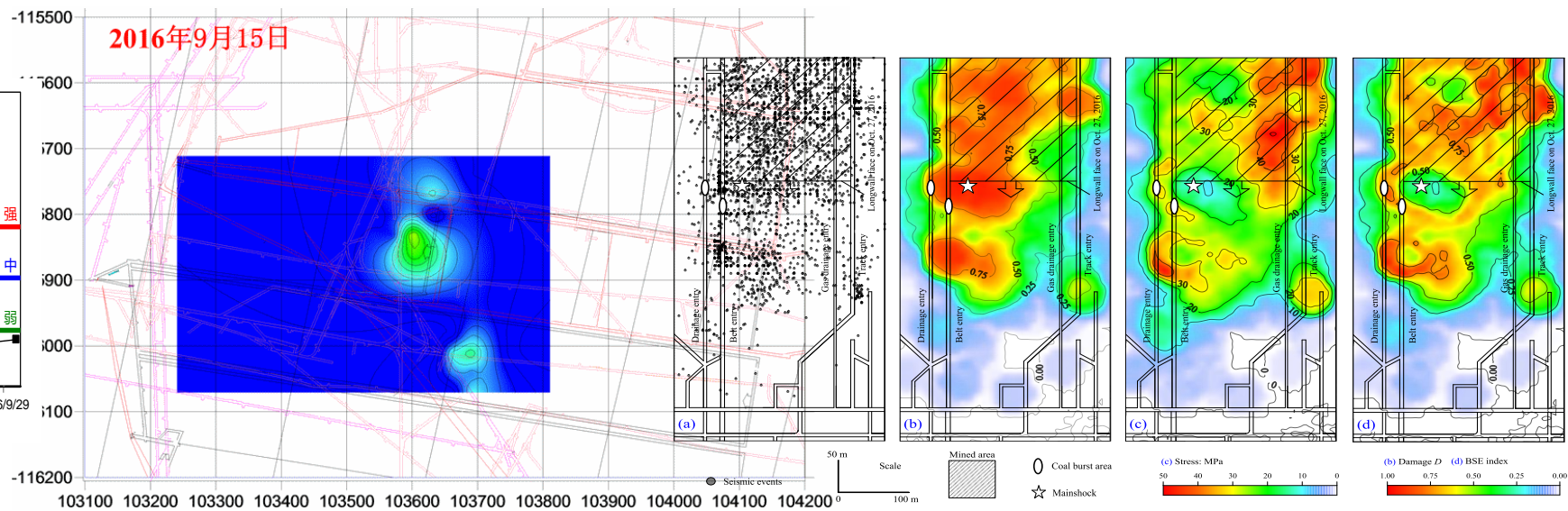
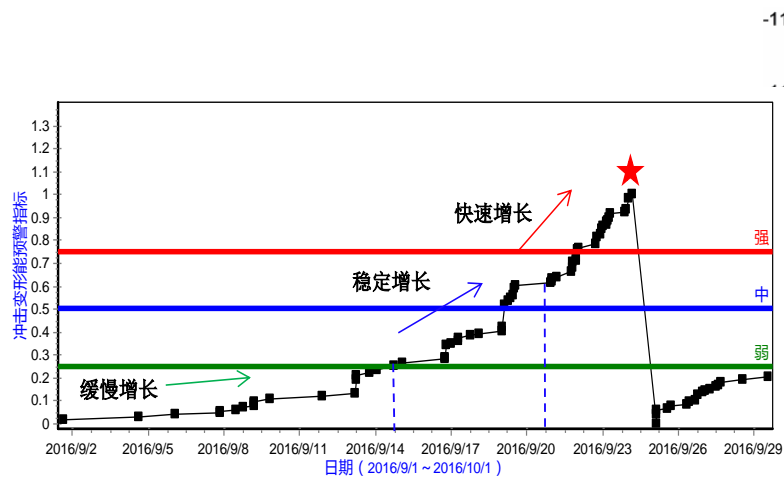
4.3) 冲击变形能监测预警技术



State Key Laboratory of Coal Resources and Safe M



冲击变形能预警 (跃进, 11次强矿震预警9次, 预警率82%)



中国矿业大学优秀博士学位论文 (2015)



5) 区域应力场 CT 探测技术

- CT 应力场探测原理
- 弹性波(主动) CT 探测
- 震动波(被动) CT 探测
- 双震源一体化 CT 探测

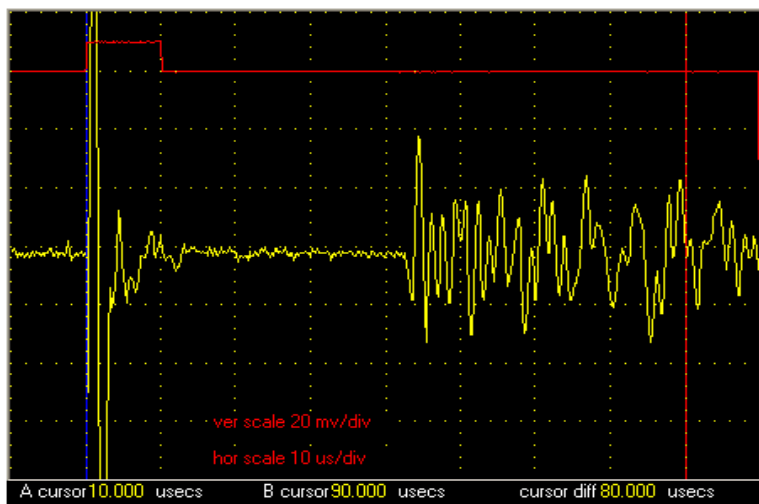
5.1) CT应力场探测原理



State Key Laboratory of Coal Resources and Safe M

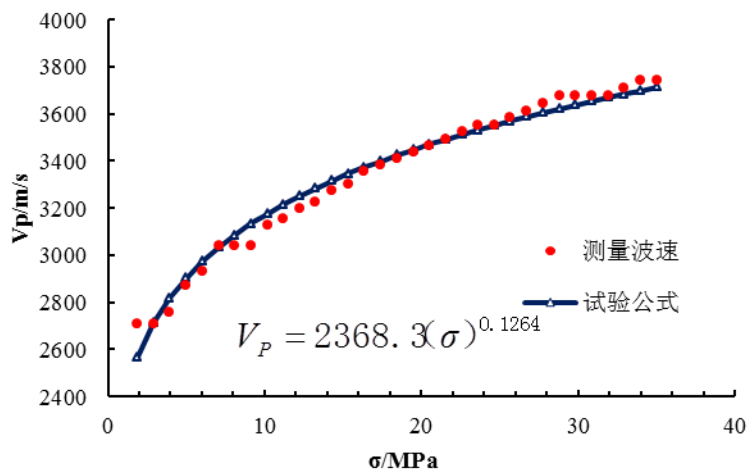
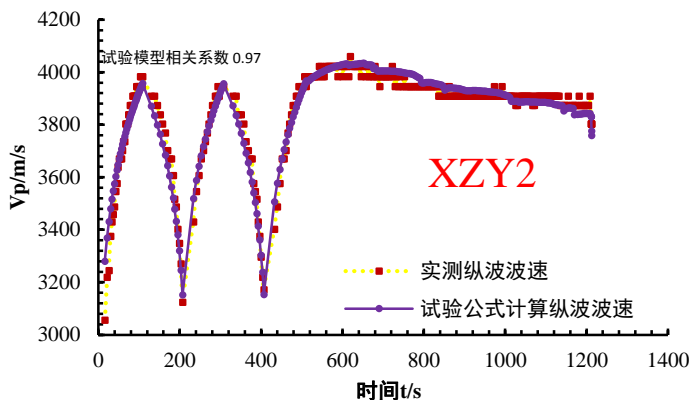


□ 应力与波速间具有正相关

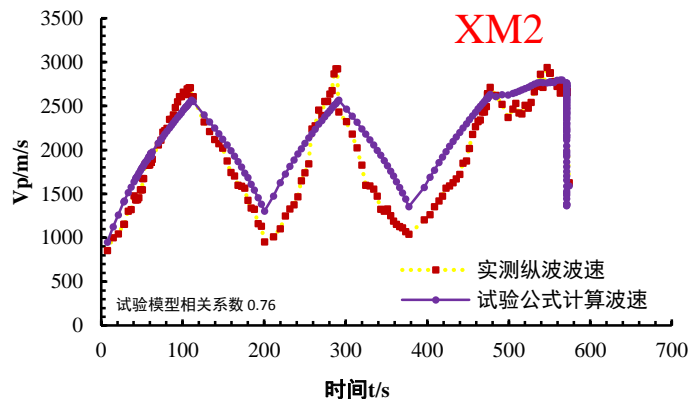


岩石

$$V_P = \varphi (\sigma)^\psi$$



煤



➤ 波速异常值 A_n

$$A_n = \frac{V_p - V_p^a}{V_p^a}$$

➤ 波速变化梯度 VG

$$A_n = \frac{VG - VG^a}{VG^a}$$

➤ 应力集中系数 φ

$$\varphi = \frac{\left(\frac{V_p}{\phi}\right)^{1/\psi}}{\sigma_p^a}$$

5.2) 弹性波(主动) CT 探测

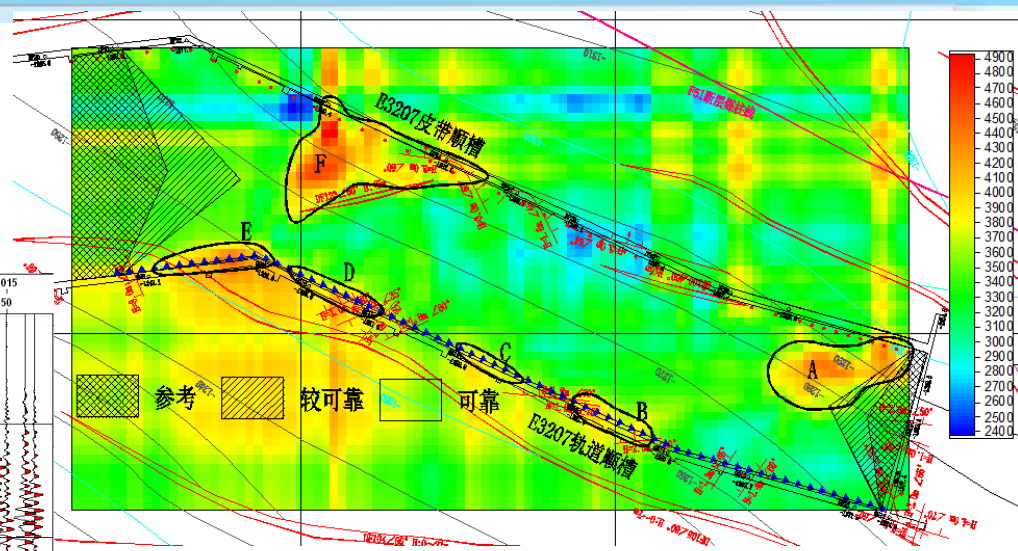
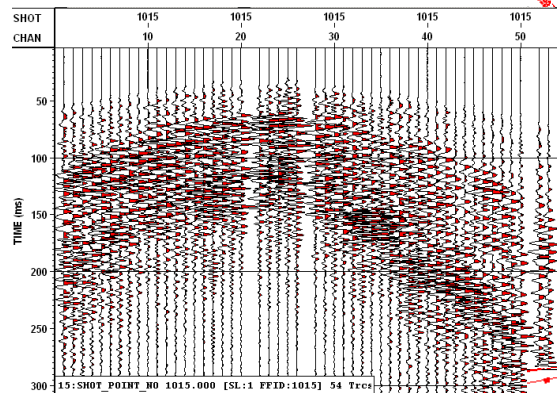
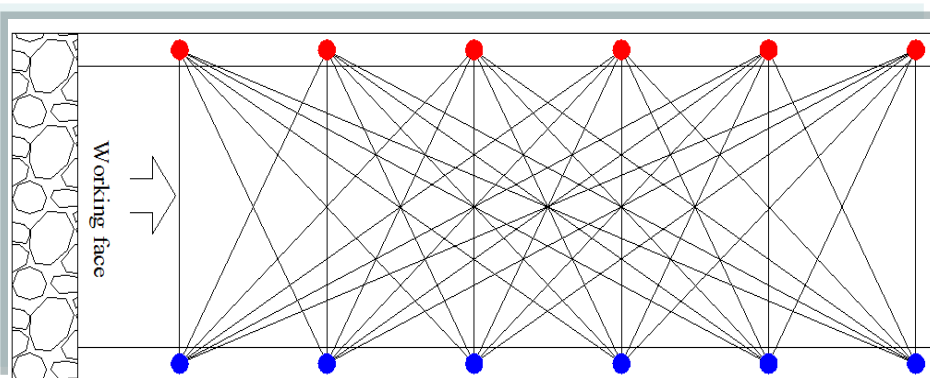


State Key Laboratory of Coal Resources and Safe M

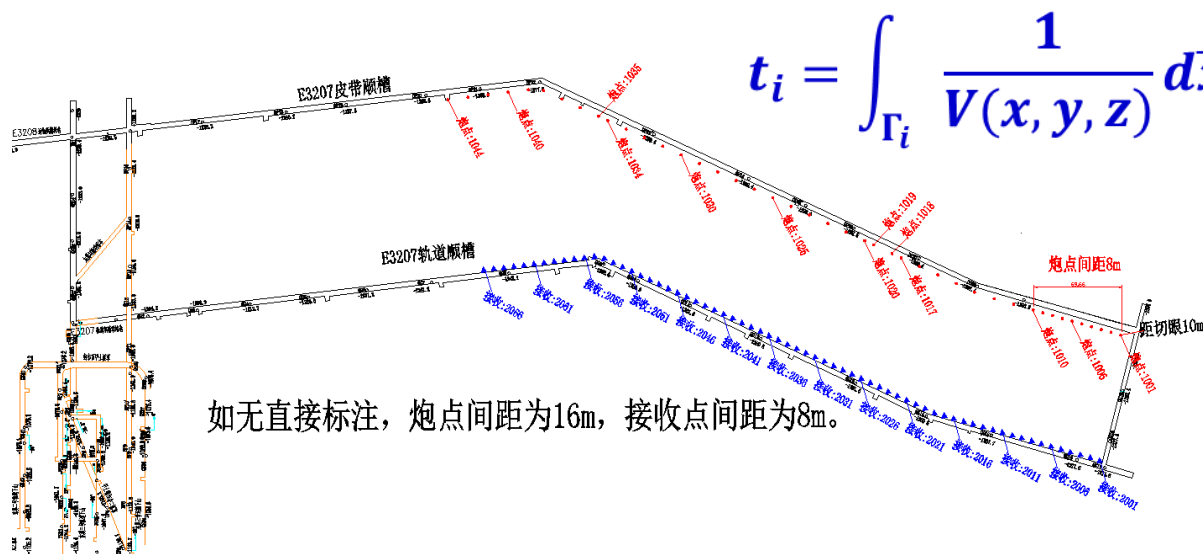


弹性波（主动）CT探测技术（2011）

星村煤矿E3207面

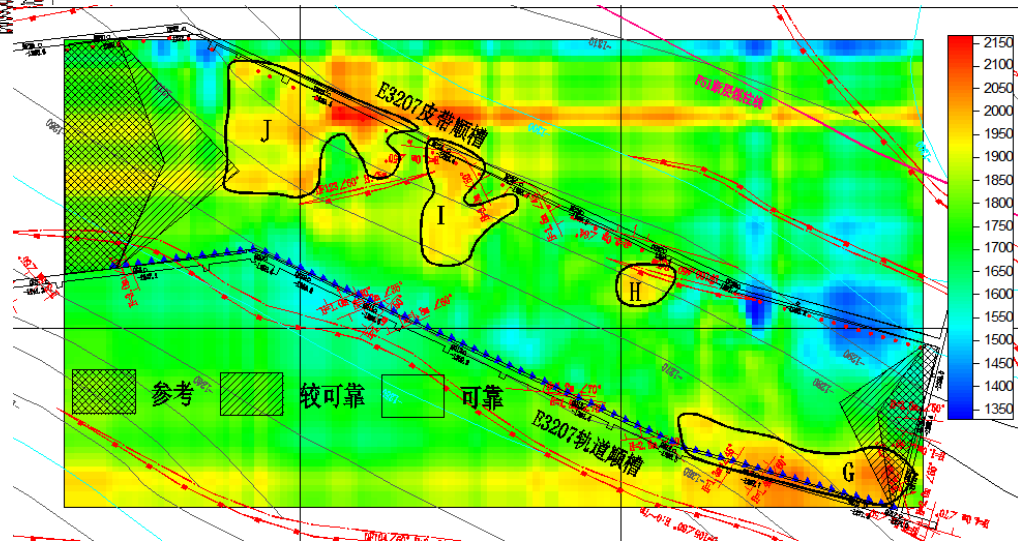


P波分布



$$t_i = \int_{\Gamma_i} \frac{1}{V(x, y, z)} d\vec{x}$$

如无直接标注, 炮点间距为16m, 接收点间距为8m.



S波分布

5.3) 震动波(被动) CT 探测

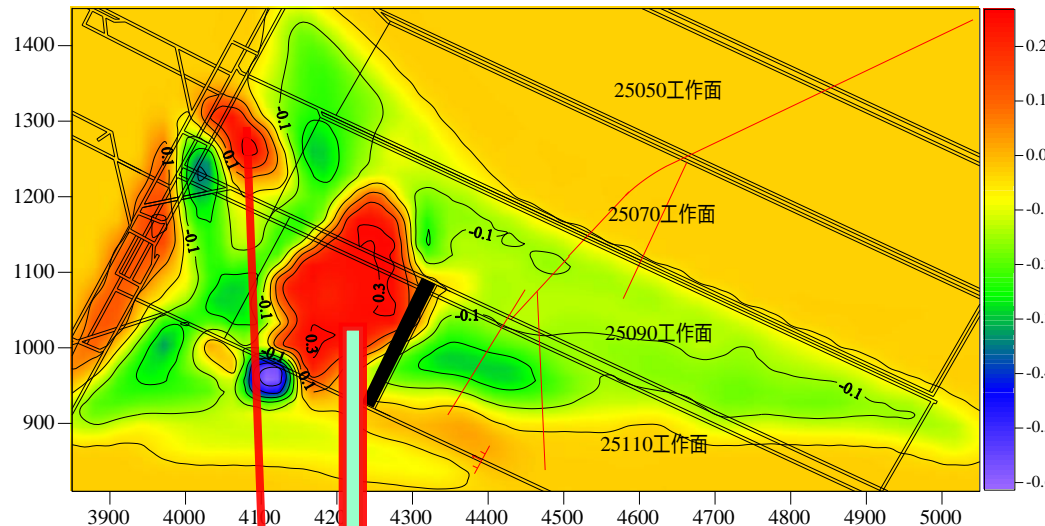
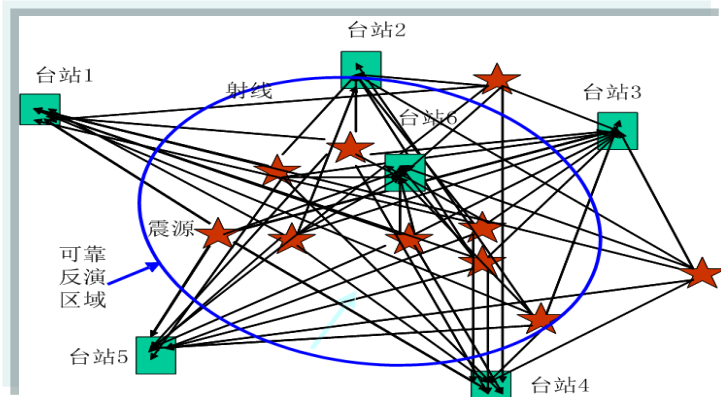
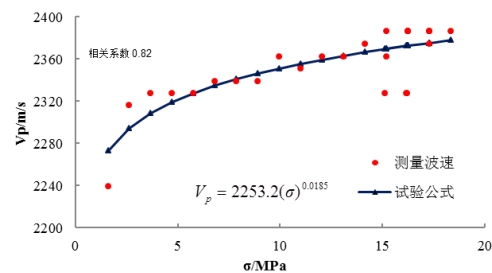
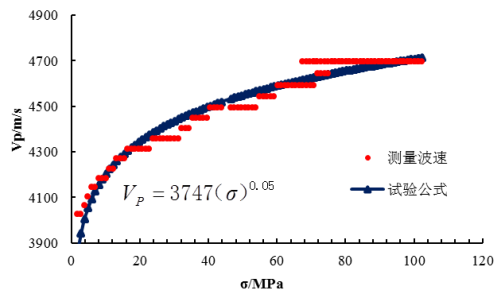
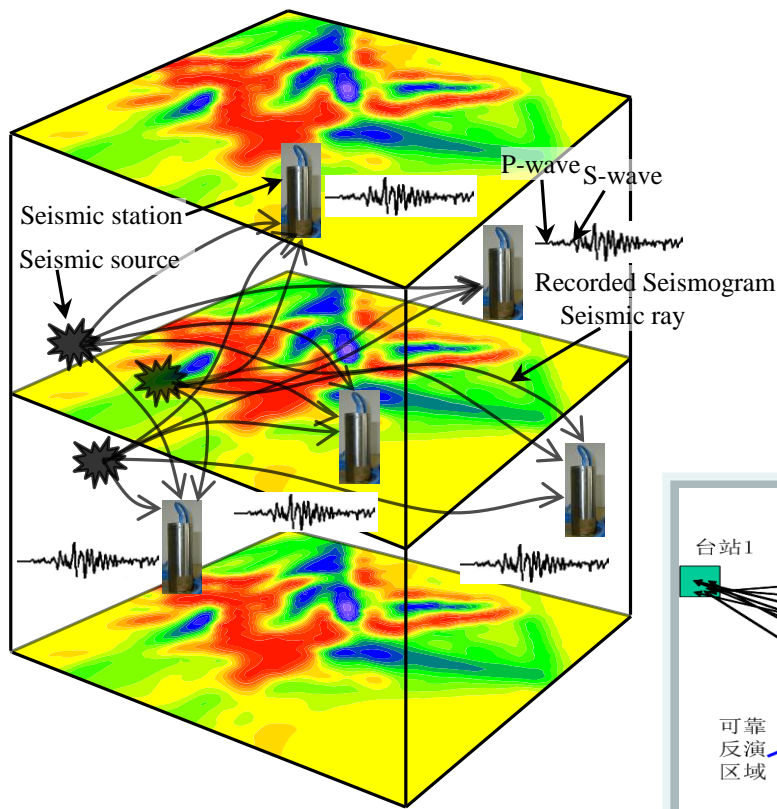


State Key Laboratory of Coal Resources and Safe M

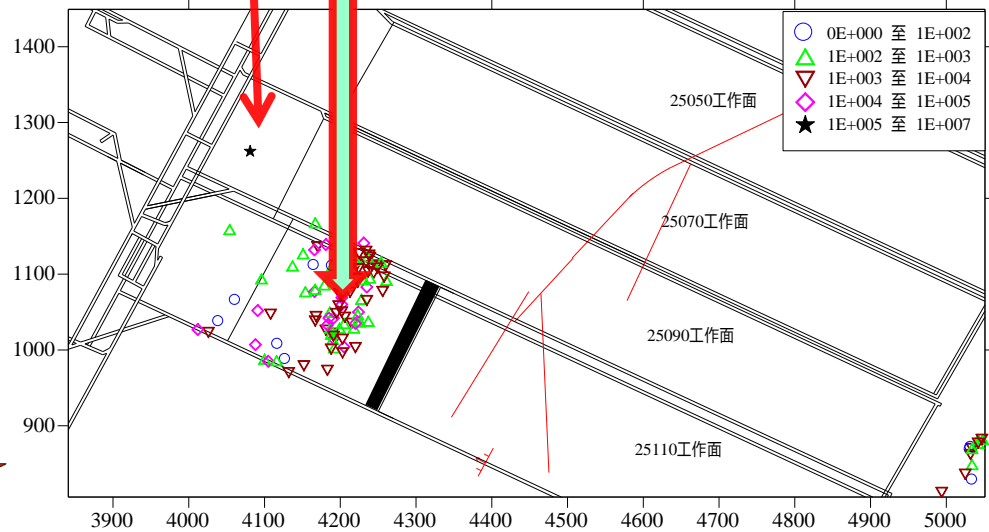


震动波 (被动) CT探测 (2011)

$$t_i = \int_{\Gamma_i} \frac{1}{V(x, y, z)} d\vec{x} + t_{i0}$$



20110508—20120607时段



20120608—20120630

山东省科技一等奖



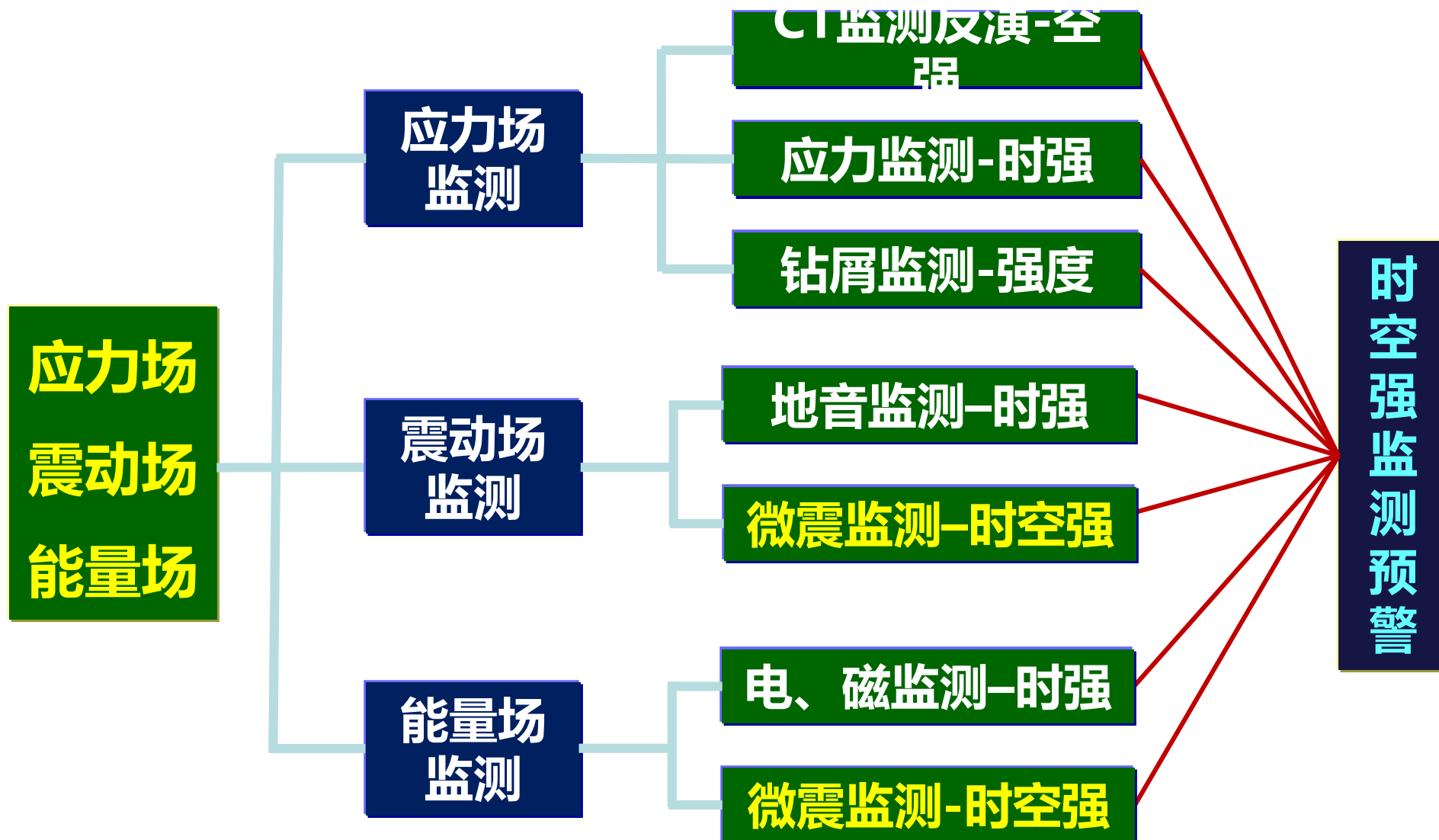
6) 冲击危险多参量监测预警技术

- 应力震动能量三场监测指标
- 冲击矿压分类监测指标体系
- 冲击危险多参量监测预警体系

6.1) 三场监测指标



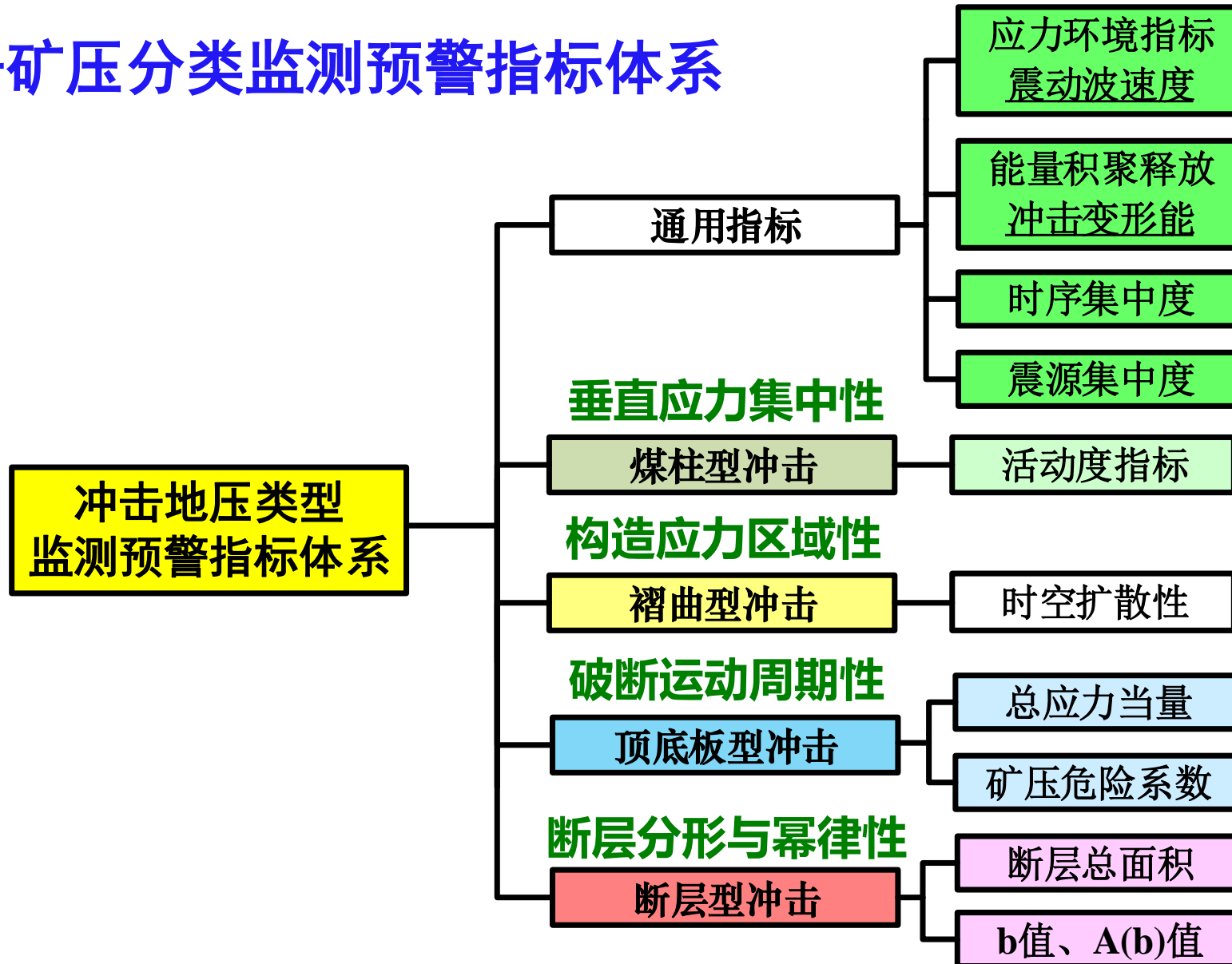
□ 应力场-震动场-能量场监测指标



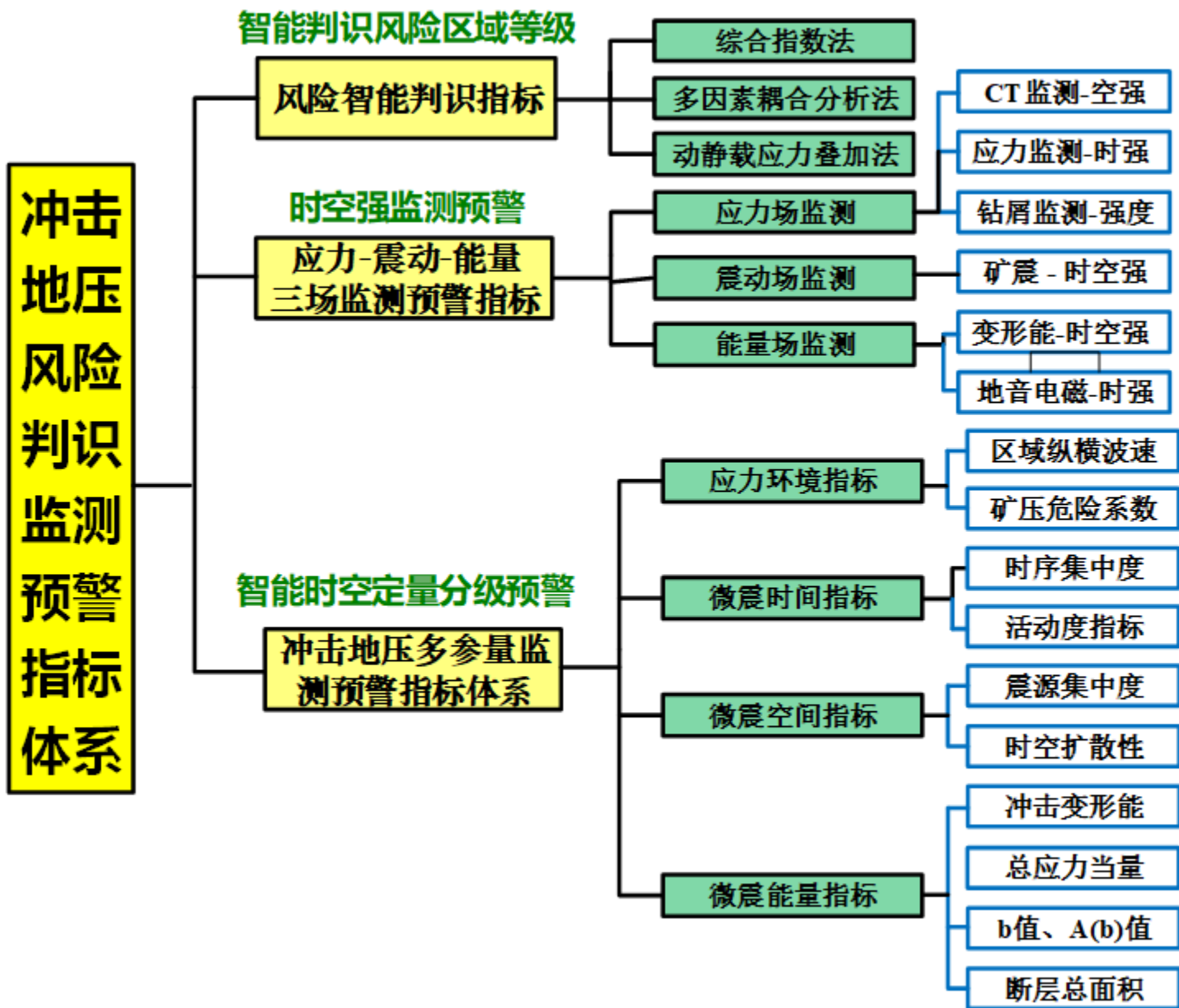
6.2) 冲击矿压分类监测指标



冲击矿压分类监测预警指标体系



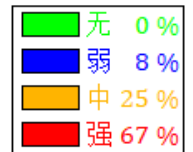
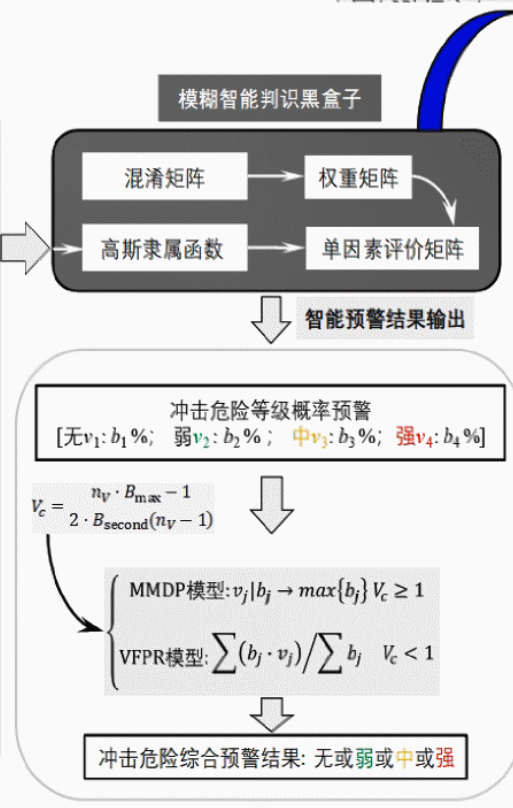
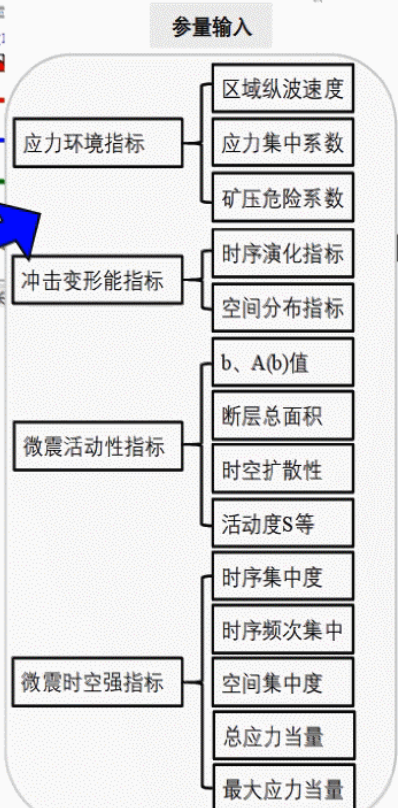
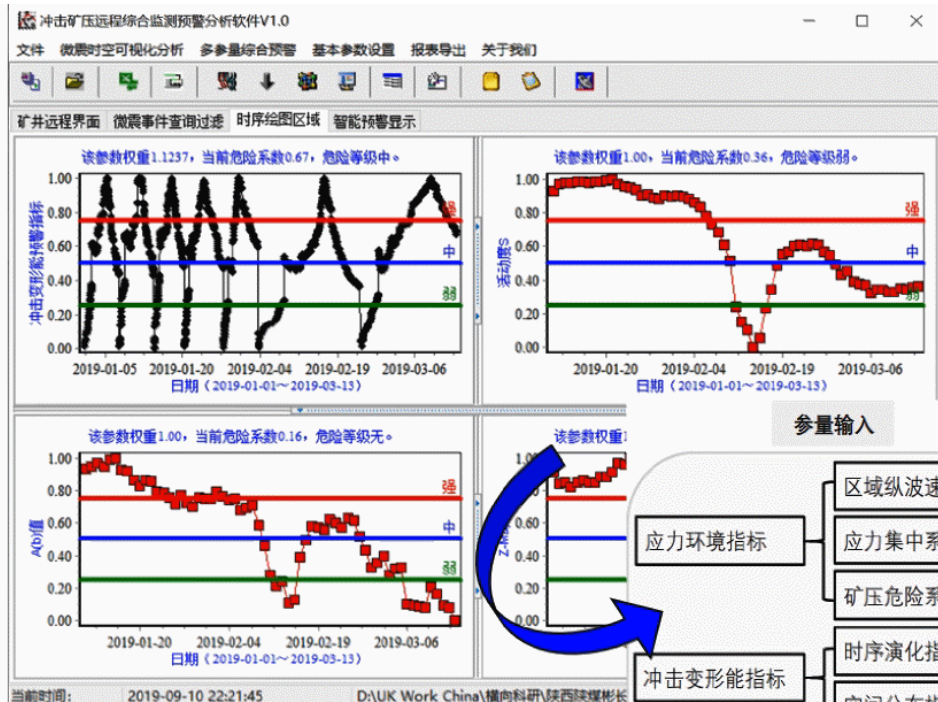
6.3) 多参量监测预警指标体系



冲击危险多参量监测预警技术

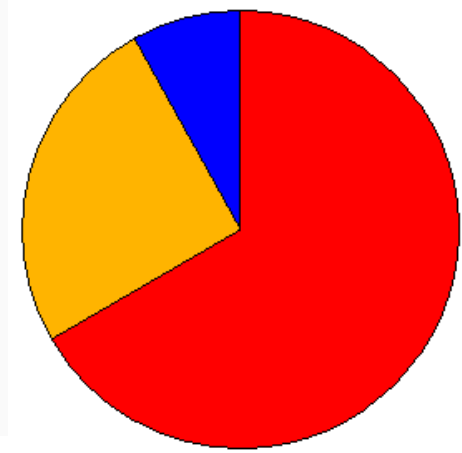


State Key Laboratory of Coal Resources and Safe Mining



综合预警: 强危险

综合预警结果





7) 顺层钻孔高压射流卸压技术

- 高压射流基本原理
- 高压射流的技术装备
- 钻孔高压射流卸压技术

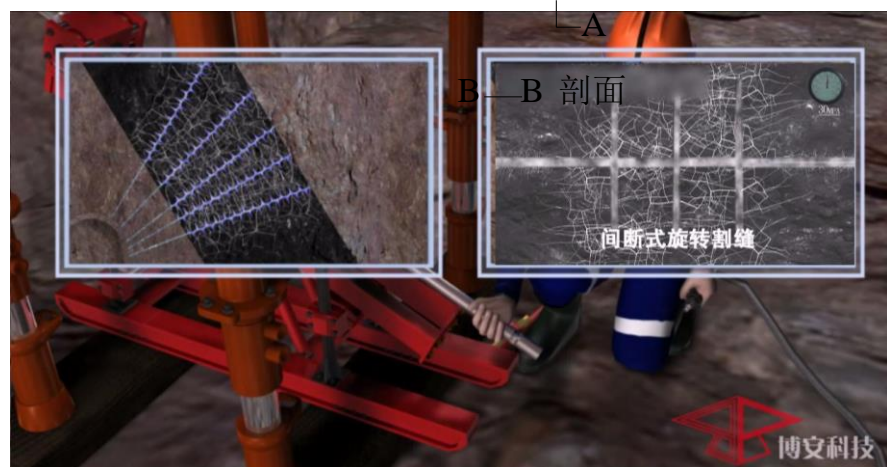
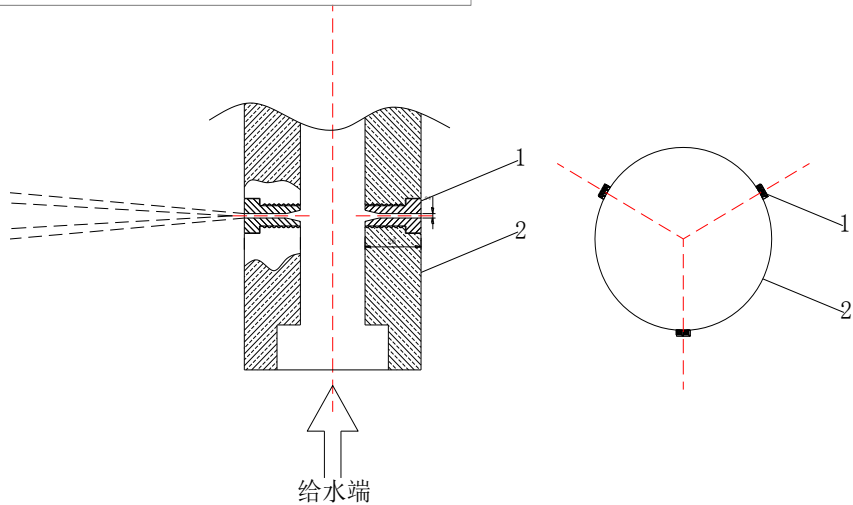
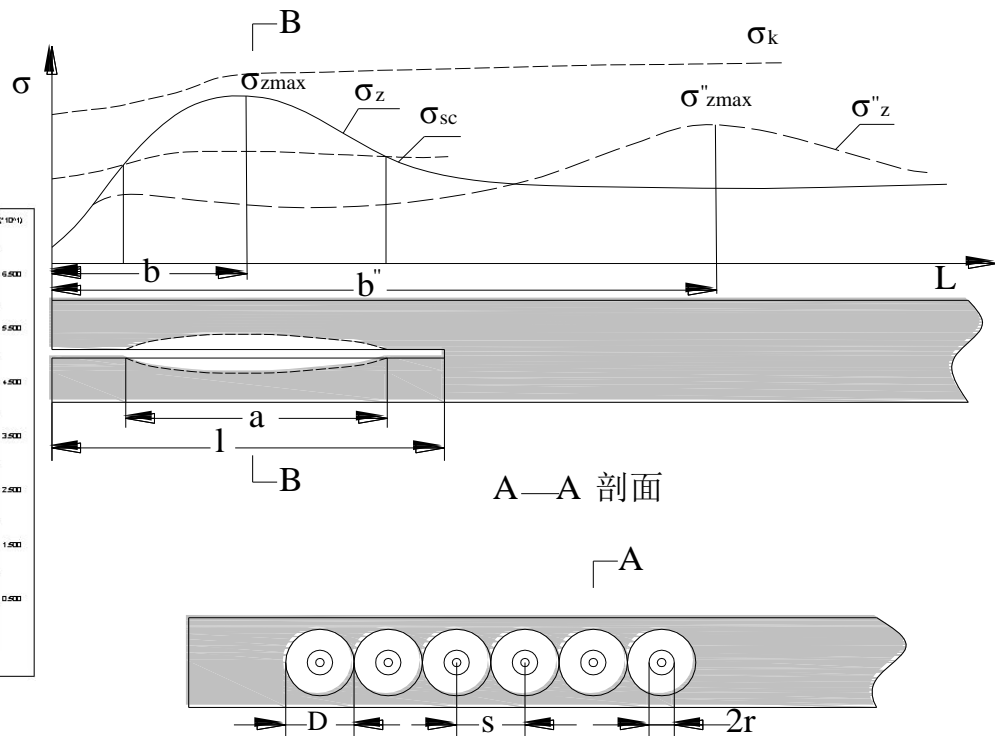
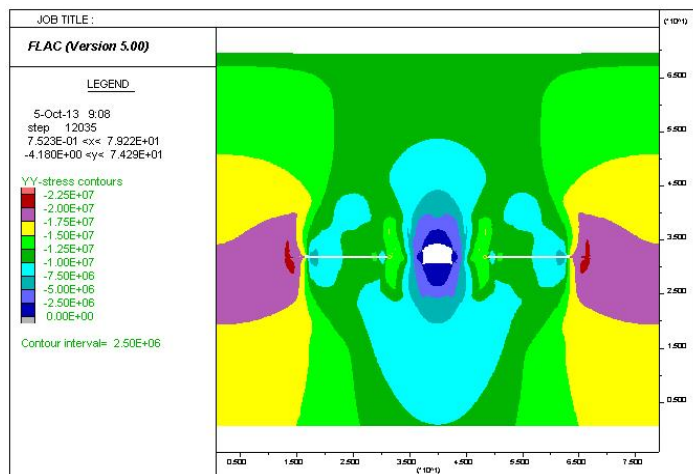
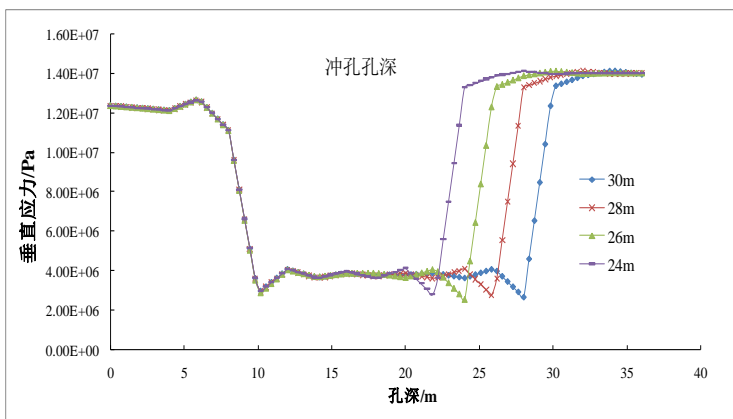
7.1) 煤体高压射流基本原理



State Key Laboratory of Coal Resources and Safe Mining



卸压、防冲、增透 (2012)



7.2) 煤体高压射流技术装备

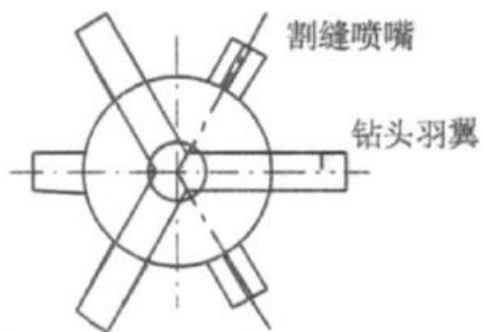
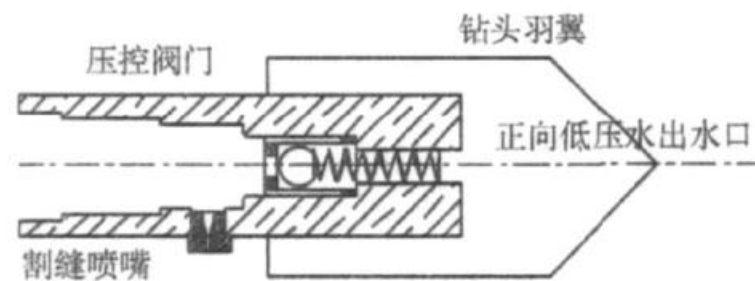


CISM

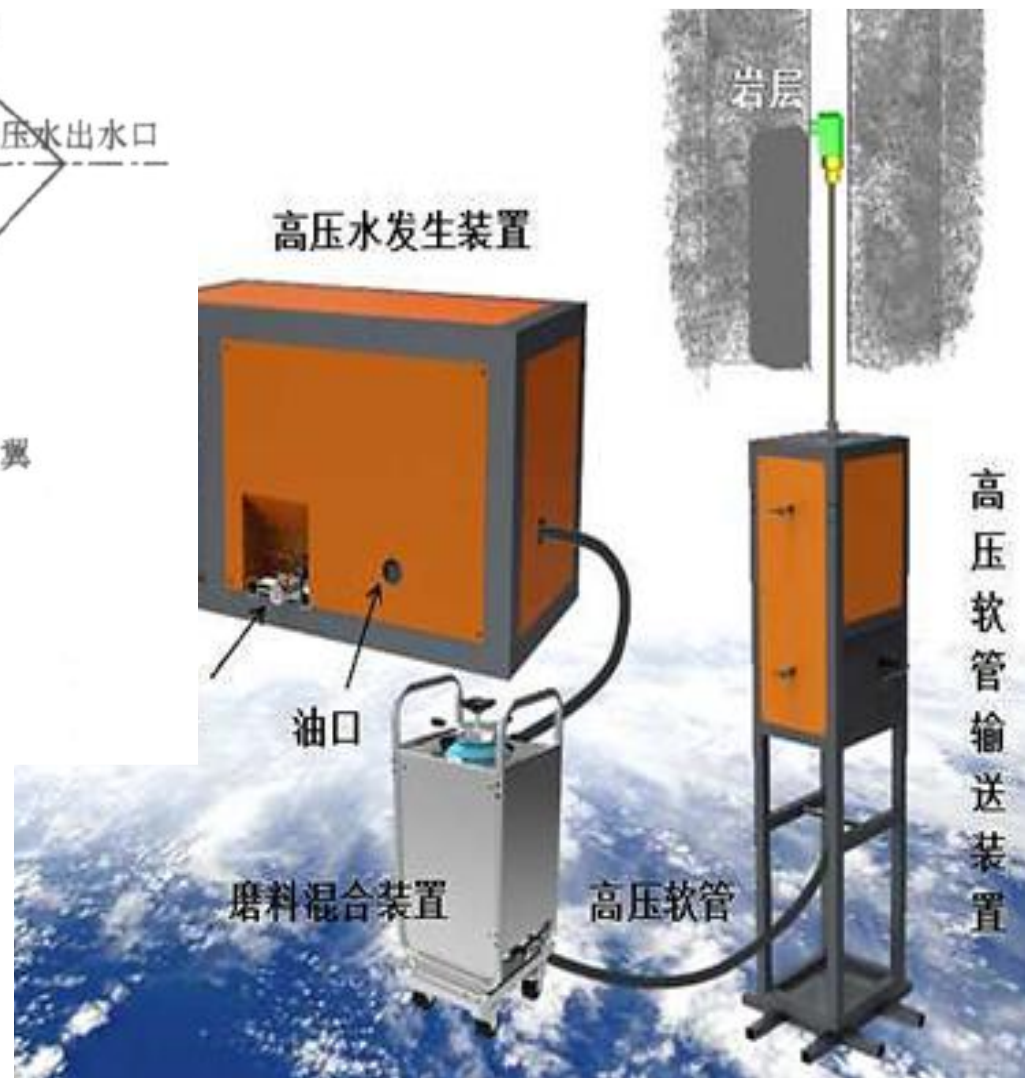
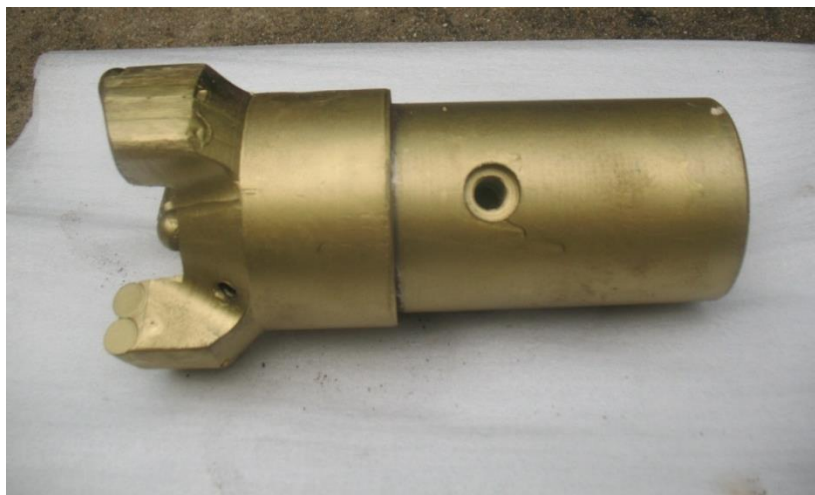
State Key Laboratory
of Coal Resources and Safe M



➤ 煤体高压射流钻割卸压技术 (2012)



左视图



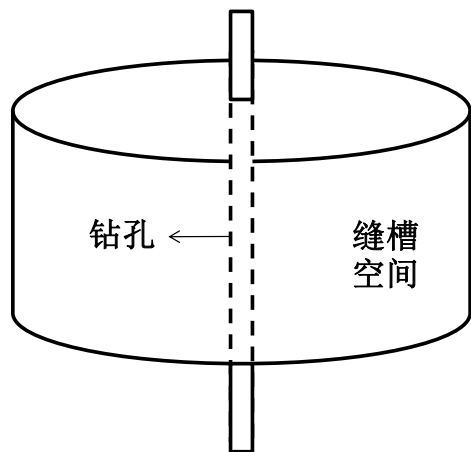
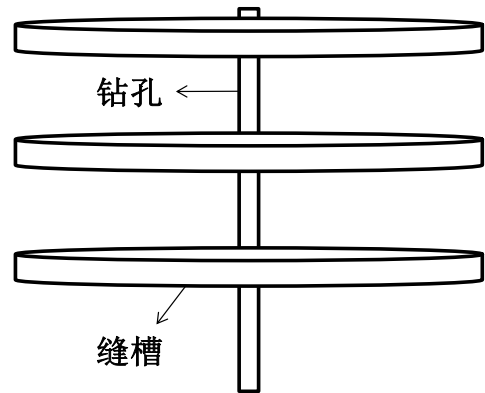
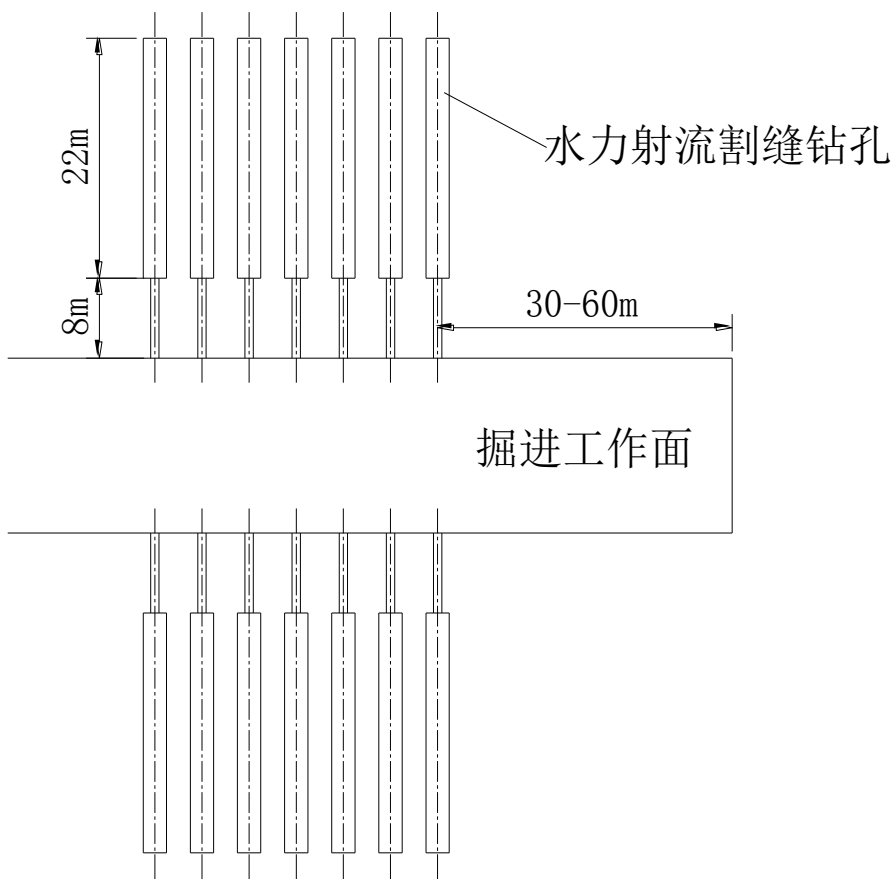
7.3) 煤体高压射流技术装备



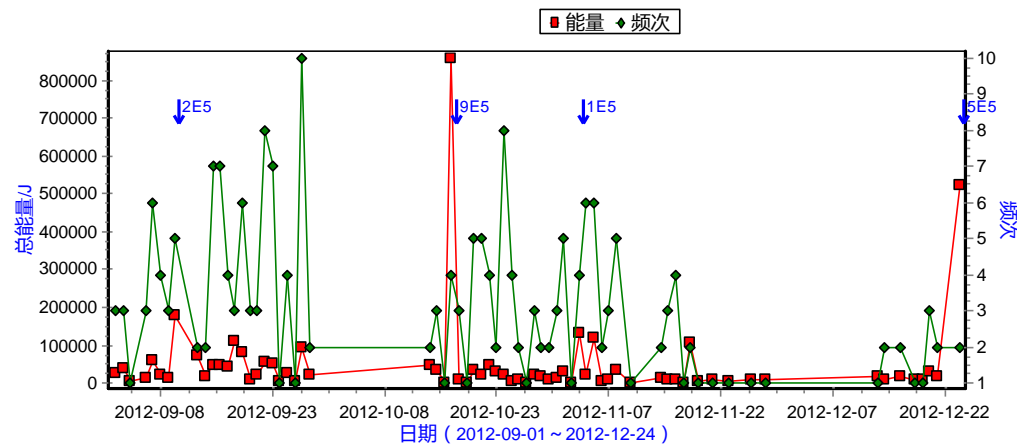
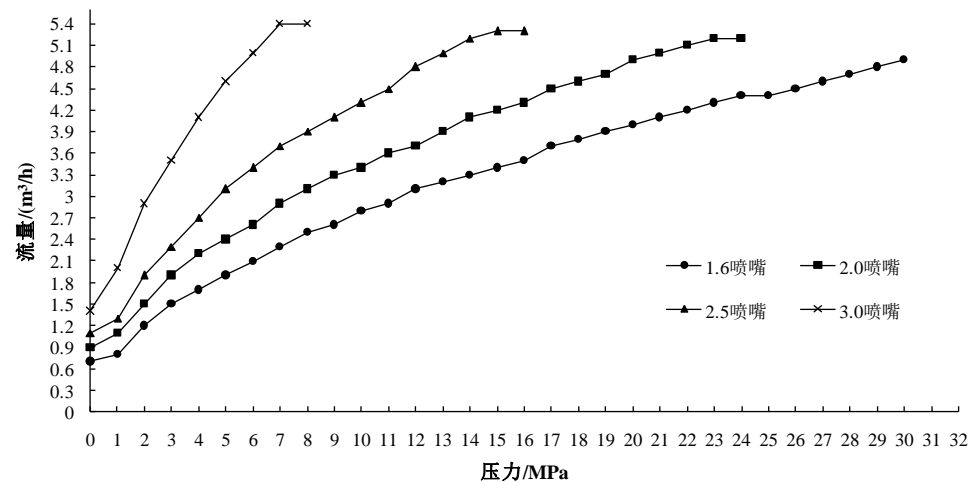
State Key Laboratory of Coal Resources and Safe M



应用：防冲、卸压、增透



喷嘴压力流量实验





8) 顶板高压定向水力致裂技术

- 定向致裂原理
- 高压定向致裂装备
- 高压定向致裂技术

8.1) 高压定向水力致裂原理

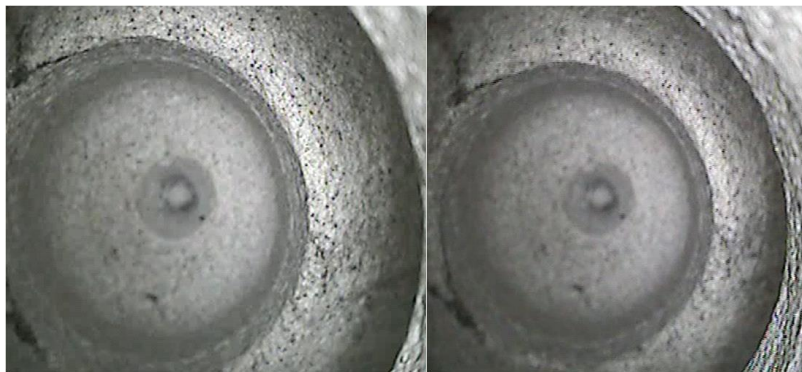
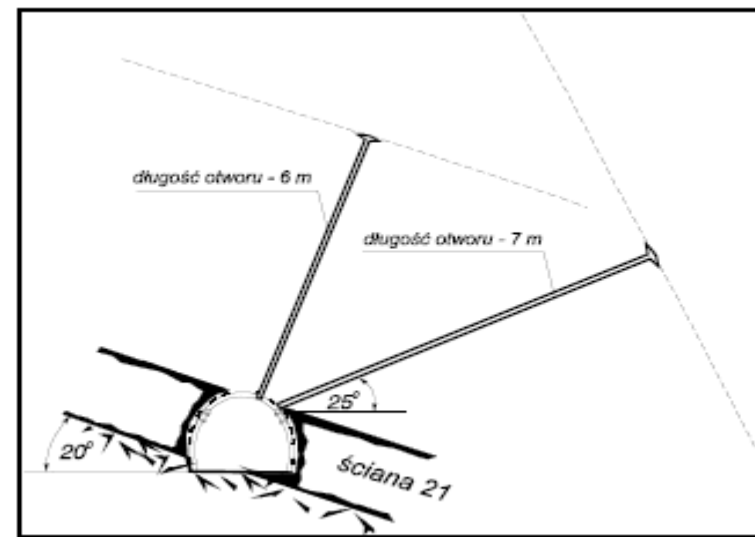
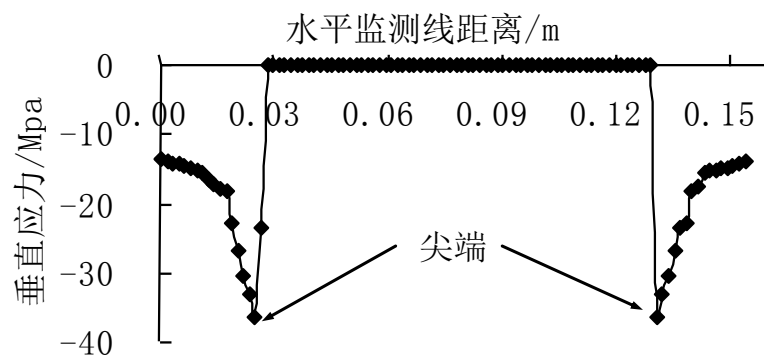
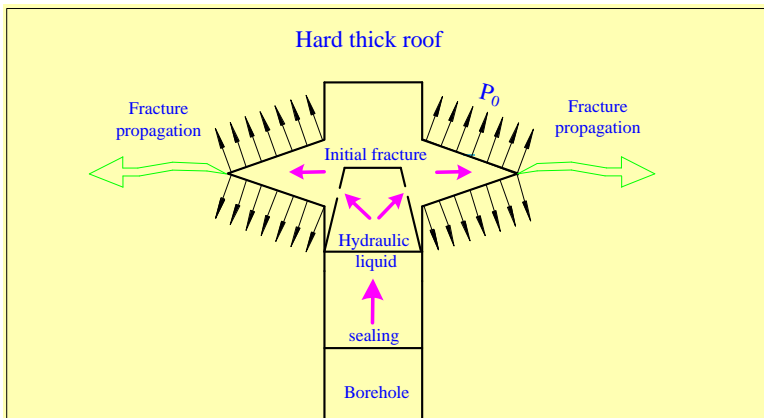


State Key Laboratory of Coal Resources and Safe M



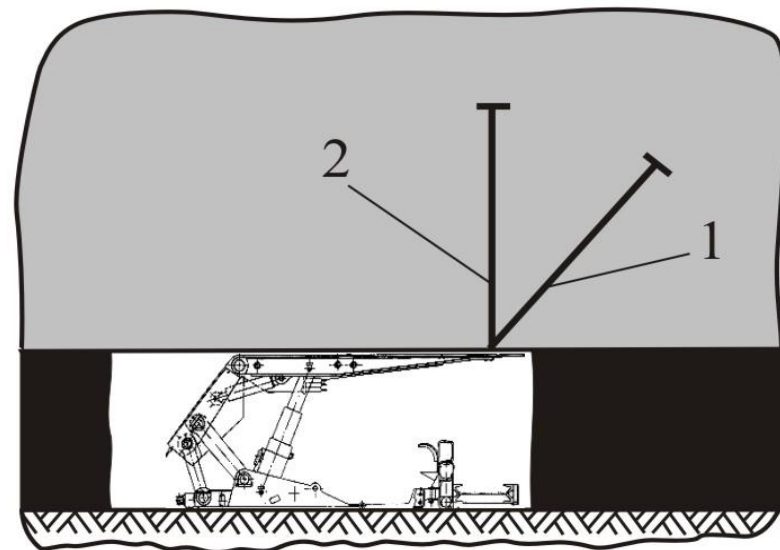
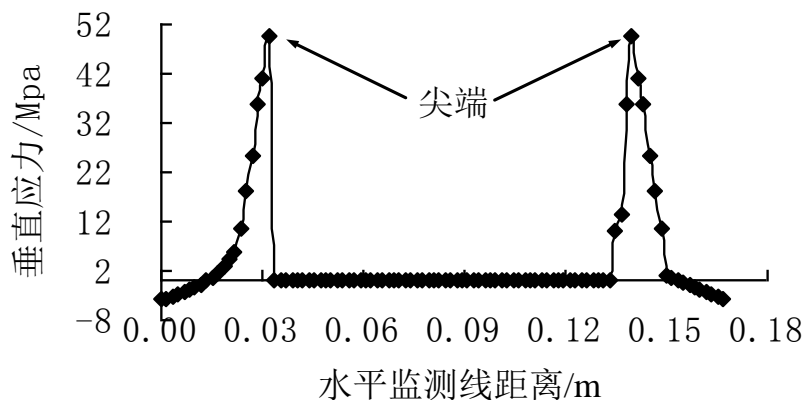
➤ 高压水力定向致裂技术 (2006)

$$P = 1.3(P_z^* + R_r)$$



1#切槽窥视图

2#切槽窥视图

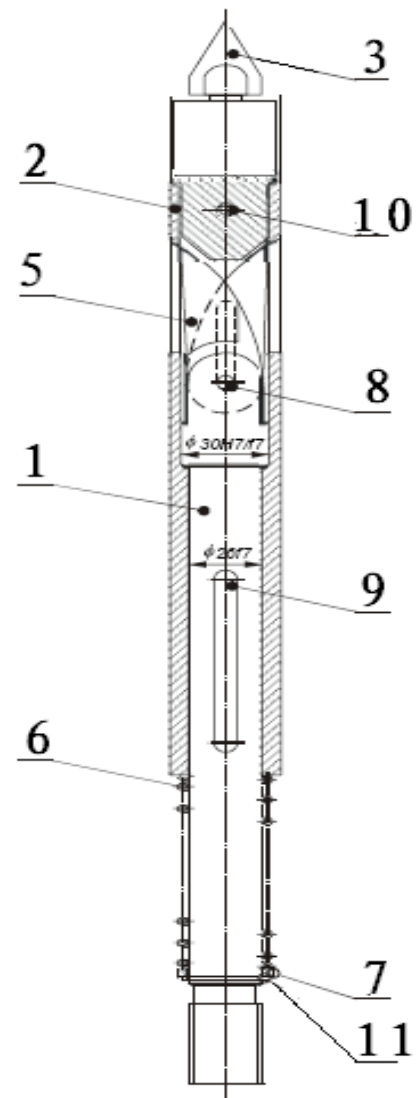


□ 山东省科技进步三等奖 (2013)

8.2) 高压定向水力致裂装备



State Key Laboratory
of Coal Resources and Safe M



封孔器



压力管



刀具



钻孔窥视仪

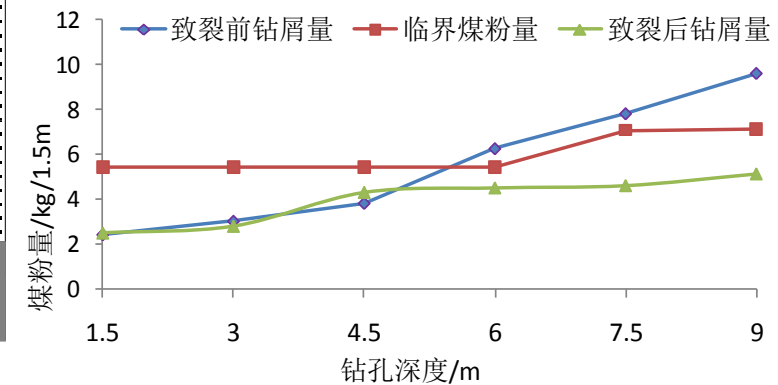
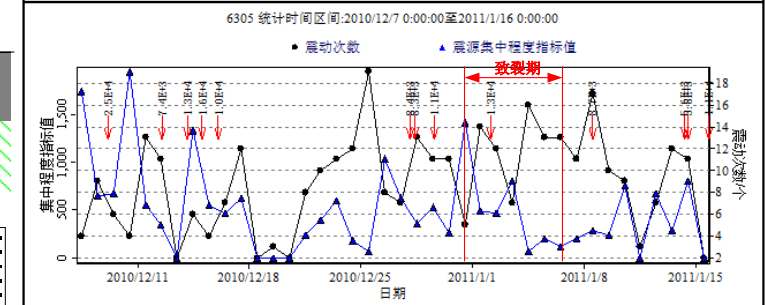
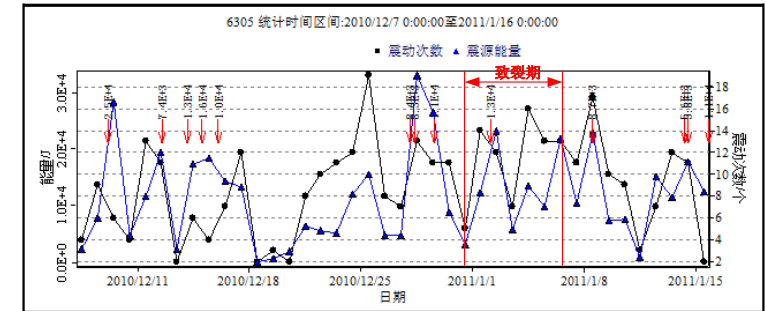
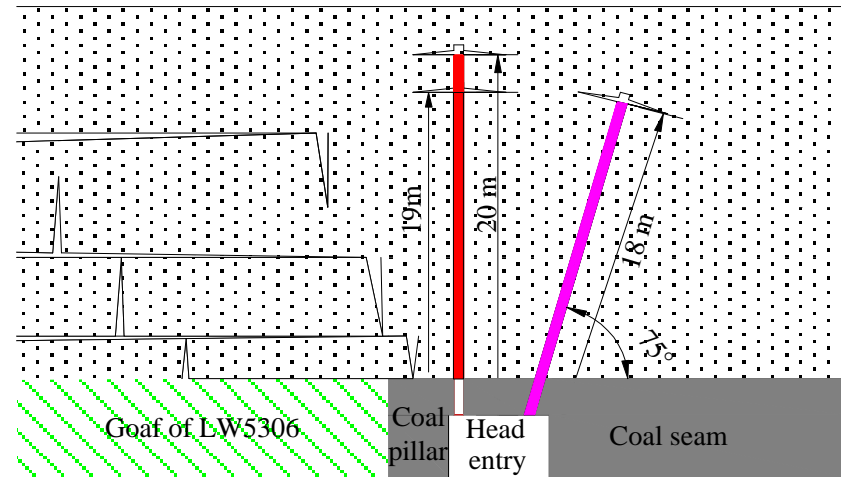
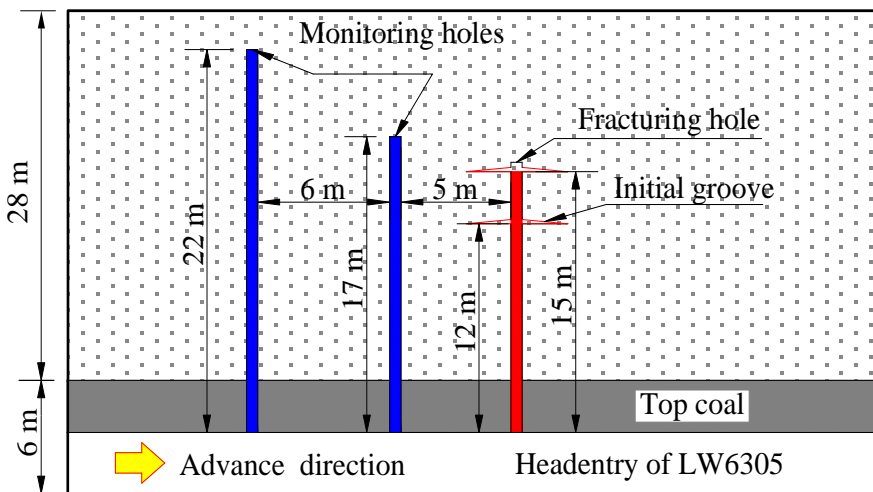
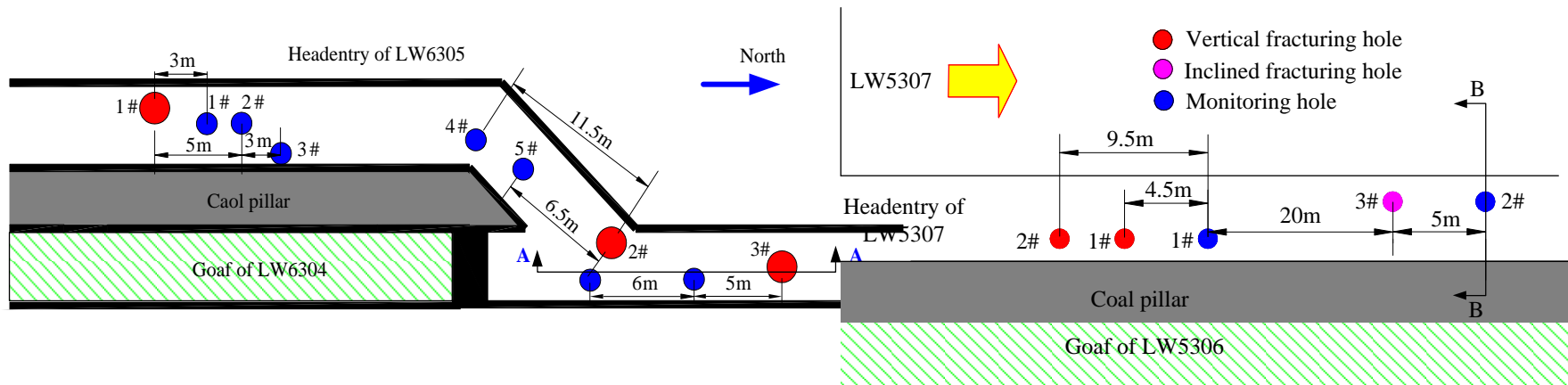
8.3) 高压定向水力致裂技术



State Key Laboratory of Coal Resources and Safe M



应用：防冲、强制放顶、护巷



8.3) 高压定向水力致裂技术



State Key Laboratory of Coal Resources and Safe Mining



□ 高压定向水力致裂——防冲、护巷

