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近距煤层巷道煤柱尺寸的优化设计

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摘　要:本文采用能描述岩体大变形特征的几何非线形程序 FLAC^{3D},以赵坡煤矿的地质采矿条件为依据,进行数值模拟研究,在极近距离煤层联合开采条件下,对巷道在单独开挖以及在工作面开采时巷道围岩的受力和变形特征进行了分析,得出了巷道煤柱留设尺寸为 3 m 时比较符合工程实际,对指导类似的工程施工有一定的借鉴意义。

关键词:FLAC^{3D};非线形大变形;近距煤层;优化
中图分类号:TD322　　**文献标识码**:A

极近距离煤层联合开采条件下,巷道煤柱留设一直是困扰煤矿安全生产的一个技术难题,巷道煤柱留设的合理性直接关系到巷道支护效果、煤矿安全生产,以及煤矿的经济效益。以往的数值模拟通常把空间问题简化为平面问题,应用二维的平面应变模型。而三维数值计算具有更客观、准确、形象等诸多优点是模拟空间结构受力及变形的重要手段。FLAC^{3D}是由美国 Itasca Consulting Group Inc. 开发的三维显式有限差分法程序,它可模拟岩土及其他材料的三维力学行为。FLAC^{3D}采用显式有限差分格式来求解场的控制微分方程,即首先由节点的应力和外力(或速度)变化和时间步长利用差分原理求节点不平衡力和速度;再根据单元的本构方程,由节点速度求单元的应变增量、应力(或是位移)增量和总应力,进而进入新的循环,并应用混合单元离散模型,可准确地模拟材料的屈服、塑性流动、软化直至大变形,尤其在材料的弹塑性分析、大变形分析以及模拟施工过程等领域有明显优势。

1　非线性大变形几何方程[2,3]

本文采用基于拖带坐标系法的 FLAC^{3D}程序进行数值模拟研究。由于经典小变形理论在计算发生大位移的平面问题时误差较大,甚至发生错误,在 FLAC^{3D}中给出了应用拖带坐标系计算大变形。陈至达教授提出了采用两个参照系统的方法来描述变形体的运动,其中一个为固定在空间的定系;另一个为嵌含在变形体中的动系,称为拖带坐标系。这种坐标系随着变形体的变形而拖带伸展、缩短、并引起坐标系的曲率改变。图 1 为一个连续变形体的大变形和大转动。随着时间的推移,A_0 连续发生变形,例如 $A_0(T_0) \rightarrow A(T)$。在 T_0 时刻,拖带坐标系$\{x^i\}$和固定坐标系$\{x^i\}$相同,即:$x^{i(0)} = x^i(x^i, T_0) = x^{i(0)}$,在 T 时刻,$x^i = x^i(x^i, T)$。

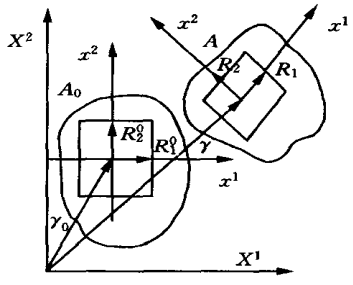

图 1　拖带坐标系

局部基矢 $\vec{g}_i^0 = \partial \vec{r}^0 / \partial x$; $\vec{g}_i = \partial \vec{r} / \partial x$。其中,$\vec{r}^0$,$\vec{r}$分别为变形体 A 在 T_0 时刻和 T 时刻每一点的局部矢量。

基矢 $\vec{g}_i^0$从未变形状态变为变形状态 $\vec{g}_i$,变形张量 F_i^j 为

$$\vec{g}_i = F_i^j \cdot \vec{g}_i^0 \qquad (1)$$

根据 $S-R$ 陈矢分解理论,

$$F_i^j = S_i^j + R_i^j = \text{应变张量} + \text{转动张量} \qquad (2)$$

有限应变张量

$$s_i^j = \frac{1}{2}(u^i|_j + u^j|_j^T) - (1 - \cos\theta) L_i^i L_j^k \qquad (3)$$

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有限平均局部转动

$$R_j^i = \delta_j + L_j^i \sin\theta + (1 - \cos\theta) L_k^i L_j^k \qquad (4)$$

局部转动的平均角

$$\theta = \arcsin\left\{ \frac{1}{2}\left[(u^1|_2 + u^2|_1)^2 + (u^2|_3 + u^3|_2)^2 + (u^3|_1 + u^1|_3)^2 \right]^{\frac{1}{2}} \right\} \qquad (5)$$

局部转动轴 $L = L^i \cdot g_j$

$$L_i^j = \frac{1}{2\sin\theta}(u_j|^i - u_i|^T) \qquad (6)$$

对于图 1 所示的滑动变形,运用大变形理论式(1)～(6)计算滑动体每一点的应变,进行合理性验证如下:

$$[s_j^i] = \begin{vmatrix} s_1^1 & S_1^2 \\ S_2^1 & S_2^2 \end{vmatrix} = \begin{vmatrix} \frac{\partial u}{\partial S_1} + (1 - \cos\theta) & \frac{1}{2}\left(\frac{\partial u}{\partial S_2} + \frac{\partial v}{\partial S_1} \right) \\ \frac{1}{2}\left(\frac{\partial u}{\partial S_2} + \frac{\partial v}{\partial S_1} \right) & \frac{\partial v}{\partial S_1} + (1 - \cos\theta) \end{vmatrix}$$

$$= \begin{vmatrix} \frac{\partial u}{\partial x} + (1 - \cos\theta) & \frac{1}{2}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) \\ \frac{1}{2}\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) & \frac{\partial v}{\partial y} + (1 - \cos\theta) \end{vmatrix} = \begin{vmatrix} 0 & 0 \\ 0 & 0 \end{vmatrix}$$

显然,利用拖带坐标系法建立非线性大变形几何方程,所获得结论非常合理。

2 计算模拟

2.1 模拟工作面的地质条件

赵坡煤矿位于山东省滕州市境内,矿井东临京沪铁路,公路四通八达。开采的 16、17 煤属于薄煤层,采深为 330～370 m,16 煤厚 1.05 m,17 煤厚 0.7 m,两煤层间距 6.5 m,考虑到经济效益,不能采取分层开采的方式,故采用联合开采、沿空留巷的方式。16、17 煤巷道不仅受本工作面的采动影响,而且还承受下区段工作面的重复采动影响,且两煤层间距很小,此外 17 煤的开采还受到 16 煤开采的影响。16 煤与 17 煤重复采动后,巷道围岩变形量大,破坏严重,需要不断维修,严重影响正常生产与安全。为了尽可能减少巷道围岩变形量、提高安全生产环境、确保经济效益,故进行巷道煤柱留设尺寸的研究是十分必要的。

2.2 计算模型

本计算分析中共设计 15 个计算方案:巷道的煤柱留设尺寸分别为 2、3、4、6、8 m,且每个不同的巷道煤柱留设尺寸分别对应 30、40、50 m 的联合开采错距,本文仅对联合开采错距为 50 m 时的 5 个方案进行分析,分别记为 Ⅰ、Ⅱ、Ⅲ、Ⅳ、Ⅴ方案。

2.2.1 模型建立与计算区域网格划分

计算模型不考虑地质构造、地下水活动等的影响,原岩应力为大地静应力场,各岩层为整合接触的连续介质。为消除边界影响,计算模型几何尺寸为沿走向(Y)取 140 m,深度(Z)取 50 m,倾斜方向(X)取 300 m,巷道跨度 3 m,高 1.8 m。根据现场地质条件,应力条件考虑埋深 350 m 的静水应力状态,垂直应力取 5.6 MPa,水平应力取 2.8 MPa,模型走向、倾斜方向均施加水平约束,底边界施加垂直约束。围岩力学性质见表 1,本构关系采用摩尔——库仑模型。由于要分析开采前后采动附加应力及位移的变化,因此开采过程采用一次性换填材料式开挖模拟采空区冒落矸石[4]。计算对象为无支护的裸巷,其计算范围和网格划分见图 2。

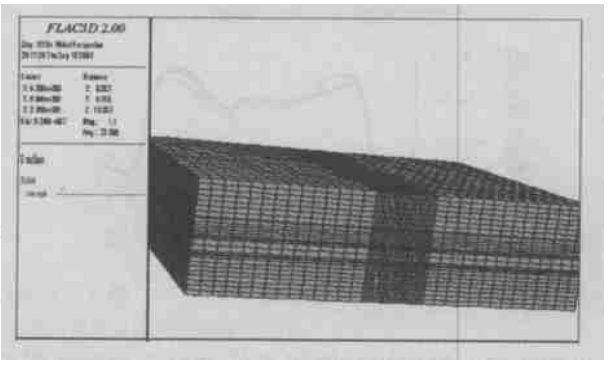

图 2 计算模型的网格划分

2.2.2 数值计算过程

首先模拟原岩应力状态,因本次计算只考虑采动应力的影响,所以在达到原岩应力平衡时,进行位移归零,然后进行巷道开挖,观察巷道围岩的最大主应力及所产生的塑性区域变化,接着进行模拟工作面的开挖,当采空距离等于联合开采错距时进行采空区充填,依次循环,直至模拟开挖结束。

2.3 数值计算结果

计算中考虑巷道为一次性开挖,工作面的开采以 10 m 为一开采布局,计算以时步控制,按每 2000 时步为一个计算时段。

2.3.1 工作面开采前巷道的计算结果

巷道煤柱尺寸为 3m 时的 16、17 煤巷围岩的塑性区域图及最大主应力色谱图分别为图 3(a)、(b)所示。

从上述结果可知,巷道的变形轮廓成对称分布,与实际变形轮廓相近。在计算到 2000 时步时可见,顶部中心的垂直位移以及计算单元节点间的最大不平衡力都有明显的收敛迹象。巷道周边的破坏区域不是很大,且最大主应力值对称分布在巷道的两帮,与实际结果相符。

2.3.2 工作面开采后巷道的计算结果

工作面开采后,五种方案下 17 煤巷道底板沿

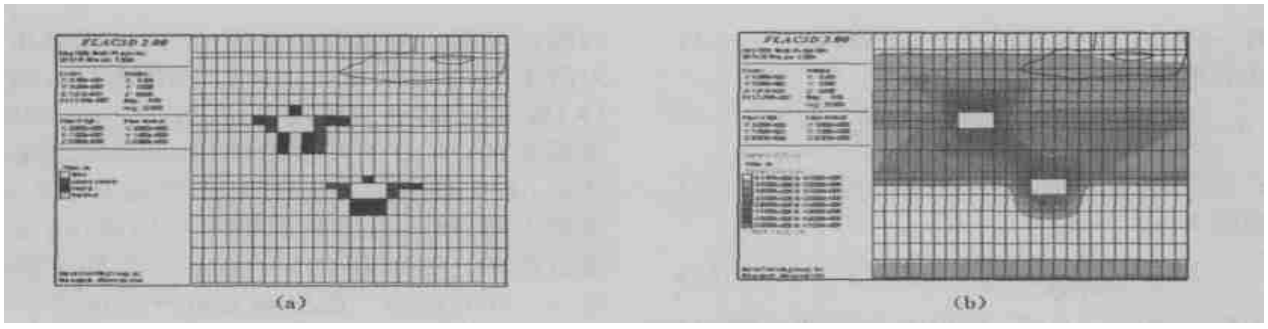

图 3　开采前巷道计算结果

(a) 巷道围岩的塑性区域图;　(b) 巷道围岩最大主应力色谱图

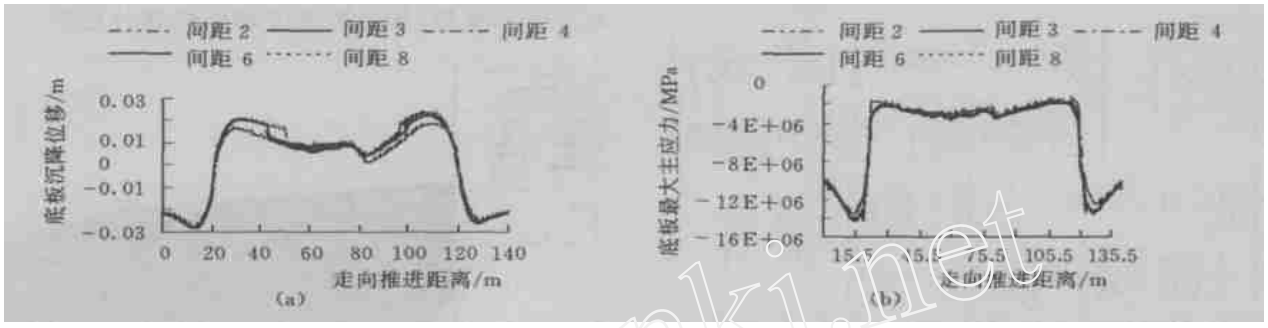

图 4　开采后位移应力计算结果

(a) 17 煤巷底板的位移曲线图;　(b) 17 煤巷底板的最大主应力曲线图

走向方向上的位移曲线图及最大主应力曲线图分别如图 4(a)、(b)所示。

从图知,每种方案中无论是底板位移还是最大主应力都成"马鞍型"分布及与中间轴呈对称分布,巷道的两端有较大的位移及应力,中间部分较小且平缓。模拟结果与工程实际能很好的吻合。从位移曲线图可知,随着巷道间距的减少,巷道两端的底鼓有减少的趋势,但第 I方案巷道中部的底鼓位移比其它方案的位移量都大,故此方案不可取。从图 4(b) 17 煤巷底板的最大主应力曲线图中可知,第 III、IV、V方案应力释放较大,巷道破坏也较严重,因此通过本次模拟认为第 II方案为最优方案。

表 1　各岩层物理力学参数测试表

岩层	厚度 /m	体积模量 K/ GPa	剪切模量 G/ GPa	密度 ρ/ kg·m^{-3}	粘聚力 C/ MPa	抗拉强度 σ_t/ MPa	摩擦角 F/ (°)
砂泥岩	32	2.19e9	7.84e8	2350	0.5	0.5	40
灰岩	6.45	2.78e9	1.59e9	2650	2.3	0.8	48
泥岩	1.6	1.33e9	6.15e8	2200	0.2	0.25	35
煤	1.75	3.81e8	3.48e8	1570	0.2	0.15	31
泥质砂岩	8.2	1.73e9	1.14e9	2300	2	0.75	48
采空区		3.6e6	1.9e6	1000	0.035	0.05	25

3　结论

(1) FLAC^{3D}能对单元进行离散化处理,使得单元尽可能多,分析更精确,自适性强,有强大的图形后处理能力,它采用了基于显示有限差分法的拉格朗日算法,使它在分析岩土工程结构的弹塑性力学行为、模拟工程施工工程等方面有独到的优势,尤其在发生塑性流动或工程失稳的情况下,采用大变形模式,更能反映客观实际,这较其它方法有很大的优势。

(2) 本文采用 FLAC^{3D}中的大变形模式,对巷道间不同的间距进行对比模拟分析,得出了在一定距离内煤柱越宽巷道受力越大,以及在此种地质条件下,开采巷道的煤柱留设尺寸为 3 m 时较符合工程实际。

(3) 对工作面开采前后巷道进行分析可知,与巷道的实际发生的变形破坏基本一致,较好地揭示了巷道的受力、变形特征,同时也说明了模拟计算的正确性。

(4) 本文的研究结果对于与此近似的地质条件下的工程施工,具有一定的指导意义和参考价值。

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矿山压力与顶板管理

ENGLISH ABSTRACTS

Simulation of the time-dependent behavior of soft rock roadway ——LU Ai-hong etc.

For the distortion and displacement of the soft rock roadway affect importantly on the stability of the whole structure, whether the rheologic behavior is calculated and simulated rightly or not is important to the choice of supports and surrounding control system. It is applied ANSYS software to analysis distortion and stress distribution on the different pressure condition. The study conclusion provides the important foundation to the supports of the surrounding.

Numerical analysis of layered medium's influence on the stability of cracked surrounding rock ——WANG Lu-ming etc.

The multi-domain boundary element method is used to solve the laneway cracked surrounding rock problem with single cranny in the layered medium. The sub-regions are obtained by dividing the region along the cranny and the interface. The boundary integral equation is established in each sub-region. The traction singular quarter-point elements are collocated in the tip of the cranny. For the splay or closed cranny, not only the regularity of displacement but also the 1/ regularity of stress in the region of the cranny tip are modeled. Qua the target, the stress intensity factors are calculated. According to the rock fracture mechanics theories, the influence of the following factors on the stability of a cracked surrounding rock is analyzed systematically: modular ratio of the mediums, the friction factor on the cranny surface for different modular ratio, the distance between the center of laneway and the horizontal interface, the obliquity angle of the interface. And some valuable conclusions are obtained. This analysis method is suitable for the laneway with optional geometric shape.

The failure and unstability analysis of roadways of lithological characters weak structure ——FAN Ke-gong etc.

To the structure characteristic of bedded rock of coal measures, this paper puts forward the concept of lithological characters weak structure and weak structure body; analyses the deformation characteristic and loss-stability mechanism of surrounding rock of roadway of lithological characters weak structure, and discusses the loss-stability model in roadside weakness structure body. There is certain reference value to the project practice in its result.

Analysis on support effect of self-moving ahead support ——SHI Yong-kui etc.

This paper introduced the main character and technical parameter of self-moving ahead support, and gave a analysis on the support power of this kind of support. The theoretic analysis and field-survey of mine-pressure prove that the structure of self-moving ahead support designed is reasonable, it's performance is stable, and it is safe and credible. It has a great generalizing value in those coalmine of having a proper condition.

Mechanical deformation and stress analyses of the narrow pillar of road driven along next goaf for fully-mechanized top-coal caving face ——LI Shun-cai etc.

In terms of mechanical surroundings of the road driven along next goaf for fully-mechanized top-coal caving face, an elastic-plastic mechanical model of the narrow pillar is established. By variation principle of total theory of plasticity, the distribution characteristics of the displacement and stress in the narrow pillar are discussed, and the distribution laws of the displacement field and the stress field in the narrow pillar are obtained preliminarily. The results can provide a theoretical basis for the study on the stability and the control of the narrow pillar.

The optimizing design of pillars measure of ally exploitation laneways in the very close quarters coal seams ——ZHANG Pei-sen etc.

According to the geological and mining conditions of Zhaopo coal mine, and using the FLAC^{3D} program which can describe the geometrical non-linear big deformation characters of rock mass, the paper performed numerical simulation research, analyzed the deformation characters and stress of the laneways under the conditions of single excavation and opening working face and of ally exploitation laneways in the very close quarters coal seams, and drew the conclusion that the 3m of pillars measure of exploitation laneways is up to the project mustard, and can be used for reference by other construction of the homothetic projects.

The study of dynamic supported technology of bolt with grouting and cable in Renlou coal mine ——XUAN Yi-qiong

By the investigation of the failure form and character of the winning headway which is affected by dynamic pressure in Renlou coal mine, this paper analyzes the reasons of supported failure and brings up the dynamic supported principle and stepped reinforcing technology of the soft rock roadway affected by dynamic pressure. By ways of analysis, the project of dynamic stepped reinforcing technology is optimized, that is guniting in time, bolting on time, grouting out of time and cable anchor enhancement. It is tested underground that applying the supported technology of bolt with grouting and cable to support new digging roadway and repair and reinforce dug roadway not only keep the roadway's stability, decrease the quantity of repairing roadway but also obtain optimistic economy performance of technique.

The numerical simulation of the support parameter of single-truss used to support the roof ——QU Hua etc.

This paper demonstrated the relation between support effect and parameter of single-truss used in the roadway of fully mechanized top coal caving face, in the method of numerical simulation to achieve the rational support parameter. It was the better support way to the length 2.0～2.2m, the angle 60°, the distance 0.2m between the roadway and the collar, and one vertical anchor bolt in the middle of the truss. This paper provided the basis for the support design and the application of the single-truss.

Analysis of sand inrush generation condition in coal mining of shallow coal seam ——WU Yong-ping etc.

Disaster of water inrush and sand inrush in shallow seam mining area in Western China has become one of the key questions that impact the safe and regular production. In this paper, by giving out the mechanics model of sand pseudo structure, based on laws of sediment Incipient motion, the forces on sand granule before sand inrush have been researched; and, according to the height of water, a theoretical formula of sand inrush generation condition was founded. Thus the theoretical reference for prediction of sand inrush was offered.

Strata pressure of combining mining in steep and close seams ——QI Tao etc.

There are more than 30 layers steep seams in the Urumqi coal mine, in which many groups seams in south section, such always is the difficult problem in caving. Sublevel caving with combining mining in the close seams have developed in such kind of seams these years, mostly observing harvest of mining stress are introduced and fringe analysis has done with three-dimensions numerical simulation in this paper.

The blasting parameters of compulsive roof cave-in for difficult-to-collapse roof in shallow seam ——LU Jun etc.

The mechanics intensity of roof in the Yu-Sheng Coalfield is not great, it belongs to the non-hardy roof. The ground pressure characteristic in the shallow seam is shallow burying, violent ground pressure, the working face always emerge massive collapse of the main roof at the first weighting. The individual jacks can not dispute the pressure which is caused by the overburden's holistic collapse and the massive collapse of the main roof. Based on the intermittent mining method of certain Coal Mine, the paper brought forward the compulsive roof cave-in method through confirming reasonable blasting parameters, achieved the continuous mining in the individual jacks longwall face.

Automatic measurement of deformation of the similar material model using image processing ——CAI Li-mei etc.

An algorithm based on area search matching was proposed. The algorithm used color information of measure points to find image grids and to measure the displacement in similar material experiment. The method was an un-touching measurement, and didn't to make special initial point. It could automaticly create searching criteria during the processing. The method was rapid and reliable. It could solve the interference problem in traditional auto grid methods and avoid the mismatching when the measure points go down to the next line of measure points.