Reasonable Layout of Roadway Based on PSO-AHP Optimization Algorithm Under Three-Dimensional Stress Field

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Reasonable layout of roadway based on PSO-AHP optimization algorithm under three-dimensional stress field

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Abstract: Reasonable roadway layout is the fundamental measure to reduce the difficulty of roadway support and improve the stability of surrounding rock. The particle swarm optimization and analytic hierarchy process (PSO-AHP) algorithm of reasonable layout of roadway under the three-dimensional field was proposed, and an engineering verification was carried out in Weijiadi coal mine. The results showed that, The dip angle $\alpha_1$ and azimuth angle $\alpha_2$ affect the distribution of the deviatoric stress of the roadway surrounding rock. Under different stress field, the sensitivity of surrounding rock to $\alpha_1$ and $\alpha_2$ are different. Changing the more sensitive layout parameters can minimize the deviatoric stress and improve the stability of roadway. The PSO-AHP optimization algorithm takes the deviatoric stress as the index to calculate the layout parameters of different parts of the roadway, and then determines the optimal layout parameters through the evaluation function. The roadway of 1104 working face was arranged with the optimal parameters obtained by PSO-AHP optimization algorithm. Compared with the original layout scheme, the deviatoric stress of surrounding rock was reduced and the position of maximum deviatoric stress is transferred. The optimum layout of roadway was combined with an asymmetric support which had a good application effect.

Keywords: reasonable layout of roadway; roadway stability maintenance; PSO-AHP optimization algorithm; deviatoric stress; asymmetric support

1. Introduction

China is a country with rapid industrial development and increasing demand, the coal is the main energy for its economic development (Kong et al. 2014). The mining depth of coal mines in China increases at an annual rate of 8-12m. As an important channel for pedestrians, transportation and ventilation, the stability of roadway becomes more difficult under the high stress field (Hakna Basarira et al. 2019; Jiang et al. 2004; Kang et al. 2014). The maintenance of roadway stability not only requires correct support design, but also reasonable layout which can reduce the difficulty of support and enhance the stability of roadway. Hence, the research on the optimization algorithm of roadway layout is profound to ensure safety production.

Many scholars have conducted deep-going researches on the determination of roadway layout. Yan H et al. (2015) studied the rational layout of multi-coal seam roadway via simulation and theoretical research methods. The optimal location of roadway was determined by analyzing the stress distribution of coal pillar in the floor, and a reasonable support scheme was proposed. Guo XF et al. (2021) studied the evolution law of plastic zone with the roadway that is located at different positions under the working face to determine the layout position of the roadway. Wang ZL et al. (2021) analyzed the fracture height of mining overburden via theoretical analysis and numerical simulation. Finally, the roadway layout parameters were determined according to the gas drainage effect. Zhang W et al. (2018) established the mechanical model of floor failure to determine the reasonable dislocation distance between roadway and island coal pillar, which carried out field application. Tu SH et al. (2013) studied the reasonable layout of roadway in thick coal seam and high gas mine through field measurement. Tai Y et al. (2020) conducted an in-depth analysis on the selection of reasonable positions of roadway with large cross-section, and explored the influence of roadway layout on roof
separation, subsidence, vertical stress and roadway failure zone. Feng GR et al. (2021) determined the optimal layout of roadway in medium thick residual coal seam based on stress, stress change rate and fracture characteristics. Wu G et al. (2018) studied the roadway layout scheme of ultra-close coal seam, and applied the numerical model of different staggered distances using FLAC\textsuperscript{3D} software. The optimal roadway layout scheme combined with the simulation results and coal recovery rate is proposed, etc.

The foregoing research results exerted a vital guiding function in the rational layout of roadway. However, the roadway was usually simplified as a plane problem, and a large number of numerical simulation schemes were established to determine the reasonable layout position in foregoing study. In fact, the roadway is in the three-dimensional stress field. Many studies revealed that the failure law of roadway surrounding rock under the three-dimensional stress field is different from those of roadway in plane problem (Lu et al. 2020, 2021; Liu et al. 2021), especially there is an included angle between roadway axial and principal stress (Guo et al. 2020). At present, there are few reports on the intelligent optimization algorithm for the reasonable layout of roadway under three-dimensional stress field. Therefore, this paper proposes the particle swarm optimization and analytic hierarchy process (PSO-AHP) algorithm of reasonable layout of roadway to decrease the difficulty of roadway support and improve the stability of roadway, which is meaningful to mine mining deployment and safe production.

2. Deviatoric stress distribution of roadway surrounding rock

2.1. Derivation of deviator stress formula of roadway surrounding rock

The underground roadway is in a three-dimensional stress field, and there is an angle relationship between the roadway axis and the in-situ stress field, as shown in Fig. 1(a). The original coordinate system of principal stress is $OXYZ$, and the principal stresses are $\sigma_x'$, $\sigma_y'$, $\sigma_z'$. There exists dip angle $\alpha_1$ and azimuth angle $\alpha_2$ between roadway and original coordinate system. The value of $\alpha_1$, $\alpha_2$ directly affect the stress distribution and failure characteristics of surrounding rock. For the sake of obtaining the stress of roadway surrounding rock, it is needful to transform the original coordinate system. The stress state of surrounding rock is shown in Fig. 1(b), and the stress is shown in Eq.(1) (Guo et al. 2020; Lin et al. 2021).

\[
\begin{bmatrix}
\sigma_x' \\
\sigma_y' \\
\sigma_z' \\
0 \\
0 \\
0
\end{bmatrix} =
\begin{bmatrix}
\frac{l_1}{m_1} & m_1^2 & n_1^2 & 2l_1m_1 & 2n_1m_1 & 2l_1n_1 \\
\frac{l_2}{m_2} & m_2^2 & n_2^2 & 2l_2m_2 & 2n_2m_2 & 2l_2n_2 \\
\frac{l_3}{m_3} & m_3^2 & n_3^2 & 2l_3m_3 & 2n_3m_3 & 2l_3n_3 \\
l_1m_1 + l_1m_2 & m_1m_2 + m_1n_1 & n_1m_1 + n_1l_1 & n_1l_1 + n_1l_2 & n_1l_2 + n_1l_3 \\
l_1m_1 + l_1m_2 & m_1m_2 + m_1n_1 & n_1m_1 + n_1l_1 & n_1l_1 + n_1l_2 & n_1l_2 + n_1l_3 \\
l_1m_1 + l_1m_2 & m_1m_2 + m_1n_1 & n_1m_1 + n_1l_1 & n_1l_1 + n_1l_2 & n_1l_2 + n_1l_3
\end{bmatrix}
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\sigma_z \\
\tau_{xy} \\
\tau_{yz} \\
\tau_{xz}
\end{bmatrix}
\]
Where \( l_1, l_2 \) and \( l_3 \) are the direction cosine between \( OX \) axis and \( O'X' \) axis, \( OY' \) axis, \( OZ' \) axis respectively; \( m_1, m_2 \) and \( m_3 \) are the direction cosine between \( OY \) axis and \( O'X' \) axis, \( OY' \) axis, \( OZ' \) axis respectively; \( n_1, n_2 \) and \( n_3 \) are the direction cosine between \( OZ \) axis and \( O'X' \) axis, \( OY' \) axis, \( OZ' \) axis respectively; \( \sigma_x, \sigma_y, \sigma_z \) are the principal stress in \( OXYZ \) coordinate system, \( \tau_{xy}, \tau_{yz}, \tau_{xz} \) are shear stress.

In \( OXYZ \) coordinate system, taking circular roadway as an example, the stress equations of any point of roadway surrounding rock are as follow: (Lu et al. 2021; Zhao et al. 2021):

\[
\begin{align*}
\sigma_x &= \frac{1}{2}(\sigma_x + \sigma_y)(1 - \frac{R^2}{r}) - \frac{1}{2} (\sigma_x - \sigma_y)(1 - \frac{4 R^2}{r^3} + \frac{3 R^4}{r^5}) \cos \theta + \tau_{xy}(1 - \frac{4 R^2}{r^3} + \frac{3 R^4}{r^5}) \sin \theta \\
\sigma_y &= \frac{1}{2}(\sigma_x + \sigma_y)(1 + \frac{R^2}{r}) + \frac{1}{2} (\sigma_x - \sigma_y)(1 + \frac{3 R^4}{r^5}) \cos \theta - \tau_{xy}(1 + \frac{3 R^4}{r^5}) \sin \theta \\
\sigma_z &= \sigma_x - 2\nu(\sigma_x - \sigma_y) \frac{R^2}{r^3} \cos \theta - 4\nu \tau_{xy} \sin \theta \frac{R^2}{r^3} \\
\tau_{xy} &= \frac{1}{2}(\sigma_x - \sigma_y)(1 + \frac{2 R^2}{r^3} - \frac{3 R^4}{r^5}) \sin \theta + \tau_{xy}(1 + \frac{2 R^2}{r^3} - \frac{3 R^4}{r^5}) \cos \theta \\
\tau_{xx} &= \tau_{xy} \sin \theta + \tau_{yy} \cos \theta (1 + \frac{R^2}{r^3}) \\
\tau_{yy} &= \tau_{xy} \cos \theta + \tau_{yy} \sin \theta (1 - \frac{R^2}{r^3})
\end{align*}
\]

(2)

Where \( R \) is the roadway radius; \( r \) is the distance between any unit of the surrounding rock element and the center of the circle; \( \theta \) is the angle between the unit and horizontal direction; \( \nu \) is the poisson’s ratio of surrounding rock; \( \sigma_x \) is radial stress; \( \sigma_y \) is tangential stress; \( \sigma_z \) is the axial principal stress; \( \tau_{xy}, \tau_{xx}, \tau_{yy} \) are the shear stress.

The principal stress transformation equations of any point of roadway surrounding rock under \( OXYZ \) coordinate system are as follows:

\[
\begin{align*}
\sigma_1 &= \frac{2\sqrt{J_2}}{\sqrt{3}} \sin(\theta' + \frac{2\pi}{3}) + \sigma_x + \sigma_y + \sigma_z \\
\sigma_2 &= \frac{2\sqrt{J_2}}{\sqrt{3}} \sin(\theta' - \frac{2\pi}{3}) + \sigma_x + \sigma_y + \sigma_z \\
\sigma_3 &= \frac{2\sqrt{J_2}}{\sqrt{3}} \sin(\theta' - \frac{2\pi}{3}) + \sigma_x + \sigma_y + \sigma_z \\
\theta' &= \frac{1}{3} \sin^{-1} \left( -\frac{\sqrt{27 J_3}}{2 (J_2)^{\frac{1}{2}}} \right)
\end{align*}
\]

(3)

Where \( \sigma_1, \sigma_2, \sigma_3 \) are the maximum, middle and minimum principal stresses of any point of roadway surrounding rock under \( OXYZ \) coordinates, respectively; \( \theta' \) is the stress lode angle of \( \sigma_x, \sigma_y, \sigma_z \);

\[
\begin{align*}
\sigma &= \begin{pmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{pmatrix} = \begin{pmatrix} \sigma_m & 0 & 0 \\ 0 & \sigma_m & 0 \\ 0 & 0 & \sigma_m \end{pmatrix} + \begin{pmatrix} \sigma_1 - \sigma_m & 0 & 0 \\ 0 & \sigma_2 - \sigma_m & 0 \\ 0 & 0 & \sigma_3 - \sigma_m \end{pmatrix} \\
\sigma_m &= \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} \\
S_i &= \sigma_i - \sigma_m
\end{align*}
\]

(5)

\( J_2 \) and \( J_3 \) are the second and third invariants of deviatoric stress respectively, and the equations are as follow:

\[
\begin{align*}
J_2 &= \frac{1}{6} \left[ (\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy} + \tau_{yx} + \tau_{yz} + \tau_{zy} + \tau_{xz} + \tau_{zx}) \right] \\
J_3 &= \frac{2}{3} (\frac{2\sigma_x - \sigma_y - \sigma_z}{3})^2 + (\frac{2\sigma_y - \sigma_z - \sigma_x}{3})^2 + (\frac{2\sigma_z - \sigma_x - \sigma_y}{3})^2 \\
+ \frac{4}{3} \tau_{xy} \tau_{xx} + \frac{4}{3} \tau_{yy} \tau_{yy} + \frac{4}{3} \tau_{xz} \tau_{xz}
\end{align*}
\]

(4)

According to the elastic-plastic mechanics theory, it is known that the object behaves as volume change and shape change under the action of external force, in which the volume deformation is controlled by spherical stress and the shape change is controlled by deviatoric stress. The plastic deformation and failure of materials are mainly the change of shape. Therefore, deviatoric stress can control the failure of rock mass, which is crucial to the plastic failure of rock (Huo et al. 2020; Zhuang et al. 2020). The basic equations are as follow:
Where $\sigma_m$ is spherical stress; $S_i$ is deviatoric stress; $S_1$ is the maximum deviatoric stress, which plays a leading role in the stress deviatoric tensor, so it is the calculated parameters of the deviatoric stress field.

By combining formula (1)-(5), the deviatoric stress at any point of roadway surrounding rock can be obtained, which is a crucial index to reflect the damage degree of surrounding rock. The possibility of surrounding rock failure is rising with increased deviatoric stress $S_1$, and vice versa.

2.2. Influence of $\alpha_1$ and $\alpha_2$ on deviatoric stress of roadway surrounding rock

In the three-dimensional stress field, the stability and failure characteristic of roadway are different under different $\alpha_1$ and $\alpha_2$ layout conditions. In order to explore the influence of $\alpha_1$ and $\alpha_2$ changes on the surrounding rock, $\sigma'_x=20\text{MPa}$, $\sigma'_y=15\text{MPa}$, $\sigma'_z=10\text{MPa}$, $R=2\text{m}$, $r=5\text{m}$ can be substituted into Eqs.(1)-(5) to calculate the deviatoric stress distribution on sidewalls, roof and floor. It is known that the inclination angle between the roadway and the horizontal plane is generally $0^\circ$~$50^\circ$ (there is a concealed inclined shaft with a dip angle of $50^\circ$) $\alpha_1$. The value range of $\alpha_1$ is $[0^\circ,50^\circ]$. The value range of $\alpha_2$ is $[0^\circ,90^\circ]$. The calculation results are shown in Fig. 2.

![Fig.2. Influence of $\alpha_1$ and $\alpha_2$ changes on distribution characteristics of deviatoric stress of roof and floor, sidewalls under three-dimensional stress field](image)

(a) Deviatoric stress distribution of sidewalls (b) Deviatoric stress distribution of roof and floor

As shown in Fig. 2, the deviatoric stress of roof and floor, sidewalls of roadway will change under different $\alpha_1$ and $\alpha_2$ conditions, and the deviatoric stress distribution of roof and floor within $\alpha_1 \in [0^\circ, 50^\circ]$ and $\alpha_2 \in [0^\circ, 90^\circ]$ is also significantly different from that of the sidewalls. Taking the sidewalls of the roadway as an example, it is assumed that the dip angle $\alpha_1=35^\circ$ and azimuth angle $\alpha_2=20^\circ$ of a roadway, as shown at point A in Fig. 2(a), the deviatoric stress of this roadway sidewalls is $13.1\text{MPa}$. In order to reduce the deviatoric stress of sidewalls, it can be adjusted $\alpha_1$, $\alpha_2$ to reduce. It is assumed that the deviatoric stress of sidewalls is reduced to $11.9\text{MPa}$. If $\alpha_1$ is changed, it is necessary to reduce $\alpha_1$ by $5^\circ$, and if $\alpha_2$ is changed, it is necessary to increase by $25^\circ$. Consequently, in the stress fields of $\sigma'_x=20\text{MPa}$, $\sigma'_y=15\text{MPa}$ and $\sigma'_z=10\text{MPa}$, The sidewalls of the roadway are highly sensitive to the change of $\alpha_1$ and low to the change of $\alpha_2$, that means a small change of $\alpha_1$ can reduce the deviatoric stress of sidewalls. For the roof and floor of roadway, when $\alpha_1$ decreases by $5^\circ$, the deviatoric stress of roof and floor can be reduced from $10.1\text{MPa}$ to $9.21\text{MPa}$; if $\alpha_2$ increases by $25^\circ$, the deviatoric stress of roof and floor will increase, and the failure of roof and floor will be aggravated. Therefore, for this roadway, if the dip angle $\alpha_1$ of the roadway is reduced by $5^\circ$, the deviatoric stress of the sidewalls, roof and floor can be reduced, and the stability of roadway can be improved.

In conclusion, the sensitivity of roadway to $\alpha_1$ and $\alpha_2$ is different under different stress field, and adjusting the sensitive layout parameters of roadway
can enhance the stability of surrounding rock. The optimal roadway layout parameters $a_1$ and $a_2$ can improve the stability of surrounding rock and reduce the difficulty of support. The stability of roof and floor, sidewalls and shoulder angle will change with the change of $a_1$ and $a_2$, and the roadway optimal layout parameters $a_1$ and $a_2$ must simultaneously consider the stability of all key positions in the roadway. Therefore, this paper comprehensively considers the influence of $a_1$ and $a_2$ on the stability of key parts of the roadway, and proposes the PSO-AHP algorithm of roadway reasonable layout under the three-dimensional stress field, so as to find the roadway optimal layout parameters $a_1$ and $a_2$.

3. PSO-AHP algorithm for roadway reasonable layout

3.1. PSO algorithm process

$$\begin{align*}
\text{v}(i,:) &= w \times \text{v}(i,:) + c_1 \times \text{rand}(0,1) \times (\text{pbest}_i - x(i,:)) + c_2 \times \text{rand}(0,1) \times (\text{gbest}_i - x(i,:)) \\
\text{x}(i,:) &= x(i,:) + \text{v}(i,:) 
\end{align*}$$

Where, $v$ is particle velocity; $x$ is the current position of the particle; $w$ is the inertia factor; $c_1$ and $c_2$ are learning factors, usually $c_1=c_2=2$; $i=1, 2, 3 \cdots n$, where $n$ is the number of particles; $pbest$ represents the individual optimal position of the particle, and $gbest$ represents the global optimal position.

The PSO algorithm for reasonable layout of roadway mainly includes the following steps: (1) Setting the range of particles and iterations. According to the range of $a_1$ and $a_2$, setting the initial position and velocity of particles. (2) Eqs. (1)-(5) are used to obtain the fitness function fun of roadway surrounding rock $S_1$ about $a_1$ and $a_2$. The particle swarm position is substituted into the fitness function to obtain the particle fitness: $fitness=fun(pop)$. (3) Calculating the individual extremum and population extremum. According to the results of particle fitness, finding the particle position and extreme value with the lowest fitness: $[bestfitness, bestindex]=\text{min}(fitness)$. The individual extremum and extremum position are substituted to the group extremum, and then the group extremum and position are: $gbest=pop(bestindex)$; $fitnessgbest=bestfitness$. The extreme value and position of individuals are: $pbest=pop$; $fitnesspbest=fitness$. (4) To obtain the optimal extremum and particle position via iterative update. According to the obtained population extremum and individual extremum position, the particle position and fitness are updated by using Eq. (6). When the individual particle position and speed exceed the specified setting value, the particle position and adjustment method are shown in Eq. (7). When the updated extremum of the particle is greater than the global optimal extremum, the particle will continue to update the iterative calculation, and the global optimal extremum and position will be finally obtained through PSO algorithm.

$$\begin{align*}
x(i, \text{find}(x(i,:) < x_{\text{min}})) &= x_{\text{min}} \\
x(i, \text{find}(x(i,:) > x_{\text{max}})) &= x_{\text{max}} \\
v(i, \text{find}(v(i,:) < v_{\text{min}})) &= v_{\text{min}} \\
v(i, \text{find}(v(i,:) > v_{\text{max}})) &= v_{\text{max}} 
\end{align*}$$

3.2. AHP analysis process

Analytic Hierarchy Process (AHP) is a simple, flexible and practical multi criteria decision-making method for quantitative analysis of qualitative problems (Piotr et al. 2016; Guo et al. 2021; Huang et
al. 2019). Through the above PSO algorithm, the optimal layout parameters \( a_1 \) and \( a_2 \) of roadway different key parts (roof and floor, sidewalls or shoulder angle) can be obtained under specific stress field conditions. The layout parameters \( a_1 \) and \( a_2 \) of each group are not exactly the same, and the fitness \( S_i \) of different key parts is also different. The basic principle of AHP is as follow:

\[
y_j = \sum_{i=1}^{n} C_{ij} w_i (8)
\]

Where \( c_{ij} \) is the evaluation score of the factor. Here, the deviatoric stress of roadway surrounding rock is substituted for calculation; \( w_i \) is the weight of factor whose value range is (0,1); \( n \) is the number of factors. Due to the deviatoric stress field of roadway surrounding rock shows a central rotational symmetry with the center of the circle, there is a relationship between the deviatoric stress at any point of roadway surrounding rock: \( S_i(\theta)= S_i(\theta+\pi) \). Therefore, it is stipulated that the factors affecting the reasonable layout of the roadway include the roof and floor (\( \theta=90^\circ \)), sidewalls (\( \theta=0^\circ \)) and shoulder angle (\( \theta=45^\circ \), \( \theta=135^\circ \)).

The analytical steps of AHP are as follows: (1) Building a judgment matrix and comparing the importance of factors affecting the reasonable layout parameters of roadways, and forming a judgment matrix, as shown in Table 1. In order to determine the relative importance of each factor, the 1-9 scale method is adopted to evaluate the importance of the factor, and the classification standard is shown in Table 2 (Gao et al. 2021; Xiong et al. 2019).

| Evaluation scale | Definition of evaluation criteria |
|------------------|----------------------------------|
| 1                | \( A_i \) and \( A_j \) are equally important |
| 3                | \( A_i \) is slightly more important than \( A_j \) |
| 5                | \( A_i \) is obviously more important than \( A_j \) |
| 7                | \( A_i \) is particularly more important than \( A_j \) |
| 9                | \( A_i \) is extremely more important than \( A_j \) |
| 2, 4, 6, 8       | It is in the middle of the above adjacent evaluation criteria |

According to the importance of different key parts of surrounding rock, the indirect judgment matrix of roadway reasonable layout parameter selection is obtained, as shown in Table 3.

| Table 3. Indirect judgment matrix for parameter selection of reasonable roadway layout |
|---------------------------------|---------------------------------|
| Roof and floor (\( \theta=90^\circ \)) | Side walls (\( \theta=0^\circ \)) | Shoulder angle (\( \theta=45^\circ \)) | Shoulder angle (\( \theta=135^\circ \)) |
|---------------------------------|---------------------------------|
| Roof and floor (\( \theta=90^\circ \)) | 1 | 4 | 3 | 3 |
| Sidewalls (\( \theta=0^\circ \)) | 1/4 | 1 | 1/3 | 1/3 |
| Shoulder angle (\( \theta=45^\circ \)) | 1/3 | 3 | 1 | 1 |
| Shoulder angle (\( \theta=135^\circ \)) | 1/3 | 3 | 1 | 1 |

AHP analytic step (2): Calculating the eigenvector \( w \) corresponding to the maximum non-0 eigenvalue of the judgment matrix, so as to obtain the weight \( w_i \) of each factor. (3) Consistency test of judgment matrix. The consistency test formula is shown in Eq. (9) (Yao et al. 2021; Zhang et al. 2021). In general, if \( CI \leq 0.1 \), it can be considered that \( w \) obtained by the judgment matrix is acceptable. Otherwise, the judgment matrix should be adjusted.

\[
\begin{align*}
CI &= \frac{\lambda_{\text{max}} - n}{n - 1} \\
\lambda_{\text{max}} &= \max_{i=1}^{n} (Aw)_{i}/nw_i
\end{align*}
\]

Where \( \lambda_{\text{max}} \) is the maximum eigenvalue of the judgment matrix.

The non-0 eigenvector \( w=(0.503, 0.087, 0.205, 0.205)^T \) and the maximum eigenvalue \( \lambda_{\text{max}}=4.084 \), \( CI=0.0209 \leq 0.1 \) of the judgment matrix in Table 3 are obtained by calculation. The judgment matrix passes the consistency test. Therefore, the comprehensive evaluation value \( y_j \) for the reasonable layout of the roadway is:

\[
y_j = c_{ij} \times 0.503 + c_{ij} \times 0.087 + c_{ij} \times 0.205 + c_{ij} \times 0.205 \quad (10)
\]

The reasonable layout parameters of roadway under three-dimensional stress field can be obtained based on PSO-AHP algorithm, and the calculation process is shown in Fig. 3.
4. Case analysis

Weijiadi coal mine is located in Baiyin City, Gansu Province, China. At present, the No.1 coal seam was being mined. Taking the transportation roadway of 1104 working face in No.1 coal seam as the research object, the reasonable layout of the roadway is analyzed by using PSO-AHP algorithm. The layout of the working face is shown in Fig. 4.

In the $O'X'Y'Z'$ coordinate system, considering the roadway slope and the actual situation of the mine, the layout range of roadway dip angle $\alpha_1$ is $[15^\circ, 17^\circ]$, and the layout range of roadway azimuth $\alpha_2$ is $[50^\circ, 65^\circ]$. The initial design parameters of the inclined roadway are $\alpha_1=17^\circ$ and $\alpha_2=50^\circ$. After the roadway was driven 40m base on the design parameters, roof caving occurred, and the height of roof caving reached
3m. It is difficult to maintain the roadway. The reasons are as follows: 1) After the mining of 109 working face, the high abutment stress which changed the stress environment of inclined roadway, was formed on the side of 1104 working face. The change of stress environment was the direct cause of roof falling event in roadway. 2) The roadway layout parameters that had not been calculated scientifically were unreasonable. The surrounding rock is sensitive to the variation of dip angle $\alpha_1$ and azimuth angle $\alpha_2$. The roadway optimal layout parameters can effectively improve the stability of surrounding rock. Therefore, it is indispensable to calculate the reasonable layout parameters of the inclined roadway based on PSO-AHP algorithm. Substituting $\sigma'_1=21.4\text{MPa}$, $\sigma'_2=35\text{MPa}$, $\sigma'_3=27\text{MPa}$ and roadway circumscribed circle $r=2\text{m}$ into Eqs. (1)~(5), and in the PSO model, the particle number $n=10$ and inertia factor $w=0.9$. The optimal layout parameters of different key parts of roadway are obtained through PSO algorithm. The relationship between global optimal solution $g_{best}$ and fitness$g_{best}$ is shown in Fig.5.

As shown in Fig. 5, three optimal layout schemes of roadway are obtained by PSO algorithm, which are $(17^\circ, 58^\circ)$, $(15^\circ, 63.7^\circ)$ and $(15^\circ, 65^\circ)$ respectively. Among the three schemes, the deviatoric stress of each key part of the roadway and the evaluation value $y_i$ obtained by AHP analysis are shown in Table 4.

| Layout scheme | Roof and floor $S_1(\theta=90^\circ)/\text{MPa}$ | Sidewalls $S_1(\theta=0^\circ)/\text{MPa}$ | $\theta=45^\circ$ $S_i/\text{MPa}$ | $\theta=135^\circ$ $S_i/\text{MPa}$ | $y_i$ |
|---------------|---------------------------------|---------------------------------|------------------|------------------|------|
| $(17^\circ, 58^\circ)$ | 10.14 | 13.03 | 8.86 | 14.53 | 11.03 |
| $(15^\circ, 65^\circ)$ | 10.54 | 10.10 | 7.74 | 13.00 | 10.43 |
| $(15^\circ, 63.7^\circ)$ | 10.49 | 10.43 | 7.73 | 13.18 | 10.47 |

As can be seen from Table 4, when the roadway layout parameters are selected as $\alpha_1=15^\circ$ and $\alpha_2=65^\circ$, the comprehensive evaluation value $y_i$ is the smallest. Therefore, this parameter group is optimal for the reasonable roadway layout.

Based on Eqs. (1)~(5), the deviatoric stress at different depths of surrounding rock under the conditions of original layout parameters and optimal layout parameters of roadway is calculated, and the results are shown in Fig. 6.

In Fig. 6, $S_1$ is the deviatoric stress of roadway surrounding rock under the original layout parameters, $S'_1$ is the deviatoric stress of roadway surrounding rock under parameter optimization. It can be seen from the Fig. 6 that after the layout parameters are changed, the deviatoric stress distribution of
surrounding rock changes. Under the original layout parameters, the deviatoric stress of surrounding rock presents an inclined “8” shape distribution, and the maximum deviatoric stress of surrounding rock is distributed at $\theta=150^\circ$ and $\theta=330^\circ$. Under the optimal parameter arrangement, the deviatoric stress distribution of roadway surrounding rock evolves from the inclined elliptical distribution in the shallow part to the skewed distribution in the deep part, and the position of the maximum deviatoric stress is transferred, which is distributed at $\theta=120^\circ$ and $\theta=300^\circ$. The deviatoric stress at different depths of the surrounding rock decreases compared with the original layout parameters. In order to explore the reduction degree of surrounding rock deviatoric stress after adjusting roadway layout parameters, the deviatoric stress reduction coefficient $k$ is defined, and its expression is as follow:

$$k = \frac{S'_1}{S_1}$$  \hspace{1cm} (11)

Where $k<1$, indicating that the deviatoric stress decreases after the optimal layout of the roadway; $k>1$, it indicates that the deviatoric stress increases. The deviatoric stress reduction coefficient $k$ after the optimized layout of the roadway is calculated, and the box diagram of the change of $k$ value of the surrounding rock is obtained, as shown in Fig. 7(a). Meanwhile, in order to accurately locate the angular position when $k>1$, the three-dimensional diagram of $k$ changing with the depth of surrounding rock $r$ and angle $\theta$ was drawn, as shown in Fig. 7(b).

It is seen from the Fig. 7 (a) that the deviatoric stress of surrounding rock can be reduced by using optimized parameters of roadway layout. Only the deviatoric stress in the shallow part of the surrounding rock will increase, and the deviatoric stress will increase to 1.2 times. The average value of $k$ at different depths is less than 1, which indicates that the overall deviatoric stress of the surrounding rock is reduced. It is conducive to roadway stability maintenance. It can be seen from Fig. 7(b) that after the optimized layout of the roadway, the deviatoric stress of the shallow surrounding rock increases. When $r=2m$, the increase range of deviatoric stress is $[40^\circ,120^\circ]$ $\cup$ $[220^\circ,300^\circ]$. With the increase of surrounding rock depth, the increasing range and amplitude of deviatoric stress decrease. The key support should be carried out in areas with large deviatoric stress of surrounding rock, and the support form should be asymmetric. After the roof falling accident occurred in the driving position of the transportation roadway in the 1104 working face, the original layout parameters of the roadway were adjusted. The research roadway in Fig. 4 was arranged according to the optimization parameters of $\alpha_1=15^\circ,\alpha_2=65^\circ$. According to the deviatoric stress distribution of surrounding rock, the asymmetric support design of roadway was carried out. The support section of roadway is shown in Fig. 8. The arch and the sidewalls of the roadway were supported by $\Phi 22mm \times 2600mm$ bolts with row spacing of $800mm \times 800mm$. The floor was supported by $\Phi 22mm \times 2600mm$ bolts with row spacing of $1000mm \times 800mm$ near the side with large deviatoric stress. Due to the skewness distribution of the...
surrounding rock deviatoric stress, three 21.6mm×7000mm anchor cables were arranged in the arch of the roadway where the deviatoric stress is large, with a row spacing of 800mm×1600mm, and one Φ21.6mm×7000mm anchor cable was arranged on the side of the arch with a small deviatoric stress, with a row distance of 1600mm.

To grasp the stability of roadway, the surface displacements of roadway roof and floor, sidewalls were monitored. The surface displacement curves of typical measuring stations are shown in Fig. 9. The deformation of surrounding rock was relatively severe within 15d after excavation and support, and the deformation of surrounding rock increases rapidly. The maximum deformation rate of roof reached 16 mm/d, the maximum deformation rate of roof reached 12 mm/d, and the maximum indenting amount of sidewalls reached 7 mm/d. From 15d to 45d, the deformation rate of surrounding rock gradually was slow down, and the deformation rate of roof, floor and sidewalls were less than 7mm/d. After 45d, the deformation of surrounding rock tended to be stable, and the deformation rate approached 0. The section of the roadway with reasonable layout and support is shown in Fig. 10.

5. Conclusion

(1) The deviatoric stress and stability of roadway are affected by roadway layout parameters which include the dip angle $\alpha_1$ and azimuth angle $\alpha_2$, and the sensitivity of roadway deviatoric stress to the variation of $\alpha_1$ and $\alpha_2$ is different. Adjusting the more sensitive layout parameter of the roadway can reduce the deviatoric stress of the surrounding rock and improve the stability of the roadway.

(2) In this paper, PSO-AHP algorithm is proposed to realize the selection of reasonable layout parameters of roadway. PSO is used to calculate the optimal layout parameters based on different key parts.
of roadway, and then the evaluation index formula constructed by AHP is used to calculate the evaluation score of each scheme. Finally, the reasonable layout parameters that are beneficial to the stability of roadway are selected.

(3) Taking the transportation roadway of 1104 working face in Weijiadi coal mine as the case, the roadway optimal layout parameters \( \alpha_1=15^\circ \), \( \alpha_2=65^\circ \) were obtained by PSO-AHP algorithm. Under this layout scheme, the overall deviatoric stress of surrounding rock is less than that of the original layout scheme. Combined with the skewness distribution characteristics of the deviatoric stress, the asymmetric support technology was proposed. The roadway section was stable and the field application effect was good.

The PSO-AHP algorithm of reasonable layout of roadway under three-way stress state proposed in the original paper plays an important guiding role in determining roadway layout parameters. But the lithology change, rock joints and integrity factors of roadway surrounding rock are not considered in this model. A more systematic optimization algorithm for roadway reasonable layout needs to be further studied.

**Author contributions**

Hongbao Zhao: Funding acquisition, Software. Hui Cheng: Data curation, Software simulation, Writing original draft. Chi Zhang: Field monitoring. Yixiao Zhang: Field monitoring.

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**Compliance with ethical standards**

**Conflict of interest** 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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