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

Hongbao Zhao

China University of Mining and Technology Beijing Campus

Hui Cheng (✉ hui1280@126.com)

China University of Mining and Technology Beijing Campus <https://orcid.org/0000-0002-1652-1885>

Chi Zhang

China University of Mining and Technology Beijing Campus

Yixiao Zhang

China University of Mining and Technology Beijing Campus

Research

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

Posted Date: November 30th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-1039194/v1>

License: This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

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

Hongbao Zhao^{1,2} • Hui Cheng¹ • Chi Zhang¹ • Yixiao Zhang¹

(1.School of Energy and Mining Engineering, China University of Mining and Technology-Beijing 100083 China;
2. State Key Laboratory of Coal Mine Disaster Dynamics and Control, Chongqing University 400030 China)

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 α_1 and azimuth angle α_2 affect the distribution of the deviatoric stress of the roadway surrounding rock. Under different stress field, the sensitivity of surrounding rock to α_1 and α_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^{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 $O'X'Y'Z'$, and the principal stresses are σ'_x , σ'_y , σ'_z . There exists dip angle α_1 and azimuth angle α_2 between roadway and original coordinate system. The value of α_1 , α_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).

(a) Distribution of roadway and principal stress field

(b) Stress state of roadway surrounding rock

Fig.1. Roadway layout and principal stress state of surrounding rock

$$\begin{bmatrix} \sigma'_x \\ \sigma'_y \\ \sigma'_z \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} l_1^2 & m_1^2 & n_1^2 & 2l_1m_1 & 2n_1m_1 & 2l_1n_1 \\ l_2^2 & m_2^2 & n_2^2 & 2l_2m_2 & 2n_2m_2 & 2l_2n_2 \\ l_3^2 & m_3^2 & n_3^2 & 2l_3m_3 & 2n_3m_3 & 2l_3n_3 \\ l_1l_2 & m_1m_2 & n_1n_2 & l_1m_2 + l_2m_1 & m_1n_2 + m_2n_1 & n_1l_2 + n_2l_1 \\ l_2l_3 & m_2m_3 & n_2n_3 & l_2m_3 + l_3m_2 & m_2n_3 + m_3n_2 & n_2l_3 + n_3l_2 \\ l_1l_3 & m_1m_3 & n_1n_3 & l_3m_1 + l_1m_3 & m_3n_1 + m_1n_3 & n_3l_1 + n_1l_3 \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{xz} \end{bmatrix} \quad (1)$$

Where l_1 , l_2 and l_3 are the direction cosine between OX axis and O'X' axis, O'Y' axis, O'Z' axis respectively; m_1 , m_2 and m_3 are the direction cosine between OY axis and O'X' axis, O'Y' axis, O'Z' axis respectively; n_1 , n_2 and n_3 are the direction cosine between OZ axis and O'X' axis, O'Y' axis, O'Z' axis respectively; $\sigma_x, \sigma_y, \sigma_z$ are the principal stress in

$$\begin{cases} \sigma_r = \frac{1}{2}(\sigma_x + \sigma_z)(1 - \frac{R^2}{r^2}) - \frac{1}{2}(\sigma_z - \sigma_x)(1 - 4\frac{R^2}{r^2} + 3\frac{R^4}{r^4})\cos 2\theta + \tau_{xz}(1 - 4\frac{R^2}{r^2} + 3\frac{R^4}{r^4})\sin 2\theta \\ \sigma_\theta = \frac{1}{2}(\sigma_x + \sigma_z)(1 + \frac{R^2}{r^2}) + \frac{1}{2}(\sigma_z - \sigma_x)(1 + 3\frac{R^4}{r^4})\cos 2\theta - \tau_{xz}(1 + 3\frac{R^4}{r^4})\sin 2\theta \\ \sigma_v = \sigma_y - 2\nu(\sigma_x - \sigma_z)\frac{R^2}{r^2}\cos 2\theta - 4\nu\tau_{xz}\sin 2\theta\frac{R^2}{r^2} \\ \tau_{r\theta} = \frac{1}{2}(\sigma_x - \sigma_z)(1 + 2\frac{R^2}{r^2} - 3\frac{R^4}{r^4})\sin 2\theta + \tau_{xz}(1 + 2\frac{R^2}{r^2} - 3\frac{R^4}{r^4})\cos 2\theta \\ \tau_{\theta v} = (-\tau_{yx}\sin\theta + \tau_{zy}\cos\theta)(1 + \frac{R^2}{r^2}) \\ \tau_{rv} = (\tau_{yx}\cos\theta + \tau_{zy}\sin\theta)(1 - \frac{R^2}{r^2}) \end{cases} \quad (2)$$

Where R is the roadway radius; r is the distance between any unit of the surrounding rock element and the center of the circle; θ is the angle between the unit and horizontal direction; ν is the poisson's ratio of surrounding rock; σ_r is radial stress; σ_θ is tangential stress; σ_v is the axial principal stress; $\tau_{r\theta}$, $\tau_{\theta v}$, τ_{rv} are the shear stress.

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

$$\begin{cases} \sigma_1 = \frac{2\sqrt{J_2}}{\sqrt{3}}\sin(\theta'_\sigma + \frac{2\pi}{3}) + \frac{\sigma_r + \sigma_\theta + \sigma_v}{3} \\ \sigma_2 = \frac{2\sqrt{J_2}}{\sqrt{3}}\sin\theta'_\sigma + \frac{\sigma_r + \sigma_\theta + \sigma_v}{3} \\ \sigma_3 = \frac{2\sqrt{J_2}}{\sqrt{3}}\sin(\theta'_\sigma - \frac{2\pi}{3}) + \frac{\sigma_r + \sigma_\theta + \sigma_v}{3} \\ \theta'_\sigma = \frac{1}{3}\sin^{-1}\left[\frac{-\sqrt{27}J_3}{2(J_2)^{3/2}}\right] \end{cases} \quad (3)$$

Where σ_1 , σ_2 and σ_3 are the maximum, middle and minimum principal stresses of any point of roadway surrounding rock under OXYZ coordinates, respectively; θ'_σ is the stress lode angle of $\sigma_r, \sigma_\theta, \sigma_v$;

OXYZ coordinate system, τ_{xy} , τ_{yz} , τ_{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):

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

$$\begin{cases} J_2 = \frac{1}{6}[(\sigma_r - \sigma_\theta)^2 + (\sigma_\theta - \sigma_v)^2 + (\sigma_v - \sigma_r)^2 + 6(\tau_{r\theta}^2 + \tau_{\theta v}^2 + \tau_{rv}^2)] \\ J_3 = \left(\frac{2\sigma_r - \sigma_\theta - \sigma_v}{3}\right)\left(\frac{2\sigma_\theta - \sigma_r - \sigma_v}{3}\right)\left(\frac{2\sigma_v - \sigma_r - \sigma_\theta}{3}\right) + 2\tau_{r\theta}\tau_{rv}\tau_{\theta v} \\ \quad - \left(\frac{2\sigma_r - \sigma_\theta - \sigma_v}{3}\right)\tau_{v\theta}^2 - \left(\frac{2\sigma_\theta - \sigma_r - \sigma_v}{3}\right)\tau_{rv}^2 - \left(\frac{2\sigma_v - \sigma_r - \sigma_\theta}{3}\right)\tau_{r\theta}^2 \end{cases} \quad (4)$$

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:

$$\begin{cases} \sigma = \begin{pmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{pmatrix} = \begin{pmatrix} \sigma_m & 0 & 0 \\ 0 & \sigma_m & 0 \\ 0 & 0 & \sigma_m \end{pmatrix} + \begin{pmatrix} \sigma_1 - \sigma_m & 0 & 0 \\ 0 & \sigma_2 - \sigma_m & 0 \\ 0 & 0 & \sigma_3 - \sigma_m \end{pmatrix} \\ \sigma_m = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} \\ S_i = \sigma_i - \sigma_m \end{cases} \quad (5)$$

Where σ_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 α_1 and α_2 on deviatoric stress of roadway surrounding rock

(a) Deviatoric stress distribution of sidewalls

In the three-dimensional stress field, the stability and failure characteristic of roadway are different under different α_1 and α_2 layout conditions. In order to explore the influence of α_1 and α_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 $0^\circ\sim 50^\circ$ (there is a concealed inclined shaft with a dip angle of 50°) α_1 . The value range of α_1 is $[0^\circ, 50^\circ]$. The value range of α_2 is $[0^\circ, 90^\circ]$. The calculation results are shown in Fig. 2.

(b) Deviatoric stress distribution of roof and floor

Fig.2. Influence of α_1 and α_2 changes on distribution characteristics of deviatoric stress of roof and floor, sidewalls under three-dimensional stress field

As shown in Fig. 2, the deviatoric stress of roof and floor, sidewalls of roadway will change under different α_1 and α_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 13.1Mpa. In order to reduce the deviatoric stress of sidewalls, it can be adjusted α_1 , α_2 to reduce. It is assumed that the deviatoric stress of sidewalls is reduced to 11.9Mpa, If α_1 is changed, it is necessary to reduce α_1 by 5° , and if α_2 is changed, it is necessary to increase by 25° . 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 α_1 and low to the change of α_2 , that means a small change of α_1 can reduce the deviatoric stress of sidewalls. For the roof and floor of roadway, when α_1 decreases by 5° , the deviatoric stress of roof and floor can be reduced from 10.1Mpa to 9.21Mpa; if α_2 increases by 25° , 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 α_1 of the roadway is reduced by 5° , 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 α_1 and α_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 α_1 and α_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 α_1 and α_2 , and the roadway optimal layout parameters α_1 and α_2 must simultaneously consider the stability of all key positions in the roadway. Therefore, this paper comprehensively considers the influence of α_1 and α_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 α_1 and α_2 .

3. PSO-AHP algorithm for roadway reasonable layout

3.1. PSO algorithm process

$$\begin{cases} v(i,:) = w \times v(i,:) + c_1 \times \text{rand}(0,1) \times (pbest_i - x(i,:)) + c_2 \times \text{rand}(0,1) \times (gbest_i - x(i,:)) \\ x(i,:) = x(i,:) + v(i,:) \end{cases} \quad (6)$$

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 $c_1=c_2=2$; $i=1,2,3,\dots,n$, 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 number of particles and iterations. According to the range of α_1 and α_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 α_1 and α_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: $[bestfitness, bestindex] = \min(fitness)$. 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: $pbest = pop$;

Particle Swarm Optimization (PSO) algorithm makes the particles search for the optimal solution in space by placing particles and providing a certain initial velocity. It shares the individual extremum with the particles in the whole particle swarm, so as to find the optimal individual extremum as the current global optimal solution. PSO algorithm adjusts its speed and position according to the current individual extremum and the current global optimal solution, and obtains the final global optimal solution and position after repeated operation (Tony et al. 2006; Li et al. 2012; Yan et al. 2014; Zhou et al. 2011). This method can obtain the reasonable layout parameters α_1 and α_2 of roadway, so as to ensure the stability of surrounding rock. The basic equations of PSO algorithm are as follow (Piotr et al. 2016; Zhang et al. 2020):

$fitnesspbest = fitness$. (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.

$$\begin{cases} x(i, \text{find}(x(i,:) < x_{\min})) = x_{\min} \\ x(i, \text{find}(x(i,:) > x_{\max})) = x_{\max} \\ v(i, \text{find}(v(i,:) < v_{\min})) = v_{\min} \\ v(i, \text{find}(v(i,:) > v_{\max})) = v_{\max} \end{cases} \quad (7)$$

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 α_1 and α_2 of roadway different key parts (roof and floor, sidewalls or shoulder angle) can be obtained under specific stress field conditions. The layout parameters α_1 and α_2 of each group are not exactly the same, and the fitness S_1 of different key parts is also different. The basic principle of AHP is as follow:

$$y_j = \sum_{i=1}^n c_{ij} w_{ij} \quad (8)$$

Where c_{ij} is the evaluation score of the factor. Here, the deviatoric stress of roadway surrounding rock is substituted for calculation; w_{ij} 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: $S_1(\theta) = S_1(\theta + \pi)$. 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

Table 3. Indirect judgment matrix for parameter selection of reasonable roadway layout

	Roof and floor ($\theta=90^\circ$)	Sidewalls ($\theta=0^\circ$)	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.

$$\begin{cases} CI = \frac{\lambda_{\max} - n}{n - 1} \\ \lambda_{\max} = \sum_{i=1}^n \frac{(Aw)_i}{nw_i} \end{cases} \quad (9)$$

Where $\lambda_{\max}$ is the maximum eigenvalue of 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).

Table 1. Judgment matrix

	A_1	A_2	$\dots$	A_n
A_1	a_{11}	a_{12}	$\dots$	a_{1n}
A_2	a_{21}	a_{22}	$\dots$	
$\dots$	$\dots$	$\dots$	$\dots$	$\dots$
A_n	a_{n1}	a_{n2}	$\dots$	a_{nn}

Table 2. 1~9 scale method grading evaluation criteria

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.

judgment matrix.

The non-0 eigenvector $w=(0.503, 0.087, 0.205, 0.205)^T$ and the maximum eigenvalue $\lambda_{\max}=4.084$, $CI=0.0209 \leq 0.1$ 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:

$$y_j = c_{1j} \times 0.503 + c_{2j} \times 0.087 + c_{3j} \times 0.205 + c_{4j} \times 0.205 \quad (10)$$

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.

Fig. 3. Flow chart of PSO-AHP algorithm for reasonable layout of roadway under three-dimensional stress field

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.

Fig. 4. Layout of 1104 working face

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 α_1 is $[15^\circ, 17^\circ]$, and the layout range of roadway azimuth α_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 α_1 and azimuth angle α_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 $\sigma'_x=21.4\text{MPa}$, $\sigma'_y=35\text{MPa}$, $\sigma'_z=27\text{MPa}$ 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 $gbest$ and $fitnessgbest$ is shown in Fig.5.

Fig. 5. Optimal layout scheme of roadway obtained by PSO algorithm

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_j obtained by AHP analysis are shown in Table 4.

Table 4. Deviatoric stress S_1 and comprehensive evaluation value y_j at each key position of roadway under different layout schemes

Layout scheme	Roof and floor $S_1(\theta=90^\circ)/\text{MPa}$	Sidewalls $S_1(\theta=0^\circ)/\text{MPa}$	$\theta=45^\circ$ S_1/MPa	$\theta=135^\circ$ S_1/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_j is the smallest. Therefore, this parameter group is optimal for the reasonable roadway layout.

(a) Original layout parameters $\alpha_1=17^\circ, \alpha_2=50^\circ$

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.

(b) Optimization layout parameters $\alpha_1=15^\circ, \alpha_2=65^\circ$

Fig. 6. Deviatoric stress distribution of surrounding rock under the conditions of original and optimal layout parameters

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:

$$k = \frac{S'_1}{S_1} \quad (11)$$

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 θ was drawn, as shown in Fig. 7(b).

(a) Box diagram of k variation at different depths of surrounding rock (b) Three-dimensional diagram of k varying with depth r and angle θ of surrounding rock

Fig. 7. Box diagram and three-dimensional diagram of k variation of roadway surrounding rock

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 $r=2\text{m}$, 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 $\Phi 22\text{mm} \times 2600\text{mm}$ bolts with row spacing of $800\text{mm} \times 800\text{mm}$. The floor was supported by $\Phi 22\text{mm} \times 2600\text{mm}$ bolts with row spacing of $1000\text{mm} \times 800\text{mm}$ near the side with large deviatoric stress. Due to the skewness distribution of the

surrounding rock deviatoric stress, three $21.6\text{mm}\times 7000\text{mm}$ anchor cables were arranged in the arch of the roadway where the deviatoric stress is large, with a row spacing of $800\text{mm}\times 1600\text{mm}$, and one $\Phi 21.6\text{mm}\times 7000\text{mm}$ anchor cable was arranged on the side of the arch with a small deviatoric stress, with a row distance of 1600mm .

Fig. 8. Schematic of roadway section support

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 7 mm/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.

Fig. 9. Monitoring results of convergence amount and convergence rate of roadway surrounding rock

Fig. 10. Section of roadway with reasonable layout and support

5. Conclusion

(1) The deviatoric stress and stability of roadway are affected by roadway layout parameters which include the dip angle α_1 and azimuth angle α_2 , and the sensitivity of roadway deviatoric stress to the variation of α_1 and α_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.

Acknowledgements

Authors gratefully acknowledge the financial support of the state key laboratory of coal mine disaster dynamics and control visiting scholar fund project(NO.2011DA105287—FW201805), Distinguished scholars of yueqi(NO.800015Z1179), Hebei Province ecological wisdom Mine Joint Fund Project(No.E2020402036) and the Basic scientific research business fee for the central university's graduate research and innovation ability improvement project (NO.2020YJSNY07).

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.

References

- Feng GR, Wang SW, Guo YX, Zhang YJ, Bai JW, Niu LK, Du YL (2021) Optimum position of roadway in the middle residual coal seam between the upper and lower longwall gobs. *Energy Sources, Part A*, 2021. DOI:10.1080/15567036.2021.1897709
- Guo XF, Li YG, Zhou GD, He ZJ, Yu HR, Xu YC (2021) Stability analysis and reasonable layout of floor drainage roadway above confined water and under mining influence. *Geofluids*, Vol. 2021 DOI:10.1155/2021/5578717
- Guo HJ, Ji M, Zhao WS(2020) Roadway support design based on in-situ stress and its asymmetrical distributions in a coal mine. *Arch Min Sci*, 65(2):299-315. DOI:10.24425/ams.2020.133194
- Gao XX, Chai GJ, and Zhu GA (2021) Layout of the first-mining working face in the protected seam for pressure relief by peak stress shift. *Shock Vib*, Vol. 2020. DOI:10.1155/2021/5555584
- Hakan Basarira, Sun YT, Li GC (2019) Gateway stability analysis by global-local modeling approach. *Int J Rock Mech Min Sci* 113:31-40. DOI:10.1016/j.ijrmms.2018.11.010
- Huo GY, Liang JP, Jing HY, Tan JX, Zhang YK, Yang X, Xie X (2020) Influence of deviatoric stress on the deformation and damage evolution of surrounding rock under unloading conditions. *Shock Vib*, 2020: Article ID 3158209. DOI:10.1155/2020/3158209
- Huang DM, Li WJ, Chang XK, Tan YL (2019) Key factors identification and risk assessment for the stability of deep surrounding rock in coal roadway. *Int J Env Res Pub He*, 16: 2802. DOI:10.3390/ijerph16152802
- Jiang YD, Zhao YX, Liu WG, Li Q (2004) Research on floor heave of roadway in deep mining. *Chinese Journal of Rock Mechanics and Engineering*, 2004(14):2396-2401.(in Chinese)
- Kong SL, Cheng YP, Ren T, Liu HY (2014) A sequential approach to control gas for the extraction of multi-gassy coal seams from traditional gas well drainage to mining-induced stress relief. *Appl Energ*, 131:67-78. DOI:10.1016/j.apenergy.2014.06.015
- Kang YS, Liu QS, Gong GQ, Wang HC (2014) Application of a combined support system to the weak floor

- reinforcement in deep underground coal mine. *J Rock Mech Min Sci*, 2014,71:143-150. DOI:10.1016/j.jrmms.2014.03.017
- Lu J, Yin GZ, Zhang DM, Li X, Huang G, Gao H (2021) Mechanical properties and failure mode of sandstone specimen with a prefabricated borehole under true triaxial stress condition. *Geomech Energy Envir*, 2021, 25:100207. DOI:10.1016/j.gete.2020.100207
- Lu J, Yin GZ, Zhang DM, Gao H, Li CB, Li MH (2020) True triaxial strength and failure characteristics of cubic coal and sandstone under different loading paths. *Int J Rock Mech Min Sci*, 2020, 135: 104439. DOI:10.1016/j.jrmms.2020.104439
- Liu YH, Zhao HB, Wang L, Wang T, Ji DL, Liu R, Wang GD. (2021) Analysis of influence of stress lode angle on stability of roadway surrounding rock. *Shock Vib*, 2021: Article ID 6617609. DOI:10.1155/2021/6617609
- Lin C, Zou DH Steve (2021) Formulation and verification of 3D in-situ stress estimation based on differential-direction drilling. *Int J Rock Mech Min Sci*, 2021,145:104833. DOI:10.1016/J.IJRMMS.2021.104833
- Li YY, Xiang RR, Jiao LC, Liu RC (2021) An improved cooperative quantum-behaved particle swarm optimization. *Soft Comput*, 2012, 16: 1061–1069. DOI:10.1007/s00500-012-0803-y
- Piotr MAŁKOWSKI, Zbigniew NIEDBALSKI and Tadeusz MAJCHERCZYK (2016) Roadway design efficiency indices for hard coal mines. *Acta geodyn geomater*, 13(2):201-211. DOI:10.13168/AGG.2016.0002
- Tu SH, Tu HS, Yuan Y, Wang C, Bai QS (2013) Optimization of layout modes of mining roadways of a working face in single and thick high gas outburst seam. *Disaster Adv*,2013,6:55-65.
- Tai Y, Lu GZ, Xia HC, Zhang WY, Liu HJ, Zhang YQ (2020) Position optimisation for a roadway under small coal mines in same coal seam: a case study. *J Geophys Eng*, 2020,17(5):870-882. DOI:10.1093/jge/gxaa036
- Tony Huang, Ananda Sanagavarapu Mohan. (2006) Micro-particle swarm optimizer for solving high dimensional optimization problems (IPSO for high dimensional optimization problems). *Appl Math Comput*,181:1148–1154. DOI:10.1016/j.amc.2006.01.088
- Wang ZL, Liu B, Han YH, Li ZY, Cao YJ, Qi FZ, Yin DW (2021) Determining the layout parameters of the gas drainage roadway: A study for sima coalmine china. *Adv Civil Eng*, 2021,(Article ID 3007807). DOI:10.1155/2021/3007807
- Wu G, Fang XQ, Bai HL, Liang MF, Hu XK (2018) Optimization of roadway layout in ultra-close coal seams: A case study. *Plos one*,2018,13(11): e0207447. DOI:10.1371/journal.pone.0207447
- Xiong XY, Dai J, and Wang X (2019) Comprehensive analysis of stability of coal seam composite roof based on analytic hierarchy process. *Adv Civil Eng*, 2019: Article ID 2042460. DOI:10.1155/2019/2042460
- Yan H, Weng MY, Feng RM, Li WK (2015) Layout and support design of a coal roadway in ultra-close multiple-seams. *J Cent South Univ*, 2015, 22(11): 4385-4395. DOI:10.1007/s11771-015-2987-7
- Yan ZP, Deng C, Li BY, Zhou JJ (2014) Novel particle swarm optimization and its application in calibrating the underwater transponder coordinates. *Math Probl Eng*, 2014: Article ID 672412. DOI:10.1155/2014/672412
- Yao QL, Xu Q, Liu JF, Zhu L, Li DW, Tang CJ (2021) Post-mining failure characteristics of rock surrounding coal seam roadway and evaluation of rock integrity: a case study. *B Eng Geol Environ*, 2021,81:1653-1669. DOI:10.1007/s10064-020-02018-z
- Zhang W, Zhang DS, Qi DH, Hu WM, He ZM, Zhang WS (2018) Floor failure depth of upper coal seam during close coal seams mining and its novel detection method. *Energ Explor & Exploit* 2018, 36(5): 1265–1278. DOI:10.1177/0144598717747622
- Zhao HB, Cheng H, Wang L, Liu YH, Ji DL, Zhang YX (2021) Distribution characteristics of deviatoric stress field and failure law of roadway surrounding rock under non-hydrostatic pressure. *Journal of China Coal Society*, 2021, 46(2): 370-381. (in Chinese). DOI:10.13225/j.cnki.jccs.2020.1877
- Zhuang H, Hu XQ, Guo L, Li MF, Wang CL, Du HK, Jin JQ (2020) Effect of initial deviatoric stress on anisotropy of marine clay during principal stress rotation. *Mar Georesour & Geotec* 2020. DOI:10.1080/1064119X.2020.1865489
- Zhou DW, Gao X, Liu GH, Mei CL, Jiang D, Liu Y (2011) Randomization in particle swarm optimization for global search ability. *Expert Syst Appl*, 2011,38(12): 15356-15364. DOI:10.1016/j.eswa.2011.06.029
- Zhang XL, Hoang Nguyen, Xuan-Nam Bui, Hong Anh Le, Trung Nguyen-Thoi, Hossein Moayedi, Vinyas Mahesh

(2020) Evaluating and Predicting the Stability of Roadways in Tunnelling and Underground Space Using Artificial Neural Network-Based Particle Swarm Optimization. *Tunn Undergr Sp Tech incorporating*, 2020,103:103517. DOI:10.1016/j.tust.2020.103517

Zhang QM, Wang EY, Feng XJ, Wang C, Qiu LM, Wang H
(2021) Assessment of rockburst risk in deep mining: an improved comprehensive index method. *Nat Resour Res*,30: 1817-1834. DOI:10.1007/s11053-020-09795-0