CHARACTERISTICS OF THE IN SITU STRESS FIELD IN THE YADIAN COAL MINE, CENTRAL CHINA: IMPLICATIONS FOR ROADWAY DIFFERENTIAL DEFORMATION

Huibin Liu, Bo Jiang,* and Wanying He

ABSTRACT: To study the in situ stress mechanism for different deformations of roadways in different directions, in this paper, we used the method of stress relief with a hollow core to measure the in situ stress of roadways with different degrees of deformation in the Yadian coal mine. The results showed that the in situ stress field was generally \( \sigma_M > \sigma_H > \sigma_V \), indicating a typical reverse faulting stress regime. The present in situ stress field was the main factor for roadway differential deformation. The \( \sigma_M \) orientations were ESE and ENE-trending, which were consistent with the regional tectonic stress field in North China. The instrument for monitoring the abscission layer deformation indicated that the NS-trending roadway (cut-hole) deformation time approached stability after approximately 1–2 months, while it was 5–10 days for its EW-trending counterpart. The study of stress gradient shows that the stress state of the Ordos Basin has changed at a depth of 600 m, which is related to multiple tectonic events from the Late Paleozoic to Cenozoic in the Ordos Basin. The comprehensive analysis results show that the differential deformation of roadways is affected by many factors, such as the buried depth of the stratum, lithology and structural characteristics, fracture development degree, mining influence, composite deformation mechanics mechanism of weak swelling rock stratum, in situ stress field, tectonic stress mechanism, fracture development, etc.

1. INTRODUCTION

There are a number of factors that contribute to in situ stress in coal mines. These include exploitation disposal of the main roadway, the supporting design, mining method and technology, strata behaviors, coal seam movements and failures, roadway deformations, the formation mechanism and control of rock burst, and coal and gas outbursts. Mining activities lead to redistribution of rock stress in the roadway. Generally, there are many kinds of in situ stress measurement methods for underground stresses in coal mines, including the stress relief method, water pressure method, and AE method. The stress relief method is the most widely used of all in situ stress measurement methods. As mining depth increases, the coal mine not only shows the increased deformation of surrounding rocks in the roadway but also has very obvious asymmetric characteristics.

There has been considerable progress in the study of the asymmetric deformation mechanism and control of deep dynamic pressure in roadways. There have also been studies on the relationship between deformation and different bedding orientations of deep sedimentary rocks under lateral pressure. The distribution of the tectonic stress field also greatly influences the stability of the roadway. The variation and distribution of the stress field have a certain relationship with the burial depth. As such, it is extremely important to study the in situ stress field to control roadway deformation effectively. Different soft rocks in the specific geomechanics environment perform by different deformation mechanisms. Soft rocks have the characteristics of large deformations, large rock pressures, and supporting difficulty. This is because the surrounding rocks are not under a single deformation mechanism but are under a variety of deformation mechanisms of “complications” and “syndromes”, that is, complex deformation mechanics. Although there has been some progress in the study and treatment of the deformation characteristics of soft rock roadway in the Yadian coal mine, a mechanism analysis has not yet been conducted. This study uses the air core packet style stress relief method to measure in situ stresses in the Yadian coal mine. This method analyzes the characteristics of the stress field, influencing factors, and the geological mechanisms of the differential deformation of a roadway. The results indicated that in situ stress was the main control factor for roadway deformation. Accordingly, an optimal layout of the development roadway and reinforcement techniques was proposed, which provide important guidance for mine safety.

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1.1. Geological Setting. The Binchang mining area is located in the Binxian-huangling fault fold belt of the north rim of the Wei river south of the Ordos Basin, central China (Figure 1).

It is a 50−70°, NW to NNW tendency monoclinal structure, on which some rolling and discontinuous secondary fold structures are superimposed. The development in the Binchang mining area from the south to the north have anticline Binxian, Lujia-Xiao Lingtai, and Qilipu-Xipo. During the development of the syncline Mengcun and Dafo Temple, the Yadian coal mine in the NW wing of the Qi Lipu-Xipo anticline was in the northeastern Binchang mining area.

The strata include the upper Triassic Hu Jiacun group (T3h), the lower Jurassic Fuxian group (J1f), the middle Yanan group (J2y), Zhiluo (J2z) and the Anding group (J 2a), the lower Cretaceous Yijun group (K1y), Luohe group (K1l), Huachi group (K1l), Neogene Pliocene Xiao Zhanggou group (N2x), the middle and lower Pleistocene (Q1+2), upper Pleistocene Malan group (Q3m), and Holocene diluvium (Q 4) of the Quaternary. The middle Jurassic Yanan group is the main coal-bearing strata, and the mining coal seams are the 1 and 4 coal seams. The mining structure subject has a tendency to an NW monoclinal structure, a stratigraphic dip of 3−5° and no faults or magmatic rocks were found. The structural complexity is simple.

1.2. Characteristics of Differential Deformation of the Roadway. The development roadway is approximately between 450 and 550 m deep in the Yadian coal mine. The floor elevation difference between the shallow and deep coal seam is 290 m. Using a single level shaft development, the bottom level is +388 m, and adopts a “three roadway type” decorate. The level tunnels and the recover dip entry located in the underlying 1 and 4 coal seam development roadway is NS-trending, using the support method. The roof cracking, floor heave, and other rock deformation and support failure appeared soon after the initial use (Figures 2 and 3). Rock deformation and support failure occurred on the roadway later. In the EW-trending mining roadway, most roofs are stable with the cable anchor support. The deformation of the development roadway and the chamber (with anchor network cable spray support) were not obvious, but deformations were produced during tunneling and after roadway formations.

2. RESULTS AND DISCUSSION

2.1. Basic Principles. The hollow inclusion measurement method belongs to the stress relief method (also known as the core method). It is a common method to measure the absolute value of in situ stress. It involves drilling a large hole where in situ stress has to be measured, followed by a small hole concentric with the large hole. Subsequently, the measuring element is installed in the small hole, and the core is extracted with the measuring element. During this process, the data derived from the measuring element are continuously recorded. This process is called core stress relief. In the process of stress relief trench excavation, elastic recovery occurs due to the core breaking away from the role of in situ stress, and a corresponding strain occurs in boreholes, which changes the recorded measurements from the reading instrument. The magnitude and direction of in situ stress are calculated using the strain and deformation of boreholes and the formula derived from elastic theory. The principle of the hollow enclosure stress relief method is described in the next section.
(1) The formula for stress distribution in the rock mass surrounding a borehole: Figure 4 presents a diagram of the two coordinate systems.

![Diagram of rectangular and cylindrical coordinate system for the drilling position.](image)

The original three-dimensional (3D) stress field at any point in the rock mass may be expressed by six components in the rectangular coordinate system \((\sigma_x, \sigma_y, \sigma_z, \sigma_{xy}, \sigma_{xz}, \sigma_{yz})\). The 3D stress field of the borehole surrounding the rock may be expressed by six components in the cylindrical coordinate system \((\sigma_r, \sigma_\theta, \sigma_z, \tau_{r\theta}, \tau_{\theta z}, \tau_{rz})\).

From the coordinate transformation method of elasticity mechanics, it can be seen that the relationship between the stress field near the borehole wall and the original rock stress field is as follows, i.e., formulas 1–6

\[
\sigma_1 = \frac{\sigma_x + \sigma_y}{2} - \frac{\sigma_x - \sigma_y}{2} \cos 2\theta + \tau_{r\theta} \sin 2\theta \cos 2\theta
\]

\[
\sigma_2 = \frac{\sigma_x + \sigma_y}{2} - \frac{\sigma_x - \sigma_y}{2} \cos 2\theta - \tau_{r\theta} \sin 2\theta \cos 2\theta
\]

\[
\sigma_3 = -\frac{1}{2} (\sigma_x - \sigma_y) \cos 2\theta + 4\tau_{r\theta} \sin 2\theta \cos 2\theta + \sigma_z
\]

\[
\tau_{r\theta} = \frac{\sigma_x - \sigma_y}{2} - \frac{\sigma_x + \sigma_y}{2} \cos 2\theta + \tau_{r\theta} \sin 2\theta \cos 2\theta
\]

\[
\tau_{\theta z} = -\frac{1}{2} (\tau_{r\theta} \sin \theta + \tau_{rz} \cos \theta) \left(1 + \frac{a^2}{r^2}\right)
\]

\[
\tau_{r z} = -\frac{1}{2} (\tau_{r\theta} \cos \theta + \tau_{\theta z} \sin \theta) \left(1 - \frac{a^2}{r^2}\right)
\]

In the above formulas, \(R\) is greater than \(a\). The direction of the \(z\)-axis in the cylindrical coordinate system is the same as that in the rectangular coordinate system. The angle \(\theta\) in the cylindrical coordinate system is positive from the counterclockwise rotation of the \(x\)-axis.

(2) The relationship between the hole wall strain and the 3D stress component of the original rock \((A = r)\) near the hole wall can be approximated as a plane stress state.

There are only three stress components; cone, cone \(Z\), and cone \(Z\). The strain values measured by four strain gauges of each resistance strain flower are cone, cone \(z\), cone 45, and cone 45 (i.e., cone, cone 135), and their relations are as follows (see Figure 5):

\[
\varepsilon_\theta = \frac{1}{E} (\sigma_\theta - \nu \sigma_r)
\]

\[
\varepsilon_z = \frac{1}{E} (\sigma_z - \nu \sigma_r)
\]

\[
\gamma_\theta = 2\varepsilon_{45} - \varepsilon_\theta + \varepsilon_z = \varepsilon_\theta + \varepsilon_z - 2\varepsilon_{-45} = \frac{\tau_\theta}{G}
\]

![Stress state diagram of a resistance strain flower.](image)

In the formula, \(\varepsilon_\theta, \varepsilon_z, \\varepsilon_{45}\), and \(\varepsilon_{-45}\) are the strain values in the circumferential, the axial direction of the borehole wall, and the direction of the borehole axis, respectively. The shear strain value is \(\gamma_\theta\).

By substituting formulas 1–3 and 5 into formulas 7–9, the relationship between the strain of the pore wall and the stress components of the original rock can be obtained as follows

\[
\varepsilon_\theta = \frac{1}{E} \left[ (\sigma_x + \sigma_y - 2) \cos \theta - 2\sigma_z \sin \theta \right]
\]

\[
\varepsilon_z = \frac{1}{E} \left[ (\sigma_x - \sigma_y) \cos \theta - 2\sigma_z \sin \theta \right]
\]

\[
\gamma_\theta = \frac{4}{E} (1 + \nu) (\tau_{rz} \cos \theta - \tau_{r\theta} \sin \theta)
\]

\[
\varepsilon_{45} = \frac{1}{2} (\varepsilon_\theta + \varepsilon_z \pm \gamma_\theta)
\]

Four equations can be obtained from the measurement results of each group of strain flowers; thus, a total of 12 equations can be obtained from the three groups of strain flowers. From this, at least six independent equations can be obtained, enabling the resolution of six components of the original rock stress.

(3) Amendment of the hollow-core inclusion strain gauge.

In the hollow inclusion strain gauge, the strain gauge is not attached to the hole wall but is approximately 1.5 mm away from the hole wall. As such, there is a difference between the measured strain and the real strain of the hole wall. To correct this difference, Vorotniki and Walton included four correction
coefficients $K_1$, $K_2$, $K_3$, and $K_4$ in formulas 10–12. These are referred to as K coefficients in the form of formulas 14–16

$$
\varepsilon_0 = \frac{1}{E} [(\sigma_x + \sigma_y) + 2(1 - \nu^2)\{(\sigma_x - \sigma_y)\cos 2\theta
- 2\tau_{xy}\sin 2\theta\}]K_z - \nu\varepsilon_0 K_4
$$

(14)

$$
\varepsilon_2 = \frac{1}{E} [\sigma_r - \sigma_\theta (\sigma_x + \sigma_y)]
$$

(15)

$$
\gamma_6 = \frac{4}{E} (1 + \nu)(\tau_{xy}\cos \theta - \tau_{xz}\sin \theta)K_3
$$

(16)

2.2. Experimental Section. 2.2.1. Test Method and the Main Equipment. In this study, the measurements mainly used a gallery rig, a KX2011 hollow-core inclusion triaxial geodetic meter (Figure 6), an SDX orientator, KJF327-F mine pressure monitoring substation, and the sensor surrounding pressure meter (Figure 6), an SDX orientator, KJF327-F mine pressure

![Figure 6. Structure diagram of a KX2011 hollow-core inclusion triaxial geodetic meter. Note: (1) installing rod; (2) director conductor; (3) director; (4) reading cable; (5) directional pin; (6) sealing ring; (7) epoxy resin cylinder; (8) cavity (with binder inside); (9) fixed pin; (10) the gap between the strain gauge and the hole wall; (11) plunger; (12) rock borehole; (13) gum output hole; (14) sealing ring; (15) guide head; and (16) strain rosette.](https://dx.doi.org/10.1021/acsomega.0c05205)

Table 1. Basic Situation of the In Situ Stress Test Point

| no. of measuring point | measuring point position         | roadway type | roadway section, m² | depth, m | lithology    |
|------------------------|---------------------------------|--------------|---------------------|---------|-------------|
| 1                      | airshaft by pass                | arched       | 19.7                | 475     | fine sandstone |
| 2                      | the return airway of no. 1 coal | arched       | 19.7                | 470     | gritstone    |
| 3                      | the belt roadway of no. 4 coal  | arched       | 15.0                | 518     | gritstone    |
| 4                      | 1101 return airway              | rectangular  | 11.8                | 544     | gritstone    |

2.2.2. Arrangement of Measuring Points. As the Yadian coal mine was in the construction phase, the primary underground construction was development and preparation of the roadway. As such, we chose four test points underground, 1# point is located to the airshaft bottom of the mine, 2# point is located to the main return way of 700 m of no. 1 coal, 3# point is located to the main entry of 810 m of no. 4 coal, and 4# point is located to 1101 air return way of 430 m (Table 1).

The stratum lithology of 1# measuring point is fine sandstone, and 2#–4# measuring points are coarse sandstone. The fine sandstone group is gray, dark gray, nearly horizontal bedding, containing a large number of plant fossil fragments, partial containing pyrite film, fracture development, calcite filling, physical and mechanical test, saturated uniaxial compressive strength of 6.69–29.14 MPa, with an average of 18.57 MPa, belonging to weak rock. The integrity and quality of the rock mass are medium. The coarse-grained sandstone formation is thick bedded, locally containing gravel, mainly composed of quartz and feldspar, a small amount of dark minerals, medium sorting, well-developed pores, and argillaceous calcareous cementation. According to physical and mechanical tests, the saturated uniaxial compressive strength is 7.25–21.62 MPa, with an average of 14.34 MPa, belonging to a weak rock. The integrity and quality of the rock mass are medium.

2.2.3. Test Process. The process used for the air core packet style stress rescission method is as follows:

1. Drilling measured hole: at selected measured points, a 130 mm diameter hole was drilled to the desired depth with a sharp bit of the same size, with a guide to the bell mouth. The first hole was drilled at a depth of between 6 and 8 cm, then another measured hole with a diameter of approximately 36 mm was drilled at a depth of 35–40 cm. The holes were cleaned after drilling.

2. Orientation: the SDX horizontal orientator was installed in front of the installing pole to lead out the conductor.

3. Installing the strain gauge: cleaning and wiping the holes, installing the strain gauge, applying appropriate pressures as required, and recording the orientator after installing the strain gauge.

4. Removing preparation: after 24 h of curing, the orientator is taken out, connected with the instrument, and the flushing experiment is started. The water temperature has to be consistent with the environmental temperature, spudding, and rescinding when instrument readings had stabilized.

5. Stress relief: when excavating the stress-release channel, as the stress-release channel deepened, the core gradually unlinked from the effect of the surrounding stress field. As such, the core experienced changing load on the installed strain gauge and the reading of the instrument due to elastic recovery. Typically, in the process of stress relief, tracking, and measuring the core, when the core footage exceeds the installation position of the strain gauge and the strain gauge readings are stable, drilling of the core is discontinued and the core is extracted. To undertake coring easily, a little more drilling was required. From past experience, the resolutive depth of the air core packet style strain gauge should be greater than 40 cm.

2.3. Test Results and Analysis. 2.3.1. Test Results. After completing field and laboratory measurements with the
KX2011 type air core packet style stress calculating program, we calculated in situ stress in the Yadian coal mine and obtained the test results, as shown in Table 2.

### Table 2. Measurement Results of In Situ Stress in the Yadian Coal Mine

| no. of measuring | position of main stress | values of main stress (MPa) | azimuth (deg) | dip (deg) |
|------------------|-------------------------|----------------------------|---------------|-----------|
| 2                | the return airway of no. 1 | σ₁ | 14.79 | 4.63 | 111.51 | −21.57 |
|                  |                          | σ₂ | 10.37 | 20.71 | −90.53 |
|                  |                          | σ₃ | 10.16 | 11.43 | −17.42 |
| 3                | the belt roadway of no. 4 | σ₁ | 15.41 | 3.4  | 96.59 | −34.89 |
|                  |                          | σ₂ | 11.59 | 23.52 | −47.14 |
|                  |                          | σ₃ | 12.01 | 120.14| −9.44 | −21.59 |
| 4                | 1101 return airway       | σ₁ | 28.10 | 10.34 | 249.08 | −22.32 |
|                  |                          | σ₂ | 14.17 | 91.49 | 70.71  |
|                  |                          | σ₃ | 17.76 | 32.39 | 25.83  |

“Note: σ₁, σ₂, and σ₃ are, respectively, the vertical principal stress, the maximum horizontal principal stress, and the minimum horizontal principal stress, and Δσ is the difference between the maximum and the minimum horizontal principal stress.

Preliminary analysis of the results of four measuring points shows that the no. 1 measuring point deviates away from the other three measuring points. As such, this point was excluded from this study. During actual measurements, the unpredictability of lithology, the crack growth degree of the measured rock mass, and the spreading direction of fractures appears to have manifested large errors in measurement results according to the data adjacent to the site. This data may be deleted.

2.3.2. Characteristics of Ground Stress and the Stress Field. According to the measured results of the three measuring points in the Yadian coal mine (Table 2), the preliminary analysis indicates that the main characteristics of in situ stress in the Yadian coal mine are as follows:

1. The σ₁/σ₀ ratio is 1.28–1.58 and the 1.18σ₁/σᵥ ratio is approximately 1.33–1.98. The stress characteristics of the in situ stress field appear as σ₁ > σᵥ > σ₃, giving priority to horizontal stress. The results indicate a typical reverse faulting stress regime, affecting the stability of the coal roadway roof and floor.

2. The σ₁ orientation was trending between ESE and ENE, with the axial angle of the central tunnel and mining gateway at 43–96°, respectively. As such, horizontal principal stresses affect the center NS-trending tunnel in digging the roadway. Under the same lithology and roadway support, these will show more obvious floor heave and roof sag phenomena.

3. Stress gradient comparison: the stress gradient in the Yadian coal mine was analyzed based on the measuring points 2 and 3, the formulas are given as follows:

   - Maximum horizontal principal stress gradient:
     \[
     \frac{15.41 - 14.79}{518 - 470} \times 100 = 1.29 \text{(MPa/100 m)}
     \]

   - Minimum horizontal principal stress gradient:
     \[
     \frac{12.01 - 10.16}{518 - 470} \times 100 = 3.85 \text{(MPa/100 m)}
     \]

   (17) vertical principal stress gradient:

   \[
   \frac{11.59 - 10.37}{518 - 470} \times 100 = 2.54 \text{(MPa/100 m)}
   \]

   (19)

The results show that the σ₁ gradient was considerably lower than the σᵥ gradient, and in a burial depth greater than 600 m this may reverse. This is related to the relatively complex tectonic evolution of the Ordos Basin.12 The Late Mesozoic to Cenozoic was an important transformation stage in the Ordos Basin, in which the regional tectonic system experienced a major transformation and peripheral basins formed with different directions and different styles of the tectonic belt. The new tectonic stage in the Ordos Basin (8–9 Ma) experienced several stages of tectonic events, such as strike-slip extension and compressional uplifting.13 Seventeen faults were deduced from the gravity and magnetic fields in Weibei Uplift belt, which formed in the NE. Further, near EW and NW of the angular distribution, lies the structural characteristics of “Du” glyph distribution. This illustrates the multiple stages and complexity of tectonic activities in the study area.

The northern and southern parts of uplift are controlled by NE–SW trending distributed large scale and long faults, which demarcate the Mesozoic and Cenozoic Weibei uplift and the Ordos Basin.14 The remote sensing imagery shows that the southern Ordos Basin is relatively regular annular and is subjected to the interaction between factors such as the Qin-Qi trough around the block. Under the influence of the Paleozoic to Cenozoic multiple tectonic movements, particularly the Yanshanian and Himalayan movements, this has caused the uplift and the formation of the circular shape.15 As such, the Yadian coal mine in the Paleozoic to Cenozoic has experienced multiple stages of tectonic evolution. This causes multiple stress adjustments and stress differences among different depths.

The results also demonstrate that the vertical stress gradient changes with increasing depth, and the region may have additional stresses from the confined effect of water, vapor, or liquid-state materials prevalent in the strata.11 The lower Cretaceous Luohuo formations are the main aquifers in the Yadian coal mine, which have a thickness of between 278.80 and 417.34 m and an average thickness of 342.92 m. According to the water discharge experimental data of the 3, 4, and 5 holes, the gushing headwaters of the Luohuo formation aquifer is +23.20 m, the water elevation is 897.25 m, and the drawdown is 19.0, 12.20, and 6.10 m, respectively. Thus, the confined water in the overlying strata may be one of the factors causing a difference in the vertical stress gradient.

4. Comparison of stress differences: The σᵥ magnitudes in the Yadian coal mine are generally less than 15 MPa, and they increase with the burial depth. However, σ₁ is greatly influenced by the burial depth, forming a discrete distribution ranging between 15 and 30 MPa, which may be associated with the local tectonic stress concentration. According to the geological profile of the coal seam and strata analysis during the tunneling of the roadway, the gurus maleic high stress area of the 1101 face is located around a small fold axis. This creates stress concentration, and the appearance of a roof abscission layer and a fracture development phenomenon. During the late process of tunneling and mining, there should be special attention should be given to the adverse impacts of maximum principal stress on roadway deformation.
2.4. Observation and the Analysis Results of the Roof Abscission Layer. ZC1101 in the Yadian coal mine is the first coal mining face in which the gateway is arranged in the EW direction, the cutting hole is arranged in the NS direction, and the air return way is located in the southern area of the haulage gate. During tunneling of the cross-heading and cutting hole, the roof abscession layer instrument was installed for monitoring roadway roof subsidence. The cutting hole length of the 1101 working face was 300 m, and its width was 6.7 m. During the tunneling process, floor heaving, roof breaking and sagging, the working slope coal collapse and other phenomena occur. The maximum floor heave is approximately 800 mm, and the maximum roof sag is approximately 170 mm. This seriously affects mine safety. During tunneling, the abscession layer instrument was installed at 1400 and 2100 m of the large deformation area of the gate road. The results showed that gateway roof subsidence achieved stability after approximately 5–10 days. The fracture development area of the local roof was reinforced by a beater anchor, which did not cause extensive deformation.

Starting from the center line of the two cross-headings, a roof abscession layer instrument was installed in each 20 meter, totaling 15 instruments that were installed. We monitored the roof abscession layer of the cutting hole (Figure 7) for 78 days after sharing, collecting data at 2 day intervals. We analyzed the representative eight points with heavy deformation, which were at 80 m (5), 120 m (6), 140 m (7), 160 m (8), 180 m (9), 200 m (10), 220 m (11), and 280 m (14) from the center line of the air return way.

The monitoring data showed that the accumulated squat is the largest at 8–11 measuring points near the adhesive maleic side. The deformation of the 5th and 7th measuring points near the gyrus maleic side was small. The location of the 14th measuring point was special and was located in the triangle area of the coal body and roadway, with limited deformation. Based on field observations, close to the 1101 working face cutting hole, the side of the transport maleic roadway develops fractures. The bottom is a gray sandy mudstone and charcoal gray mudstone, resulting in differential deformation in the local area of the cut.

The results of the roof subsidence and time relationship graph (Figure 8) were analyzed. In addition to the eight points, the remaining seven point deformation reduced gradually in approximately 30–40 days and stabilized. This indicates that the stabilization time of roadway deformation under the combined effects of ground stress and mining is around 1–1.5 months. As the 8th measuring point is in the middle of the cutting hole, it tends to be stable for a relatively long time, i.e., approximately 2 months.

The main characteristics of the NS coal roadway deformation appear to be of greater concern than the EW roadway in the Yadian coal mine. Additionally, the second stage of the development roadway and three periods of the preparation roadway have the same characteristics. As such, during later production, special support measures should be taken for the SN excavation roadway and the mining gateway, and comprehensive monitoring should be carried out to avoid construction errors and accidents.

2.5. Factors Influencing Different Roadway Deformations. 2.5.1. Buried Depth of Coal Seam, Strata, and Rock Burst. According to the dynamic behavior in the Hujiahe, Mengcun, and Tingnan, the critical depth of rock burst in the mining area was approximately 500–600 m. The coal seam burial depth of the development roadway in the Yadian coal mine was 450–550 m, and the main no. 1 mining coal seam of the first 1101 face was buried between 400 and 750 m; these are medium to deep-buried coal seams. The rock mechanics laboratory of the Beijing Mining Research Institute investigated bump proneness, with the results demonstrating that Yadian coal has a single-axle compression strength for the no. 4 coal seam of 13.43 MPa. Its roof strata bending energy index was 22.71 kJ, which indicates that this coal seam and roof have a weak bump proneness.

2.5.2. Abnormal In Situ Stress. Combined with the in situ stress test of Jiaogang mine on the southern edge of the Binchang mining area, the mechanical test results and stress analysis results of the Yadian coal mine as well as the in situ stress test results showed that the maximum σ_v is between 10 and 16 MPa (Table 3). σ_v is discrete, ranging between 6 and 30 MPa (Figure 9), showing that the vertical stress is more stable in the region with gravity stress. The horizontal stress distribution was very unstable, and local scope created stress aggregation, causing the floor heave of the roadway, roof...
subsidence, rip spalling, and other roadway deformation phenomena. The maximum principal stress of the central roadway and the underground parking is between 12.30 and 15.41 MPa, which belongs to the medium stress area; the maximum principal stress in the return air gateway area of the 1101 working face is about 28.10 MPa, which belongs to the high stress area. Therefore, the magnitude, direction, and uneven distribution of the horizontal stress were key factors for roadway deformation in the study area.

2.5.3. Regional Tectonic Stress Field and Structural Development Characteristics. The Ordos Basin occurs in a strong fault depression in the Cenozoic periphery and has experienced three tectonic evolutions. The conversion process of tectonic stress was as follows:

1. In the Paleocene—Oligocene, the local tensile stress direction was NW—SE to NWW—SEE;
2. In the Miocene, the tensile stress direction converted into an NE—SW to NNE—SSW direction;
3. Since the Pliocene is influenced by the Tibet plateau uplifting, the mechanism of tectonic dynamics conversion and tensile stress converted to an NW—SE direction.\(^{\text{13}}\)

The present geological stress at the southeastern margin of the Ordos Basin is controlled by the tectonic stress field in North China, and the \(\sigma_{HH}\) direction is mainly ENE—WSW.\(^{\text{4}}\) The results in the Yadian coal mine show that the \(\sigma_{HH}\) orientation is in the ENE and ESE directions. This has good consistency with the regional stress field. Together with the roadway deformation characteristics, it shows that the E—W bearing stress is one of the main factors causing different deformations of E—W and N—S roadways.

2.5.4. Lithology of Rock Formations. The Yadian mine has a long service time and an array of factors that should be considered, including mine construction and transportation, water supply, drainage, and ventilation. The main roadway was arranged under the no. 4 coal seam under the strata of the Jurassic Fuxian group (\(J_{1f}\)) mudstone, sandy mudstone, and the upper Triassic Tongchuan group (\(T_{3h}\)) interbedded powder fine sandstone. According to the engineering geology drilling core records, the rock quality designation (RQD) values of mudstone and sandy mudstone ranged from 8.8—83.0%, averaging 28.66%, and the RQD value of fine sandstone was 54.2%. The Z and M values were used to evaluate the quality of rock, with the results analyzed in a similar manner to that of the RQD value method. The results showed that the quality of a fine sandstone rock was better, followed by siltstone and gritstone, and the worst was mudstone. The floor strata of no. 4 coal were also given priority to gray, gray black mudstone, occasional fine sandstone, and mostly sand—mud interbedded. There was also locally developing fissure containing abundant fossils of plant roots, which can easily expand under the influence of water. Therefore, the characteristics and integrity of roadway rocks are other factors causing deformation.

2.5.5. Mining Factors. Tunneling of the N—S development roadway broke the original stress balance, and the ESE- and ENE-trending horizontal stress was further enhanced, forming new additional stresses. The roadway was influenced by this new stress field, and the most serious deformation area of the roadway was located in the roadway intersection area. This is because in the process of tunnel construction, the disturbance range of the strata is larger, creating a stress concentration and causing the deformation of the roadway. As such, the size and degree of perturbed strata are also influencing factors of roadway deformation.

2.5.6. Deformation Mechanism. In the Yadian coal mine, the rock of the roadway is mainly gray black and gray flaggy sandy mudstone with little incant medium, thick layered gritstone and oyster gray fine sandstone. The intensity is low, but rich in clay minerals. As such, they expand easily under the influence of water, combined with gangue mudding expansion by filed construction water and roof leakage, causing gradual floor heave of the roadway. The no. 1 coal floor was mainly composed of gray, gray black mudstone and sandy mudstone, part of which is siltstone, containing abundant plant root fossils. These are easy to expand when encountering water. In the no. 4 coal floor, the compressive strength of mudstone and sandy mudstone was 9.21 MPa and that of fine sandstone was 14.28 MPa, all less than 25 MPa.

The coal floors of no. 1 and 4 coal seams were soft rocks. Influenced by the regional tectonic stress, it develops throughout fractures in the rock, and the density of the fractured rock mass of no. 4 coal seam, roof, and floor was approximately 3—7 m. The fracture spacing was 0.4 m, and the fracture direction was nearly N—S cutting complete and larger thick sandstone into squares throughout. During the construction process of the main return way, a large area of roof fall that grew approximately 20 and 1 m wide was found. Two cross-heading at the 1101 face locally also developed fractures with consequent layers throughout, by approximately 10 a/m, because of the soft coal and shorter extensions; the direction of these joints is nearly N—S. The rock was the broken strata, and the phenomena of roof falling had occurred during the process of tunneling.

Therefore, under the background of the regional stress field, mining and driving activities affect the original stratum balance state. In addition, the roadway has the characteristics of a large buried depth, poor integrity of rock stratum, and nearly S—N development of structural fractures. The coal seam floor is easy to argillaceous expansion. The underground roadway is affected by the near E—W horizontal geostress, showing that the deformation of the S—N roadway is severe, while the E—W roadway deformation has weak characteristics. Combining soft rock engineering mechanics and rock mechanics theory,\(^{\text{50}}\) the roadway deformation mechanism of the Yadian coal mine is composite mechanics of a weak expansible rock layer (IAB),

### Table 3. Stress Measurement Results of the Main Roadway in Jiangjiahe Coal Mine

| no. of point | \(\sigma_{H} (\text{MPa})\) | \(\sigma_{V} (\text{MPa})\) | \(\sigma_{H} (\text{MPa})\) | depth (m) |
|-------------|-----------------|-----------------|-----------------|----------|
| 1           | 9.03            | 4.81            | 15.34           | 650      |
| 2           | 6.94            | 3.91            | 15.27           | 370      |

Figure 9. Scatter diagram of crustal stress distribution.

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tectonic stress mechanism ($\Sigma_{t}$), and fracture development deformation ($\Delta_{IDE}$).

3. CONCLUSIONS AND SUGGESTIONS

(1) In the Yadian mine, the stress field characteristics were $\sigma_{H} > \sigma_{1} > \sigma_{V}$; the results show that the horizontal stress is dominant, and the numerical value presents two pole states and discrete distribution; the maximum horizontal stress is 30 MPa, the minimum is 15 MPa, and the directions are ENE and ESE; the regional stress is 15.41 MPa, which belongs to the middle stress area. The maximum principal stress of the air return area of the 1101 face roadway was significantly greater than that of the E–W roadway. This a direct reflection of this type of stress; hence, optimizing the development roadway layout may address the issues of deformation and roadway stability.

(2) The interbedded soft rock formed expansion under the influence of water causes swelling of the roadway. The development of local fissures throughout causes roof breakage, and the ground stress causes differential deformation of the roadway, which are mutually complementary. The roadway deformation mechanism of the Yadian coal mine comprises composite mechanics of the weak expansive rock layer ($1_{0B}$), tectonic stress mechanism ($1_{t}$), and joint and fissure development deformation ($1_{IDE}$).

(3) The maximum principal stress in the main roadway and the shaft station of the Yadian coal mine is between 12.3 and 15.41 MPa, which belongs to the middle stress area. The maximum principal stress of the air return area of the 1101 face is approximately 28.10 MPa, which belongs to the high stress area. Accordingly, the effect of rock bursts during the process of later mining will be more serious than other areas. Thus, we should effectively identify, evaluate, prevent, and treat rock bursts.

■ AUTHOR INFORMATION

Corresponding Author
Bo Jiang — School of Resources and Geosciences, China University of Mining and Technology, Xuzhou 221116, China; orcid.org/0000-0001-6112-3168; Email: jiangbo@cumt.edu.cn

Authors
Huibin Liu — School of Resources and Geosciences, China University of Mining and Technology, Xuzhou 221116, China; Bin County Coal Co., Ltd., Xianyang 712000, China; orcid.org/0000-0003-3771-1220
Wanying He — Bin County Coal Co., Ltd., Xianyang 712000, China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.0c05205

Notes
The authors declare no competing financial interest.

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