In-situ stress measurements and stress accumulation level analysis of coal mines in northern Ordos Basin

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Highlights

- For rock masses around 350m, $k$ tends to 1 and the mines enter a critically deep state
- The principal stresses tested by KE have error about 15% with that of OC, ASR, and HF
- $\sigma_H$ dominant orientation is basically consistent with that of focal mechanism solution
- The fracture stress of mines is lower than friction limit state, and its level is low

Abstract

For non-directional drilling cores, the sample selection and test method for Kaiser effect (KE) in-situ stress measurement were proposed, and the magnitude and direction of its principal stresses were theoretically derived. Based on this method, the KE of 423 samples in Burtai and Baode coal mines in northern Ordos Basin (NOB) were tested. The results show that $\sigma_H$, $\sigma_h$, and $\sigma_v$ vary with depth and location, and their values increase with increasing of depths. Generally, horizontal stresses play a leading role. There are main stress regimes in NOB: $\sigma_H > \sigma_h > \sigma_v$ (Burtai, <172m; Baode, <170m) and $\sigma_H > \sigma_v > \sigma_h$ (Burtai, 170-800 m; Baode, 170-400 m), and the $\sigma_v > \sigma_H > \sigma_h$ stress regime is mainly distributed in moderately deep to deep coal mines. For rock masses with a depth of 350m, $k ((\sigma_H + \sigma_h) / 2\sigma_v)$ tends to 1, indicating that deep critical state will gradually emerge. The test results were compared with those of overcoring method (OC), elastic strain recovery (ASR) and micro-hydraulic fracturing (HF). The relative errors of $\sigma_H$, $\sigma_h$, and $\sigma_v$ are 14.90%, 19.67%, 15.47% (Burtai) and 10.74%, 22.76%, 19.97% (Baode), and they are all within a reasonable range required by the project, which verifies the reliability of KE method. The dominant orientation of $\sigma_H$ (Burtai, NE-NNE; Baode, NEE) was obtained by using paleomagnetic technology, which is consistent with that (NE-NEE) of earthquake focal
mechanisms in this area. Based on Byerlee-Anderson theory, the stress accumulation level of mine rock mass was discussed. Under dry rocks or hydrostatic pressure rocks, the friction coefficient of faults is both low, which is less than the lower limit (0.6) of strike-slip faults slip, indicating that the fracture stress with a low level around the study area is lower than the friction limit stress. The stress accumulation level in Baode mine is slightly larger than that in Burtai mine.

**Keywords:** In situ stress; Kaiser effect; Drilling core; Paleomagnetic technology; Stress accumulation level

1. **Introduction**

In the long process of geological evolution, the crustal rock mass is continuously adjusted and evolved under the coupling of water and rock corrosion, pressure dissolution, high-temperature thermal stress, and long-term creep, resulting in the in-situ stress distribution with time-space complexity and variability. It is not only the key factor to determine the stability of the regional structure, but also an important force source to affect the stability of roadways such as mining engineering (Yuan, 2017; Qian, 2012). With the increase of demand for energy and mineral resources and the increase of mining intensity, deep environment mining has been carried out successively. There are problems such as "three highs and one disturbance" of high in-situ stress, high in situ temperature, high water pressure and strong mining disturbance, which will become the focus and difficulty in deep mining rock mechanics and engineering (Xie et al., 2015). Accurately obtaining the distribution and accumulation level of in-situ stress is the way to solve the above problems.

Since 1932, Lieurace (1933) took the lead in testing the surrounding rock stress in spillway tunnel with the method of surface stress relief at the bottom of Hoover Dam. Since then, in-situ stress testing technology has developed rapidly, and it has been widely used in many fields, such as energy utilization of oil, gas, water, geothermal, resource development of coal mines, metal mines, earthquake prediction, nuclear waste disposal, and so on (Su, 2002). So far, there are dozens of in-situ stress testing methods, but no unified classification standard has been formed. They can be classified according to data sources and can be roughly divided into five...
categories: core-based methods, borehole-based methods, geological methods, underground space-based methods and geophysical methods (seismological methods) (Zang and Stephansson, 2013; Wang, 2014; Stephansson and Brown, 2015). However, different test methods reveal different scales of stress information, and the scope of application is also different. Therefore, several methods need to be used jointly, which are complementary to each other, and finally determine the stress state of the rock mass, to reduce the error caused by different scales of stress information.

The development of acoustic emission (AE) monitoring system has created conditions for the accurate identification of the Kaiser effect (KE) and its application. Since Kaiser discovered KE phenomenon in 1957 (Michihiro et al., 1985), the KE of sandstone and crystalline rock was first confirmed by Goodman (1963), Kurita and Fujii (1979), and most show good KE, such as marble, gneiss, granite, gabbro, greenstone, porphyry, chalcopyrite, and so on, except Kiruna magnetite (Holcomb, 1983; Li and Nordlund, 1993). Then Kanagawa et al. (1976) first tried to apply KE to in-situ stress test. To obtain the exact KE point, the uniaxial double cyclic loading mode was proposed (Yoshikawa and Mogi, 1989), and the cyclic peak load ($\sigma_P$) must be higher than the estimated previous maximum stress ($\sigma_{H_{\text{max}}}$), and $\sigma_P$ is 30%–80% of the uniaxial compressive strength ($\sigma_C$). At the same time, the deformation rate analysis method (DRA) for testing in-situ stress was proposed. The principle of AE-DRA combined method has been described, the AE method and the DRA method have been mutually confirmed, and the vertical stress of siliceous slate in metal mines (Xie et al., 2010) and gypsum rock (Ge et al., 2015) has been determined. Although the mechanism of KE has not been completely solved, the method can meet the engineering needs by comparing the results of KE test and field measurement (Qin et al., 1993). At present, KE research is mainly focused on hard magmatic rock, metamorphic rock and sedimentary rock, while systematic on coal measures sedimentary rock is less.

When the main stress state is $\sigma_H > \sigma_h > \sigma_v$, $\sigma_H > \sigma_v > \sigma_h$ and $\sigma_v > \sigma_H > \sigma_h$, it is conducive to the activities of reverse fault, strike-slip fault and normal fault (Anderson, 1942; Byerlee, 1978). The change of in-situ stress value around the fault is complex. The HF test results of nearly 1,000 fault block oil wells around the normal and inverse fault areas show that $\sigma_h$ is parallel to the fault trace (Sun and Zhang, 2004). According to Mohr-Coulomb criterion (Hoek
and Brown, 2019), when $\tau \geq \mu \sigma_n$, sliding instability occurs along the fault plane. After analyzing a large number of test data on rock friction and sliding, it is concluded that when the normal stress ($\sigma_n$) is less than 100 MPa, the internal friction coefficient ($\mu$) of most crustal rocks is between 0.6 and 1.0 (Byerlee, 1978). The results of KTB drilling on the continental crust in the German deep hole drilling site show that Byerlee's law applies from the surface to a depth of 9.1 km, and the permeable fracture rocks in the range of 3–7 km are very close to Coulomb fracture line when $\mu$ is about 0.6. A large number of rock friction mechanical tests in the Three Gorges dam area show that (Lavrov, 2003), Byerlee's law is also applicable to granite, limestone, sandstone and other rocks in the dam area. The rock friction strength is between $\tau = 1.10 \sigma_n$ and $\tau = 0.65 \sigma_n$, with an average value of $\tau = 0.85 \sigma_n$. According to Byerlee's law, the angle between the maximum principal stress of Anderson fault and fault plane is 23°–30°, which is Byerlee-Anderson theory. $\mu$ can quantitatively reflect the friction strength of around fault. When $\mu > 0.6$, the strength of around fault is higher; when $\mu > 0.6$, that is medium; when $\mu < 0.3$, that is weak. Also, the direction of $\sigma_H$ and $\sigma_h$ can be roughly inferred according to rock vein, large anticline and syncline.

Shendong mining area is located in the north Ordos Basin. It is the largest mining area of coal mine in China. With the increase of mining depth, nonlinear dynamic phenomena occur successively, such as floor heave, spalling, large area roof weighting, gas emission, and so on, which are closely related to in-situ stress. In this paper, based on drilling cores, the KE for testing in-situ stress was carried out. The distribution law of in-situ stress has been analysed, and the stress accumulation level has been evaluated. It has theoretical guiding significance and engineering application value for the mining of Burtai and Baode mines.

2. Geological setting of the study area

Burtai mine is located in the south of Dongsheng country, Ordos City. Its geotectonic division belongs to the mid-eastern of Yimeng uplift and the northeast of Yishan slope in Ordos syncline, North China platform. It is known from the regional structure outline map (Zhang et al., 2009; Zhao et al., 2019; Zhao et al., 2018; Ye et al., 2006; He, 2013), Burtai mine is located in the northeast of Wuhai-Ejin Horo banner-Jungar banner deep crust fracture (F11) with a
length of 450 km in EW—NEE. The fractures around it are relatively developed, such as
Ordos-Dongsheng crust fracture (F10) with a length of 200 km in NEE, and East Dongsheng
basement fracture (F20) with a length of 50km in NW. The complex, broken, uneven and
intersecting basement faults lead to the structure of a prism and lattice pattern, which controls
the development of fault structures in the upper overburden (Fig. 1 (b)), and constitutes a
migration channel for the rise of reducing fluid in deep. It has an important influence on the
oil, gas, water and sandstone type uranium deposits in a deep basin. In coal mining, fracture
structure is closely related to mine design, production management, disaster prevention and
control and mining damage.

Fig. 1. Regional tectonic outline of Burtai mine and Baode mine. (a), location of northern Ordos
Basin (He, 2013); (b), tectonic distribution of northern Ordos Basin. Notes: F1, Ural mountain;
F2, Hetao basin; F3, Daqing mountain; F4, Northern margin of Ordos Basin; F5, Horinger; F6,
Hanggin banner-Ejin Horo banner; F7, Wuhai North; F8, Dalad banner; F9, Hanggin banner-
Togtoh; F10, Ordos-Dongsheng; F11, Wuhai-Ejin Horo banner-Jungar banner; F12, Uxin
banner-Shenmu-Fugu; F13, Linfen-Lishi-Pianguan; F14, Leap Hetao basin; F15, Leap Ural
mountain ; F16, Leap Ural mountain and Daqing mountain; F17, Leap Daqing mountain; F18,
South Linhe; F19, Boundary between northern margin of Ordos Basin fault and Lingle fault;
F20, East Dongsheng; F21, Leap near NE fault.

The structural form in Burtai mine is a complex syncline, which is composed of a series
of asymmetric secondary gentle open short-axis folds with a dip of 42°–70° in NNW. Within
the envelope, the Yan'an formation strikes N10°W–N50°W. The well field structure is
generally a nearly horizontal monoclinic structure (Fig. 1 (b)), with the stratum strike of
N20°W, the trend of S70° W, the dip of less than 5° and inclined in SW. During field
exploration, no large fault, collapse column structure and magmatic rock intrusion were found.
 Except for a reverse fault with a drop of 0.54m, the rest are medium and small normal faults
with a drop of less than 12m, and the strike is NW.

In the process of coal mining, it is found that small and medium-sized folds and faults are
widely developed, which have a great impact on coal mining. It is considered that (Jia, 2008;
Qing, 2011), the coal-bearing strata of Yan'an formation are in unconformity contact with its
lower Yanchang formation, its upper Zhiluo formation or Yijinhuoluo formation. In the late
Middle Jurassic, under the N24–45°E-direction compression, Yimeng uplift took place, and the shallow structural level longitudinal bending fold deformation took place in the Jurassic, forming the capping-sliding type compound syncline structural style. Conjugate shear joints with NNE direction are developed on the outer side of the secondary fold envelope. In the Cretaceous, under the action of N46–65°E nearly horizontal extension, shear and fault rise and fall lead to the occurrence of extensional detachment deformation in a large range, thus forming the widespread development of strata slip faults in Yan’an formation, with accompanied by a large number of high angle normal faults and traction folds. Folds and faults directly affect the distribution of the local stress field.

Baode mine is located in Baode County, Shanxi Province. Its geotectonic division belongs to the northeast in Ordos coal accumulating basin, the north section of West Shanxi fold belt, the west of Shanxi Fault uplift, the west of Lvliang structure, and the east of Yellow River graben. The fractures around it are relatively developed, such as Linfen-Lishi-Pianguan crust fracture (F13) in NS, Uxin banner-Shenmu-Fugu crust fracture in NE (F12), and F21 in NW. The strike of faults in the region is dominated by near NS, followed by near WE. The regional tectonic stress field is mainly affected by the Yanshan and Himalayan movement (Yang et al., 2014). In the Yanshan period, the compressional stress is dominant, the extensional stress is secondary, and NW-SE compressive stress and NEE-SWW tensile stress are developed. In Himalayan period, the compressional stress changes to NE-SW, the azimuth of $\sigma_1$ is N150°E, the dip is 3°, the azimuth of $\sigma_3$ is N31°E, and the dip is close to 0°, which leads to a large number of tension joints and weakened compression joints. In the Yanshan period, the fold of axial nearly EW deflected to the axial NW. The superposition of two-periods of tectonic movement causes the direction of $\sigma_1$ to change from NW-SE to NE-SE.

The Baode mine field is dominated by slightly inclined monoclinic strata. The coal seam is nearly NS trending and inclined to the west, with a dip of 3°–10°. Fold and fault are relatively weak, but joints are very developed. The overall axial direction of the fold is nearly EW. The normal faults account for the majority, and their strike is NE, NW and nearly NS. The joints are significantly affected by lithology, that of Ordovician limestone are relatively developed, and that of coal seam is quite different. The shear joints account for the majority, and the X and goose-type shear joints are developed, which are filled by calcite vein. The landform of
Baode mine is characterised by distinct undulating hills. Under the long-term water erosion, the thickly covered surface loess becomes thousands of gullies. The special topography will affect the stress distribution in the mine field.

3. The methods of KE on borehole core for testing in-situ stress

3.1 Sample preparation and test methods

For the directional rock block with undisturbed shallow bedrock surface or chamber, generally, six or nine small samples (Qin et al. 1993) are drilled in different directions on the parent rock block, and the samples are cylindrical or square, with a width to height ratio of 1:2. However, the core of ground drilling is different from that of the shallow layer, most of the drilling holes are straight holes, and it is difficult to achieve core orientation. The diameter of the parent rock core is mostly about 75 mm, so it is impossible to drill as required, so it is necessary to reduce drilling number of small samples. KE for testing in-situ stress based on the non-directional core assumes that the vertical stress is one of the principal stresses and the other two are horizontal stresses, it is necessary to process four small cylindrical samples, one along the core axis, three along the perpendicular to the core axis, and drill in 0°, 45° and 90° or 0°, 60° and 120° anticlockwise. The diameter and height are 25 and 50mm, which conforms to the rock mechanics test standard. The on-site coring location and sample processing process are shown in Fig. 2, and a total of six drilling holes (Red; Burtai, five; Baode, one) were selected for AE testing. Generally, the influence of core sampling damage on KE can be ignored (Lavrov, 2003).

Fig. 2. Coring and processing of the samples. (a), sampling location in Burtai mine; (b), sampling location in Baode mine; (c), on-site coring (BK220); (d), sampling from rock core; (e), processed samples. Notes: red, the core sampling location tested by AE; light green, the on-site test location by OC.

Before the test, 2–4 sensors are used to collect data for small samples, which are placed in the middle of the sample side, as far as possible away from the upper and lower end faces. To ensure the coupling effect between sensor and end face, vaseline or butter is used as the coupling agent, and the sensors are fixed with adhesive tape or plasticine. According to
previous research experience (Qin et al., 1993), in this paper, AE monitoring system is set up with preamplifier gain of 40dB, valve value of 45dB and sampling rate of 1MHz.

When the load rate is 0.05–0.25 kN/s or the displacement rate is 0.05–0.6 mm/min in uniaxial loading, the AE effect is better. With the increase of the sample moisture content will lead to the decrease of AE count and energy, so the natural or dry sample should be used (Yang et al., 2018). When triaxial loading test is adopted, the stratum stress where the sample is located can be estimated in advance, to set the confining pressure and load the axial load at a constant rate. When the rock is buried shallowly and confining pressure is low, the KE can be used to testing in-situ stress directly by uniaxial loading.

For identification of KE points, most scholars choose AE count or count accumulation as parameters, but the author finds that the comprehensive identification method, which is mainly AE count or count accumulation, supplemented by AE energy rate or count rate increment (RI), is easier to determine the KE point. To avoid the interference of friction AE at the initial stage of loading, KE points are usually identified using uniaxial double-cycle loading. Since more AE are produced by crack closure at the beginning of loading, generally, the surge point of the first cycle AE should not be selected, but that of the second loading cycle AE should be used as KE point (Fig. 3). Moreover, the first cyclic peak load $\sigma_p$ is less than $\sigma_{Hmax}$, $\sigma_p$ is about 30% of $\sigma_C$. Specific identification method of this paper: first, based on AE count or count cumulative versus time, find the counting group, then identify the surge point according to AE energy rate or RI versus time, mutual verification, and comprehensively determine KE point. If there are multiple KE points under cyclic loading or they are not obvious, AE-DRA method can be used to try. The loading mode is multiple cyclic loading controlled by load and displacement. The first cycle $\sigma_p$ is less than $\sigma_{Hmax}$, and the next cycle $\sigma_p$ is greater than $\sigma_{Hmax}$ and less than $\sigma_C$. It is suggested that the reasonable $\sigma_p$ in the first cycle is less than 27% of $\sigma_C$ in siltstone, fine sandstone and coarse sandstone, 40% of $\sigma_C$ in sandy mudstone, 17% of $\sigma_C$ in medium sandstone, 13% of $\sigma_C$ in mudstone and limestone, and it does not exceed 63%–70% of $\sigma_C$ in nest cycles (Yang et al., 2018). If further KE point recognition is still not ideal, the method of calculating the fractal dimension by G-P algorithm can be used to try. In this paper, three methods are used. Fig. 3. KE point recognition by AE during gradual increase cyclic loading. Notes: $\sigma_{Fi}$, the KE point stress corresponding to $\sigma_p$ in the $i$ cycle; $\sigma_{Ki}$, the KE point stress corresponding to $\sigma_{Hmax}$.
3.2 Processing of test data

There are different opinions on the determination of principal stress direction of non-directional drilling core (Li and Dong, 2009; Fa et al., 2017). This section attempts to clarify the magnitude and direction of the principal stress and establish the corresponding calculation equation. For the plane stress state, the stress components $\sigma_x$, $\sigma_y$ and $\tau_{xy}$, $\tau_{yx}$, on the element body are known, and the normal stress ($\sigma_{\alpha}$) and shear stress ($\tau_{\alpha}$) on any inclined section ($\alpha$ slope) can be obtained by analytical method:

$$
\begin{align*}
\sigma_a &= \sigma_x \cos^2 \alpha + \sigma_y \sin^2 \alpha - 2\tau_{xy} \sin \alpha \cos \alpha \\
&= \frac{\sigma_x + \sigma_y}{2} + \frac{\sigma_x - \sigma_y}{2} \cos 2\alpha - \tau_{xy} \sin 2\alpha \\
\tau_a &= \left(\sigma_x - \sigma_y \right) \sin \alpha \cos \alpha + \tau_{xy} \left(\cos^2 \alpha - \sin^2 \alpha \right) \\
&= \frac{\sigma_x - \sigma_y}{2} \sin 2\alpha + \tau_{xy} \cos 2\alpha
\end{align*}
$$

(1)

If the corresponding Mohr stress circle is established, $\sigma_{\alpha}$ and $\tau_{\alpha}$ on $\alpha$ slope can also be obtained from it. Then, two principal stress values can be determined as follows:

$$
\begin{align*}
\sigma_1 &= \frac{\sigma_x + \sigma_y}{2} + \left[\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2\right]^{\frac{1}{2}} \\
\sigma_2 &= \frac{\sigma_x + \sigma_y}{2} - \left[\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2\right]^{\frac{1}{2}}
\end{align*}
$$

(2)

If the angle between $x$-axis and direction of $\sigma_H$ on the unit is $\beta$, and clockwise direction is negative, then:

$$
\tan 2\beta = \frac{-2\tau_{xy}}{\sigma_x - \sigma_y}
$$

(3)

To determine the angle between two principal stresses and $x$-axis, first, calculate $\beta$ and $\beta \pm 90^\circ$ from Eq. (3), and then compare the magnitude of $\sigma_x$ and $\sigma_y$. If $\sigma_x > \sigma_y$, the angle between the maximum principal stress ($\sigma_1$) and $x$-axis is $\beta$; if $\sigma_x < \sigma_y$, the angle between $\sigma_1$ and the $x$-axis is $\beta \pm 90^\circ$; if $\sigma_x = \sigma_y$, then $\beta = -45^\circ$. That is to say, $\sigma_1$ is always inclined to the larger of $\sigma_x$ and
σ_v, while σ2 is inclined to the smaller of them. At the same time, it can be known that the angle between x-axis and the direction of σ_H is within ± 90. So, β calculated from Eq. (3) is the angle between x-axis and direction of σ_H (Li and Dong, 2009; Fa et al., 2017); in fact there is a certain deviation.

From Eqs. (1) to (3), the magnitude and relative directions of two horizontal principal stresses can be calculated using the least-squares method. If it is not possible to obtain the KE point stress of the axial sample along with the core, σ_v can be calculated by the logging density through the following equation.

\[
\sigma_h = \frac{\sigma_{0v} + \sigma_{90v}}{2} + \left[ \frac{\sigma_{0v} - \sigma_{90v}}{2} \left( 1 + \tan^2 \beta \right)^{\frac{1}{2}} \right],
\]

\[
\sigma_h = \frac{\sigma_{0v} + \sigma_{90v}}{2} - \left[ \frac{\sigma_{0v} - \sigma_{90v}}{2} \left( 1 + \tan^2 \beta \right)^{\frac{1}{2}} \right],
\]

\[
\tan 2\beta = \frac{2\sigma_{45v} - \sigma_{90v} - \sigma_{0v}}{\sigma_{0v} - \sigma_{90v}}.
\]

\[
\sigma_v = \int_0^H \rho(h) g dh.
\]

With an increase of depth, the mechanical properties of the rock are different from those of shallow, and the stress is more significantly affected by pore fluid, which can be characterised by pore pressure. The KE can only measure the relative constant deformation stress of the memory rock, that is, the effective stress. The real in-situ stress value should be the effective stress plus the pore pressure, so the expressions of σ_H, σ_h and σ_v considering the pore pressure are as follows:

\[
\sigma_h = \frac{\sigma_{0v} + \sigma_{90v}}{2} + \left[ \frac{\sigma_{0v} - \sigma_{90v}}{2} \left( 1 + \tan^2 \beta \right)^{\frac{1}{2}} + \alpha P \right],
\]

\[
\sigma_h = \frac{\sigma_{0v} + \sigma_{90v}}{2} - \left[ \frac{\sigma_{0v} - \sigma_{90v}}{2} \left( 1 + \tan^2 \beta \right)^{\frac{1}{2}} + \alpha P \right],
\]

\[
\sigma_v = \int_0^H \rho(h) g dh + \alpha P.
\]

### 3.3 Core orientation using Paleomagnetic technology

For non-directional drilling core, the angle between σ_H and 0° mark line can be obtained from above, while the azimuth of σ_H relative to the geographic north pole requires
paleomagnetic orientation technology. The sample is processed into a cylinder with a diameter and height of 25 and 20 mm along the core axis, each testing point processes more than five to seven samples. Draw a straight line along the side parallel generatrix (0° mark line of KE sample) with the top of the core facing upwards, and establish the relative coordinate system rotating around the central axis of the sample, that is, a right-hand coordinate system (Fig. 4).

Where, $X$-axis is the extension direction of sample cross-section dot $O$ toward 0° mark line; $Y$-axis is 90° clockwise rotation of $X$-axis; $Z$-axis is the vertical downward direction of sample axis; $OH$ is the magnetic north direction, the angle between it and $X$-axis is the magnetic declination ($D$), which determines the azimuth of the geographical north pole, $D$ is positive along clockwise and negative along counterclockwise; $I$ between $OJ$ vector direction and the horizontal plane is the magnetic dip, $I$ is positive in the northern hemisphere and negative in the southern hemisphere.

![Fig. 4. Schematic diagram of relative coordinate system on geomagnetic sample](image)

In the paleomagnetic test, 2G superconducting magnetometer in the USA and MMDT80 thermal demagnetization meter in the UK are used by thermal demagnetization method. First, the natural remanence (NRM) in samples are measured, and then the samples are demagnetised and cleaned every 50 °C. The magnetic declination $D_a$, magnetic inclination $I_a$ and magnetization of viscous remanence (VRM) in samples are measured. Then, $D$ and $I$ of VRM in the relative coordinate system are obtained by using the principal vector analysis method.

Secondly, the average $D_a$ and the average $I_a$ of VRM at each testing point are counted, and the magnetic declination ($D_0$) of the sampling location relative to the geographic north pole is queried (Burtai, -4.65°; Baode, - 4.18°), then the azimuth of the sample marker line relative to the geographical north pole is $D_0 - D_a$. Finally, according to the angle $\beta$ ($\beta_0$ or $\beta_0 + 90°$) between the 0° mark line and $\sigma_H$, the azimuth ($\alpha_N$) of $\sigma_H$ relative to the geographic north pole is calculated as:

$$\alpha_N = D_0 - D_a - \beta$$  \hspace{1cm} (6)
4. Measurement and analysis of in situ stress

4.1 Distribution characteristics of in-situ stress in Burtai mine

Five boreholes of Burtai mine were selected for in-situ stress testing. They are BK212, BK209, BK213, BK207 and BK220. Their depths are 490–610m with an average of 546m. A group of cores were collected at intervals of about 100m from each borehole, and samples were screened and processed according to the requirements of section 3.1, and KE test was carried out. 343 cores were processed, 338 cores KE stress were obtained. The KE has 263 obvious, accounting for 77.8% of the total, 60 less obvious, accounting for 17.8%, and 15 very insignificant, and accounting for only 4.4%. In the end, a total of 89 groups of in-situ stress data were obtained from five boreholes, among which 35 groups failed to obtain the small core along the core axis, so $\sigma_v$ could not be tested. Therefore, linear fitting was carried out according to 54 groups of measured $\sigma_v$, and then $\sigma_v$ at depths of measuring points were calculated by the fitting equation.

4.1.1. In-situ stress variation with depth in Burtai mine

Fig. 5 (a-f) show the distribution of $\sigma_H$, $\sigma_h$, $\sigma_v$, $k$, and azimuth of $\sigma_H$ at measuring points. The characteristics of the present stress field of five boreholes and nearby areas in Burtai mine are as follows:

(1) In the range of 610m depth, $\sigma_H$ is 1.52–21.04 MPa, $\sigma_h$ is 1.07–15.76 MPa, $\sigma_v$ is 2.01–20.55 MPa, which is a general stress level compared with the statistical results of in-situ stress testing in mainland China (Kang et al., 2010). The three principal stress values have certain discreteness but increase with the increase of depth (Fig. 5 (a-f)). The fitting equations are as follows:

$$
\begin{align*}
\sigma_H &= 2.0386 + 0.0241 \times H \\
\sigma_h &= 1.2091 + 0.0172 \times H \\
\sigma_v &= -0.5257 + 0.0273 \times H
\end{align*}
$$

Among them, the data of BK209 is too discrete, the fitting coefficient is low, and others are more than 0.7. The large discreteness of data is mainly caused by the heterogeneity of rocks caused by different lithology, structure, bedding, and so on. It can be seen from Eq. (7) that $\sigma_v$
increases most rapidly with the increase of depth. In shallow mine, the horizontal stress is large. In deep mine, $\sigma_v$ tends to be close to $\sigma_H$.

(2) According to the experience judgment standard (Wang, 2014), there are 39 with $\sigma_h < 10$ MPa, accounting for 44% of the total; 42 with $\sigma_h < 18$ Mpa, accounting for 47%; 8 with $\sigma_H > 18$ Mpa, accounting for 9% (Table 1). Among them, there are 34 groups above 350m, 29 groups with $\sigma_h < 10$ MPa, accounting for 85%; 55 groups below 350m, 11 groups with $\sigma_h < 10$ MPa, accounting for 20%, and 66% with $10 < \sigma_h < 18$ Mpa. Therefore, the in situ stress field in Burtai mine is low above 350m and medium below 350m.

Table 1 Distribution of in-situ in different mines

(3) There are main stress regimes: $\sigma_H > \sigma_h > \sigma_v$ (<172 m, I) and $\sigma_H > \sigma_v > \sigma_h$ (170–800 m, II). There are 15 with I, accounting for 17% of the total; 46 with II, accounting for 52%. The former appears as a reverse fault stress mechanism, and the latter appears as a strike-slip fault stress mechanism. The $\sigma_v > \sigma_H > \sigma_h$ stress regime is mainly distributed below 800m, according to Eq. (7), and it is deeper than that (600 m) of the same stress regime in underground coal mines in China (Kang et al., 2010), which is consistent with the southern Qinshui Basin (825 m) and western Guizhou province (750 m) (Chen et al., 2017). The stress state is in good agreement with a large number of extensional structures such as slip faults developed in Yan’an formation in Burtai mine field.

(4) The ratio of $\sigma_H$ to $\sigma_v$ is 0.19–2.33, with an average of 1.20 and a mean square deviation of 0.37; the ratio of $\sigma_h$ to $\sigma_v$ is 0.14–1.97, with an average of 0.83 and a mean square deviation of 0.31; $k$ is 0.16–2.06, with an average of 1.02 and a mean square deviation of 0.32. Among 89 groups of principal stress data, there are 61 in $\sigma_H > \sigma_v$, accounting for 68.5% of the total. Generally, horizontal stress plays a leading role. The results are in accordance with the transverse isotropic crustal stress model, and it can be expressed as follows:

$$\sigma_H = \frac{1-v}{v_xz} \cdot \sigma_v$$

(8)

When $v = 0.25$, $v_xz = 0.5$, $\sigma_H = 1.5 \sigma_v$, the smaller $v_xz$ is, the larger $k$ is, This model can better reflect the in-situ stress characteristics of sedimentary rock strata.

(5) The variation of $k$ with depth is shown in Eq. (9). Compared with $k$ envelope (Eq. (10)) obtained by Brown and Hoek in the world (Jia, 2008). In general, the progressive value is
different, but they are basically the same in the progressive value of the inner envelope. It can be seen from Fig. 6 (a) that there are 41 data of \( k > 1 \), accounting for 46.1%. Above 350m, the \( k \) range is wider. With the increase of depth, the \( k \) range becomes narrower. At 350m, \( k = 0.98 \), close to 1. The rock mass is in a deep critical state.

\[
\begin{align*}
    k &= \frac{126}{H} + 0.625 \\
    &\quad \text{for } \frac{35}{H} + 0.285 < k < \frac{350}{H} + 0.6 \\
    &\quad (9) \\
    k &= \frac{800}{H} + 0.4 \\
    &\quad \text{for } \frac{100}{H} + 0.3 < k < \frac{1500}{H} + 0.5 \\
    &\quad (10)
\end{align*}
\]

(6) The ratio of \( \sigma_H \) to \( \sigma_h \) is 1.07–2.96, with an average of 1.53 and a mean square deviation of 0.44. The difference between \( \sigma_H \) and \( \sigma_h \) is generally large. Meanwhile, the maximum shear stress \(((\sigma_1 - \sigma_3)/2)\) is 0.31–6.89 MPa, with an average of 2.05 MPa and a mean square deviation of 1.18 MPa. It leads to a mixed extension of rock-shear type, which provides conditions for the development of joint and fault, which is also one of the mechanical reasons for the development of small and medium-sized faults in the Yan'an Formation. According to statistics from Jia (2008), the Yan'an formation in Burtai mine has developed small and medium-sized high angle normal faults, which are composed of small graben, horst, stepped fault and stepped fault. They are the direct evidence of large shear stress in the rock mass.

(7) The in-situ stresses at the same depth are different with different lithology, for example, the sand mudstone \( \sigma_H \) of 11–13 groups in BK209 is 2.18 times that of the medium sandstone of 21 and 22 groups in BK212; the sand mudstone \( \sigma_H \) of the 61–63 groups in BK209 is 1.42 times that of the siltstone of 41–43 groups in BK209; the sand mudstone \( \sigma_H \) of 51–53 groups in BK220 is 1.36 times that of the fine sandstone of 41–43 groups in BK207, and so on. The most important reason is that \( \sigma_c \) of sandy mudstone is generally high, 30–60 MPa, some of which are over 80 MPa, and the bearing stress is large, while \( \sigma_c \) of sandstone is low, mostly less than 30 MPa, with high porosity and weak cementation, so the bearing stress is small.

**Fig. 5.** The relationship between \( \sigma_H, \sigma_h \) and \( \sigma_v \) vs. depth. (a), BK212; (b), BK209; (c), BK213; (d), BK207; (e), BK220; (f), \( \sigma_H, \sigma_h \) and \( \sigma_v \) vs. depth in Burtai mine; (g), \( \sigma_H, \sigma_h \) and \( \sigma_v \) vs. depth
in Baode mine.

**Fig. 6.** Scatter plot of $k$ vs. depth and its relationship. (a), $k$ vs. depth in Burtai mine; (b), $k$ vs. depth in Baode mine.

### 4.1.2. In-situ stress direction in Burtai mine

Sixteen parent rock core from 100 to 603m depths in Burtai mine are selected for paleomagnetic orientation. The strata are respectively Yijinhuoluo formation, Zhiluo formation and Yan'an formation. The lithology is mainly siltstone, fine sandstone, medium sandstone, coarse sandstone, and so on. One of the measuring points fails to obtain the principal stress direction by KE, so it is impossible to determine the azimuth relative to coordinate North of that. **Fig. 7** shows stereoscopic projection and the orthogonal projection of the magnetization directions of some samples. **Table 2** shows the test results of the samples. **Fig. 8** (a) shows the $\sigma_H$ azimuth half-rose of samples.

**Table 2** Paleomagnetic test results of core samples

The change of remanent magnetization direction after demagnetization and magnetization intensity and direction of samples can be seen in **Fig. 7**. The changing trend of magnetization vector of the same group of samples is basically the same, and the difference of different lithologic samples is large. D131 and D132 of coarse sandstones in BK207 thermal demagnetization are from 50° to 500°. After each step, the magnetic declination and dip of VRM are both relatively stable. However, but the magnetization vector of D511 and D512 of medium sandstones turns, and the intensity is weakened after demagnetization at 500°, so this point should be abandoned. The principles to be followed in the selection of thermal demagnetization points are $\alpha_{95}$ confidence ErAng ± error < 16; more than three selected points; temperature above 100°–200°, and so on. **Fig. 7.** Thermal demagnetization curves of samples in BK207. (a), D131; (b), D132; (c), D511; (d), D512.

Among the 63 measuring points in **Fig. 8** (a), there is 22 $\sigma_H$ orientation between N30°E and N75°E, accounting for 34.92% of the total, and 14 between N30°E and N75°E, accounting for 22.22%. Therefore, the dominant orientation of $\sigma_H$ in Burtai mine is NE-NNE, followed by
Study of focal mechanism solution, HF and hole wall collapse in Ordos area show that the orientation of $\sigma_H$ is NE-NEE. That obtained by paleomagnetic combined with KE is consistent with the above results, and some measuring points are quite different, which is mainly related to the local geological structure, rock mass structure and test process error. Through a large number of mine geological structure observation and surface geological survey (Jia, 2008), it is believed that the fault strike of the mine field is mainly NNE, followed by NW, and the basic pattern of the extensional structure is the capping-sliding type. So the orientation of $\sigma_H$ is parallel to the fault trend. When the angle between the orientation of $\sigma_H$ and the axial direction of the roadway is $0^\circ$–$30^\circ$, which is conducive to the stability of it.

4.2 Distribution characteristics of in-situ stress in Baode mine

The borehole beside Baode power plant was selected for the in-situ stress test. The depth of borehole is 416m. A group of cores were collected every 50m. 85 cores were processed, 85 cores KE stress were obtained. The KE has 44 obvious, accounting for 51.8% of the total, 19 less obvious, accounting for 22.4%, and 22 very insignificant, and accounting for only 25.8%. In the end, a total of 24 groups of in-situ stress data were obtained, including 13 groups of measured $\sigma_v$ and 11 groups of calculated $\sigma_v$ by the fitting equation.

4.2.1. In-situ stress variation with depth in Baode mine

(Fig. 5 (g) shows the distribution of $\sigma_H$, $\sigma_h$, $\sigma_v$, $k$, and the azimuth of $\sigma_H$ at measuring points. The characteristics of the present stress field of the power plant and nearby areas in Baode mine are as follows:

(1) In the range of 420m depth, $\sigma_H$ is 3.99–15.15 MPa, $\sigma_h$ is 0.71–9.63 MPa, $\sigma_v$ is 1.26–10.01 MPa. The three main stress values are all discrete but increase with the increase of depth (Fig. 5 (g)). The fitting equations are as follows:
\[ \begin{align*}
\sigma_h &= 3.5656 + 0.0161 \times H \\
\sigma_h &= 0.7081 + 0.0189 \times H \\
\sigma_v &= -0.5935 + 0.0267 \times H
\end{align*} \] (11)

(2) There are 23 with \(\sigma_h < 10\) MPa, accounting for 96% of the total, and only one with 10
\(<\sigma_h < 18\) Mpa (Table 1). Therefore, the in situ stress in Baode mine belongs to the low in situ
stress field as a whole.

(3) There are main stress regimes: \(\sigma_H > \sigma_h > \sigma_v (<170\text{m}, I)\) and \(\sigma_H > \sigma_v > \sigma_h (170–400\text{ m},\)
II). There are 10 with I or II, accounting for 42% of the total respectively. The \(\sigma_v > \sigma_H > \sigma_h\)
stress regime is mainly distributed at a depth below 400m, according to Eq. (11), and it is
shallower than that (600–750 m) of the same stress regime in underground coal mines in China
(Kang et al., 2010; Chen et al., 2017).

(4) The ratio of \(\sigma_H\) to \(\sigma_v\) is 0.72–3.61, with an average of 1.76 and a mean square deviation
of 0.81; the ratio of \(\sigma_h\) to \(\sigma_v\) is 0.31–1.68, with an average of 0.96 and a mean square deviation
of 0.34; \(k\) is 0.66–2.44, with an average of 1.36 and a mean square deviation of 0.50. Among
24 groups of the principal stress data, there are 20 in \(\sigma_H > \sigma_v\), accounting for 83.3% of the total.

(5) The variation of \(k\) with depth is shown in Eq. (12). It is similar to the envelope line of
\(k\) obtained by Brown and Hoek in the world, but there are some differences in the progressive
value, which is close to that of 0.3 and 0.5 of the inner and outer envelope lines. According to
Fig. 6 (b), there are 18 data of \(k > 1\), accounting for 75%. Above 350m, the \(k\) range is wider.
With the increase of depth, the \(k\) range becomes narrower. At 350m, \(k = 1.02\), close to 1. Much
like the Burtai Mine, the rock mass is in a deep critical state.

\[ k = \frac{72}{H} + 0.817 \quad \begin{align*}
70
\ \ 
\frac{H}{H}
\ \ 
+ 0.32 < k < \frac{210}{H} + 0.46
\end{align*} \] (12)

(6) The ratio of \(\sigma_H\) to \(\sigma_h\) is 1.07–7.38, with an average of 2.04 and a mean square deviation
of 1.42. The difference between \(\sigma_H\) and \(\sigma_h\) is generally large. Meanwhile, \((\sigma_1 - \sigma_3) / 2\) is 0.24–
4.44 MPa, with an average of 1.46 MPa and a mean square deviation of 0.86 MPa, which leads
to large shear stress in the rock mass, providing favorable conditions for development of joint
and fault in Baode mine.
4.2.2. In-situ stress direction in Baode mine

Eight parent rock cores from 99.1 to 340.6m in Baode power plant are selected for paleomagnetic orientation. The strata are Shangshihezi formation, Shanxi formation, Taiyuan formation and Fengfeng formation respectively. The lithology is mainly fine sandstone, medium sandstone, sandy mudstone, mudstone and limestone. Table 2 shows the test results of the samples. Fig. 8 (b) shows $\sigma_H$ azimuth half-rose of samples.

Among the 19 measuring points in Fig. 8 (b), there is 14 $\sigma_H$ orientation between NS and N45°E, accounting for 73.7% of the total. Therefore, the dominant orientation of $\sigma_H$ in Baode mine is NEE, which is generally consistent with the NNE-NE obtained from the regional focal mechanism solution.

5. Discussion

5.1 Comparison of in-situ stress test results

5.1.1. Comparison of in-situ stress test results in Burtai mine

In-situ stress testing of three boreholes (Fig. 2, light green) by OC in the first and second panels of Burtai mine was carried out by Anhui University of science and technology. The depth is 348m. KE stresses of three measuring points close to their depth are selected and compared with that. Their locations are different, but the terrain is flat, so we still try to analyze them.

Table 3 Comparison of test results between KE and OC, HF

According to Table 3, the seven stresses of KE are greater than that of OC, accounting for 77.8% of the total. The relative error of $\sigma_H$ is 6.44%–25.37%, that of $\sigma_h$ is 10.94%–34.49%, that of $\sigma_v$ is 12.66%–19.35%, and that of three principal stress is 14.90%, 19.67% and 15.47% respectively. Therefore, the error of test results between KE and OC is small. Considering the different test locations, the error is within the reasonable range of engineering, which can meet the geological evaluation and stability of engineering, and verify the reliability of KE for testing in-situ stress.
In-situ stress testing by HF in Yitai mining area and Hongqinghe area of Dongsheng coal field was carried out (Liu, 2011), and KE stresses of ten measuring points close to their depth are selected and compared with that. The three measuring points were calculated by Eq. (7), and the results are shown in Table 3. The eighteen stresses of KE are greater than that of HF, accounting for 54.5% of the total. The relative error of $\sigma_H$ is 9.81%–45.24%, that of $\sigma_h$ is 0–51.73%, that of $\sigma_v$ is 0.65%–81.80%, and that of three principal stress is 21.40%, 17.64% and 23.79%, respectively. Due to the influence of geological structure and depth, the relative error is relatively large above 100m, and the test result is also discrete. However, considering the change of the location of measuring points and the occurrence of the coal seam, the test result error is still within the reasonable range required by the project. Therefore, the test results of the two methods are consistent to a certain extent.

Three major tectonic movements of Indochina, Yanshan and Xishan occurred in the Mesozoic and Cenozoic strata in Ordos Basin. At the end of the Jurassic, the basin was subject to horizontal tectonic compression in NWW-SEE and the second tectonic thermal event. It formed $\sigma_H$ in NWW-SEE and EW and NW-SE conjugate shear fractures in the Jurassic Yan'an Formation (Gao et al., 2020; Ju et al., 2019). From the late Cretaceous to Paleogene, the basin was subjected to NNE-SSW horizontal tectonic compression and the third tectonic thermal event, resulting in strata denudation thickness of 600–3200m (Ma et al., 2020; Meng, 2016; Ng et al., 2017). Under tectonic compression and uplift denudation, $\sigma_H$ in NNE-SSW and NS and NE-SW conjugate shear fractures were formed in the Late Jurassic, Cretaceous and Neogene. Under the thrust or nappe action of peripheral faults into the basin, the basin is uplifted as a whole, and low angle or interlayer sliding occurs, forming slip thrust fault, which releases the energy accumulated by orogeny movements around the basin, and the strata are not deformed obviously (Li et al., 2014; Wu et al., 2017; Xiao et al., 2020). However, most of the basement faults have been activated, and the deep fractures have obvious control on the shallow ones.

During field exploration, 11 large and medium-sized faults are developed in the northern Shenmu mine area of Shenfu coal field, all of which are tensional high angle normal faults with strike NW and dip of 55°–80°. The drop is 10–80m, and the extension is less than 16km. It can be inferred that the $\sigma_1$ direction is roughly N40°E–N80°E (Ju et al., 2015; Ju et al., 2020; Li et al., 2019). Based on the research results of focal mechanism solution, HF, hole wall collapse,
OC, fault sliding vector and earthquake surface rupture (Ju et al., 2017; Wang et al., 2018; Deng and Sheng, 2015; Sheng et al., 2015), it is considered that the present $\sigma_1$ direction in north Ordos area is NE-NEE. There are six points of ten measuring points $\sigma_1$ in N28.3°E–N54.1°E in Yitai mining area, and four are in N18.9°W–N63.6°W, most of which are in NE; the orientations of the three fracture surfaces of the hydraulic fracture holes are N65.0°E, N61.0°E, and N54.0°E in Hongqinghe mining area, generally in NE-NEE. In situ stress test of 42 coal seam in Burtai mine was performed by Taiyuan University of technology. $\sigma_1$ is about N30°E, which is vertical to the roadway axis of 42103 working face, and there is large tectonic stress. The results in this paper show that the dominant orientation of $\sigma_H$ in Burtai mine is NE- NNE, followed by NW, and that of $\sigma_H$ in Baode mine is NEE (section 5.1.2). It is related to the Triassic and Jurassic tectonic movement in the Ordos Basin. $\sigma_H$ in NWW-SEE is formed by the Yanshan movement, and $\sigma_H$ in NNE-SSW is the product of Himalayan movement. The two-periods of tectonic movement since Mesozoic resulted in the deflection of $\sigma_H$ orientation in Shendong mining area. At the same time, the dominant orientation of $\sigma_H$ in Burtai mine is also roughly consistent with the main fault strike (near NEE) of surface Huhewusu ditch in south. Therefore, the present $\sigma_H$ orientation in Shendong mining area obtained by KE combined with paleomagnetic orientation is consistent with the above results, and some measuring points are quite different, which is mainly related to the local geological structure, rock mass structure, topography and landform, and error of the test process.

5.1.2. Comparison of in-situ stress test results in Baode mine

In-situ stress testing of three boreholes (Fig. 2, light green) by OC in the third panel of Baode mine was carried out by Anhui University of science and technology. The depth is 485m. KE stresses of three measuring points close to their depth are selected and compared with that. Eq. (11) is used to calculate the 2 # and 6 # measuring points. According to Table 4, the seven stresses of KE are greater than that of OC, accounting for 77.8% of the total. The relative error of $\sigma_H$ is 8.46%–12.41%, that of $\sigma_h$ is 27.18%–35.65%, that of $\sigma_v$ is 34.82%–45.59%, and that of principal stress is 9.91%, 30.82% and 39.84% respectively, among which that between fitting equation and OC is the largest.
The stress values measured by KE is compared with that measured by ASR (Xu, 2018), and the cores of the same depth in the same borehole is selected. The samples of 51–53 and 62–64 groups in Table 4 are selected by KE, and that of BD-2 (275.5m) and BD-6 (346.0m) are selected by ASR, among which the average values of $\sigma_H$, $\sigma_h$ and $\sigma_v$ of 51–53 groups are 8.28, 6.16 and 7.31 MPa, respectively, and that of $\sigma_H$, $\sigma_h$ and $\sigma_v$ of BD-2 are 6.8, 4.7 and 7.3 MPa, with relative errors of 17.90%, 23.71% and 0.08%; the average values of $\sigma_H$, $\sigma_h$ and $\sigma_v$ of 62–64 groups are 8.34, 6.91 and 9.41 MPa respectively, and that of $\sigma_h$, $\sigma_h$ and $\sigma_v$ of BD-6 are 7.9, 7.3 and 9.4 MPa, with relative errors of 5.22%, 5.68% and 0.13%. The average relative errors of the principal stresses for them are 11.56%, 14.69%, and 0.11%, respectively.

Table 4 Comparison of test results between KE and OC, ASR

Therefore, the error of e test results of KE method and ASR method is small, and that of KE and OC is larger. Considering the different test locations, and the two groups of data are calculated by Eq. (11). If the two groups are removed, the errors are within the reasonable range of the project, which can meet the requirements of engineering geological evaluation and stability analysis. So, Reliability of KE has been verified.

5.2 Analysis of stress accumulation level of rock

Based on the Byerlee Anderson theory and in-situ stress test results, the stress state of boreholes in two mines is drawn, as shown in Fig. 9. None of the six boreholes has a measured point with $\mu > 0.6$, and $\sigma_H$ is all on the left of the lower limit of Byerlee range, and $\mu < 0.3$. Below 350m, a small amount of data in Burtai mine is between $0.6 > \mu > 0.3$, which indicates that with the increase of depth, the stress accumulation level is increasing. Therefore, it can be concluded that the friction strength of the faults around the boreholes in two mines is weak, the stress level is low, and they are in a relatively calm period, and the faults and surrounding areas are in a relatively stable state.

Fig. 9. The relationship between principal stress vs. $\mu$. (a), principal stress vs. $\mu$ in Burtai mine; (b), principal stress vs. $\mu$ in Baode mine.

The sliding failure caused by the increase of shear stress is a common fracture phenomenon in the earth's crust. The main controlling factors are the maximum shear stress
and the normal stress of vertical shear plane. Therefore, the $\mu_{md}$ and $\mu_{mh}$ calculated based on in-situ stress are also indicators to characterize the regional stress accumulation level (Jamison and Cook, 1980). The relationship between $\mu_m$ and $\mu$ is as follows:

$$
\mu_m = \frac{\mu}{(1+\mu^2)^{0.5}} \quad (13)
$$

The expressions of indexes $\mu_{md}$ and $\mu_{mh}$ are as follows:

$$
\begin{align*}
\mu_{md} &= \frac{\sigma_1 - \sigma_3}{\sigma_1 + \sigma_3} \\
\mu_{mh} &= \frac{\sigma_1 - \sigma_3}{\sigma_1 + \sigma_3 - 2P_0}
\end{align*} \quad (14)
$$

Where $\sigma_1, \sigma_3$ and $P_0$ represent the maximum principal stress, the minimum principal stress and the pore pressure respectively. In the shallow low permeability rocks of the crust, $P_0$ is roughly equal to the static pressure of the water column (Townend and Zoback, 2000). To some extent, $\mu_{md}$ and $\mu_{mh}$ only represent the stress accumulation level, independent of the stress direction. The larger the value is, the greater the shear stress around the fault is, the higher the stress accumulation level is, the greater the possibility of fault activity is, and vice versa (Jamison and Cook, 1980). The shallow $\mu_m$ is mostly 0.7, the deep $\mu_m$ is 0.5 (Tuncay and Ulusay, 2008), so when $\mu_m$ is 0.5–0.7, the crustal stress accumulation is in its friction limit state; when $\mu_m$ is close to 0.5–0.7, the stress accumulation level is higher; when $\mu_m$ is less than 0.3, that is lower.

Figure 10 gives the distribution of $\mu_{md}$ and $\mu_{mh}$ with depth in two mines. In dry rock, the $\mu_{md}$ in Boertai mine is 0.04–0.76, with an average of 0.24 and a mean square deviation of 0.14, among which, $\mu_{md} > 0.1$, accounting for 87.6% of the total, and only two points with $\mu_{md} > 0.6$, and they are 0.76 and 0.75, 66 points with $\mu_{md} < 0.3$, accounting for 74.2% and 85 points with $\mu_{md} < 0.5$, accounting for 95.5%; the $\mu_{md}$ in Baode mine is 0.03–0.76, with an average of 0.32 and a mean square deviation of 0.19, among which, $\mu_{md} > 0.1$, accounting for 87.5%, and only three points with $\mu_{md} > 0.6$, and they are 0.60, 0.76 and 0.61 respectively, 13 points with $\mu_{md} < 0.3$, accounting for 54.2%, 19 points with $\mu_{md} < 0.5$, accounting for 79.2%; the average values of $\mu_{md}$ are is 0.33 (Burtai), 0.42 (Baode) above 170m, and they are both 0.23 below 170m. In hydrostatic pressure rock, after four outliers are removed in Burtai mine, $\mu_{mh}$ is 0.05–0.89, with an average of 0.32 and a mean square deviation of 0.19, among which, $\mu_{mh} > 0.1$, accounting
for 91.8% of the total, only 8 points with $\mu_{mh} > 0.6$, 49 points with $\mu_{mh} < 0.3$, accounting for
57.6%, 71 points with $\mu_{mh} < 0.5$, accounting for 83.5%; after two outliers are removed in Baode
mine, $\mu_{mh}$ is 0.04–0.74, with an average of 0.31, with an average of 0.31 and a mean square
deviation of 0.19, among which, $\mu_{mh} > 0.1$, accounting for 86.4%, and only one with $\mu_{mh} > 0.1$,
and it is 0.74, 13 points with $\mu_{mh} < 0.3$, accounting for 59.1%, 17 points with $\mu_{mh} < 0.5$,
accounting for 77.3%; the average values of $\mu_{mh}$ are is 0.47 (Burtai), 0.50 (Baode) above 170m,
and they are 0.35 (Burtai), 0.32 (Baode) below 170m.

Fig. 10. Scatter plot of $\mu_{md}$ and $\mu_{mh}$ vs. depth and its relationship. (a), $\mu_{md}$ vs. depth and its
relationship in Burtai mine; (b), $\mu_{md}$ vs. depth and its relationship in Baode mine; (c), $\mu_{mh}$ vs.
depth and its relationship in Burtai mine; (d), $\mu_{mh}$ vs. depth and its relationship in Baode mine.

No matter in dry rock s or hydrostatic pressure rocks, the friction coefficient of faults in
the two mines is low, the average values of $\mu_{md}$ are 0.23–0.33, 0.23–0.44, $\mu_{mh}$ are 0.35–0.47,
0.32–0.50, which are less than the lower limit (0.6) of strike-slip faults slip. It shows that the
fracture stress state around the study area is lower than the friction limit state, which is at a low
level as a whole, and the risk of seismic activity is low. Historically, the number of earthquakes
in Ordos City and its vicinity was not many, and the intensity was not high, and the regional
in-site stress is in the accumulation stage, which does not exclude the possibility of small and
micro earthquakes. From the comparison of mine, the stress accumulation of Baode mine is
greater than that of Burtai mine.

6. Conclusions

Based on elastic mechanics and paleomagnetic reorientation technology, the in-situ stress
test method based on KE of borehole core is established. This method is used to test and analyze
the distribution characteristics of present stress in and around the boreholes of Burtai mine and
Baode mine, and the test results are compared with that of OC, ASR and adjacent mine HF.
Based on Byerlee-Anderson theory, the stress accumulation level of the rock mass is discussed.
The main conclusions are as follows:

(1) For the non-directional drilling core, based on the elastic mechanics, the magnitude
and direction of the principal stress measured by KE are derived. The angle between the direction of $\sigma_H$ and the marker line is $\beta_0$ or $\beta_0 + 90^\circ$. The azimuth of $\sigma_H$ relative to the geographic north pole is calculated as $D_0 - D_a - \beta$.

(2) The $\sigma_H$, $\sigma_h$, and $\sigma_v$ in two mines increase with increasing of depths. The ratios of $\sigma_H$, $\sigma_h$ to $\sigma_v$ are 1.20, 0.83 (Burtai), 1.76 and 0.96 (Baode), respectively. $k$ is 1.02 (Burtai) and 1.36 (Baode). Generally, horizontal stresses play a leading role. The ratio of $\sigma_H$ to $\sigma_h$ is 1.53 (Burtai) and 2.04 (Baode), and $(\sigma_1-\sigma_3)/2$ is 2.05 MPa (Burtai) and 1.46 MPa (Baode). There are main stress regimes in NOB: $\sigma_H > \sigma_h > \sigma_v$ (Burtai, <172m; Baode, <170m) and $\sigma_H > \sigma_v > \sigma_h$ (Burtai, 170-800 m; Baode, 170-400 m), and the $\sigma_v > \sigma_H > \sigma_h$ stress regime is mainly distributed in moderately deep to deep coal mines. For rock masses with a depth of 350m, $k ((\sigma_H+\sigma_h)/2\sigma_v)$ tends to 1, indicating that deep critical state will gradually emerge.

(3) The test results were compared with that of OC, ASR and HF. The relative errors of $\sigma_H$, $\sigma_h$, and $\sigma_v$ are 14.90%, 19.67%, 15.47% (Burtai) and 10.74%, 22.76%, 19.97% (Baode), and they are all within a reasonable range required by the project, which can meet the requirements of the geological evaluation and stability analysis of the engineering rock mass. Therefore, it verifies the reliability of KE method.

(4) The dominant orientation of $\sigma_H$ in Burtai mine is NE-NNE, followed by NW, and that of $\sigma_H$ in Baode mine is NEE. It is related to the Triassic and Jurassic tectonic movement in the Ordos Basin. $\sigma_H$ in NWW-SEE is formed by the Yanshan movement, and $\sigma_H$ in NNE-SSW is the product of Himalayan movement, which is consistent with that (NE-NEE) of earthquake focal mechanisms in this area.

(5) Under dry rocks or hydrostatic pressure rocks, the friction coefficient of faults are both low, the average values of $\mu_{md}$ are 0.23–0.33 (Burtai), 0.23–0.44 (Baode), $\mu_{mh}$ are 0.35–0.47 (Burtai), 0.32–0.50 (Baode), which is less than the lower limit of strike-slip faults slip, indicating that the fracture stress with a low level around the study area is lower than the friction limit stress. The stress accumulation level in Baode mine is slightly larger than that in Burtai mine.
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Declaration of Interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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