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高应力煤巷围岩控制关键技术研究

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摘要:针对深井高应力煤巷帮部煤壁整体偏移、锚杆剪切破断、巷道围岩变形剧烈等支护难题,以城郊矿二水平西翼回风大巷为工程背景,采用 YTJ-20 型岩层探测记录仪实测、微梯形与矩形断面巷道力学结构分析、FLAC^{3D}数值模拟及现场试验监测分析相结合的方法,观测了巷道围岩裂隙演化规律,探究了不同地应力、侧压系数对巷道稳定性的影响特征,并提出了微梯形断面巷道支护设计方案。研究结果表明:煤巷呈大松动圈发育特征,围岩碎胀变形范围大、变形持续时间长、支护难度大,高地应力是其主要影响因素;力学结构对比分析表明微梯形断面受力小于矩形断面巷道,有利于增加巷道的抗冲击性;数值模拟显示微梯形巷道应力集中、塑性区发育范围及围岩变形量相较于矩形煤巷均有所减小,尤其帮部位移减小量明显,微梯形巷道断面有利于巷道围岩稳定性控制。断面形状优化设计及合理支护技术是实现高应力煤巷围岩变形有效控制的关键。结合现场深井高应力煤巷围岩条件,基于悬吊理论与数值模拟优化确定了微梯形巷道合理支护设计参数,跟踪监测结果显示巷道顶板下沉量达到 20 mm 时趋于稳定,两帮移近量为 82 mm,底鼓量为 126 mm,表明深井高应力煤巷顶板采用锚网带+锚索梁、帮部采用锚网带的联合支护方案的围岩控制效果良好,可满足深井高应力煤巷长期稳定要求。

关键词:高地应力;煤巷;断面形状;围岩稳定性控制

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Research on key control technology of surrounding rock in high stress roadway

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Abstract: Coal roadway in deep buried depth with high stress conditions has many difficult support problems, such as overall rib deformation, anchor bolt shear fracture, which seriously restricts the continuation of mining and tunneling, and affects the safe and efficient mining. Taking the Level-II west wing return-air roadway of Chengjiao Mine as the engineering background, the evolution law of surrounding rock fissures of the roadway is observed by YTJ-20 type on-site rock formation detector, the design of slight-trapezoidal shape roadway is proposed by mechanics model analyses theoretical of slight-trapezoidal shape and rectangular shape, FLAC^{3D} software is used to simulate the plastic zone evolution and deformation characteristics in surrounding rock under different ground stress conditions. The results show that: the surrounding rock has a large loose circle of rock, including large deformation range, fast initial deformation, long deformation duration and difficulty in supporting, high geo-stress is the main reason for the deformation and failure of the surrounding rock. The stress structure analysis shows that the force of the micro-trapezoidal shape has a relatively lower stress, which is beneficial to increase the impact resistance for the roadway, and also has a better surrounding rock control effect. The slight-trapezoidal shape has a relatively lower stress, which is beneficial to increase the anti-shock resistance for the roadway, and also has a better surrounding rock control effect. The

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roadway in slight-trapezoidal shape has a lower stress concentration, plastic zone and deformation than rectangle shape, especially the displacement of the side was significantly reduced, which is helpful for the stability control of the deep buried roadway with high geo-stress. The optimized shape design and reasonable support technology are the key to realize the effective control of surrounding rock deformation in high geo-stress coal roadway. Combined with the surrounding rock conditions of high stress coal roadway, the reasonable support parameters were determined based on suspension theory and numerical simulation. The tracking monitoring results show that the roof sinking reaches 20 mm and tends to be stable, two rib deformation reaches 82 mm, and floor heave is 126 mm, indicating that the deep well high stress coal roadway is designed as a micro-trapezoidal section, the roof plate adopts the anchor net belt + anchor cable beam joint support scheme, and the rib is supported by anchor net belt support. The rock control effect is good and can meet the long-term stability requirements of coal roadway.

Key words: high stress; coal roadway; section shape; surrounding rock stability control

0 引言

随着煤炭开采强度的不断提高,我国煤矿以8~12 m/a的速度向深部发展,许多矿井陆续进入深部开采,深部巷道呈现高地应力、岩层胶结性差、松散破碎等特征^[1-3],加之采掘生产设备趋向于大型化,对巷道断面尺寸提出了更高的要求,尤其是巷道断面设计不合理时,围岩变形严重,巷道难以满足安全高效开采需要^[4-5]。针对深部巷道断面形状及围岩稳定性控制问题,国内外学者进行了相关研究并取得了一系列成果。李桂臣等^[6]对巷道断面形状进行了数值模拟,提出了巷道支护“等效开挖”和“无效加固区”的概念;孟庆彬等^[7]针对不同断面形状的巷道进行优化设计,确定了深部高应力巷道最优断面形状;张百红等^[8]采用空心包体应力解除法实测了深井巷道地应力,分析了地应力对巷道稳定性的影响特征;付强等^[9]研究了巷道截面形状对围岩变形、压力和塑性区分布的影响规律,指出梯形巷道两帮受压均匀、水平位移最小;王沉等^[10]针对淮北矿区深部“三软”煤层工作面半圆拱梯形巷道超前支护难题,进行了断面优化设计;王方田等^[11]分析了松软破碎围岩巷道变形特征及关键影响因素,建立了巷道围岩结构力学模型,探究了巷道应力与塑性区演化规律,优化设计了全断面注浆加固技术参数;赵宾等^[12-13]对高强度重复采动作用下矩形巷道围岩应力演化与变形特征进行了研究;王卫军等^[14-15]针对深部高应力巷道围岩大变形问题,采用Kastner等理论研究了支护阻力对深部高应力巷道围岩变形的影响特征,提出了巷道围岩稳定性新支护理念。宋卫华等^[16]分析了采动矿压与正断层上盘正应力的关系,提出了大断面矩形巷道过断层的安全措施;吴建星等^[17]将高应力厚煤层动压巷道围岩看作一个整体承载结构,提出采用顶帮强力锚杆锚索与底板预应力全长锚固注浆锚索联合支护技术;刘泉声等^[18]在淮南矿区深部岩巷地应力场与支

护基础上,提出了高应力岩巷超高强锚杆支护及辅助注浆、能量释放控制措施。杜华溢等^[19]模拟研究了非均匀应力对巷道围岩应力和变形破坏特征的影响,提出了不同围岩条件的巷道支护对策。陈新年等^[20]探究了倾斜煤层直角梯形巷道围岩应力的分布规律及破坏特征。上述研究多集中于巷道断面形状及巷道支护问题,而对深井高应力巷道变形机理及控制技术研究较少,尤其是高应力煤巷断面形状优化设计及围岩控制技术。城郊矿二水平西翼回风大巷处于高地应力环境,采用矩形巷道布置,煤壁发生整体偏移、剪断锚杆,巷道支护效果不佳,造成采掘接替紧张。针对上述问题,以二水平西翼回风大巷为背景,对巷道围岩结构及应力变化规律进行系统研究,提出巷道断面形状优化方案及合理围岩控制技术。

1 工程概况

城郊矿二水平西翼回风大巷反掘段平均埋深836.6 m,巷道沿二₂煤层顶板掘进,为煤层大巷。二₂煤层厚度为2.6~4.5 m,平均3.2 m,煤层倾角3°~10°,平均6°。煤的普氏系数 $f=0.9\sim1.0$,层理、节理较发育。基本顶岩性为砂质泥岩,厚度2.55~5.20 m,平均3.94 m,属于较稳定岩层;直接顶主要为细粒砂岩,厚度1.40~2.72 m,平均2.06 m;伪顶为厚度0.43 m泥岩;底板主要由砂质泥岩和粉砂岩组成。煤岩层物理力学参数见表1。

表1 煤岩力学参数

Table 1 Coal and rock mechanics parameters

| 岩性 | 体积模量/ GPa | 剪切模量/ GPa | 内摩擦角/ (°) | 黏聚力/ MPa | 抗拉强度/ MPa | 密度/ (kg·m ⁻³) |
|------|--------------|--------------|--------------|-------------|--------------|------------------------------|
| 砂质泥岩 | 4.3 | 2.6 | 32 | 4.0 | 2.1 | 2 400 |
| 煤层 | 1.7 | 1.0 | 28 | 1.0 | 0.8 | 1 600 |
| 泥岩 | 3.2 | 1.8 | 30 | 1.1 | 1.5 | 2 000 |
| 细粒砂岩 | 8.0 | 4.0 | 35 | 3.5 | 2.8 | 2 700 |

巷道初步设计采用矩形断面,围岩变形严重。采用 YTJ-20 型岩层探测记录仪进行围岩结构观测,各测点顶孔观测结果如图 1 所示。

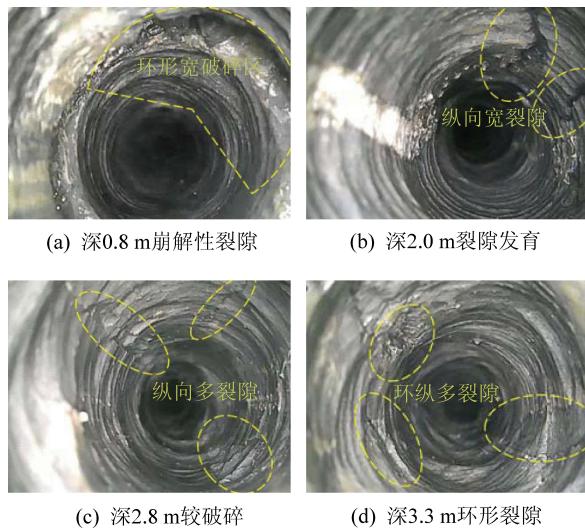


图 1 深井巷道顶板裂隙发育

Fig.1 Roof fracture development in deep roadway

围岩松动圈探测表明二水平回风大巷围岩呈大松动圈发育特征,围岩碎胀变形范围大、初期围岩收敛变形速度快、变形持续时间长、支护难度大,巷道松动圈分布特征如图 2 所示。

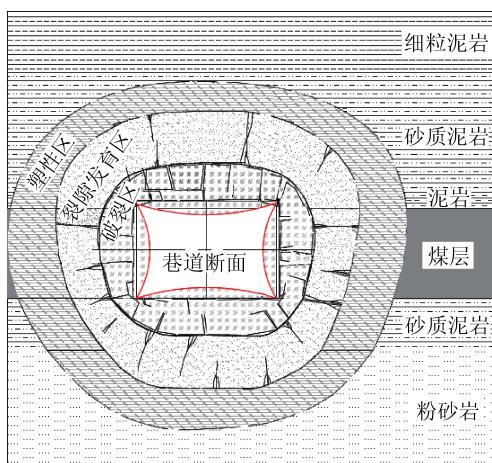


图 2 巷道松动圈分布特征

Fig.2 Distribution characteristics of loose surrounding around roadway

现场探测结果表明,高应力作用下煤巷变形呈现以下特征:①巷道围岩受高应力作用效应明显。巷道埋深大,地应力测试表明最大主应力达到 22.3 MPa,处于高应力水平,水平应力对巷道顶、底板的影响具有明显方向性,高地应力是巷道围岩产生变形破坏失稳的主要原因。②巷道帮部煤体变形显著。表现为靠近巷道煤壁处煤岩体发生整体偏移,处于煤体内的锚杆发生剪切破断,支护效果差。③底鼓严重。回风大巷底板未支护,在两帮煤体发生整体偏移的过

程中,应力不断向底板转移,底板区域应力集中,使得巷道底板向上隆起,发生严重的底鼓现象。

为改善巷道围岩控制效果,提出在矩形巷道基础上使其两帮向外倾斜一定角度,呈微梯形断面形状布置,尝试通过优化巷道断面实现高应力煤巷围岩稳定性控制。

2 巷道围岩力学分析

巷道开挖后,煤体原有应力的平衡状态被破坏,围岩应力重新分布,巷道两帮受侧向均布载荷作用,其围岩应力分布情况如图 3 所示,其中, a 为矩形巷道宽度; b 为巷道高度; c 为梯形巷道底板宽度; θ 为巷帮倾角。

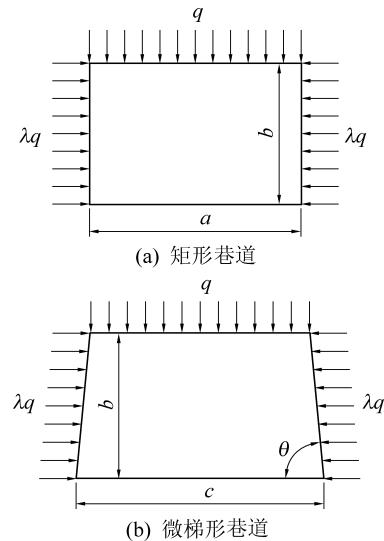


图 3 巷道力学模型

Fig.3 Mechanical model of roadway

矩形巷道中顶板均布载荷设为 q ,两帮考虑侧压影响受力设为 λq ,垂直巷道帮部力为

$$F_1 = \int_0^b \lambda q dx = \lambda qb \quad (1)$$

其中: λ 为侧压系数。同理对微梯形巷道进行力学积分:

垂直巷道帮部的分力为

$$F_1 = \int_0^b \lambda q \sin \theta dx = \lambda qb \sin \theta \quad (2)$$

沿巷道帮部的分力为

$$F_2 = \int_0^b \lambda q \cos \theta dx = \lambda qb \cos \theta \quad (3)$$

由矩形和微梯形受力可知:①在垂直巷帮方向上矩形巷道受力为 λqb ,微梯形巷道受力为 $\lambda qb \sin \theta$,微梯形受力小于矩形巷道;②梯形巷道沿巷道帮部向上的作用力为 $\lambda qb \cos \theta$,当顶板来压强烈时,作用于帮部的力与沿巷道帮部力起到一定平衡作用,减少帮部受力,在一定程度上可

增加巷道的抗冲击性,微梯形巷道比矩形巷道具有更好的围岩稳定效果。

3 煤巷围岩稳定性数值计算

3.1 不同地应力下巷道变形模拟分析

地应力测试结果表明西翼回风大巷为高应力巷道。高应力巷道围岩力学特征与浅部不同,浅部巷道围岩在低围压作用下主要表现为弹性力学性质,而深部巷道围岩地质条件复杂,处于“三高一扰动”

环境中,围岩的力学性质由弹性向延塑性转化,使得巷道围岩变形严重。为探究400、600、800、1 000 m不同埋深条件下巷道稳定性,设计了4种不同地应力:10、15、20、25 MPa,建立FLAC^{3D}数值模型,尺寸:长×宽×高=50 m×20 m×50 m,模型限制侧向和底部的位移,在上边界分别施加相应地应力补偿。本构模型采用摩尔-库仑模型,矩形巷道宽×高为5.2 m×3.2 m。巷道围岩塑性区、应力及变形结果如图4—图6所示。

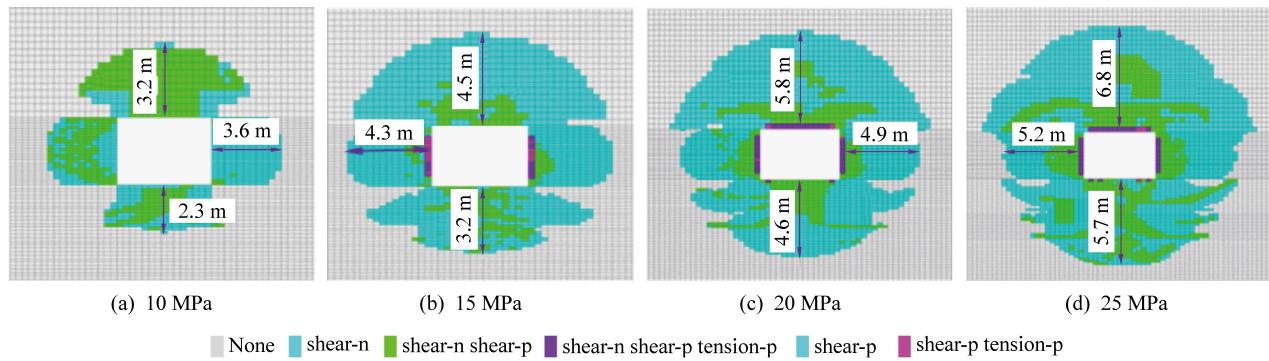


图4 不同地应力时巷道围岩塑性区分布特征

Fig.4 Plastic zone distribution of roadway surrounding rock with diverse geo-stress

由图4可知:①随着地应力增加,巷道塑性区发育范围逐渐增大,帮部塑性区在增至一定程度后,变化幅度减缓。②在地应力为10 MPa时巷道围岩全部表现为剪切破坏,帮角处不明显;随着地应力的增加,巷道帮部围岩处出现拉剪破坏,顶底板及帮部塑性区逐步贯通。③随着地应力增加,底板围岩拉剪破坏加剧,将出现严重底鼓现象。由图5可知:①巷道帮部垂直应力呈“增大→下降→稳定”趋势;②随地应力增加,峰值至煤帮距离越大,由4 m增至6 m;③垂直应力峰值随地应力增大而增大,分别为16.3、25.0、33.1、39.4 MPa,但增加幅度逐步下降。

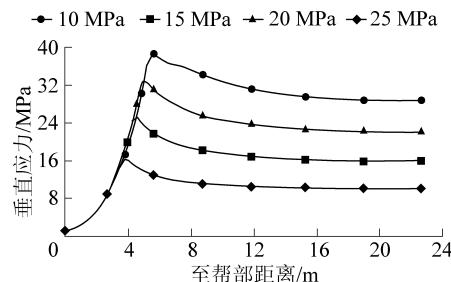


图5 不同地应力时巷道围岩应力变化

Fig.5 Stress of roadway rock with diverse geo-stress

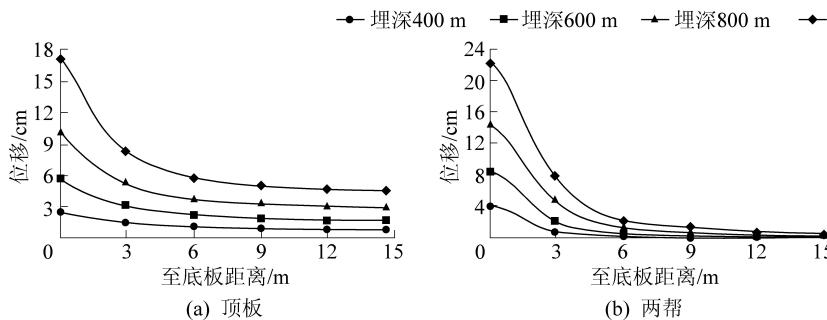


图6 不同埋深时巷道围岩变形

Fig.6 Deformation of roadway surrounding rock with diverse depth

由图6可知:随着地应力的增加,顶底板及两帮变形均呈增大趋势,顶板、底板及帮部位移量随至巷道表面距离的增加而减小,具有相似变化趋势。

3.2 巷道变形模拟分析

结合现场回风大巷地质条件,分别在矩形与微梯形巷道上边界施加载荷18.5 MPa模拟覆岩载荷,煤巷围岩应力及塑性区位移如图7、图8所示。

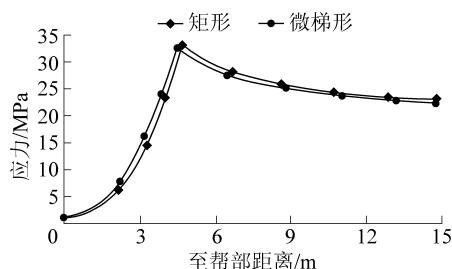


图 7 煤巷应力变化

Fig.7 Stress change of coal roadway

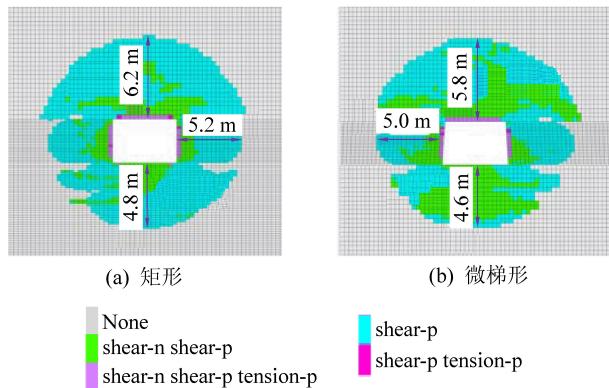


图 8 煤巷塑性区分布特征

Fig.8 Plastic zone distribution of coal roadway

由图 7 可知:矩形煤巷最大垂直应力为 33.3 MPa,微梯形煤巷为 32.6 MPa,减小了 0.7 MPa;矩形煤巷集中应力最大值在 5.2 m 处,微梯形煤巷在 4.7 m 处,应力集中范围相较于矩形有所减小。由图 8 可知:矩形与微梯形煤巷围岩塑性区发育特征类似,矩形煤巷顶板、底板及两帮发育程度分别为 6.2、4.8、5.2 m,微梯形煤巷相对分别减少了 0.4、0.2、0.2 m,整体稳定性较好。

为探究巷道开挖后围岩变形特征,垂直于巷道顶板、帮部与底板方向分别设置长度为 15 m 的 3 条监测线,各布置了 50 个监测点,不同断面形状巷道围岩变形监测数据如图 9 所示。

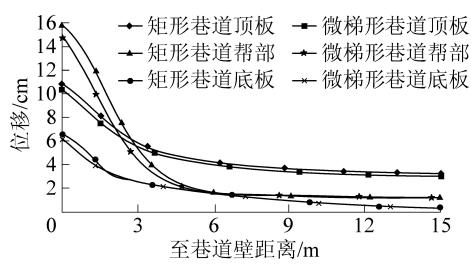


图 9 巷道围岩变形

Fig.9 Deformation of roadway surrounding rock

由图 9 可知:矩形巷道与微梯形巷道围岩表面位移的分布规律基本一致,顶板下沉量分别为 107.8、103.3 mm;底鼓量分别为 64.7、60.1 mm;两帮

移近量分别为 164.3、156.7 mm,相比矩形巷道,微梯形巷道的顶底板及帮部位移均有一定减小,尤其是帮部位移减小量明显。

3.3 不同侧压系数下巷道变形模拟分析

回风大巷属于高应力煤巷,水平构造应力大于垂直自重应力,增加了巷道矿压显现及巷道围岩破坏的剧烈程度,造成深部高应力巷道支护更加困难。矩形断面巷道承受侧压力的性能较差,梯形巷道断面顶板暴露面积较矩形小,可减少顶板来压,并能承受稍大的侧压。不同侧压系数下巷道围岩塑性区模拟结果如图 10—11 所示。

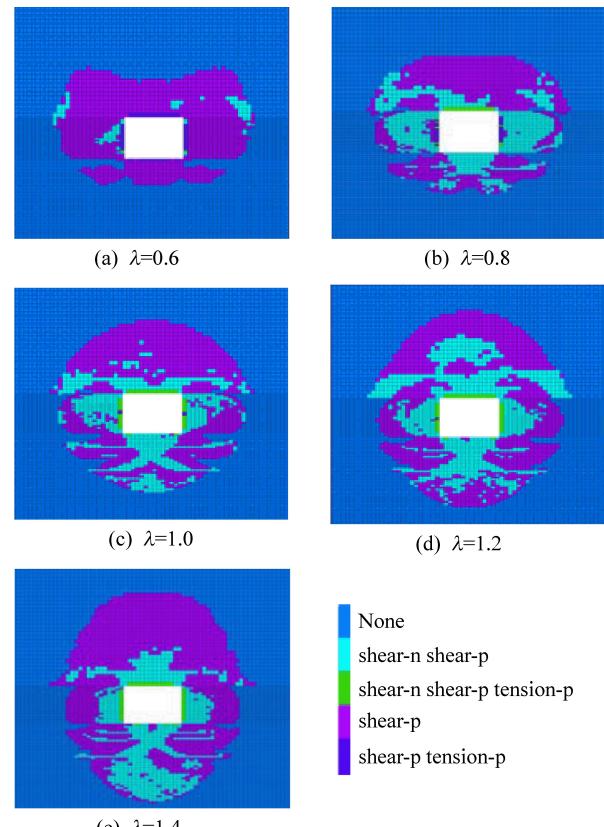


图 10 矩形巷道塑性区分布特征

Fig.10 Plastic zone distribution of recatangle roadway

由图 10、图 11 可知:①随侧压系数逐步增加,塑性区呈“蝶形”、“扁椭圆形”到“竖椭圆形”发展趋势,竖向塑性区范围呈递增趋势。②相同侧压系数下微梯形巷道塑性区发育程度略小于矩形巷道,表明微梯形巷道断面有利于巷道围岩稳定性。

4 巷道围岩控制技术及现场实践

4.1 巷道支护参数设计

针对深井高应力煤巷围岩变形特征,设计巷道断面为微梯形,断面尺寸为底宽 5.31 m,顶宽 5.11 m,高 3.20 m。运用悬吊理论,顶板采用锚网带+锚索梁联合支护方案,顶板锚杆采用 $\phi 22 \text{ mm} \times 2500 \text{ mm}$ 型高

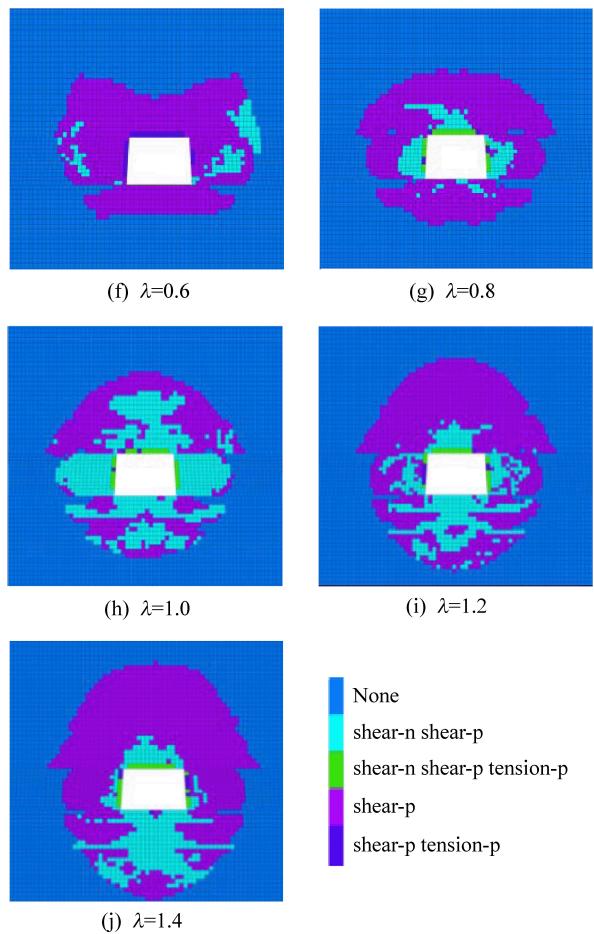


图 11 微梯形巷道塑性区分布特征

Fig.11 Plastic zone distribution of slight-trapezoidal shap roadway

强锚杆,锚杆间排距为 $750\text{ mm} \times 700\text{ mm}$ 。根据邻近巷道帮部支护工程类比,帮部采用锚网带支护,锚杆为 $\varnothing 22\text{ mm} \times 2500\text{ mm}$ 型高强锚杆,锚索直径 21.6 mm ,长度大于 4300 mm ,同排梁端距 900 mm ,配合钢筋网、M5钢带及M托盘支护,锚杆间排距为 $700\text{ mm} \times 700\text{ mm}$ 。顶板锚索规格: $\varnothing 21.6\text{ mm} \times 8200\text{ mm}$,间排距为 $1200\text{ mm} \times 1400\text{ mm}$ 。巷道支护如图12所示。FLAC^{3D}数值模拟结果如图13所示。

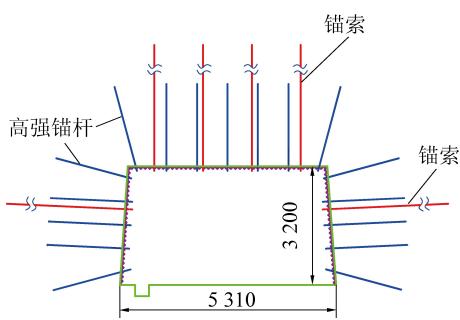


图 12 巷道支护设计

Fig.12 Profile of roadway support design

由图13可知,微梯形巷道在支护条件下顶板、底板及帮部塑性区发育程度分别为 4.0 m 、 4.4 m 、 3.8 m ,

较无支护状态减少了 1.8 m 、 1.2 m 、 0.2 m ,顶板与帮部塑性区发育程度显著降低。表明该设计参数可以实现高应力煤巷围岩变形有效控制。

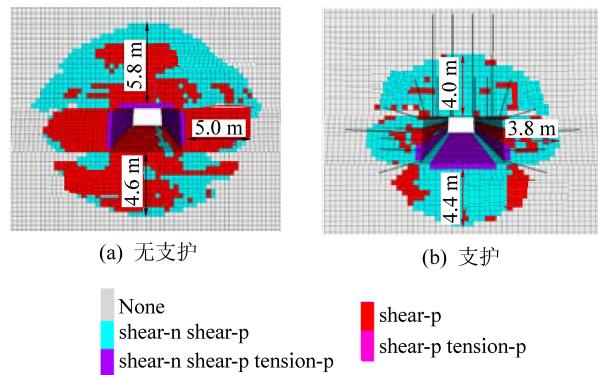
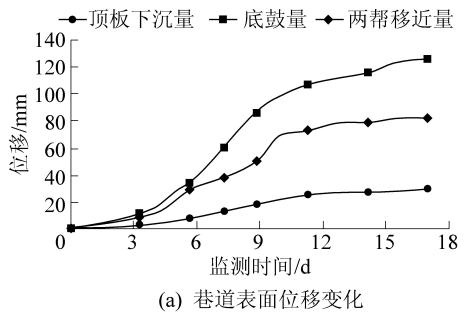


图 13 微梯形巷道塑性区分布特征

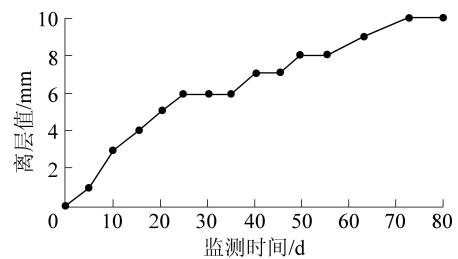
Fig.13 Plastic zone distribution of micro trapezoidal

4.2 现场监测分析

在回风大巷掘进过程中试验微梯形巷道断面形状及支护设计参数,现场采用LBY-3B型(丁字型)顶板离层仪监测顶板,并采用十字位移法每隔 50 m 设置1组“十字”观测点对顶板、两帮、底板位移进行观测,定期监测巷道的表面位移与顶板离层量,监测结果如图14所示。



(a) 巷道表面位移变化



(b) 顶板离层变化

Fig.14 Surrounding rocks displacement change with time

微梯形巷道围岩变形监测结果显示顶板变形速度相对缓慢,下沉量达到 20 mm 时趋于稳定,顶板离层量最大值 10 mm ,总体变形量较小。巷道两帮移近量为 82 mm ,底鼓达到了 126 mm ,表明巷道底鼓较严重,需加强底板治理。

现场监测表明巷道断面设计为微梯形,顶板采用高强锚杆,通过高预紧力充分调动围岩的自稳能

力,同时配合锚索及钢筋网护顶护帮强化支护,有效控制了顶板离层并抑制了围岩变形,对巷道围岩变形起到了很好的控制作用,能满足回风大巷长期稳定的要求。

5 结 论

1)现场探测分析了深井煤巷围岩松动圈发育特征,巷道围岩受高应力作用效应明显,围岩碎胀变形范围大,变形持续时间长、支护难度大,呈大松动圈发育特征。

2)为改善巷道围岩控制效果,提出了微梯形断面形状设计方案,力学结构分析表明微梯形受力小于矩形巷道,有利于增加巷道的抗冲击性,具有更好的围岩稳定效果。

3)采用FLAC^{3D}进行了矩形与微梯形断面对比分析,表明微梯形巷道应力集中、塑性区发育范围及围岩变形量相较于矩形煤巷均有所减小,微梯形巷道断面有利于巷道围岩稳定性。

4)现场进行了微梯形巷道试验,顶板采用锚网带+锚索梁联合支护方案,帮部采用锚网带支护,监测结果表明巷道围岩控制效果好,能满足回风大巷长期稳定要求。

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