Research Article

Current Tectonic Stress State in an Iron Mine District, North China, Based on Overcoring, Hydraulic Fracturing, and Acoustic Emission Stress Measurements

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1. Introduction

The considered iron mine is geographically located in the Qian’an area, Hebei Province, North China, and is one of the largest deep-concave open-pit iron mines in China. The ore production capacity is approximately 18 million tons per year. Since this century, this iron mine has been operated below the surface. The mine pit is approximately 2900 m long and 1000–1400 m wide [1]. According to the latest mining scheme, the ultimate slope height of this mine is designed to reach 760 m, and the deep-concave mining depth is 540 m, which is currently one of the highest rock slopes of open-pit mines in China. With increasing mining depth, the slope constantly increases and steepens, and the technical difficulties of slope stability control and maintenance and subsequent mining are becoming increasingly significant. In fact, bench sliding and other failure events obviously increase, and in particular, the deformation and destruction of local slopes in stopes occasionally occur.

To ensure the safe and efficient production of the mine, a systematic analysis of the stability of the mining system is necessary. There are various factors that affect the stability and safety of mine slopes, such as the in situ stress state, engineering geological environment, and hydrogeological conditions [1, 2]. Among all the influencing factors, the stress condition is one of the most fundamental factors since most failure events in open-pit mines are induced by the action of crustal stress. Additionally, the estimation of the
in situ stress magnitude and direction yields indispensable engineering parameters needed to accurately evaluate the behavior of mining excavations [3, 4]. More importantly, understanding the in situ stress state in a given mine district is a necessary prerequisite for determining engineering rock mass attributes, analyzing slope stability, and realizing scientific excavation design and decision-making in mining engineering [2, 5]. Hence, in situ stress measurements can provide a fundamental basis for slope stability evaluation and excavation optimization design for more efficient mining and can yield the added benefit of contributing to a greater understanding of the regional structure and tectonics in mine districts [6], which is of great practical significance.

To this end, in this study, in situ stress measurement activities involving overcoring, hydraulic fracturing, and acoustic emission techniques were performed in the iron mine during different periods, and a large number of valuable stress data were determined. Accordingly, the distribution characteristics of the in situ stress field, including value and direction, were investigated, a comparison between these methods was made to ensure reliable measurement results, and the linkage between the stress field and regional geological tectonics was examined. Notably, the integrated application of three stress measurement techniques in a single mine is rare worldwide. The comparison and verification between measurement results obtained with different methods are crucially important to guarantee the accuracy and reliability of the stress data.

2. Geological Setting and Seismicity

The iron mine district is surrounded by several large faults, such as the Lengkou fault, Yejiu fault, and Luanxian–Laoting fault (Figure 1(a)) [7]. The fault structures in this district are well developed and numerous, and faults of various scales and directions formed during different periods exhibit crisscross patterns. According to geological survey results, more than 40 faults (i.e., F1–F40) have been identified (Figure 1(b)) [1], and many small faults have not been counted. Based on the fault strike, these faults can be roughly divided into six groups, namely, NEE, NE, NE, near-S–N, NW, and near-E–W directions. Among them, the NEE, NE, and near-E–W faults exhibit large-scale characteristics and appear in groups. Among the faults in the mine district, F3, F5, and F28 are the main ore-controlling structures. In addition, F8 running through the southwest of the stope and F5 running at the bottom of the stope impose a notable influence on the slope stability. Additionally, some faults distributed along the E–W direction, such as the F13, F14, and F24 faults, do not directly contribute to the formation of the sliding surface of the slope, but these faults obliquely intersect with the slope, cutting the slope, destroying the integrity of the slope rock mass, and adversely affecting the slope stability.

In terms of seismicity, the Tangshan area, which is close to the Qian’an area, is a well-known earthquake-prone area in North China and has been plagued by numerous destructive earthquakes throughout its long history (Figure 1(a)). Notably, the Tangshan and Luanxian areas experienced Ms 7.8 and Ms 7.1 earthquakes, respectively, in 1976 [8], and small and medium earthquakes frequently occur. In contrast, the seismicity in the Qian’an area is relatively low overall. In 1999, an Ms 4.2 earthquake occurred in the Qian’an–Qinglong border area [9]. Recently, two small earthquakes have been recorded in the Qian’an area, namely, the Ms 2.1 earthquake in 2018 and Ms 2.5 earthquake in 2019, with focal depths of 13 km and 12 km, respectively. Thus, the tectonism in the Qian’an area is active to a certain degree.

3. In Situ Stress Measurements Using Different Techniques

3.1. Overcoring Method. The overcoring (OC) technique recommended by the ISRM [10] is a popular and well-established method to indirectly determine rock stresses and accurately describe the crustal stress field. This technique measures the expansion of cored rocks using a strain gauge after they are separated from subsurface stresses, and the recorded strain is then converted into evaluated stresses based on the mechanical properties of the cored rocks [11]. This method is limited to certain depths and requires an accessible test site, such as a tunnel, but can be suitably used in underground facilities. According to the acceptable layout principles for OC measurement points [12, 13], three measuring points (A1, A2, and A3) used for OC measurements were arranged in a transport tunnel of the iron mine. The horizontal projection positions of these three measuring points are shown in Figure 2. The depths of points A1, A2, and A3 from the Earth’s surface were 81 m, 91.5 m, and
56 m, respectively. The spacing between points A1 and A2 was 50.5 m, and the interval between points A2 and A3 was 81.8 m. The OC boreholes occurring at these measuring points were approximately horizontally drilled into the tunnel wall, and the main measurement steps are shown in Figure 3. The drilling depth was roughly four times the tunnel span to guarantee that the installation position of the strain gauge was located in the original rock stress zone. As such, the stress state at the measuring points was assumed not to be affected by engineering disturbance.
The employed OC device, instruments, and measurement procedures strictly followed the recommendations provided by the ISRM [10]. To overcome the limitations of the traditional OC method and guarantee accurate measurement, a newly developed temperature effect correction technique and an improved hollow inclusion strain gauge were adopted in our measurements. The resistance temperature interference of the long wire was significantly eliminated, and the measurement accuracy of the hollow inclusion strain gauge was greatly improved. Detailed descriptions of these techniques can be found in Cai et al. [14]. During stress relief, borehole strain and temperature change data at the measuring points measured by each hollow inclusion strain gauge were continuously and automatically recorded via a data collector. According to the stress relief curve of each test point, the final stable strain values could be obtained. After temperature calibration and correction, the three-dimensional stress tensor at each point was computed using relevant equations (Equations (1)–(4)) [15]. The calculated stresses strongly depended on the elastic modulus and Poisson’s ratio of the cored rocks, which were determined through biaxial tests using Equations (5)–(6).

\[
\epsilon_\theta = \frac{1}{E} \{ \{ (\sigma_z + \sigma_y) K_1 + 2(1 - \nu^2) [ (\sigma_y - \sigma_x) \cos 2\theta 
- 2\tau_{xy} \sin 2\theta] K_2 - \nu \sigma_z K_4 \} \},
\]

(1)

\[
\epsilon_z = \frac{1}{E} [ \sigma_z - \nu (\sigma_x + \sigma_y) ] ,
\]

(2)

\[
\gamma_{\theta z} = \frac{4}{E} (1 + \nu) (\tau_{yx} \cos \theta - \tau_{xz} \sin \theta) K_3 ,
\]

(3)

\[
\epsilon_{\pm45^\circ} = \frac{1}{2} (\epsilon_\theta \pm \epsilon_z \pm \gamma_{\theta z}) ,
\]

(4)

where \(E\) is the elastic modulus, \(\nu\) is Poisson’s ratio, \(\epsilon_\theta\) is the circumferential strain, \(\epsilon_z\) is the axial strain, \(\gamma_{\theta z}\) is the shear strain, \(\epsilon_{\pm45^\circ}\) is the strain measured by the strain foil, which exhibits a \(\pm45^\circ\) separation angle with the borehole axis, \(\theta\) is the separation angle between the strain foil and \(X\)-axis, and \(K_1, K_2, K_3, K_4\) are correction coefficients to eliminate the effect of the colloid [17].

\[
E = K_1 \left( \frac{P_0}{\epsilon_\theta} \right) \frac{2R^2}{(R^2 - r^2)} ,
\]

(5)

\[
v = \frac{\epsilon_\theta}{\epsilon_z} ,
\]

(6)

The employed OC device, instruments, and measurement procedures strictly followed the recommendations provided by the ISRM [10]. To overcome the limitations of the traditional OC method and guarantee accurate measurement, a newly developed temperature effect correction technique and an improved hollow inclusion strain gauge were adopted in our measurements. The resistance temperature interference of the long wire was significantly eliminated, and the measurement accuracy of the hollow inclusion strain gauge was greatly improved. Detailed descriptions of these techniques can be found in Cai et al. [14]. During stress relief, borehole strain and temperature change data at the measuring points measured by each hollow inclusion strain gauge were continuously and automatically recorded via a data collector. According to the stress relief curve of each test point, the final stable strain values could be obtained. After temperature calibration and correction, the three-dimensional stress tensor at each point was computed using relevant equations (Equations (1)–(4)) [15]. The calculated stresses strongly depended on the elastic modulus and Poisson’s ratio of the cored rocks, which were determined through biaxial tests using Equations (5)–(6).

\[
\epsilon_\theta = \frac{1}{E} \{ \{ (\sigma_z + \sigma_y) K_1 + 2(1 - \nu^2) [ (\sigma_y - \sigma_x) \cos 2\theta 
- 2\tau_{xy} \sin 2\theta] K_2 - \nu \sigma_z K_4 \} \},
\]

(1)

\[
\epsilon_z = \frac{1}{E} [ \sigma_z - \nu (\sigma_x + \sigma_y) ] ,
\]

(2)

\[
\gamma_{\theta z} = \frac{4}{E} (1 + \nu) (\tau_{yx} \cos \theta - \tau_{xz} \sin \theta) K_3 ,
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(3)

\[
\epsilon_{\pm45^\circ} = \frac{1}{2} (\epsilon_\theta \pm \epsilon_z \pm \gamma_{\theta z}) ,
\]

(4)

where \(E\) is the elastic modulus, \(\nu\) is Poisson’s ratio, \(\epsilon_\theta\) is the circumferential strain, \(\epsilon_z\) is the axial strain, \(\gamma_{\theta z}\) is the shear strain, \(\epsilon_{\pm45^\circ}\) is the strain measured by the strain foil, which exhibits a \(\pm45^\circ\) separation angle with the borehole axis, \(\theta\) is the separation angle between the strain foil and \(X\)-axis, and \(K_1, K_2, K_3, K_4\) are correction coefficients to eliminate the effect of the colloid [17].

\[
E = K_1 \left( \frac{P_0}{\epsilon_\theta} \right) \frac{2R^2}{(R^2 - r^2)} ,
\]

(5)

\[
v = \frac{\epsilon_\theta}{\epsilon_z} ,
\]

(6)
<table>
<thead>
<tr>
<th>Point</th>
<th>Depth (m)</th>
<th>E (GPa)</th>
<th>$\nu$</th>
<th>Maximum principal stress $\sigma_1$ Value (MPa)</th>
<th>Direction (°) Dip (°)</th>
<th>Intermediate principal stress $\sigma_2$ Value (MPa)</th>
<th>Direction (°) Dip (°)</th>
<th>Minimum principal stress $\sigma_3$ Value (MPa)</th>
<th>Direction (°) Dip (°)</th>
<th>$\sigma_h/\sigma_v$</th>
<th>$\sigma_H/\sigma_v$</th>
<th>$(\sigma_H + \sigma_h)/2\sigma_v$</th>
<th>$\sigma_H/\sigma_h$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>81</td>
<td>49.88</td>
<td>0.20</td>
<td>4.07</td>
<td>272.2 -7.3</td>
<td>2.38</td>
<td>3.9 -13.3</td>
<td>1.10</td>
<td>-74.8</td>
<td>1.10</td>
<td>1.88</td>
<td>1.49</td>
<td></td>
</tr>
<tr>
<td>A2</td>
<td>91.5</td>
<td>65.68</td>
<td>0.26</td>
<td>4.26</td>
<td>90.6 -0.8</td>
<td>2.86</td>
<td>180.6 -2.9</td>
<td>2.68</td>
<td>-87.0</td>
<td>1.07</td>
<td>1.59</td>
<td>1.33</td>
<td></td>
</tr>
<tr>
<td>A3</td>
<td>56</td>
<td>30.60</td>
<td>0.36</td>
<td>3.68</td>
<td>98.1 -7.2</td>
<td>2.33</td>
<td>189.7 -6.2</td>
<td>2.03</td>
<td>319.8</td>
<td>1.15</td>
<td>1.81</td>
<td>1.48</td>
<td></td>
</tr>
</tbody>
</table>

TABLE 1: OC stress measurements in the iron mine.
where $P_0$ is the applied biaxial pressure and $R$ and $r$ are the outside and inside radii, respectively, of overcoring.

3.2. Hydraulic Fracturing Method. The hydraulic fracturing (HF) technique, developed from oil field practices, is a feasible procedure to directly determine the in situ stress field based on certain necessary assumptions and can yield stress information at greater depths than the OC method. This technique involves the pressurization of a drill hole until a fracture occurs. This technique is also suggested by the ISRM [18] and has been widely used in mining, civil, and petroleum engineering applications. HF stress measurements were conducted in three exploration boreholes in the iron mine for hydrogeological investigation, marked as KB, KD, and KE in Figure 2. In these three boreholes, HF measurements were completed using a single-loop HF device (Figure 4) at five, three, and three locations, respectively. The accuracy of the HF method is highly dependent on the obtained pressure–time records. According to the relationship between the injection pressure and time, the characteristic hydraulic pressure parameters (i.e., $P_b$, $P_s$, and $P_t$) and tensile strength of the rocks within nine of the selected test intervals in the three boreholes were successfully identified, as listed in Table 2 [19].

Notably, for the HF method, the effective identification of the characteristic hydraulic pressure parameters is a key issue. In the tests, the breakdown pressure $P_b$ was very clear in the pressure–time records, and the peak pressure of the first injection cycle in the pressure–time records was identified as $P_b$. To date, more than 10 approaches have been proposed to identify the instantaneous shut-in pressure $P_s$ from recorded pressure–time curves. However, because of the complexity of rock conditions, no method has been recognized as a standard approach [20, 21]. The inflection point method [22] and the exponential pressure-decay method [23] were adopted to determine $P_s$. These two methods generally yield comparable $P_s$ values, and the mean value was chosen for determining the final shut-in pressure. Moreover, accurate interpretation of the fracture reopening pressure $P_r$ is vitally important to improve the determination accuracy of $\sigma_H$. $P_r$ was graphically estimated by superimposing the pressure–time curve of the fracture initiation cycle on that of the subsequent repressurization cycle, and the pressure at the deviation point between the two curves was regarded as $P_r$ [2]. In addition, as the pressure sensor was placed at the surface, the $P_b$, $P_s$, and $P_r$ values determined based on the pressure–time curve should be added to the water column pressure at the depth of the test section.

Based on the hydraulic pressure measurement results, the minimum ($\sigma_h$) and maximum ($\sigma_H$) horizontal principal stresses can be calculated as follows:

$$\sigma_h = P_s, \quad (7)$$

$$\sigma_H = 3P_s - P_r - P_0, \quad (8)$$

where $P_0$ is the pore pressure, which is equivalent to the hydrostatic pressure.

The vertical stress ($\sigma_v$) can be estimated based on the overburden weight, as follows:

$$\sigma_v = \gamma H, \quad (9)$$

where $\gamma$ is the mean rock density, which is assumed as 2.65 g/cm$^3$, and $H$ is the depth.
The direction of the induced hydraulic fracture was observed and interpreted by running an oriented impression packer across the fractured section. To obtain clear fracture traces, a high pressure and a long holding time are needed to reopen the fractures, and the soft rubber on the impression packer can be compressed into the fractures. After the pressure is released, the impression packer shrinks and separates from the borehole wall, leaving fracture traces on the impression packer surface. Since the induced fracture direction conforms with the impression packer surface. Since the induced fracture direction conforms with the impression packer surface. Since the induced fracture direction conforms with the impression packer surface.

The in situ stress magnitude and orientation of the two boreholes, respectively, as shown in Figure 2, with final depths of 406 m and 498 m, respectively. During field operation, original oriented core specimens were recovered from the rock formation. To evaluate rock stresses based on the Kaiser effect, subsamples with six orientations are needed to resolve the six independent components ($\sigma_{x}$, $\sigma_{y}$, $\sigma_{z}$, $\tau_{xy}$, $\tau_{yz}$, and $\tau_{zx}$) of the second-order stress tensor (Figure 5).

Intact cylindrical subsamples with a diameter of 25 mm were drilled from core specimens obtained at different depths along multiple orientations and prepared following ISRM recommendations for uniaxially loaded samples [28]. Subsamples were collected at six depths in borehole K1 and seven depths in borehole K3, where the stress states were to be measured. After the directions of the subsamples were established, uniaxial compression tests with AE measurements were carried out of the oriented samples in the laboratory using a digital AE system and a rock mechanics servo-controlled testing device. According to the recorded acoustic activity, the Kaiser effect point in each test was determined by using the abrupt point of the slope of the cumulative AE count–time curve, and the complete stress tensor was accordingly inferred. The relevant calculation was completed with a self-developed calculation program. The in situ stress magnitude and orientation of the two boreholes at the various depths are listed in Table 3 [1].

Finally, a total of 25 groups of stress tensors, including three types, were determined, ranging from 56 to 490 m below the surface. This large amount of stress data is expected to accurately reflect the stress field distribution trend within the whole mine area in space. Note that some shallow stress measurements derived from the OC and HF methods were carefully analyzed, as they may be influenced by terrain effects [11, 29]. To evaluate the data quality and ensure the comparability of the different stress indicators, all the data records were ranked based on the worldwide accepted WSM quality ranking system [30]. The OC measurements could be classified into the D category, and the HF data could be ranked into the B, C, and D categories. However, there is no available ranking standard for stress data obtained by the AE method, and these data were evaluated and compared to the other two types of data.

### Table 2: HF stress measurements in the iron mine.

<table>
<thead>
<tr>
<th>Borehole</th>
<th>No.</th>
<th>Depth (m)</th>
<th>Pressure parameters (MPa)</th>
<th>Principal stresses (MPa)</th>
<th>$\sigma_{H}$ direction</th>
<th>$\sigma_{H}/\sigma_{v}$</th>
<th>$\sigma_{H}/\sigma_{H}$</th>
<th>$(\sigma_{H} + \sigma_{h})/2\sigma_{v}$</th>
<th>$\sigma_{H}/\sigma_{h}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>KB</td>
<td>1</td>
<td>83.66</td>
<td>2.83 2.08 1.66 0.74 0.76</td>
<td>5.36 3.96 2.16 1.66 2.21</td>
<td>/</td>
<td>0.75</td>
<td>0.98</td>
<td>0.86</td>
<td>1.30</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>116.37</td>
<td>5.93 4.50 4.08 1.06 1.43</td>
<td>6.68 4.08 3.07</td>
<td>N77.0°E</td>
<td>1.33</td>
<td>2.18</td>
<td>1.75</td>
<td>1.64</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>155.68</td>
<td>12.57 7.57 6.98 1.44 5.00</td>
<td>11.93 6.98 4.11 1.70</td>
<td>N88.0°E</td>
<td>1.70</td>
<td>2.90</td>
<td>2.30</td>
<td>1.71</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>181.83</td>
<td>12.91 9.13 7.83 1.70 3.78</td>
<td>12.65 7.83 4.80 1.63</td>
<td>/</td>
<td>1.63</td>
<td>2.64</td>
<td>2.13</td>
<td>1.62</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>119.17</td>
<td>11.78 6.84 8.00 2.38 3.36</td>
<td>13.21 8.00 4.80 1.63</td>
<td>/</td>
<td>1.00</td>
<td>1.65</td>
<td>1.33</td>
<td>1.65</td>
</tr>
<tr>
<td>KD</td>
<td>2</td>
<td>274.81</td>
<td>11.72 6.89 6.26 2.10 4.83</td>
<td>9.79 6.26 7.26 1.10</td>
<td>N77.0°E</td>
<td>0.86</td>
<td>1.35</td>
<td>1.11</td>
<td>1.56</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>302.71</td>
<td>11.78 8.42 8.00 2.38 3.36</td>
<td>13.21 8.00 4.80 1.63</td>
<td>/</td>
<td>1.00</td>
<td>1.65</td>
<td>1.33</td>
<td>1.65</td>
</tr>
<tr>
<td>KE</td>
<td>2</td>
<td>186.20</td>
<td>13.02 5.62 5.42 1.12 7.40</td>
<td>9.53 5.42 4.92 1.10</td>
<td>/</td>
<td>1.10</td>
<td>1.94</td>
<td>1.52</td>
<td>1.76</td>
</tr>
</tbody>
</table>

Boreholes K1 and K3 are located on the east and west banks of the mine, respectively, as shown in Figure 2, with final depths of 406 m and 498 m, respectively.
4. Determined State of the In Situ Stress

4.1. Stress Magnitude. The OC measurement results (Table 1) for the iron mine district indicate that the maximum and intermediate principal stresses are close to horizontal, and the included angle with the horizontal plane is less than 13.3°, which are deemed the maximum (σ_H) and minimum (σ_h) horizontal principal stresses, respectively. The minimum principal stress of all measuring points is nearly vertical, with the largest deviation angle of 15.2° from the vertical, which is denoted as the vertical (σ_v) principal stress. This suggests that the hypothesis of the HF and AE stress measurements, namely, that one principal stress component is vertical, is reasonable. Note that for the convenience of analysis together with the other two kinds of data, the three principal stresses measured via the OC method are labeled σ_H, σ_h, and σ_v. Combining these three types of stress indicators, the stress state was analyzed with regard to the magnitude and direction of the principal stresses.

At all 25 test points in the mine district, the stress field type of 11 test points was characterized by σ_H > σ_v > σ_h (reverse faulting stress regime), accounting for 44% of the total test points; 13 test points were characterized by σ_H > σ_h > σ_v (strike-slip faulting stress regime), accounting for 52% of the total points; and only one test point indicated σ_v > σ_H > σ_h (normal faulting stress regime), accounting for 4% of the total points. Three combinations of principal stresses indicated the diversity and complexity of the stress state but revealed prevailing reverse and strike-slip faulting stress regimes. The state of the in situ stress dominated the mode of fault activity. Accordingly, based on Anderson’s faulting theory [31], the present-day stress state favors the

Figure 5: Illustration of tetrahedral stress distribution.

Table 3: AE stress measurements in the iron mine [1].

<table>
<thead>
<tr>
<th>Site No.</th>
<th>Depth (m)</th>
<th>σ_H (MPa)</th>
<th>Direction</th>
<th>σ_h (MPa)</th>
<th>Direction</th>
<th>σ_v (MPa)</th>
<th>σ_h/σ_v</th>
<th>σ_H/σ_v</th>
<th>(σ_H + σ_h)/2σ_v</th>
<th>σ_H/σ_h</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>110</td>
<td>5.64</td>
<td>N84.60°E</td>
<td>4.11</td>
<td>N54.0°W</td>
<td>3.06</td>
<td>1.34</td>
<td>1.84</td>
<td>1.59</td>
<td>1.37</td>
</tr>
<tr>
<td>2</td>
<td>140</td>
<td>8.23</td>
<td>N81.97°E</td>
<td>3.89</td>
<td>N80.3°W</td>
<td>4.11</td>
<td>0.95</td>
<td>2.00</td>
<td>1.47</td>
<td>2.12</td>
</tr>
<tr>
<td>3</td>
<td>200</td>
<td>10.22</td>
<td>N81.98°E</td>
<td>4.72</td>
<td>N80.2°W</td>
<td>5.36</td>
<td>0.88</td>
<td>1.91</td>
<td>1.39</td>
<td>2.17</td>
</tr>
<tr>
<td>4</td>
<td>260</td>
<td>12.72</td>
<td>N81.82°E</td>
<td>5.98</td>
<td>N81.8°W</td>
<td>6.93</td>
<td>0.86</td>
<td>1.84</td>
<td>1.35</td>
<td>2.13</td>
</tr>
<tr>
<td>5</td>
<td>310</td>
<td>16.35</td>
<td>N82.37°E</td>
<td>8.01</td>
<td>N76.3°W</td>
<td>8.22</td>
<td>0.97</td>
<td>1.99</td>
<td>1.48</td>
<td>2.04</td>
</tr>
<tr>
<td>6</td>
<td>370</td>
<td>17.90</td>
<td>N81.98°E</td>
<td>8.25</td>
<td>N80.2°W</td>
<td>9.87</td>
<td>0.84</td>
<td>1.81</td>
<td>1.32</td>
<td>2.17</td>
</tr>
<tr>
<td>1</td>
<td>160</td>
<td>7.18</td>
<td>N83.91°E</td>
<td>4.34</td>
<td>N60.9°W</td>
<td>4.11</td>
<td>1.06</td>
<td>1.75</td>
<td>1.40</td>
<td>1.65</td>
</tr>
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<td>190</td>
<td>9.55</td>
<td>N81.11°E</td>
<td>4.12</td>
<td>N88.9°W</td>
<td>5.06</td>
<td>0.81</td>
<td>1.89</td>
<td>1.35</td>
<td>2.32</td>
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<tr>
<td>3</td>
<td>250</td>
<td>11.95</td>
<td>N82.95°E</td>
<td>6.65</td>
<td>N70.5°W</td>
<td>6.85</td>
<td>0.97</td>
<td>1.74</td>
<td>1.36</td>
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<tr>
<td>4</td>
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<td>14.85</td>
<td>N82.70°E</td>
<td>8.09</td>
<td>N73.0°W</td>
<td>8.86</td>
<td>0.91</td>
<td>1.68</td>
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<td>5</td>
<td>370</td>
<td>18.26</td>
<td>N82.6°E</td>
<td>10.08</td>
<td>N74.0°W</td>
<td>9.78</td>
<td>1.03</td>
<td>1.87</td>
<td>1.45</td>
<td>1.81</td>
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<td>22.25</td>
<td>N81.66°E</td>
<td>10.93</td>
<td>N83.4°W</td>
<td>11.26</td>
<td>0.97</td>
<td>1.98</td>
<td>1.47</td>
<td>2.04</td>
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<tr>
<td>7</td>
<td>490</td>
<td>24.25</td>
<td>N83.03°E</td>
<td>12.34</td>
<td>N69.7°W</td>
<td>12.81</td>
<td>0.96</td>
<td>1.89</td>
<td>1.43</td>
<td>1.97</td>
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Lithosphere
activities of reverse faults and strike-slip faults, which agrees well with the nature of faulting motion in this district. The focal mechanism solutions near the mine district reveal that the deep stress condition obviously promotes the strike-slip behavior of faults [32], indicating that the shallow stress state is comparable to the deep stress state. The reverse and strike-slip faulting stress fields belong to the geodynamic field, while the normal faulting stress field is a geostatic field. Thus, the mine area was particularly governed by the horizontal stress, indicating a typical geodynamic field type. Furthermore, statistics suggest that the reverse faulting regime generally occurs in shallow rocks, while the strike-slip faulting regime primarily occurs in the deeper part, reflecting the transformation of the stress regime in longitudinal space. This also shows that with increasing depth, \( \sigma \) in the three-dimensional stress tensor changes from the minimum stress component to the intermediate stress component, and its dominance gradually increases. In addition, the results reveal that the distribution of the various stress field types is largely dominated by the nature of the tectonic stress. The dominant stress field types and the secondary and local stress field types in the different tectonic stress action areas exhibit distinct combination relationships and distribution characteristics. The so-called local stress field refers to the stress regime that differs from the regional stress field type after the additional stress caused by the lithology and local factors is superimposed on the regional stress. The resulting structure in this stress regime is generally referred to as a low-order structure [33]. The local additional stress is generally lower than the regional stress, so the local change in the stress state is usually limited.

As indicated in Tables 1–3, in the specific depth ranges, the magnitude of \( \sigma_{H} \) ranges from 2.16 to 24.25 MPa, averaging 10.91 MPa, and that of \( \sigma_\theta \) varies between 1.66 and 12.34 MPa, averaging 5.97 MPa. Particularly, when the burial depth exceeds 370 m, \( \sigma_{H} \) is greater than 18 MPa, demonstrating a high stress level in the mine area in accordance with the criterion of the stress value in the engineering area [34]. This is supported by other geological measurements or observations in the area. The high stress level is probably the result of the continuous action of driving forces due to the movement of tectonic plates around the district. Hence, at a depth greater than 370 m, the presence of a high stress level must be considered when devising the slope structure and mining system. Furthermore, the three-dimensional stress field indicates that \( \sigma_{H} \) and \( \sigma_\theta \) are compressive, which agrees with the regional tectonic analysis results.

According to the compilation of the available stress data, Figure 6 shows the variations in the three principal stresses (\( \sigma_{H}, \sigma_\theta \), and \( \sigma_v \)) with the depth. Obviously, the three principal stresses linearly increase with the depth, especially \( \sigma_{H} \), which rapidly increases with the depth and is far greater than the stress gradients of \( \sigma_\theta \) and \( \sigma_v \). The stress magnitude as a function of the depth in the mine district can best be represented as

\[
\sigma_{H} = 0.0469H + 0.5849 \quad \left( R^2 = 0.9081 \right),
\]

\[
\sigma_\theta = 0.0222H + 1.0827 \quad \left( R^2 = 0.8756 \right),
\]

\[
\sigma_v = 0.0260H + 0.1866 \quad \left( R^2 = 0.9960 \right).
\]

The correlation coefficients higher than 0.8 of Equations (10)–(12) indicate that the three principal stresses exhibit a notable linear dependence and a high linear growth tendency, which agrees with general knowledge. Notably, the stress magnitudes measured via the three methods strictly comply with the same distribution equations. In particular, the AE test results follow the trends of the measurements derived from the more conventional OC and HF methods. This suggests that the quality of the stress data measured via the AE technique is excellent. The established fitting expression of the principal stresses shown in Figure 3 constitutes the model of the stress field in this mine district, which can provide real stress boundary conditions for numerical simulations related to later underground excavation design and slope stability evaluation. Additionally, the evolution of the fitting lines indicates that the influence of the vertical stress is enhanced. Notably, the stress value at the surface is not zero but very small, which is a common phenomenon and may be associated with the erosion of materials on the surface [13]. Moreover, over the past decades, many studies have been performed on the relationship between the principal stresses in the crust and the depth [35–38], and most of them suggest that there exists
an approximately linear relationship between the horizontal and vertical stresses and the depth. According to the consistency between the vertical stress measured via the OC method and the theoretical calculation results as well as the origin of the vertical stress, the vertical stress at any depth in the crust could be reasonably predicted. However, the magnitude of the horizontal principal stress in deep parts must be carefully extrapolated based on the distribution equation derived from the data in the shallow part because the causes of the horizontal stress are more complex than those of the vertical stress, such as global or regional tectonic movement, denudation, rock creep, and temperature change, and most of these factors are variable, which may lead to notable horizontal stress changes in different depth ranges. In addition, a high horizontal stress has been measured at the surface or in shallow layer in many areas worldwide, but there is no clear conclusion regarding this phenomenon yet. Therefore, it is essential to collect additional stress data under different topographical, geological, and structural conditions to correctly explain these issues.

In addition to stress gradient analysis, the evolution of various stress ratios with the depth is given special attention because these ratios can finely characterize the stress condition in the mine district. Figure 7 depicts the variations in four typical stress ratios, i.e., $K_h$ ($\sigma_h/\sigma_v$), $K_H$ ($\sigma_H/\sigma_v$), $K_{hv}$ (($\sigma_H + \sigma_v)/2\sigma_v$), and $K_{Hh}$ ($\sigma_H/\sigma_h$), versus the depth. Within the measured depth range, the distribution characteristics of $K_h$, $K_H$, and $K_{hv}$ are similar and insensitive to the depth, all of which indicate that the closer to the surface, the more dispersed the data distribution is. Moreover, with increasing depth, these stress ratios tend to become concentrated and reach a stable value. Specifically, $K_h$ ranges from 0.75 to 1.70, averaging 1.05 (Figure 7(a)), indicating a small difference between $\sigma_h$ and $\sigma_v$. In general, $\sigma_H$ is approximately 0.98–2.90 times $\sigma_v$, with an average value of 1.85 (Figure 7(b)), which indicates that the iron mine district is mainly affected by horizontal tectonic movement and that the horizontal tectonic stress rather than gravity governs the stress setting in this area. This recognition has also been reached in many other areas worldwide [39, 40]. The previous hypothesis is that the tectonic stress in the hillside region has been completely released, but the measured results contradict this assumption. Moreover, this result supports the concept that horizontal tectonic activities, such as plate movement and block collision, regulate the genesis of a shallow stress field. The existence of relatively high horizontal tectonic stress can impose a considerable influence on the stability of high and steep slopes, which must be given enough attention. Additionally, $K_{hv}$ is concentrated between 0.86 and 2.30, averaging 1.45 (Figure 7(c)), which falls within the range of $K_{hv}$ obtained by Brown and Hoek [41] using worldwide data. Theoretically, with increasing depth, the variance between the three principal stresses becomes statistically insignificant; namely, the value of $K_{hv}$ decreases and approaches 1.0, thus reaching a state of the hydrostatic pressure. The $K_{hv}$ value determined in this study appears to follow this tendency, although the test depth is only a few hundred meters. Moreover, from the perspective of tectonics, the $K_{hv}$ value is slightly high for a district supposedly affected by active tectonic movement [42].

$\sigma_H$ is approximately 1.30–2.32 times $\sigma_h$, averaging 1.78 (Figure 7(d)), which indicates that the stress tensor exhibits high directivity, and the differential stress in the horizontal principal stresses is relatively high. In accordance with the Mohr strength theory, the difference between the horizontal principal stresses is closely related to the shear stress. A sufficiently high shear stress can overcome the shear strength of rocks and cause rock fracture, which creates favorable stress conditions for the generation and development of faults, joints, and other structures. This is probably one of the mechanical incentives for the widespread development and dense distribution of fault structures in this district. Moreover, the field investigation and slope failure mode analysis results show that shear failure is one of the main slope failure

![Figure 7: Variations in the four stress ratios versus the depth: $K_h$ (a); $K_H$ (b); $K_{hv}$ (c); $K_{Hh}$ (d).](http://pubs.geoscienceworld.org/gsa/lithosphere/article-pdf/doi/10.2113/2022/3251234/5741493/3251234.pdf)
patterns. Hence, the presence of a high shear stress should be given more attention in future slope and stope designs.

4.2. Stress Direction. The stress directions in the iron mine district obtained via the three techniques are visualized through respective rose diagrams (Figure 8). Clearly, the $\sigma_H$ direction determined via the OC method is constrained in a small range, i.e., N86.1°W–N89.4°W, averaging N86.1°W. The $\sigma_H$ directions in the four test intervals interpreted via the HF technique are also notably restricted, at N77.0°E, N77.0°E, N77.0°E, and N77.0°E, averaging N79.75°E. Similarly, the stress orientations derived from the AE technique are limited between N81.11°E and N84.60°E, averaging N82.51°E. Apparently, the maximum included angle of the average $\sigma_H$ direction measured via the three methods is only 14.15°. Thus, the $\sigma_H$ directions determined via the three methods are relatively similar.

The stress orientations obtained via the three techniques are plotted in depth and map profiles, as shown in Figure 9, and a rose diagram is embedded in the depth profile to show the statistics and average stress directions. These stress direction data indicate a dominant stress field direction of a NEE–SWW or nearly E–W orientation, which changes slightly with the depth. Similar observations have also been reached in the famous KTB project in Germany [43]. Because the measurement results of the different measurement methods are similar, it can be confidently considered that the measurement results of the in situ stress are credible. Thus, the performance of the three measurement techniques and the reliability of the measurement data are satisfactory.
Notably, locally anomalous stress conditions occur in the mine district, which can most likely be attributed to the complicated geological structure in the study area. Influenced by the boundary conditions of tectonic deformation, the derived local stress field rotates, which does not completely agree with the prevailing regional tectonic stress field direction.

Moreover, the prevailing stress orientation identified in the mine district agrees well with other stress measurements in the vicinity. According to OC stress measurements, Ding and Liang [44] and Li et al. [45] suggested that the stress field in the Tangshan region is a compressive stress field with a dominant stress direction close to E–W. Feng et al. [46] carried out stress measurements adopting the HF method in the Qian’an area and revealed that the stress field in the district varies between N47°W and N82°W, with an average orientation of N64.6°W. Furthermore, Li and Wang [47] and Li et al. [48] obtained extensive stress measurement data in North China based on OC measurements, and these data indicated a prevailing E–W stress orientation (with small deviations) in this region. In addition, the analysis of the focal mechanism solutions of the Tangshan Ms 7.8 earthquake in 1976 and the aftershock sequence shows that these earthquakes were governed by a unified tectonic stress field in North China, whose principal compressive stress direction is nearly E–W, and these events were the rupture results of strike-slip faults under the action of near-E–W horizontal compression [49]. The principal compressive stress axes of the Tangshan Guye Ms 4.8 earthquake in 2012 and the Tangshan Ms 4.5 earthquake are close to the E–W orientation, and the T-axes approach the S–N direction [32]. Huang and Wan [50], Liu et al. [51], and Li et al. [8] compiled extensive focal mechanism data in North China and revealed that the principal compressive stress axis is oriented along a general E–W direction, although some local variation in the orientation was observed. The consistency of the stress field direction with the principal compressive stress direction derived from these focal mechanism solutions indicates that the stress tensor not only agrees with earthquakes in this area but also agrees with the concept that the maximum horizontal stress direction is mainly represented by the tectonic principal compressive stress [52].

In contrast, the high-quality stress direction data obtained via the various stress measurement techniques and the stress directions interpreted based on focal mechanism solutions for earthquakes that occurred in North China are shown in Figure 10 [53], which is dedicated to describing the stress model of the Chinese mainland and exploring the correlation between tectonic stress and seismicity. The \(\sigma_{H}\) orientations available from the map around the mine district (demarcated in a yellow pentagram) yield consistent information; notably, the \(\sigma_{H}\) orientations follow a general NEE–EW direction. Notably, the dominant \(\sigma_{H}\) orientation obtained in this study is identical to the tectonic stress field indicated by the other stress indicators (Figure 10). Consequently, the stress field orientation in this mine area agrees well with that in the Qian’an and Tangshan regions and even in North China. The high consistency in the direction probably occurs because these areas are governed by the same regional tectonic stress field. This also reflects that North China, including the study area, is impacted by an approximately E–W-trending compressive stress field. The above observation results strengthen the predominant \(\sigma_{H}\) orientation determined in this study. Therefore, the measurement results can reflect the current in situ stress environment of the shallow crust in this mine area.

Additionally, numerous studies have shown that the current tectonic stress field orientation often remains relatively stable in a fairly large landmass, and it is closely associated with the geological structure and modern crustal movement [11, 54–56]. The analysis results of this paper also show that the \(\sigma_{H}\) orientation is basically the same in all of North China, although there are anomalies or inconsistencies in local regions. The distribution of the crustal stress direction is one of the most direct clues for the study of the driving force of plate movement. Zoback et al. [55] investigated global patterns of the tectonic stress field using plate tectonics theory and noted that the principal compressive stress axis of the Chinese mainland and adjacent blocks is the same as the tectonic motion direction of the peripheral plates, and the tectonic stress field inside the plates is triggered and governed by plate motion. North China is sandwiched between the Indian plate, Eurasian plate, and Pacific plate and is principally dominated by compression caused by the notable collision of the Indian plate with the western Chinese mainland and the subduction of the Pacific plate below the eastern Chinese mainland; the direction of the former is NEE–SWW or approximately E–W, while the latter is oriented NWW–SWW [8]. The mine district is located at the intersection of the compression and subduction zones of these two plates, which jointly affect the stress field pattern in this district. In contrast, the influence of the Indian plate seems to be stronger than that of the Pacific plate given the obtained dominant NEE–SWW or approximately E–W stress field orientation in the mine area.

5. Correlation between the Stress Field and Geological Tectonics

5.1. Geological Evolution. The origin of the in situ stress is quite complicated and is not fully understood to date. It is generally believed that the generation of the crustal stress field is primarily correlated with various dynamic processes in the crust, including both historical tectonic movements and geological phenomena that are still active today. Hence, the stress state in a particular region is affected by various geological factors [57]. As internal stress in geological bodies, the in situ stress is likely affected by regional geological structures. Moreover, the geological structures formed under different stress conditions are often different. Therefore, different geological structure models can reflect the tectonic stress states at the time of their formation to a certain extent. The existing forms of most geological structures in strata are the result of multistage tectonic movements, so it is necessary to investigate the relationship between the stress field and geological structures in the iron mine district from the perspective of tectonic evolution stages and sequence generation in this region.
In general, the stress field in a specific area is related to its geology and tectonic history. During the long tectonic history, the structural development and evolution in the mine area mainly experienced three typical stages: the Mesozoic Indosinian movement, the Yanshanian movement, and the Cenozoic Himalayan movement. Different tectonic movements and different stages of the same tectonic activity created tectonic stress fields along different directions, resulting in the generation, superposition, and transformation of various geological structures [15]. The Indosinian movement period was a period of large-scale collision and amalgamation and was also a period in which folds and faults were widely developed in the Chinese mainland. The prototype of the compound syncline structure framework in the mine district probably originated from the collision and docking of the North China block and the Yangtze block along the Dabie Mountain orogenic belt from the late Indosinian movement to the early Yanshanian movement. Therefore, under the action of a near-S–N compressive stress, this district and other parts of North China were uplifted overall, and a series of NEE, NE, and near-E–W faults were formed in this district. During the later period, due to the imbalance of S–N compression, twisting movement from west to south and from east to north occurred, resulting in NE-trending folds, and second-order small folds developed within the syncline structure. The $\sigma_1$ direction of the tectonic stress field approaches the S–N orientation, which is the first-stage tectonic stress field in this district (Figure 11(a)).

Figure 10: Present-day stress orientation in the mine district (after Xie et al. [53]).

![Diagram showing present-day stress orientation in the mine district](http://pubs.geoscienceworld.org/gsa/lithosphere/article-pdf/doi/10.2113/2022/3251234/5741493/3251234.pdf)
During the Yanshanian movement, because of the westward subduction and compression of the North American plate and the Izu–Bonin–Mariana plate, the Chinese mainland rotated counterclockwise, and notable intraplate deformation generally occurred in the eastern part of the Chinese mainland. Furthermore, the Yangtze block moved northward relative to the North China block. Under the action of these driving forces, the mine area was subjected to NW–SE-trending lateral compression and NNE–NE-trending sinistral compression and torsion, and faults and fold structures were further developed, with more significant structural differentiation. The folds formed at the later stage overlapped preexisting folds, resulting in the superposition of fold structures. In addition, this area was affected by the eastern reflex arc of the Qilianshan–Lüliangshan–Helanshan epsilon-type structure; the early NE-trending fault was reformed, and a NW-trending compressional and torsional fault emerged. Moreover, some structures approaching the E–W direction were transformed into NW–SE-trending structures, and new fault systems were formed along this direction. E–W-trending tectonic movements have continued to occur since the late Yanshanian movement. The \( \sigma_1 \) direction of the tectonic stress field is the NW–SE orientation, which is the second-stage tectonic stress field (Figure 11(b)).

During the Himalayan movement, the Indian plate intensely collided with the Eurasian plate along the NNE orientation, resulting in compound stress and a tensile force creeping eastward in the North China block was formed. During this period, the regional tectonic stress field was converted from a compression shortening mechanism into a tension extension mechanism. Compared to the Yanshanian tectonic movement, the stratum deformation during the Himalayan tectonic movement was weaker, which was primarily manifested in the development of secondary fold and fault structures and imposed a certain transformation effect on the structures formed during the Yanshanian period. However, the normal faulting activities were intense, and a large body of NNE–NE-trending normal faults were formed under the action of the NWW–SEE tensile stress. At the same time, a stress field of dextral coupling action along the near-NE orientation was generated, and the \( \sigma_1 \) direction developed into the NEE–EW orientation, which is the third-stage tectonic stress field (Figure 11(c)).

According to the above analysis, the new and old tectonic systems in this mine district are closely correlated. The new tectonic system exhibits inheritance from the older tectonic system, and at the same time, this reflects the role of regeneration in producing new tectonic traces. Similarly, the \( \sigma_1 \) orientation in the mine district changed from the S–N direction during the first-stage tectonic movement into the NW–SE direction during the second-stage tectonic movement and finally progressively developed into the NEE–EW direction during the third-stage tectonic movement. The tectonic movements at the different stages are accompanied by the evolution of the stress field, which in turn leads to tectonic activities with different characteristics. Thus, the stress field in a particular area interacts with the regional geological structure.

5.2. Comparison between the Stress Field and Geological Tectonics. As shown in Figure 9, the \( \sigma_{11} \) orientation at the majority of the measurement points is clearly oriented along the NEE–EW direction, and individual measurement points are oriented along the NWW–SEE direction, which agrees with the \( \sigma_1 \) directions of the second- and third-stage tectonic stress fields analyzed earlier. This suggests that the present-day stress field in the mine district basically inherited the third-stage tectonic stress field while partially retaining the characteristics of the second-stage tectonic stress field. The contemporary stress field in the mine area could be regarded as the result of dynamic action and tectonic movement during the different geological periods, and the \( \sigma_1 \) direction of the tectonic stress field that affects the modern tectonic activity in this area is NEE–EW, which agrees well with the geological structure analysis results for the mine area.

The stress field in the mine district has experienced the construction and transformation of multistage tectonic movements, but now it is directly affected by neotectonics, and the stress field is governed by the modern tectonic stress field of NEE-trending horizontal compression and NNW-trending horizontal tensile stress. At the same time, the stress measurements indicate that the stress field in the district occurs in the regional tectonic stress field and conforms with the direction of the regional tectonic principal stress. Therefore, in a sense, this also indicates the correctness of
the measurement results obtained via the three measurement techniques. In addition, the active structures and regional stress field characteristics of a given region determine the mode of fault activity in the region. The determination of the stress field direction in the mine district is helpful to gain insight into the movement modes of faults. Given the effect of the NEE–SWW or near-E–W-trending regional compressive stress field, the current activities of the NNE–NE-trending faults distributed in this area are likely principally subjected to dextral strike-slip, while the current activities of the NW-trending faults tend to be sinistral strike-slip. This basically coincides with the contemporary motion nature of faults interpreted via geological surveys. Hence, our stress measurement results strongly support the mechanical origin and action mechanism of faults in this region. Moreover, even the variability in the $\sigma_{1H}$ direction among stress provinces is roughly identical to that in neotectonic features, which further validates that the current stress pattern is a main controlling factor of the deformation process throughout the continental plate [58].

Through the above analysis, a certain linkage between the stress field and geological structure exists in the study area, which is not just an accidental phenomenon. Furthermore, many smaller-scale studies have highlighted the role of third-order stress sources, such as geological structures, in the crustal stress model [11]. In addition, numerous field measurements and research results worldwide suggest that the horizontal tectonic stress plays a leading and controlling role in the present-day stress field, and the $\sigma_{1H}$ orientation largely depends on the current tectonic stress field. In this district, the $\sigma_{1H}$ direction is also related to historical geological structural elements because the present-day stress field inherits the previous stress field and is further developed. The field investigation and research show that the tectonic stress field in this district where the iron mine is located is still changing, and the $\sigma_{1H}$ axis tends to deflect toward the E–W direction.

In summary, the distribution of the present-day stress field is often the result of multistage tectonic movement, and the influence of each stage of tectonic movement on the stress field also varies. The relationship between geological structures and the stress field is very complex. Studying the stress field from the perspective of tectonic evolution stages can yield relatively comprehensive and accurate results. The present-day stress state provides us with a window to clarify the recent geological past and future of the mine area since it is the manifestation of the ongoing structural evolution of the crust [52]. The Earth has experienced multiple tectonic activities, both large and small, resulting in complexity and variability in the stress field. Based on our measured results, we can also find that even at the same depth level within the same mine area, the stress state at different measuring points may be considerably different. Even though the stress field in a given area can be relatively continuous, it is probably heterogeneous from one area to another. This also suggests that it is almost impossible to obtain accurate data on the in situ stress via mathematical calculation or other speculative methods. The only effective means to ascertain the state of the crustal stress in a certain region is to conduct field stress measurements. In contrast, when investigating the relationship between the stress field and geological structures, a comprehensive analysis should be performed in combination with the measured in situ stress state, geological structure analysis, and other geological surveys.

6. Conclusions

The obtained 25 sets of high-quality OC, HF, and AE stress measurements enhance the stress database for North China and provide us with excellent opportunities to characterize the stress field characteristics of the iron mine district and to study the tectonic evolution from the perspective of geomechanics. The major findings are as follows:

(1) The three combinations of the principal stresses indicate the diversity and complexity of the stress state, which are characterized by $\sigma_{1H} > \sigma_3 > \sigma_v$ and $\sigma_{1H} > \sigma_v > \sigma_3$, revealing prevailing reverse and strike-slip faulting stress regimes. The $\sigma_{1H}$, $\sigma_v$, and $\sigma_h$ values in the mine district increase according to a nearly linear relationship with the depth. $K_v$ ranges from 0.75 to 1.70, averaging 1.05, indicating a small difference between $\sigma_h$ and $\sigma_v$. $\sigma_{1H}$ is approximately 0.98–2.90 times $\sigma_v$ with an average value of 1.85, which suggests that the mine district is mainly affected by horizontal tectonic movement, and the horizontal tectonic stress rather than gravity governs the stress state in this area. The measured results contradict the hypothesis that the tectonic stress in the hillside region has been thoroughly released. Additionally, $K_w$ is concentrated between 0.86 and 2.30, averaging 1.45. The $K_w$ value is slightly high for a district supposedly affected by active tectonic movement. $\sigma_{1H}$ is approximately 1.30–2.32 times $\sigma_h$, averaging 1.78, which indicates that the stress tensor exhibits notable directivity, and the differential stress in the horizontal principal stresses is relatively high.

(2) The $\sigma_{1H}$ directions determined via the three methods are relatively similar. The stress direction data indicate a dominant stress field direction of NEE–SWW or an approximately E–W orientation, which changes slightly with the depth. Moreover, the prevailing stress direction identified in the mine area agrees well with that revealed by focal mechanism solutions and other stress measurements in the vicinity. The mine area is subjected to the action of an approximately E–W trending compressive stress field. Thus, the measurement results can reflect the current in situ stress environment of the shallow crust in this area. The intense collision of the Indian plate with the western Chinese mainland and the subduction of the Pacific plate below the eastern Chinese mainland jointly affect the stress field pattern in this district.

(3) The new tectonic system exhibits inheritance from the older tectonic system, and at the same time, this
reflects the role of regeneration in producing new tectonic traces. Similarly, the $\sigma_1$ orientation in the mine district changed from the S–N direction during the first-stage tectonic movement to the NW–SE direction during the second-stage tectonic movement and finally gradually developed into the NEE–EW direction during the third-stage tectonic movement. The tectonic movements at the different stages are accompanied by the evolution of the stress field, which in turn causes tectonic activities with different characteristics. The present-day stress field in this district generally inherited the third-stage tectonic stress field while partially retaining the characteristics of the second-stage tectonic stress field. The present-day stress field in this area can be regarded as the result of dynamic action and tectonic movement during the different geological periods, and the $\sigma_{1t}$ direction of the tectonic stress field that affects the modern tectonic activity in this area is the NEE–EW direction.

Data Availability

The experimental data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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