In situ Stress Measurement in Kilometer-Deep Mine and Its Relationship with Minefield Fault Structure

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Abstract: In view of the complicated geological stress structure and fuzzy distribution characteristics of a kilometer-deep mine, the KX-81 hollow inclusion stress relief method was used to test in situ stress in Shuanghe Coal Mine at the level of −1100. On the basis of the field test data, the 3D grid diagram of the principal stress distribution in the deep mining area of Shuanghe Coal Mine was drawn, and the relationship between the in situ stress distribution characteristics and the fault structure in the wellfield was studied. Results showed that 1) the directions of σ₁ and σ₃ at each measurement point were horizontal, and the other principal stress σ₂ was vertical. 2) The maximum principal stress value was 1.26–1.48 times of the self-weight stress value, indicating that the horizontal tectonic stress plays a leading role in the in situ stress of the mine. 3) The horizontal and vertical stresses at a depth of about 1090 m were estimated according to the theory. A comparison revealed that the theoretical values were lower than the field measured values. The area was found to be dominated by horizontal tectonic forces belonging to the dynamic stress field. 4) The direction of σ₁ at each measurement point was 114.70°–124.72°, with an average of 120°. The direction was NWW–SEE. In accordance with the distribution law of the fault structure in the wellfield, the consistency between the wellfield geological structure and the measured direction of the maximum principal stress was analyzed and verified. The research results provide technical basis for deep well roadway layout and stability control and improve the scientific nature and reliability of surrounding rock control of high stress roadway in deep wells under complex geological structures.

Key words: kilometer deep mine; in situ stress test; stress relief method; roadway surrounding rock control; fault structure; tectonic stress

The complexity of geological structural stress in deep mining areas is closely related to mine depth. Deep coal mines can seriously damage the two sides, roof, and floor of a roadway, thereby affecting normal use of the roadway and posing a serious threat to mine safety production. This threat is mainly caused by the unknown magnitude and distribution of in situ stress in roadway construction and later maintenance. Therefore, analyses on the relationship between the in situ stress distribution law and the fault structure are of great significance for roadway support in deep mining areas. Wang Zhen [1] measured the in situ stress of a −750 level Xinji No. 2 mine by using hollow inclusion strain method and obtained the distribution law of in situ stress and the maximum principal stress was horizontal stress. Zhao Shankun [2] conducted in situ stress tests on seven mines in Shuangyashan mining area via hollow inclusion 3D stress relief method; they concluded that the maximum principal stress direction is in the NW-SE direction, and the regional stress field is distributed in the shape of a “mountain.” Wang Zhixin [3] used the small borehole hydraulic fracturing method to test the in situ
stress in Xiegou Mine and studied the in situ stress distribution characteristics, thereby providing reference for roadway layout. Zhang Zhongyuan[4] used the hollow inclusion stress relief method to systematically test the in situ stress of a −1200 level Jinchuan No. 3 mine, and they determined that the direction of maximum principal stress is basically consistent with the minefield stress field. Their in situ stress data were of great significance for roadway support design and construction. Wang Lianguo[5] conducted an in situ stress test in Huozhou mining area by the drilling stress relief method; they obtained the in situ stress distribution rule in the mining area and verified that the in situ stress field is dominated by horizontal stress. Cai Zengxiang[6] tested the in situ stress of a mine in Yunnan Province by adopting the stress relief method, and their results are of great significance for the design and construction of roadway support. Qin Zhongcheng[7] tested the in situ stress of Guotun Coal Mine by the stress relief method and obtained the distribution law of in situ stress. Liu Zelin[8] measured the in situ stress of −950 to −1150 horizontal Xincheng Mine by using the methods of casing stress relief and acoustic emission, and they reported that the deep in situ stress is dominated by the horizontal stress. Zhang Wenbin[9] tested the in situ stress of Changping Coal Mine by using the stress relief method of borehole core, and they obtained the distribution law of in situ stress. Their results provided reference basis for the layout and support design of unexploited roadways in the panel area. Therefore, the method of combining minefield geological structure and in situ stress measurement was adopted to study the in situ stress distribution law of Shuanghe Coal Mine.

By referring to the research results of many scholars, this paper adopted the stress relief method[10] to measure the in situ stress in Shuanghe Coal Mine, study the in situ stress value and distribution rule, and analyze its relationship with the fault structure of the wellfield. This work is believed to have important reference value for reducing roadway deformation in the underground of Shuanghe Coal Mine.

1. In situ stress testing

At present, the stress relief method and hydraulic fracturing method[11–14] are the most widely used in situ stress tests for mines in China. The in situ stress measurement of Shuanghe Coal Mine adopted the hollow inclusion stress relief method, which has high precision and low cost. The measured data obtained by this test method were closest to the stress distribution state of the virgin rock.

1.1. Fundamental

The rock mass at a certain point in the original state of the mine was in the tripartite compression state. The rock containing kx type hollow inclusion triaxial stress meter was removed from the virgin rock mass by using a sleeve. Given the elastic action, the rock core could expand and deform, and the 3D expansion and deformation after stress relief were measured. Confining pressure was applied to the rock core by confining pressure machine, and the elastic modulus was determined. The stress value and direction of virgin rock mass were obtained through Hooke’s law.

1.2. Measurement instrument

This test of Shuanghe Coal Mine adopted the KX-81 hollow inclusion triaxial stress meter, which has three strain rosettes evenly distributed at equal intervals within the same circle. Each strain rosette contains four strain gauges. The stress meter enables temperature compensation[15], which further reduces the measurement error. The structure of the stress meter is shown in Fig. 1.

In addition, in this test, an installation rod equipped with a directional device and YHY-16 mine intrinsic safety strain instrument were used to observe and record the dynamic changes of three strain rosettes of each stress meter in the process of hollow inclusion relief in real time. The main drilling tools included a 108 mm diamond bit, 38 mm diamond bit, 108 mm core-taking sleeve, and so on. The complete testing device in the underground coal mine is shown in Fig. 2.
1.3. Measurement steps
ZLJ1100 drilling machine was used to drill a 108 mm-diameter hole to the surrounding rock, and the hole depth was 10–15 m. After leveling the bottom of the hole, a conical bit was used to make a horn-shaped guide hole. The drill pipe was then removed and replaced with a small hole bit with a diameter of 38 mm, and the hole depth was about 40 mm. The type KX-81 hollow inclusion stress meter with curing agent was sent to the predetermined position of the hole with an installation instrument, and the pin was cut by force so that the curing agent was distributed in the gap between the stress meter and the inner wall of the hole. After 24 h, the curing agent was completely solidified, and the cable was connected to the strain instrument. The rock core containing kx-81 type hollow inclusion triaxial stress meter was relieved from the rock mass. When the number on the instrument did not change with the increase in the sleeve core distance, then it was regarded as end of relief. Fig. 3 shows the specific measurement steps.
1.4. Layout of measurement points

The testing process of in situ stress is highly complicated. Among many processes, the location of in situ stress measurement point should be carefully selected. The selection of in situ stress measurement points should meet the following requirements: relatively complete rock mass without large fractures, representative stratigraphic regions, large excavation bodies away from goaf, unaffected virgin rock stress area, and complex regional structures away from faults. Therefore, the above principles should be followed in the selection of in situ stress measurement points to avoid the impact of their interference sources. According to the actual geological conditions on the site of Shuanghe Coal Mine, three measurement points were arranged for the in situ stress test based on comprehensive analysis and consideration. The locations of the measurement points are shown in Fig. 5, and Table 1 presents the technical features of the designed measurement points.

![Fig. 4 Schematic of the stress relief process of KX-81 hollow inclusion](image)

**Fig. 4** Schematic of the stress relief process of KX-81 hollow inclusion

| Measurement point serial number | Measurement point location | Measurement point depth/m | Drilling hole parameters |
|---------------------------------|----------------------------|---------------------------|-------------------------|
|                                 |                            |                           | Hole depth/m | Azimuth ° | Dip angle ° |
| 1#                               | Water exploration chamber in the lower car yard of No.1 mining area | 1085           | 11.27       | 60         | 10.5       |
| 2#                               | auxiliary shaft bypass of  | 1089           | 11.27       | 270        | 10.0       |

![Fig. 5 Location of in situ stress measurement point in Shuanghe Coal Mine](image)

**Fig. 5** Location of in situ stress measurement point in Shuanghe Coal Mine

**Table 1** Design technical characteristics of in situ stress measurement point
2. In situ stress measurement results

2.1. Strain gauge relief results of each measurement point

The in situ stress test of Shuanghe Coal Mine adopts YHY-16 type 16-channel mine intrinsic safety strain instrument. In this test, in situ stress was measured at three measurement points in Shuanghe Coal Mine at the level of −1100, and the core with KX-81 hollow inclusion was removed from the rock layer (Fig. 6). During the relief process, the curve relationship between rock core distance and strain value of each measurement point was measured by the mine intrinsic safety strain instrument (Figs. 7–9). On the basis of the strain and relief distance curve, the strain value was 0 before the borehole reached the strain gauge, and no obvious change was found thereafter. When the borehole was close to the strain gauge, the strain value was negative due to the stress movement during the drilling process. When the borehole reached the strain gauge, the strain value increased abruptly and then reached a maximum. When the borehole passed through the strain gauge and was separated from the strain gauge for a certain distance, the strain value became stable and its curve moved toward a certain strain value without obvious change. Obtaining the stable strain value of a strain gauge is the basis of accurate measurements of in situ stress and the horizontal longitude of Shuanghe Coal Mine. In summary, the strain process of the entire hollow inclusion core of type KX-81 could be divided into three periods: the period of no strain change, the period of strain surge, and the period of strain stability.

![Fig. 6 Rock cores obtained by the stress relief method](image)

![Fig. 7 Stress relief curves of measurement point No.1](image)

![Fig. 8 Stress relief curves of measurement point No.2](image)

![Fig. 9 Stress relief curves of measurement point No.3](image)

2.2 Rock mechanics parameters

When the stress relief work was completed, the core in the same layer was drilled at the corresponding measurement points and the laboratory rock mechanics experiment was carried out to improve the calculation results of in situ stress. Through two cycles of loading and unloading, the elastic modulus
determination curve was obtained. Finally, E and U of the virgin rock were obtained according to Equations (1) and (2) [16], and the mechanical parameters are shown in Table 2.

\[
E = K \frac{2P}{1 - \frac{2}{g_{72}} / \varepsilon_p}
\]

\[
U = \frac{\varepsilon_u}{\varepsilon_z}
\]

In the formula, E refers to elastic modulus, GPa; U refers to Poisson’s ratio; P refers to the sensor confining pressure value, MPa; R refers to core outer diameter, mm; r refers to the small hole inner diameter of rock core, mm; \(\varepsilon_p\) refers to circumferential strain values; and \(\varepsilon_z\) refers to axial strain values.

### Table 2 Rock mechanics parameters

| Core group          | Elastic modulus /GPa | Poisson's ratio |
|---------------------|----------------------|-----------------|
| Measurement point 1 | 38.88                | 0.29            |
| Measurement point 2 | 38.66                | 0.31            |
| Measurement point 3 | 38.66                | 0.31            |

2.3. In situ stress calculation results

According to the measured strain data of the three measuring points in Shuanghe Coal Mine and E and U obtained by confining pressure machine test, E and U were substituted into Equations (3), (4), and (5)[17] to determine the principal stress value and its orientation of the three measurement points. The measured results of in situ stress are shown in Tables 3 and 4.

\[
\varepsilon_p = \frac{1}{E} \left[ \left( \sigma_x + \sigma_y \right) k_1 + 2(1-\nu^2) \left[ \left( \sigma_y - \sigma_z \right) \cos 2\theta - 2\tau_{zx} \sin 2\theta \right] k_2 - \nu \sigma_z k_3 \right]
\]

\[
\varepsilon_z = \frac{1}{E} \left[ \sigma_z - \nu \left( \sigma_x + \sigma_y \right) \right]
\]

\[
\gamma_{\theta} = \frac{4}{E} \left( 1 + \nu \right) \left( \tau_{xy} \cos \theta - \tau_{xz} \sin \theta \right) k_i
\]

In the formula, \(\gamma_{\theta}\) refers to shear strain values; \(\sigma_x, \sigma_y, \sigma_z\) are the normal stresses in the x, y, and z directions, respectively, MPa; "\(\theta\)" is the strain gauge angle, (°); \(\tau_{xy}, \tau_{yz}, \) and \(\tau_{zx}\) are the shear stresses at the measurement point, MPa; and \(k_i - k_i\) is the correction factor for calculation.

### Table 3 Measured results of in situ stress at each measurement point

| Measurement point serial number | Principal stress | Measurement /MPa | Azimuth / (°) | Dip angle/ (°) |
|---------------------------------|------------------|------------------|--------------|---------------|
| 1#                              | \(\sigma_1\)     | 40.10            | 114.70       | 6.39          |
|                                 | \(\sigma_2\)     | 28.93            | -76.10       | -73.00        |
|                                 | \(\sigma_3\)     | 20.94            | 177.18       | -15.70        |
| 2#                              | \(\sigma_1\)     | 34.41            | 121.13       | 3.11          |
|                                 | \(\sigma_2\)     | 26.14            | -76.88       | -71.04        |
|                                 | \(\sigma_3\)     | 17.70            | 165.50       | -17.60        |
| 3#                              | \(\sigma_1\)     | 39.01            | 124.72       | -1.58         |
|                                 | \(\sigma_2\)     | 27.41            | -83.33       | 81.67         |
|                                 | \(\sigma_3\)     | 19.43            | 159.31       | 9.72          |
### Table 4 In situ stress measurement results

| Measurement point | \( \sigma_{\text{max}} \) /MPa | \( \sigma_{\text{min}} \) /MPa | \( \sigma_v \) /MPa | \( \sigma_{\text{max}} / \sigma_v \) | \( \sigma_{\text{min}} / \sigma_v \) |
|-------------------|-----------------|-----------------|---------------|-----------------|-----------------|
| 1#                | 40.10           | 20.94           | 27.13         | 1.48            | 1.91            |
| 2#                | 34.41           | 17.70           | 27.23         | 1.26            | 1.94            |
| 3#                | 39.01           | 19.43           | 27.30         | 1.43            | 2.01            |

Note: \( \sigma_v \) is the vertical principal stress.

According to Equations (6) and (7) \(^{[18]} \), the theoretical value of horizontal stress and vertical stress of about 1090 m deep in Shuanghe Coal Mine was calculated.

\[
\sigma_v = \gamma H \quad (6)
\]

\[
\sigma_h = \gamma H (1 - \mu) \quad (7)
\]

In the formula, \( \sigma_h \) refers to horizontal stress; \( \sigma_v \) refers to vertical principal stress, MPa; \( \gamma \) refers to weight density of rock, kN/m\(^3\); and \( H \) refers to thickness of overlying rock mass (buried depth), m.

In the above formula, the average unit weight of overburden \( \gamma = 2.4 \times 10^4 \) kN/m\(^3\), and the depth of the measurement point was about 1090 m. The following values were obtained: \( \sigma_v = 26.16 \) MPa and horizontal stress \( \sigma_h = 11.75 \) MPa. A comparison revealed that the theoretical value was lower than the field measured value, which showed that the place was greatly affected by the horizontal tectonic strain and was a dynamic stress field.

### 3 Distribution law of in situ stress

To intuitively analyze the measured results of in situ stress in Shuanghe Coal Mine, the calculation results of the measured data at various measurement points in Shuanghe Coal Mine are summarized in Fig. 10.

Moreover, to visually display the spatial state of the ground stress components at each measurement point of Shuanghe Coal Mine, as shown in Fig. 11, the principal stress values and directions of each measurement point of Shuanghe Coal Mine were respectively drawn in the 3D spatial coordinate system.

As shown in Tables 3 and 4 and Figs. 10 and 11, based on the spatial distribution state of in situ stress at each measurement point of Shuanghe Coal Mine, the stress size, direction, and rock mass in situ stress distribution law in the test area of the mine were obtained as follows:

(1) \( \sigma_1 \) and \( \sigma_3 \) in each measurement point were horizontal, and the other principal stress \( \sigma_2 \) was vertical. The dip angle of \( \sigma_1 \) was 1.58°–6.39°, with an average of 3.70°. The dip angle of \( \sigma_3 \) was 9.72°–17.60°,
with an average of 14.34°. The other principal stress $\sigma_2$ had a dip angle of 71.04°–81.67°, with an average of 75.24°.

(2) According to the measured in situ stress data of Shuanghe Coal Mine, the vertical principal stress value within the buried depth range of 1085–1089 m was 27.13–27.30 MPa.

(3) The measured ratio of $\sigma_{\text{max}, h}/\sigma_{\text{min}, h}$ was 1.91–2.01, that is, $\sigma_{\text{max}, h} = (1.91–2.01) \cdot \sigma_{\text{min}, h}$, and $\sigma_{\text{max}, h}$ were significantly different, indicating that shear stress was dominant in the rock mass. The maximum principal stress was 1.27–1.48 times of the self-weight stress, with an average of 1.39, indicating that the in situ stress in Shuanghe Coal Mine was mainly horizontal tectonic stress.

(4) The maximum principal stress longitude of each measurement point is between 114.70° and 124.72°, with an average of 120°. It is in the NWW-SEE direction on the whole and closely distributed, with an average strike of NW60°.

4. Relationship between in situ stress and movement of wellfield geological structure

Geographically, geological structure is the general term for the morphology of various components of the crust or lithosphere and their mutual combination and features. The types of geological structure include graben, syncline, anticline, and fault. In a long geological time period, the crustal material produces an internal stress effect due to the geological structure movement and other reasons. This stress is called in situ stress, which is the general term of crustal stress. Different geological structures produce varying distributions of in situ stress. The analysis of the relationship between in situ field and geological structure movement is important for the stability control of roadways and the selection of support parameters.

Shuanghe Coal Mine is located in the southeast of Jining coalfield. It is a synclinal structure, with Sanhejian Coal Mine in the south and Longgu Coal Mine and Longdong Coal Mine in the east. The central part of the wellfield is the main fold in this area. The two wings are tangent by DF18 and DF20, and a graben is formed at the axis. The shallow part in the southwest is accompanied with secondary undulation, which complicates the folds in the area. The general structural characteristics are as follows: wide and gentle folds dominate, accompanied with a certain number of faults (Fig. 12), which are as follows:

Laozhai syncline is located in the central part of the wellfield and is axial to the northwest with an amplitude of 10–70 m. It is the main fold in this area. The two wings are tangent by DF18 and DF20, and a graben is formed at the axis. Secondary undulations occur in the southwest shallow area, which complicate the folds in the area. The syncline is controlled by 2D seismic, 3D seismic, and many exploration profiles with a clear shape.

A total of 38 faults can be found in Shuanghe wellfield. The eastern and southern parts of the wellfield are controlled by the regional south-to-north Sunshidian fault and north-to-east Zhangzhuang fault, respectively, and they constitute the boundary of the wellfield. Under the influence of two major faults, 35 minor normal faults and 1 reverse fault occurred in the wellfield. Except for two boundary faults, there were only four faults with a drop of >30 m, and the rest of the faults had a small drop.

On the basis of the geological structure of the wellfield and the geological condition of Shuanghe Coal Mine, the tectonic stress direction of the wellfield was NWW-SEE and the orientation was between NW50° and NW60°. The in situ stress direction basically coincided with the maximum principal stress direction [19].

5. Conclusion

The hollow inclusion stress relief method was used to test the in situ stress at the −1100 level of Shuanghe Coal Mine. The main conclusions are as follows:

(1) $\sigma_1$ and $\sigma_3$ were horizontal and $\sigma_2$ was vertical in all measurement points of Shuanghe Coal Mine.
The maximum dip angles were 6.39° for σ₁, 17.60° for σ₃, and 71.04° for σ₂. 
(2) The maximum principal stress was 1.27–1.48 times of the self-weight stress, with an average of 1.39, indicating that the horizontal tectonic stress played a leading role in the mine. 
(3) The maximum principal stress horizontal longitude of each measurement point was between 114.70° and 124.72°, with the overall NWW-SEE direction and the average strike being NW60°. The analysis of the fault structure of the wellfield and the geological condition of Shuanghe Coal Mine revealed that the geological structure of the wellfield basically coincided with the measured maximum principal stress direction.

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