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Abstract. Li Lou Iron Mine was the most productive underground mining iron mine in China. Up to now, no original rock stress measurement had been carried out. In order to understand the distribution characteristics and variation law of in-situ stress in mining area, a digital hollow inclusion strain gauge based on double temperature compensation was used to measure 7 measuring points at 3 levels, and three-dimensional in-situ stress data of 7 measuring points were obtained. According to the measured results, the average ratio of horizontal stress to vertical stress was 2.36, and the main stress field in Li Lou mining area was horizontal tectonic stress. The direction of maximum principal stress was NNE-SSE, in which the north was near NE and the south was near SE, which was basically parallel to the strike of fault structure in the mining area. The maximum horizontal principal stress, the minimum horizontal principal stress and the vertical principal stress changed linearly with the increase of depth.

Keywords: In-situ stress measurement, Hollow inclusion strain gauge, Double temperature compensation, Regularities of distribution.

1. Introduction

In-situ stress was the undisturbed natural stress existing in the stratum, which was the fundamental force that caused the deformation and destruction of the stope and roadway in the mining project[1-2].

Li Lou Iron Mine was the largest underground mining iron mine in China[3]. High-stage empty field and post-filling mining method was used in Li Lou Iron Mine[4]. The mining process was accompanied by intense mining disturbance, and the existence of a large number of empty areas made the problem of surrounding rock fragmentation increasingly prominent, and the data of rock mechanics in mines were relatively scarce.

The in-situ stress state of Li Lou Iron Mine was obtained by measuring the in-situ stress at 7 measuring points at three levels of -300, -350 and -400, the distribution characteristics of in-situ stress were mastered, and the linear regression equation of three principal stresses in Li Lou Mine was obtained, which provided data support for the three-dimensional numerical simulation calculation of Li Lou Mine in the future. It provided a scientific basis for the overall support design and support mode of the roadway in Li Lou mining area, provided an important reference for the deep development design, and provided guidance for the optimization of mining design and stope structural parameters.

2. Measuring principle and measuring point arrangement

2.1. Front-end digital hollow inclusion strain gauge

The in-situ stress measurement could be divided into two categories: direct measurement method and indirect measurement method[5]. The indirect method was used to measure the in-situ stress of Li Lou Iron Mine. The instrument used was the latest hollow inclusion strain gage developed by Academician Cai Meifeng of Beijing University of Science and Technology[6-7]. The new instrument had dual temperature compensation circuit, which realized the idea of complete temperature compensation put forward by academician Cai Meifeng. The instrument had very high acquisition accuracy and stability, and had the functions of instantaneous acquisition, drift self-compensation and intermittent mining.

The hollow inclusion strain gauge consisted of 12 resistance strain gauges embedded in the epoxy resin cylinder. Each strain flower had four strain gauges, which were fitted along the circumference of the epoxy resin cylinder at 120 degrees apart. Then the outer layer was poured with epoxy resin, so the resistance strain gauge was well embedded in the tube wall. The outer layer was poured 0.5mm thick, and a temperature compensating strain gauge was pasted on the top of the stress gauge.

4 equations could be obtained by measuring the measured strain of each strain and calculating the equation of ground stress. The three strain flowers could get 12 equations, which at least 6 were independent equations. Therefore, 6 components of the original rock stress could be calculated. The least square method was used to find the optimal solution, so as to obtain the three-dimensional in-situ stress state of the measuring point [8].

2.2. Measuring point arrangement

Before in-situ stress measurement, the selection of surveying location, topography, lithology, fault and other factors needed to be considered comprehensively [9-10]. The in-situ stress measurements at 7 measuring points had been completed in Li Lou Iron Mine, and the core of each measuring point had been catalogued to fully grasp the occurrence characteristics of surrounding rocks in the measuring point area. Coring was carried out for the survey points in mining area, and the integrity of the rock was also counted. The coring positions were all dolomite marble. The coordinates of 1[#] measuring point (300-1) were (401986,3583852,-300), RQD was 0.29; 2[#] measuring point (350-1) coordinates were (401708,3584701,-350), RQD was 0.80;3[#] Measuring point (350-2) coordinates were (401765, 3585155, -350), RQD was 0.67; 4[#] measuring point (350-3) coordinates were (401944, 3583744, -350), RQD was 0.34; 5[#] measuring point (400 -1) Coordinates were (401781, 3585189, -400), RQD was 0.32; 6[#] measuring point (400-2) coordinates were (401767, 3584949, -400), RQD was 0.56; 7[#] measuring point (400-3) coordinates were (401992, 3583440, -400) and the RQD was 0.72.

3. In-situ stress measurement results

3.1. Stress relief results

7 stress relief curves had been obtained in this paper. The stress relief curves at 1[#] measuring point were listed only in length, as shown in Fig.1. Finally, the strain value was stable, and this stable value was used as the original data for calculating in-situ stress. A90, A0 and C135 corresponded to 12 strain gauges, and the subscript numbers (90, 0, 45, 135) indicated the reading of the angle between the strain gauge and the direction of borehole axis.
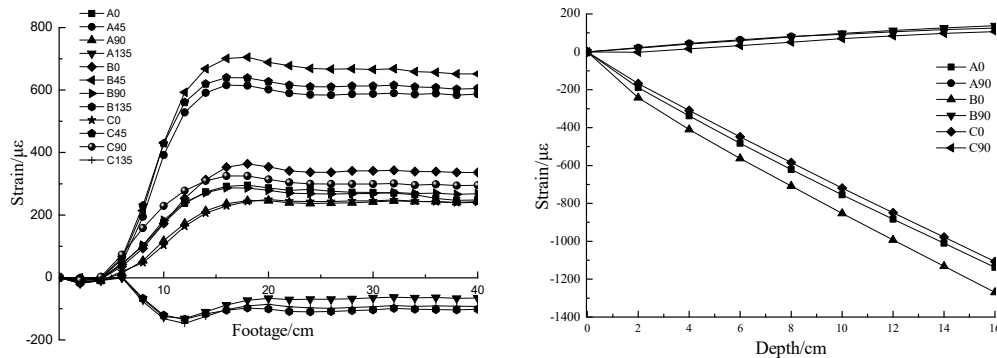
Fig.1 300-1-point stress relief curve   **Fig.2** 300-1 confining pressure formulation results

3.2. Confining pressure formulation results

The elastic modulus and Poisson's ratio of rocks at various measuring points in Li Lou Iron Mine would be measured by confining pressure calibration test. 70 series confining pressure calibrator with high-pressure biaxial test system was used in this paper. The final calculation results were: $1^{\#}$ measuring point elastic modulus was 30.70GPa, Poisson's ratio was 0.11; $2^{\#}$ measuring point elastic modulus was 30.74GPa, Poisson's ratio was 0.17; $3^{\#}$ measuring point elastic modulus was 37.36GPa, Poisson's ratio was 0.20; $4^{\#}$ measuring point elastic modulus was 49.58GPa, Poisson's ratio was 0.22; $5^{\#}$ measuring point elastic modulus was 49.680GPa, Poisson's ratio was 0.24; $6^{\#}$ measuring point elastic modulus was 33.34GPa, Poisson's ratio was 0.21; $7^{\#}$ measuring point elastic modulus was 52.67GPa, Poisson's ratio was 0.23. Limit and space, only the calibration curves of $1^{\#}$ measurement points was listed in Figure 2.

3.3. Temperature calibration results

Temperature calibration results at 7 measuring points in Li Lou mining area were carried out. Because of the high accuracy of the hollow inclusion strain gauge, the changes of thermal sensitivity and the number of strain gauges were monitored in real time. Therefore, the additional strains of the relative thermal sensitivity of strain gauges were selected for temperature calibration in the temperature calibration test. This part of the additional strain value should be removed from the original strain value measured during the stress relief process, so that the true stress variation caused by the stress relief could be obtained, as shown in Table 1.

Table 1. Final strain data for calculation of in-situ stress state(10-6)

location	A_0	A_{45}	A_{90}	A_{135}	B_0	B_{45}	B_{90}	B_{135}	C_0	C_{45}	C_{90}	C_{135}
300-1	323	692	291	-64	386	760	315	-97	288	703	347	-93
350-1	536	717	185	-58	-39	803	86	638	1022	673	319	788
350-2	362	581	381	163	323	632	347	55	346	610	306	27
350-3	217	457	216	274	193	359	322	215	306	567	324	219
400-1	250	208	238	196	170	401	563	306	184	310	420	289
400-2	231	457	353	132	207	283	155	57	190	214	122	74
400-3	219	474	280	128	515	551	396	256	346	564	464	336

3.4. Calculation results of principal stress of each measuring point

The three-dimensional in-situ stress state of each measuring point was obtained by calculating the elastic modulus (E) and Poisson's ratio (V) obtained from the strain value and confining pressure calibration corrected by temperature compensation. The results were shown in Table 2.

Table 2. In-situ stress measurement results

| Location | Maximum principal stress σ_1 | | | Intermediate principal stress σ_2 | | | Minimum principal stress σ_3 | | |
	Figure /MPa	Direction /°	Dip /°	Figure /MPa	Direction / °	Dip / °	Figure /MPa	Direction / °	Dip / °
300-1	10.99	60.34	3.94	4.44	18.81	84.74	4.18	330.10	3.47
350-1	21.21	194.11	-5.03	6.69	305.7	-76.53	3.84	283.00	12.46
350-2	15.42	167.76	2.98	6.89	76.92	15.61	6.09	88.28	-74.09
350-3	17.31	38.03	-0.26	8.25	307.46	-65.43	7.09	308.16	24.57
400-1	14.65	8.31	7.77	12.07	246.38	75.53	7.83	280.00	-12.13
400-2	8.43	172.54	-4.29	4.74	262.19	4.65	2.40	305.12	-83.67
400-3	24.16	179.16	2.10	12.08	257.14	-80.01	9.07	269.53	9.76

4. Distribution of in-situ stress field and relationship with geological structure

4.1. Distribution law of in-situ stress field

According to the 7 in-situ stress data of the Li Lou mining area in Table 2, the existence of the stress field distribution could be known:

(1)Each of the measuring points in the Li Lou mining area had two principal stresses very close to the horizontal direction, and the inclination angle was not more than 15°; another principal stress was approximately perpendicular to the vertical direction, and the angle with the vertical direction was not more than 30°.

(2)The maximum principal stress direction of the Li Lou mining area was distributed in a nearly horizontal direction. The angle between the maximum principal stress and the horizontal plane of the 7 measuring points was not more than 8°; according to the situation of obtaining the core in the stress relief of 300-1, 350-1, 400-1, 400-2, the analysis point was analyzed. The surrounding rock bedding and joint development, the maximum principal stress and the horizontal plane angle were 3.94°, 5.03°, 7.77°, 4.29°, which showed that the maximum principal stress was close to the horizontal distribution, and reflected that the mining area was dominated by horizontal tectonic stress.

(3)The principal stress of the near-vertical direction of 5 measuring points was close to the self-weight stress γH (γ was the bulk density of the rock, and H was the depth of the measuring point). The ratio was 0.65~0.84; The minimum horizontal principal stress of the 300-1 measuring point was approximately equal to the vertical principal stress, and the ratio was 0.94. As shown in table 3. The result of 400-2 was smaller than that of other measuring points at the same level, because the location of the measuring point just passed through a joint and the joint developed in the near NE direction, which resulted in the smaller stress value measured at this point. According to the requirements of the code, the data of this point were not used. Generally, the stress in the near vertical direction of Li Lou mining area was smaller than that in the gravity direction, which was related to the existence of goaf above the point. Li Lou mining area was located in the eastern side of the positive and negative anomaly zone of gravity field in large area of North China Plain, which was one of the reasons for the dispersion of vertical stress in this in-situ stress measurement, but it still accorded with the law of increasing with the depth on the whole.
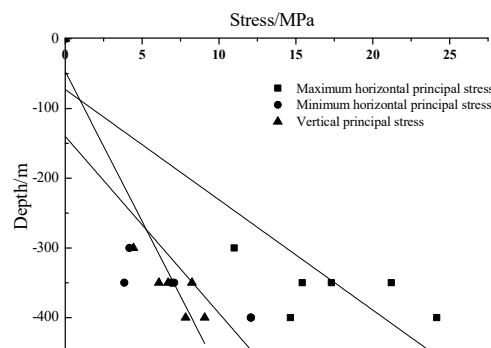
Table 3. Correlation stress ratio of each measuring point

Location	$\sigma_{h.max}/_{hmin}$	$\sigma_{h.max}/\sigma_v$	$\sigma_v/\gamma H$
300-1	2.47	2.47	0.55
350-1	5.52	3.17	0.71
350-2	1.78	2.53	0.65
350-3	2.53	2.1	0.87
400-1	1.87	1.21	0.75
400-2	-	-	-
400-2	2.66	3.51	0.84

Note, σh.max maximum horizontal principal stress, σh.min minimum horizontal principal stress, σv vertical principal stress

(4)The in-situ stress in Li Lou mining area belonged to medium level. The direction of maximum principal stress in Li Lou mining area was NNE-SSE, which was basically consistent with the trend of faults in the area.

In order to analyze the variation law of in-situ stress field with depth, 3 principal stress values of 6 measuring points(The release position of 400-2 measuring point happened to pass through a developing joint, which resulted in the measurement strain value being smaller than the actual value. Therefore, this measuring point result was removed in linear regression) in Li Lou mining area were analyzed by linear regression method. Finally, the variation law of 3 principal stress values with burial depth was obtained: The maximum horizontal principal stress, the minimum horizontal principal stress and the vertical principal stress all increased with the increase of depth, and the growth relationship was approximately linear, as shown in Figure 3.

Fig. 3 Li Lou Mining Area Linear regression lines of principal stresses with depth

The regression equation of the in-situ stress of Li Lou measuring point:

$$\sigma_{hmax}=-0.4842+0.0498H \ (MPa) \tag{1}$$

$$\sigma_{hmin}=-1.2066+0.0255H \ (MPa) \tag{2}$$

$$\sigma_{z}=-0.3417+0.0208H \ (MPa) \tag{3}$$

4.2. Relationship between in-situ stress and geological structure in mining area
The area of Lilou mining area was controlled by fertilizer interruption fracture system in a large scale, and was affected by longitudinal faults (F1, F2, F3) and oblique faults (F4, F2). Longitudinal faults were axial faults due to inverted folds, and their properties were reversed faults; oblique faults were normal-translational faults[11].

The measured in-situ stress results showed that the direction of the maximum principal stress at the 7 measuring points in Li Lou was NNE-SSE, which was basically perpendicular to the strike of the above-mentioned fertilizer fracture and basically paralleled to the strike of the three longitudinal and obliqued faults F4 in the mining area. The maximum principal stress direction of the 7 survey points in Li Lou mining area was NS direction, which was basically parallel to the strike of the main faults in the area. The direction of action also reflected the characteristics of the tectonic stress field in the whole area where Li Lou was located.

5. Conclusion

(1)The in-situ stress field in Li Lou mining area was characterized by horizontal tectonic stress as the main stress and vertical stress as the supplement, and influenced by geological structure and different burial depth, the in-situ stress field of each survey point in the mining area would be different.

(2) The maximum horizontal principal stress of Li Lou -300 reached 10.99MPa, and the direction was NNE. The maximum principal stress of -350 was 21.21MPa, the minimum was 15.42MPa, the average was 17.98MPa, and the direction was SSE. The maximum principal stress of -400 was 24.16MPa, the minimum horizontal principal stress was 14.65MPa, the average was 19.405MPa, and the direction was SSE. This showed the complexity and variability of the in-situ stress state.

(3)The in-situ stress in Li Lou mining area was medium; the ratio of maximum horizontal principal stress to vertical stress was 2.43 on average; and the direction of maximum principal stress in mining area was NNE-SSE.

(4)The ratio between the maximum horizontal principal stress and the minimum principal stress at 7 measuring points in Li Lou mining area was between 1.78~2.66, with an average of 2.26, subject to large shear forces. This created favorable stress conditions for the development of faults and joints in rock mass, which was one of the important factors affecting the wall rock fragmentation in the north wall of Li Lou mining area.

(5)The first in-situ stress measurement in Li Lou mining area had been realized, and the distribution of in-situ stress at the measured points had been obtained, which provided important scientific guidance for the layout and supported of mine roadways in the future and the optimization of stope structural parameters.

Acknowledgments

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