In-situ measure to internal stress of shotcrete layer in soft-rock roadway

Shulin Fang · Jian Zhang

Abstract In order to solve the difficult conditions of soft rock, water-trickling and hard-maintain of main air-return roadway in Tarangaole Colliery, high pretensioned stress and intensive bolt-shotcrete support program was designed and mechanical property of shotcrete layer was specially monitored through utilizing a type of concrete stress meter with oscillating chord after the program was carried out. It was indicated that, due to rock pressure and support resistance, the interior of shotcrete layer would emerge diverse stresses in axial, radial and tangential directions. With time passing internal stresses in three directions, whose average values were −0.061, 0.043 and 0.517 MPa respectively, fluctuated first and then tended to stability slowly. The axial and radial stresses were relatively smaller than tangential stress which was 11, 12 times the two formers respectively. Along the section of roadway, axial and tangential stresses distributed symmetrically and increased gradually from the top of arch to the waist of wall, but reduced at the foot of wall. Radial stresses reduced from the top of arch to the waist of arch first, and then increased in the waist of wall. Axial stresses were tensile substantially, except for stresses in arch vault tending to compressive, but all the radial stresses were compressive. Nevertheless, tangential stresses in the wall were compressive and tangential stresses in the arch were tensile. During the period of roadway excavating, the stress of shotcrete layer was less than its ultimate bearing capacity, with no significant stress concentration. At the end of this article, some suggests are given to shotcrete support design.

Keywords Soft-rock roadway · Shotcrete layer · Internal stress measure · Oscillating-chord stress meter

1 Introduction

Bolt-shotcrete is considered as an effective and economical support to colliery roadway (He and Sun 2004; Jing and Li 2008). After the roadway is supported by bolt-shotcrete, it is very important to track and monitor the working status of bolt-shotcrete structure, especially the sprayed concrete layer (shotcrete layer), whose stress and deformation conditions are directly related to roadway safety. However,

there are few literatures about mechanical site-measure to shotcrete layer in colliery roadway, but a few ones in highway tunnel, railway tunnel, side slope, hydraulic tunnel, dam foundation and underground engineering (Lai et al. 2005; Jia et al. 2006; Li et al. 2007). Their measure tools and methods are more diverse and field data's are more useful, which can be a reference to shotcrete layer measure.

Soft rock, water-trickling and hard-maintain exist in main air-return roadway of Tarangaole Colliery in Erdos City. In order to overcome these difficulties, high pretensioned stress and intensive bolt-shotcrete support program was designed and mechanical property of shotcrete layer was specially monitored through utilizing concrete stress meter with a type of oscillating chord after the program was carried out in the roadway (Kang 2000; Li et al. 2007; Kang et al. 2007; Kang and Wang 2007). The measurement

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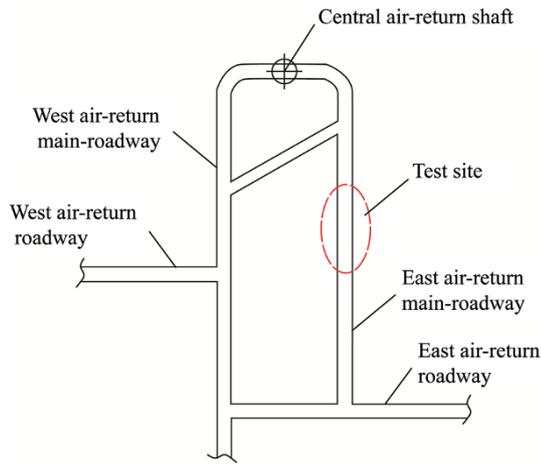
Fig. 1 Layout of measure roadway

items included internal axial stress, radial stress and tangential stress in shotcrete layer. Measure results showed that, during the period of roadway excavating, the stress of shotcrete layer was less than its ultimate bearing capacity and its deformation was also limited, those two aspects of which indicated that the high pretension press and intensive bolt-shotcrete support technology met the surrounding rock control requirements for main air-return roadway in Tarangaole Colliery.

2 Project overview

2.1 Production and geology conditions

Tarangaole Colliery is an constructing mine, designed shaft developing and plate extracting, whose industrial square sets out the main shaft, auxiliary shaft and central air-return shaft. Currently three shafts were fully completed and two main air-return roadways located in the east and west sides of air-return shaft are being tunnelled. This measure site is just selected in the part of east air-return main-roadway, whose layout is shown in Fig. 1.

East air-return main roadway is about 570 m depth, excavated along the roof of coal seam 3-1. Coal seam 3-1 is served as the main seam in Tarangaole Colliery, whose dip is 1°–5° and thickness is 0.21–6.50 m (average 2.91 m). The roof lithology of coal seam 3–1 is mainly sandy mudstone or siltstone, locally fine-grained sandstone or coarse sandstone and the floor lithology is mainly sandy mudstone. Average compressive strength of rock is 14.5 MPa, moisture content is 0.81 %–13.65 % and softening coefficient is 0.05–0.51. Specific lithologies of roof and floor are shown in Fig. 2.

Seam	Histogram (1:200)	Thickness (m)	Depth (m)	Lithology
18		22.2	553.6	Egg conglomerate
19		1.3	554.9	Mudstone
20		2.0	556.9	Coal
21		2.8	559.7	Mudstone
22		3.65	563.3	No.3-1 Coal
23		1.3	564.6	Sandy mudstone
24		0.5	565.1	Coal
25		0.9	566	Sandy mudstone
26		0.5	566.5	Coal
27		7.9	574.4	Sandy mudstone

Fig. 2 Rock comprehensiv histogram

2.2 Support program

The shape of east air-return main-roadway is designed to semicircle, wall height 1,800 mm, arch height 2,850 mm, bottom width 5,700 mm and basal area 23.0 m². According to the production and geology conditions, high-pretension-press & intensive & once Support theory and the
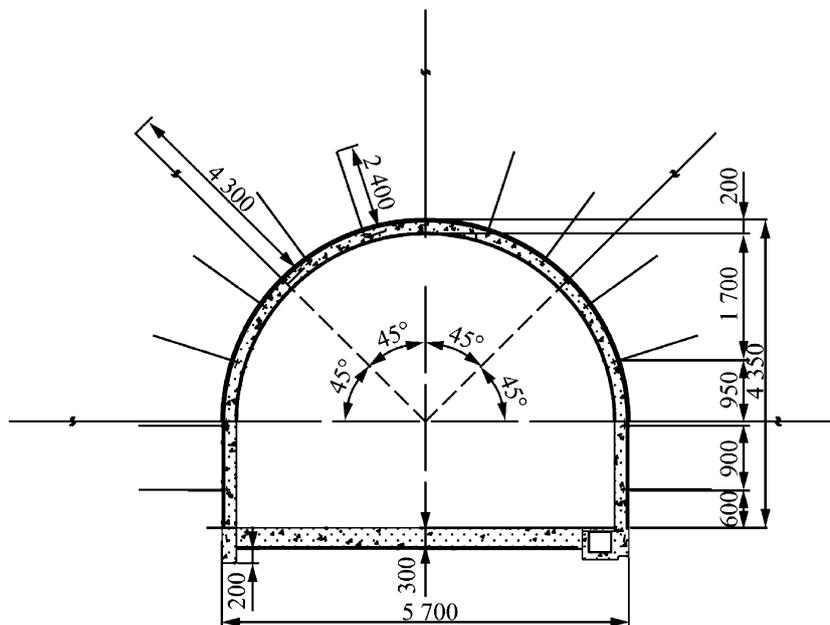
**Fig. 3** Sectional drawing of main air-return roadway support (Unit: mm)

requirements of specification (Kang 2000; GB 50086-2001; Kang et al. 2008, 2009), High Pretensioned Stress and Intensive Bolt-Shotcrete Support program is adopted. Specific parameters are as follows:

2.2.1 Bolt model

MSGLW-500/22 × 2,400, diameter: ϕ22 mm, length: 2.4 m, yield strength: 500 MPa, elongation: 20 %. 13 bolts are arranged in each row (arch arranged 9, wall arranged 2 on each side) and interval & row spacing is 900 × 900 mm. Anchoring method: elongated anchoring, two resin agents (MSK2335 + MSZ2360). Preload: initial tightening torque 400 N·m, anchoring force 190 kN or more. Set accessories: high strength vaulted tray, 150 mm × 150 mm × 12 mm; W-shaped steel plate: thickness 5 mm, length 450 mm, width 280 mm; steel mesh: ϕ16 mm; steel welded mesh, 100 mm × 100 mm, 2.0 m × 0.9 m.

2.2.2 Cable model

SKP18.9-1 × 19/1860/4300, diameter: ϕ22 mm, length: 4,300–5,800 mm (in accordance with the specific distance from coal seam 3-1 to egg-conglomerate), yield strength: 1,860 MPa, elongation: 4 %. Arrangement: arch arranged 5, spacing 2,180 mm, row spacing 1,800 mm; arranged 1 wall on each side, spacing 1,650 mm, row spacing 1,800 mm. Anchoring: lengthened anchor, three resin agents (MSK2335 + 2×MSZ2360). Anchor preload of each cable is not less than 250 kN.
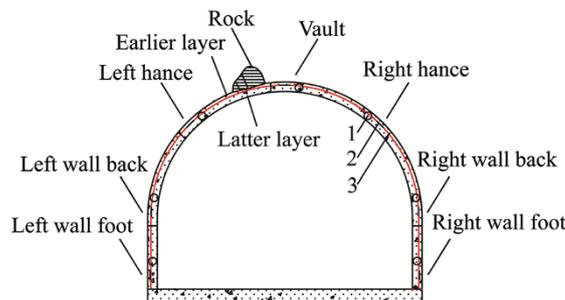
1–Axial stress meter; 2–Radial stress meter; 3–Tangential stress meter

Fig. 4 Measure points arrangement of measure section

2.2.3 Shotcrete mix

Cement:sand:gravel = 1:2:2, water-cement ratio: 0.4–0.5, jet thickness: initial spray 30–50 mm, re-spray 150–170 mm, design strength: no less than C25.

Figure 3 shows the support parameters.

3 Measure design

Due to rock pressure, the interior of shotcrete layer will emerge diverse stresses along the axis of roadway, perpendicular to roadway axis (i.e. roadway radial, Zheng 1988) and the peripheral tangential of roadway. In order to study the actual stress properties of shotcrete layer, a method of installing integrated measure stations is designed to monitor the three internal stresses (Wang 1988; Xu 2009; Li et al. 2010).

Axial stress meter   Radial stress meter   Tangential stress meter

(a) Step 1 Fixing stress meter

(b) Step 2 Shotcreting and burring stress meter   **(c)** Step 3 Leading wires and connectors
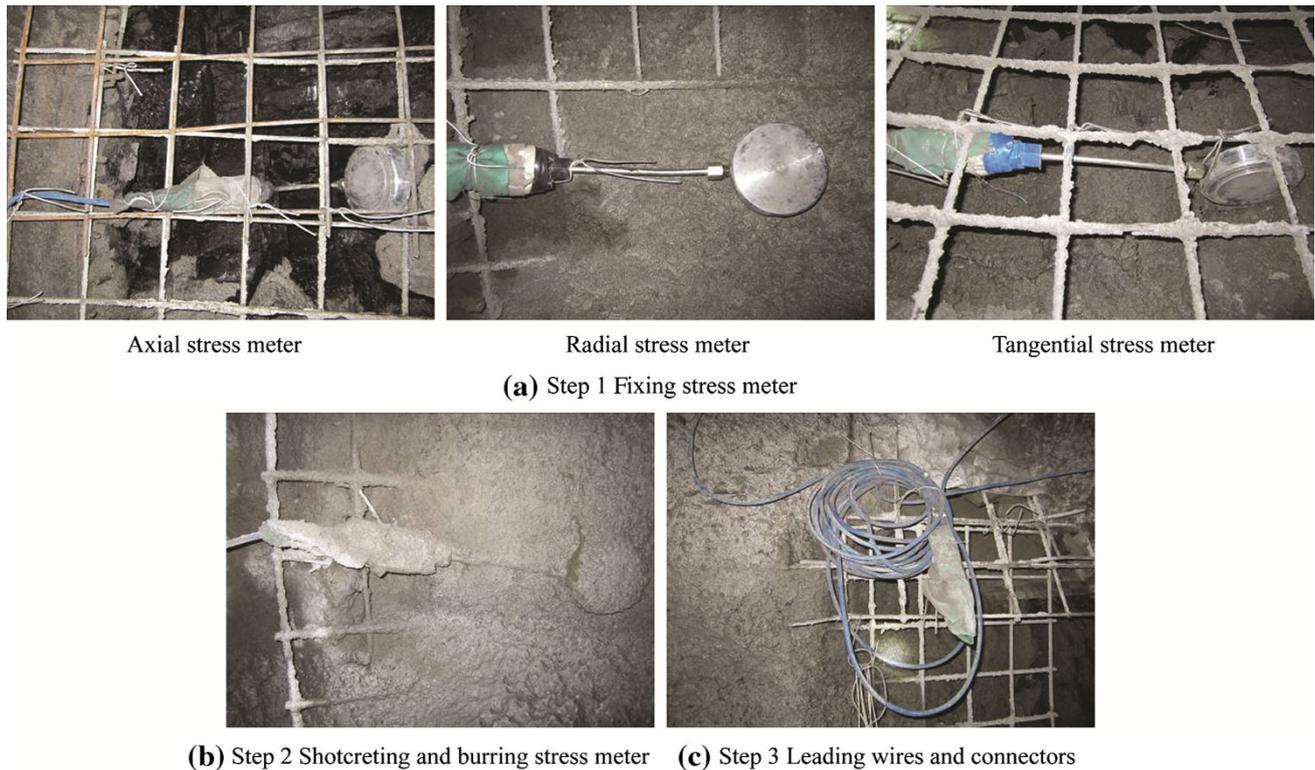
Fig. 5 Photos of stress meter installation process

3.1 Measure section arrangement

According to the underground tunnel conditions and measure purposes, measure stations are set at 35 m distance from the ingate in east air-return main-roadway (variable slope segment of roadway). Seven measure points are arranged on the vault, left & right hances, left & right wall backs and left & right wall feet of each Sect. 3 direction stresses (axial stress, radial stress and tangential stress) are monitored at each point. Figure 4 shows measure points arrangement of one section.

3.2 Measure content, instrument and method

The contents of this measure test are shotcrete layer internal axial stress, radial stress and tangential stress, including stresses variation with time and spatial distribution patterns.

GSJ-2A concrete stress meter with oscillating chord is utilized as measure instrument. This type of stress meter comprises a pressure disc and a vertical chord sensor, associated with a frequency detector. Its working principle is: the disc produces stress in effect of vertical press; stress is converted to a frequency signal by the sensor; frequency signal is measured by the detector. The stress can be calculated through the following formula:

$$P = A(f^2 - f_0^2) - B(f - f_0) \tag{1}$$

where P is the internal stress of shotcrete layer, MPa; f and f_0 are measure frequency and initial frequency of the sensor respectively, Hz; A and B stand for calibration coefficient, MPa/Hz^2 or MPa/Hz^2.

The methods and steps of this measure test are shown in Fig. 5. Firstly, the pressure disc of stress meter should be fixed to steel mesh along different directions with the wire. Then concrete is sprayed and the meter must be completely buried in concrete. Afterwards, measure wires should be lead to the unaffected area along the roadway surface and the connectors should be wrapped with waterproof canvas. Finally, through the frequency detector, dates of shotcrete layer stress are measured.

4 Measure result and analysis

After measure station is installed, it takes nearly three months to monitor the stress dates which are listed in Table 1. Figures 6 and 7 show stress measure values in time and space respectively.

4.1 Shotcrete layer stress variation with time

Figure 6 is temporal variation curve of internal stresses of shotcrete layer. As can be seen from Table 1 and Fig. 6:

(1) Throughout the measure period, internal axial stress of shotcrete layer fluctuated firstly and then tended to

Table 1 The measure values of shotcrete layer stresses

| Stress (MPa) Time (days)	Axial stress							Radial stress							Tangential stress						
	Left foot	Left back	Left hance	Arch vault	Right hance	Right back	Right foot	Left foot	Left back	Left hance	Arch vault	Right hance	Right back	Right foot	Left foot	Left back	Left hance	Arch vault	Right hance	Right back	Right foot
1	0.009	0.013	−0.052	0.002	−0.019	−0.082	−0.063	0.005	0.002	0.015	0.035	0.016	0.009	0.018	0.700	0.906	−0.023	−0.086	0.121	0.013	1.238
2	0.024	0.022	−0.063	0.003	−0.020	−0.109	−0.073	0.016	0.005	0.041	0.022	0.017	0.024	0.014	0.681	0.901	−0.037	−0.113	0.162	0.027	1.276
3	−0.078	0.028	−0.040	0.004	−0.021	−0.121	−0.071	0.011	0.009	0.029	0.030	0.019	0.041	0.018	0.683	0.904	−0.047	−0.126	0.171	0.105	1.286
4	−0.090	0.003	−0.044	−0.030	−0.022	−0.127	−0.013	0.013	0.011	0.024	0.019	0.021	0.030	0.023	0.680	0.898	−0.045	−0.131	0.160	0.118	1.293
5	−0.075	−0.045	−0.051	−0.021	−0.015	−0.058	−0.017	0.016	−0.053	0.039	0.040	0.025	0.045	0.019	0.680	0.902	0.013	−0.063	0.126	0.972	1.289
6	−0.078	−0.093	−0.020	−0.018	−0.023	−0.088	−0.028	0.012	−0.064	0.063	0.024	0.017	0.042	0.020	0.686	0.905	0.009	−0.092	0.111	0.983	1.285
7	−0.075	−0.140	−0.028	−0.025	−0.027	−0.076	−0.033	0.017	−0.041	0.074	0.031	0.018	0.044	0.021	0.690	0.914	−0.001	−0.081	0.063	0.976	1.330
8	−0.067	−0.111	−0.045	−0.026	−0.021	−0.084	−0.041	0.014	−0.046	0.066	0.037	0.019	0.053	0.022	0.695	0.921	−0.007	−0.089	0.015	0.986	1.367
9	−0.075	−0.119	−0.141	−0.025	−0.018	−0.105	−0.122	0.013	−0.053	0.045	0.044	−0.015	0.045	0.015	0.696	0.926	−0.015	−0.110	−0.032	0.997	1.369
10	−0.067	−0.132	−0.154	−0.016	−0.024	−0.096	−0.141	0.007	−0.022	0.055	0.072	−0.006	0.053	0.023	0.691	0.922	−0.095	−0.100	−0.003	0.991	1.358
11	−0.066	−0.141	−0.165	−0.025	−0.012	−0.104	−0.156	−0.012	−0.029	0.046	0.064	−0.003	0.053	0.027	0.689	0.920	−0.115	−0.108	−0.011	0.996	1.359
12	−0.078	−0.143	−0.171	−0.026	−0.041	−0.114	−0.164	−0.027	−0.046	0.036	0.052	−0.009	0.041	0.021	0.688	0.919	−0.130	−0.118	−0.024	1.004	1.371
13	−0.087	−0.137	−0.177	−0.023	−0.044	−0.117	−0.171	−0.025	−0.042	0.033	0.043	−0.010	0.032	0.018	0.684	0.915	−0.138	−0.121	−0.033	1.009	1.346
14	−0.063	−0.046	−0.087	−0.024	−0.036	−0.142	−0.176	−0.022	−0.035	0.009	0.041	−0.009	0.057	0.024	0.688	0.918	−0.145	−0.146	−0.035	0.996	1.341
28	−0.080	−0.030	−0.036	−0.022	−0.039	−0.117	−0.073	−0.010	−0.016	0.034	0.047	0.032	0.040	0.012	0.687	0.927	−0.149	−0.121	−0.029	1.030	1.374
30	−0.017	−0.057	−0.030	−0.030	−0.045	−0.060	−0.067	0.041	0.058	0.090	0.137	0.040	0.102	0.041	0.697	0.905	−0.062	−0.065	0.062	0.993	1.419
32	−0.003	−0.053	−0.065	−0.036	−0.041	−0.059	−0.078	0.047	0.062	0.091	0.154	0.041	0.117	0.044	0.692	0.918	−0.056	−0.063	0.078	0.988	1.407
34	−0.011	−0.050	−0.036	−0.049	−0.047	−0.074	−0.082	0.036	0.052	0.076	0.127	0.039	0.108	0.036	0.688	0.917	−0.067	−0.079	0.051	1.000	1.425
36	−0.005	−0.106	−0.038	−0.054	−0.056	−0.079	−0.088	0.042	0.063	0.071	0.130	0.040	0.114	0.039	0.685	0.911	−0.061	−0.083	0.055	1.000	1.378
37	−0.005	−0.077	−0.003	−0.034	−0.065	−0.081	−0.101	0.026	0.068	0.070	0.134	0.038	0.115	0.045	0.684	0.913	−0.076	−0.085	0.058	1.001	1.391
39	−0.038	−0.114	−0.013	−0.021	−0.083	−0.103	−0.094	0.013	0.034	0.047	0.078	0.046	0.081	0.041	0.687	0.912	−0.090	−0.107	0.002	1.024	1.363
41	−0.031	−0.081	−0.022	−0.049	−0.078	−0.097	−0.110	0.030	0.063	0.053	0.107	0.051	0.089	0.047	0.710	0.935	−0.072	−0.101	0.031	1.016	1.390
55	−0.046	−0.057	−0.028	−0.047	−0.072	−0.111	−0.095	0.004	0.061	0.039	0.070	0.065	0.074	0.056	0.720	0.949	−0.099	−0.115	−0.006	1.050	1.347
57	−0.034	−0.079	−0.022	−0.043	−0.068	−0.098	−0.078	0.034	0.096	0.052	0.103	0.070	0.086	0.065	0.715	0.944	−0.069	−0.103	0.028	1.038	1.358
58	−0.028	−0.081	−0.043	−0.014	−0.064	−0.067	−0.091	0.051	0.085	0.083	0.127	0.049	0.092	0.083	0.717	0.943	−0.052	−0.072	0.051	1.041	1.365
61	−0.042	−0.085	−0.063	−0.017	−0.072	−0.074	−0.093	0.038	0.077	0.076	0.104	0.037	0.078	0.078	0.714	0.942	−0.065	−0.078	0.029	1.050	1.397
62	−0.016	−0.048	−0.041	−0.032	−0.064	−0.093	−0.094	0.036	0.101	0.057	0.103	0.064	0.104	0.072	0.698	0.927	−0.067	−0.097	0.028	1.035	1.377
63	−0.024	−0.041	−0.022	−0.042	−0.054	−0.099	−0.080	0.035	0.107	0.051	0.098	0.062	0.096	0.068	0.691	0.920	−0.068	−0.103	0.023	1.041	1.379
65	−0.034	−0.033	−0.016	−0.027	−0.067	−0.108	−0.086	0.049	0.085	0.042	0.136	0.059	0.086	0.064	0.694	0.918	−0.054	−0.112	0.060	1.052	1.356
68	−0.029	−0.035	−0.024	−0.017	−0.068	−0.141	−0.097	0.043	0.066	0.009	0.141	0.030	0.090	0.072	0.695	0.919	−0.060	−0.145	0.065	1.063	1.369
78	−0.050	−0.039	−0.034	−0.022	−0.063	−0.126	−0.089	0.027	0.075	0.054	0.113	0.037	0.070	0.064	0.680	0.909	−0.071	−0.130	0.037	1.071	1.370
AVG	−0.044	−0.068	−0.057	−0.026	−0.045	−0.097	−0.089	0.018	0.023	0.049	0.077	0.028	0.066	0.038	0.671	0.890	−0.063	−0.098	0.044	0.865	1.312
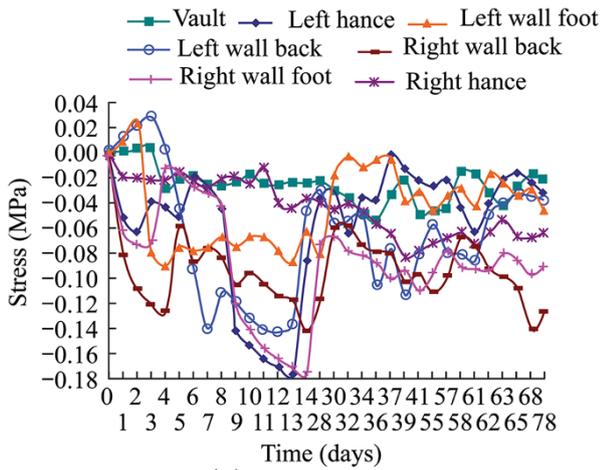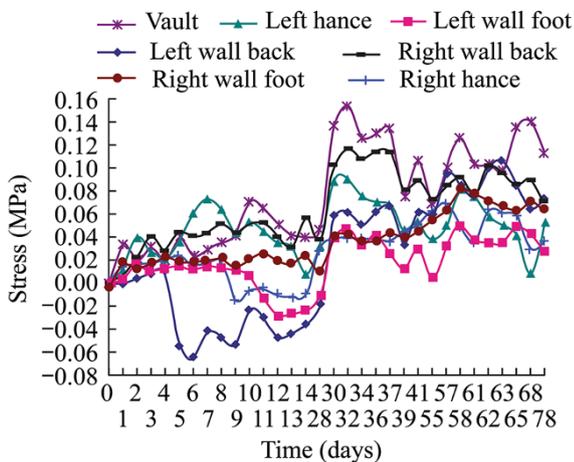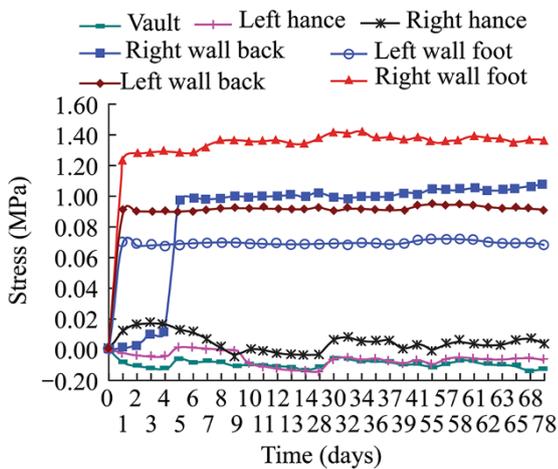
Fig. 6 Temporal variation curves of internal stresses of shotcrete layer (+ compressive stress, − tensile stress)
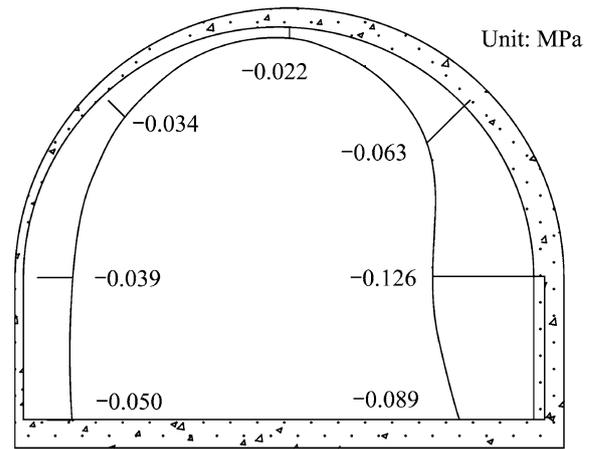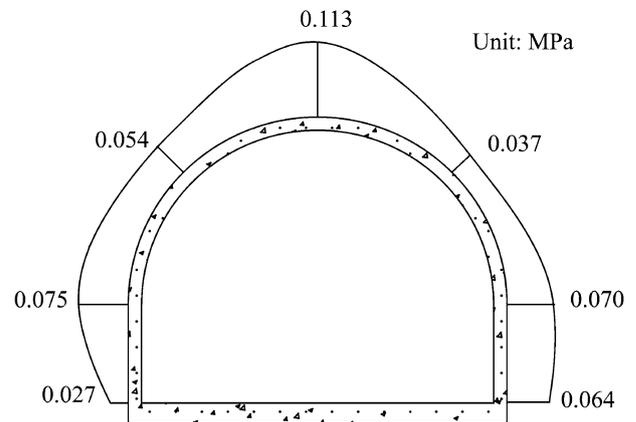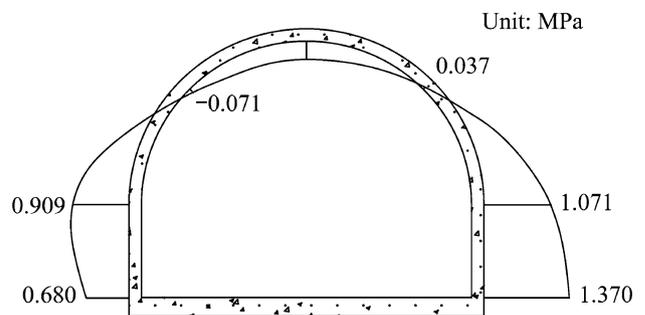

Fig. 7 Internal stresses spatial distribution diagrams of shotcrete layer around roadway cross section (+ compressive stress, − tensile stress)

stability whose average value was −0.059 MPa (tensile stress). In the initial half month, in addition to the vault and waist of arch, stresses of remaining five measure

points fluctuated in growth and the maximum was −0.177 MPa (left arch waist). Subsequently, the stresses decreased rapidly and then basically tended to stability after the 32th day. Eventually in all observed dates, the data were: arch vault −0.022 MPa, left arch waist −0.034 MPa, right arch waist −0.063 MPa, left wall waist −0.039 MPa, right wall waist −0.126 MPa, left wall foot −0.050 MPa, right wall foot −0.089 MPa. The average value of axial stresses was −0.061 MPa.

(2) As the same with axial stress, internal radial stress of shotcrete layer stabilized slowly after fluctuation. Unlike the former, the latter changed smaller (0.043 MPa) and substantially compressive stress. Only the stresses of left wall back, left wall foot and right arch waist skirting were tensile early, but latter converted to compressive. In the initial month, remaining stresses fluctuated in growth and the maximum was 0.154 MPa in the 29th day (arch vault). Subsequently, the stresses remained stable. Eventually observed dates were: arch vault 0.113 MPa, left arch waist 0.054 MPa, right arch waist 0.037 MPa, left wall waist 0.075 MPa, right wall waist 0.070 MPa, left wall foot 0.027 MPa, right wall foot 0.064 MPa. The average value of radial stresses was 0.043 MPa.

(3) Each internal tangential stress of shotcrete layer varies. These stresses of four measure points, which were located in the lower part of roadway, quickly increased to 0.6 MPa or more within 5 days. Tangential stress of right wall foot reached a maximum (1.425 MPa) 0.5 days later, these stresses remained changing stably, by less than 5 %. The remaining stresses of three measure points, which were located in the higher part of roadway, did not change significantly and always maintained slight fluctuations (no more than 0.2 MPa). Eventually in observed dates, there were: arch vault −0.130 MPa, left arch waist −0.071 MPa, right arch waist 0.037 MPa, left wall waist 0.909 MPa, right wall waist 1.071 MPa, left wall foot 0.680 MPa, right wall foot 1.370 MPa. The average value of tangential stresses was 0.517 MPa.

(4) As can be seen from temporal variation curve, stresses take place in the interior of shotcrete layer within short time just after concrete was sprayed. This explains why the roadway should be shotcreted in time after it was excavated. Shotcrete can prevent surrounding rock form weather, and improve its stress state more immortally.

4.2 Shotcrete layer stress spatial distribution

Figure 7 shows final stress spatial distribution along the roadway surrounding in 78th day. As can be seen:

(1) Overall, though the stresses in three directions were not consistent with time variation, their spatial distribution had largely followed a common feature, that is all of the three internal stresses distributed evenly and symmetrically along the section of roadway, with no significant stress concentration. Axial and tangential stresses increased gradually from the top of arch to the waist of wall, but reduced in the foot of wall. While, due to weight of shotcrete, radial stresses reduced from the top of arch to the waist of arch firstly, and then increased in the waist of wall. It is thus clear that force and displacement of the arch-wall connection are both larger than the other part, which should be shotcreted to be thicker.

(2) The axial and radial stresses were relatively smaller than the tangential stress. The latter was 11 times, 12 times the two formers respectively. However, considering the characteristics of the measure method, the tangential stress measured here actually included some weight of shotcrete layer. If the impact of weight was excluded, the gap between the three stresses would decrease.

(3) Axial stresses were substantially tensile stresses, except for stresses in arch vault tended to compressive. Nevertheless, all of radial stresses were compressive stresses. Tangential stresses in the wall were compressive, but tangential stresses in the arch were tensile. This is the reason that cracks and damages often appear at the top of roadway sprayed by concrete. Therefore tangential tensile strength of top shotcrete should be designed to enhance.

5 Conclusions

(1) Due to rock pressure and support resistance, the interior of shotcrete layer will emerge diverse stresses in axial, radial and tangential directions within short time just after the concrete was sprayed, which can be monitored through utilizing a type of concrete stress meter with oscillating chord. Shotcrete can improve stress state of surrounding rocks and the roadway should be shotcreted timely after it was excavated.

(2) With time passing, internal stresses in three directions fluctuated firstly and then tended to stability, whose average values were −0.061, 0.043 and 0.517 MPa respectively. The axial and radial stresses were relatively smaller than tangential stress, which was 11 times, 12 times the two formers.

(3) Axial and tangential stresses increased gradually from the top of arch to the waist of wall, but reduced

at the foot of wall. While, due to weight of shotcrete, radial stresses reduced from the top of arch to the waist of arch firstly, and then increased in the waist of wall. All of the three internal stresses distributed evenly and symmetrically along the section of roadway, with no significant stress concentration.

(4) Axial stresses were tensile substantially, except for stresses in arch vault tended to compressive, but all of radial stresses were compressive. Nevertheless, tangential stresses in the wall were compressive and tangential stresses in the arch were tensile.

(5) Stress and deformation of the arch and wall connection are both larger than other parts, and tangential stress of arch top is tensile. The two parts should be shotcreted to be thicker and designed to be stronger.

References

He MC, Sun XM (2004) China coal mine soft rock roadway supporting design and construction guide theory and technology. Science Press, Beijing

Jia JQ, Wang HT, Li XH, Hu GZ, Li HM, Li KX (2006) Stress measure and stability analysis of support system of large-span underground space. Chinese J Rock Mech Eng 25(2):3667–3672

Jing HW, Li YH (2008) Soft rock engineering support theory and technology. China University of Mining and Technology Press, Xuzhou

Kang HP (2000) Development and application of high strength roof bolt support technology. Coal Sci Technol 28(2):1–4

Kang HP, Wang JH (2007) Roadway bolting theory and set of technologies. Coal Industry Press, Beijing

Kang HP, Wang JH, Lin J (2007) High pretensioned stress and intensive bolting system and its application in deep roadways. J China Coal Soc 32(12):1233–1238

Kang HP, Jiang TM, Gao FQ (2008) Design for pretensioned rock bolting parameters. J China Coal Soc 33(7):721–726

Kang HP, Lin J, Wu YZ (2009) High pretensioned stress and intensive cable bolting technology set in full section and application in entry affected by dynamic pressure. J China Coal Soc 34(9):1153–1159

Lai HP, Xie YL, Yang XH (2005) Mechanical characteristic of highway tunnel in loess. J Chang'an Univ (Nat Sci Edition) 25(6):53–56

Li YS, Li XP, Dai YF, Peng YP (2007) Mechanical property testing and numerical calculating on surrounding rock mass and support system of tunnel. Rock Soil Mech 258(7):1348–1358

Li PF, Zhang DL, Zhao Y, Zhou Y, Fang Q, Zhang X (2010) Study of mechanical characteristics of secondary lining of large-section loess tunnel. Chin J Rock Mech Eng 29(8):1690–1696

GB 50086-2001, Specifications for bolt-shotcrete support. The National Standards Compilation Group of People's Republic of China

Wang HW (1988) Bolt-shotcrete support. Coal Industry Press, Beijing

Xu LS (2009) Mechanical measure and analysis on composite lining structure of highway tunnel with large cross section. J Chongqing Jiaotong Univ (Nat Sci) 28(3):528–530

Zheng YR (1988) Underground engineering shotcrete design guidelines. China Railway Press, Beijing