ABSTRACT: Owing to differences in deformation characteristics of roadways with different section shapes and depths, it is difficult to determine the support form and grouting depth of a roadway, which can cause serious deformation to the roadway. To address the challenges in determining the shape and grouting depth of a roadway section when the mine depth is known, the loose zone range of the roadway was tested using the acoustic method, and the loose zone evolution law under different conditions was performed by numerical simulations. The research results revealed that when the ratio of the maximum principal stress to the minimum principal stress is \( \eta > 3 \), the distribution of the rock loosening zone under different cross-sectional shapes was roughly “butterfly-shaped”, and the “smoother” the cross section in the design of the roadway, the smaller the range of the rock loosening zone. With the increase of burial depth, the rock loosening zone and sealing depth also increase; the rock loosening zone and burial depth have a power function relationship the rock loosening zone range = \( a \cdot \) burial depth\(^{b} \); the sealing depth and burial depth have a linear relationship \( R = aH + b \).

INTRODUCTION

China has the highest coal output worldwide and is heavily dependent on coal resources. It is estimated that coal will account for 50% of China’s primary energy consumption in 2050, which implies that the status of coal as the primary energy source in China will remain unchanged in the foreseeable future. However, because of increased coal mining, a few remaining coal resources are easy to be extracted. Therefore, coal mining in China needs to be extended to greater depths underground.

With a continuous increase in mining depth, the ground stress on the mining layer increases, leading to dynamic disasters, such as coal-gas outbursts and rock bursts in some mines. Stricter requirements are proposed for coal mining and roadway support technologies consequently. While the mining depth is greater, it is more difficult to provide roadway support, and the stability of the roadway is lower. Therefore, it is important to study the distribution of the roadway loose zone to guide roadway support.

After the excavation of an underground roadway, the surrounding rock stress is redistributed from a three-dimensional stress state to a two-dimensional stress state. As the stress changes, the rock mass around the roadway is gradually broken, forming a broken zone pointing toward the roadway; this zone is called the surrounding rock loosening zone. Owing to the high in situ and complex stresses in deep mining, the damage range of the surrounding rock loosening zone is particularly apparent in deep mines. Establishing reasonable roadway support parameters is an effective measure to ensure roadway stability and avoid large deformation of roadway and rock plastic flow. The evaluation of the distribution of the loose zone yields reference values for the selection of support parameters; therefore, such an evaluation is of great significance for solving the problem of deep mine roadway support.

Many scholars have conducted research on the distribution of plastic zones in surrounding rock. Zuo\(^1\) systematically studied macro/meso failure mechanism of deep rock or coal-rock combined body under different loading conditions and proposed a combined grouting control technology for surface and underground. Zhao\(^2\) analyzed the sudden change characteristics of the butterfly leaf in the butterfly-shaped plastic zone of roadway surrounding rock and proposed a theory for the mechanism of butterfly-shaped rock-burst in a coal seam. Li\(^3\) and Tang\(^4\) studied the stress and strain of a rock mass after the excavation of a roadway and used the elastoplastic mechanics equation to derive analytical solutions for the stress and displacement at different stages. Zhu\(^5\) and Mohammad\(^6\) used...
an improved elastoplastic model to analyze the supporting and dilatancy forces of a deep mine roadway and determined the principal reason for the deformation of the surrounding rock.

Malkowski studied the influence of the choice of numerical model on the size of the calculated fracture zone and proposed that the choice of geomechanical parameters and the choice of physical model are the key issues in numerical modeling. Based on the nonlinear Mohr–Coulomb criterion, Zhang derived analytical solutions for the stability and supporting force of a shallow double roadway; furthermore, they analyzed the influence of buried depth, load, pore water pressure, and nonlinear coefficients on the supporting force. Cao proposed a combination plan of an arched beam with a support, improved the calculation method for the surrounding rock pressure, and established a mechanical model of the floor beam. Malkowski studies the impact of different numerical analysis methods on rock numerical simulation, which helps to indicate the best statistical approach for model input data (a statistical). Xu applied the sonic method in a field test to accurately obtain the longitudinal wave velocity of a rock mass at different depths; they measured the range of the loose zone through the change in wave velocity. Wang combined the construction characteristics of the excavation and support of underground caverns and proposed a method to determine the loose zone using data collected by the high-density resistivity method. In addition, they studied the relationship between the degree of deformation and conductivity of the surrounding rock. Chen conducted geological radar tests on mine roadways and roadways and obtained the range of the loosening circle of the surrounding rock of a roadway with a large buried depth, which effectively controlled the roof collapse. Malkowski and Majcherczyk proposed that endoscopy research is one of the main ways to control the rock mass damage area and proposed a method to correctly evaluate the rock mass quality using the endoscopic rock mass factor. Kang used a numerical simulation software (UDEC) to study the changing law of support stress with changes in the support conditions and surrounding rock properties. Wang used a combination of theory, simulation, and field methods to study the formation and development of the plastic zone in the surrounding rock of deep-buried soft rock roadways. Guo used FLAC software, combined with field measurements, to study the distribution and shape of the plastic zone and failure zone under mining conditions, as well as the influence of excavation disturbance on roadway deformation; they determined reasonable roadway support parameters. Sun used numerical simulations to study the effect of the bolt and surrounding rock on the stress field when they are coupled in strength, stiffness, and structure. Huang used FLAC software to study the deformation characteristics of roadways for different cross-sectional shapes and found that the cross-sectional shape had a significant effect on the plastic zone in the surrounding rock of a roadway. Hu and Huang studied the influence of weak intercalation on the progressive failure mode of the rock surrounding roadways, using similar material in a simulation experiment; the results revealed that the weak intercalation increased the range of the failure zone, which caused an uneven stress distribution, thus affecting the stability of the rock surrounding the roadway. Liu performed a detailed numerical simulation of the stability and deformation of a roadway under different roof support schemes, using a deep mine as the experimental background. Based on the results, they proposed a new roadway support scheme that significantly improved the stability of the surrounding rock of the roadway. Malkowski has carried out long-term experiments on the roadway using different support schemes and monitoring methods, showing the importance of geotechnical monitoring in assessing the stability of an underground excavation. Based on the M-C criterion, Wang deduced the analytical solutions of stress and surrounding rock in the broken zone and plastic zone of the circular roadway. Zhao studied the distribution of the deviatoric stress field and strain energy density of the surrounding rock under triaxial stress, and the results showed that for the $\sigma_1$ dominant stress field, it is necessary to pay attention to the $\sigma_1$-shaped expansion of the surrounding rock plastic zone. Xue proposed the two lines of the yield and failure criteria to investigate the stress drop. Further, by the discontinuous solution of abutment pressure, the loading and unloading effect of stress is discussed considering coal damage.

Taking the geological conditions of the Yuxi coal mine in China as the engineering background, this study used an acoustic method to test the loose zone range of the central auxiliary transportation roadway. Additionally, numerical simulations were utilized to study the loose zone evolution law under different cross-sectional shapes and depths. The results of this research are important for guiding the selection of roadway shapes and roadway support.

**Figure 1. CT-2 surrounding rock fissure detector.**

The principle of the single-hole acoustic wave testing method is that the integrity of rock can be reflected by the different acoustic velocities in different media. The acoustic velocity propagation in dense rocks is fast, and the measured acoustic velocity has a larger value. In broken rock, because the cracks are filled with gas, the acoustic velocity spreads slowly, and the measured acoustic velocity is small. Using this principle, the acoustic wave velocity can be measured at different depths in a borehole, and the wave velocity curve can be drawn after the on-site test is completed. This curve can then be combined with on-site engineering geological data to determine the zone of rock loosening. The CT-2 surrounding rock fissure detector was selected for this test; it consists of three parts: the host, probe, and power supply. The probe and plugging device are composed of a transmitting transducer and receiving transducer.
which are connected through a slotted plastic sealed tube; further, the measuring tube is composed of copper.

The steps for detecting the zone of rock loosening using the single-hole acoustic wave testing method are as follows.

(1) Drilling construction and cleanup: In the field test site, drill a 5 m borehole perpendicular to the roadside. Once the hole was formed, water was used to remove the rock powder and gravel in the hole, until no rock slag remained in the hole.

(2) Instrument verification and equipment installation: A battery was installed in the instrument, and the display and circuit of the instrument were checked. The push-pull measuring rod and transceiver were connected. The receiving and transmitting probes were installed at the bottom of the drilling hole via the measuring rod. Additional accessories were inserted into an appropriate position in the hole, and a water stop plug was used to block the drilling hole. Subsequently, the coupling agent (water) was injected at the end of the measuring rod. There was a continuous water outflow.

(3) Data measurement and organization: The instrument was initiated to measure the wave velocity of the surrounding rock at different depths using a copper metal measuring rod; four groups of data were recorded at each depth. The data were recorded at depth increments of 0.1 m until the test was completed. The average of the four groups of data, measured at each depth, was calculated. Considering the wave velocity as the ordinate and the distance from the roadway side as the abscissa, the relationship between the wave velocity and distance from the roadway side was plotted.

**Overview of the Test Site.** Shanxi Lan Hua Ke Chuang Yuxi Coal Mine Co., Ltd. (hereinafter, referred to as "Yuxi coal mine") is under the jurisdiction of Hudi Township, Qinshui County. The thickness of the No. 3 coal seam is 5.12–7.20 m, with an average thickness of 5.85 m. The original gas content of the mine is 26.38 m³/t, the gas pressure is 1.65 MPa, and the buried depth is 505–862 m. The coal seam is prone to outbursts. The mine has a designed production capacity of 2.40 Mt/a and a service life of 50.7 y. The roof of the coal seam is composed of mudstone, sandy mudstone, siltstone, and fine-grained sandstone; the coal seam floor is composed of mudstone. The comprehensive stratigraphic column of the mine is presented in Figure 2. The underground is deployed according to three main lanes, i.e., the central auxiliary transport roadway, central belt conveyor roadway, and main return-air roadway. Along with across-seam borehole to eliminate the coal and gas outburst, three auxiliary lanes of the panel are constructed in the coal seam, i.e., two gas drainage roads and a return-air roadway. The three roadways are deployed along the coal seam.

The central auxiliary transportation roadway is deployed in the rock layer under the No. 3 coal seam floor. The roadway is buried at a depth of approximately 660 m, and its length is approximately 1507 m. It is a permanent mine roadway. The shape of the roadway is a straight wall semicircle, with a width of 5.4 m, a height of 4.3 m, and a cross-sectional area of 20.1 m². The surrounding rocks of the roadway are mainly sandy mudstone, siltstone, and shale. The cross-sectional view of the roadway is illustrated in Figure 3a. The central auxiliary
transportation roadway starts from the third connection roadway and heads northward at a slope of 3‰ to the sixth lane. The construction method of the EBZ230 type roadheader has been used for the cutting and self-loading of rocks, and the support is an anchor network cable spray support. In this study, based on the actual conditions of the roadway surrounding rock in the Yuxi coal mine, the single-hole acoustic wave testing method was used to determine the range of the loosening zone of the surrounding rock. The measurement locations selected were 80, 85, and 90 m south of the connection roadway of the fourth rock roadway in the central auxiliary transportation roadway of the Yuxi coal mine. Before the test, a 75 mm drill rod was selected, and the construction hole depth was set to 4 m; additionally, the inclination angle for downward drilling was set to 5°. The specific locations and drilling layouts are presented in Figure 3b.

Test Results. According to the field measurements, the range of the loosening zone of the central auxiliary transportation roadway in the Yuxi coal mine was obtained, as shown in Figure 4. This figure shows that, within 2.9 m from the side of the roadway, the acoustic wave velocity of the central auxiliary transportation roadway 1–1 borehole is 1145–1457 m/s, with an average of 1335 m/s. In the range of 2.9–3.4 m from the side of the roadway, the acoustic wave propagation velocity increases

Figure 3. Cross-sectional view of the roadway and the specific locations and drilling layouts.

Figure 4. Variation of wave speed with distance in central auxiliary transport roadway.
significantly, between 1685 and 1800 m/s, with an average of 1739 m/s, an increase of 30% indicating that the rock mass compaction in this range is relatively high. Beyond 3.4 m, the acoustic wave propagation velocity is 1410–1684 m/s, with an average of 1612 m/s, indicating that the surrounding rock in this section is in an elastoplastic zone. Therefore, it can be determined that the loose zone of the central auxiliary roadway for the borehole 1−1 test is 2.9 m. In the range of 2.7 m from the roadside, the acoustic wave velocity of borehole 1−2 in the central auxiliary transportation roadway is 1226–1581 m/s, with an average of 1404 m/s. Beyond 2.7 m, the acoustic wave propagation velocity increases significantly, remaining between 1395 and 2028 m/s, with an average of 1720 m/s—an increase of 22%—indicating that the surrounding rock in this section is in an elastoplastic zone. Therefore, it can be determined that the loose zone of the central auxiliary roadway for the borehole 1−2 test is 2.7 m. Similarly, similarly, the ranges of loosening zones of the central auxiliary roadway in the borehole test of 2−1, 2−2, 3−1, and 3−2 is evaluated to be 2.7, 2.7, 2.7, and 2.8 m, respectively. In summary, the range of the loosening zone of the surrounding rock in the central auxiliary transportation roadway of the Yuxi coal mine is 2.7–2.9 m.

Numerical Simulation of the Evolution of the Rock Loosening Zone. In the process of measuring the loose zone of the rock roadway on-site, its specific damage range could be obtained; however, the change law of the loose zone under different conditions could not be determined. In addition, the field test was characterized by a high cost, significant engineering effort, and a long construction period. Therefore, this study used numerical simulation to determine and analyze the change law of the loose zone of a rock roadway, for different shapes and depth conditions of the roadway. The research results provide technical guidance for the construction design of the Yuxi coal mine.

Establishment of Mathematical and Physical Models. Owing to the effects of geological conditions, the surrounding rock of the roadway has a heterogeneous structure comprising bedding and joints such that the roadway rock mass is a medium experiencing heterogeneous, discontinuous, and complex stress conditions. To simplify the problem, the following assumptions were made.

1. The rock surrounding the roadway is an ideal elastoplastic body, which meets the Mohr–Coulomb yield criterion.
2. Each rock stratum has a layered distribution, and the rock mass is a homogeneous isotropic body.
3. Because the dip angle of the rock stratum is small, it can be treated as a horizontal rock stratum.
4. The influence of groundwater seepage can be ignored.

The equilibrium equation of elasticity with solid deformation is as follows:

\[-L \sigma = F \]  

(1)

where \(L\) is the differential operator, \(\sigma\) is the stress, and \(F\) is the volume force.

The central auxiliary transportation roadway of the Yuxi coal mine was selected as the engineering background for the rock roadway. The Mohr–Coulomb criterion was selected as the rock failure criterion, and the in situ stress corresponding to the buried depth was loaded onto the upper part of the built model (the average rock density was 2500 kg/m³). A rolling boundary condition was adopted for the left and right sides of the model, and a fixed boundary condition was adopted for the lower part. The physical model is established, as shown in Figure 5.

![Figure 5. Physical model.](Image)

In accordance with the actual roof and floor lithology of the central auxiliary transportation main roadway in the Yuxi coal mine, the model rock roadway was located in sandy mudstone; the roof lithology comprised mudstone and fine sandstone, and the floor lithology comprised siltstone and fine sandstone. The specific mechanical parameters, which were selected based on the geological parameters and relevant reports of the Yuxi coal mine, are listed in Table 1.

### RESULTS AND DISCUSSION

#### Numerical Simulation Analysis of Rock Loosening Zone for Different Roadway Shapes. The main forms of roadway excavation are rectangles, trapezoids, and straight-walled semicircles. Owing to the different section shapes, the distribution of the loose zone of the rock roadway is also different. To compare the numerical analysis results with the on-site measurement of the loose zone in the central auxiliary transportation roadway, identical conditions (burial depth of 660 m and cross-sectional area of 20 m²) were simulated. The influence of the section shape on the distribution of the loose zone of the roadway was assessed by changing the shape of the section. Through simulation, the distribution maps of the loose zones of the rock roadways with straight-walled semicircular, rectangular, and trapezoidal cross-sectional areas after roadway excavation were obtained, as shown in Figure 6. Figure 6a shows that the range of the loose zone of the straight-walled semicircle is approximately 3 m. This result is consistent with the field test result of the loose zone of the central auxiliary transportation roadway (2.7–2.9 m), which verifies the reliability of the numerical simulation results. Figure 6 revealed that the distribution of the zone of rock loosening under different cross-sectional shapes was roughly “butterfly-shaped”. This is because, when the unevenness of the regional stress field distribution is high, the loose zone shows a “butterfly” distribution in shape. When the confining pressure ratio reaches 3.5, the butterfly-shaped plastic zone of the surrounding rock of the roadway only expands in scope, and the shape of the plastic zone no longer changes. 29 Mathematically, this is expressed as follows:

\[\eta = \frac{P_1}{P_3}\]  

(2)

where \(\eta\) is an indicator reflecting the unevenness of the regional stress field distribution; \(P_1\) is the maximum confining pressure of the regional principal stress field (MPa); and \(P_3\) is the minimum confining pressure of the regional principal stress field (MPa).
To further study the influence of different roadway shapes on the loose zone, the loose zone around the roadway was divided into the following three areas: the apex angle of the roadway, side of the roadway, and bottom angle of the roadway. Figure 6a shows the loose area of a straight-walled semicircular roadway, which is symmetrically distributed around the center of the roadway. At the bottom angle of the roadway, a notable loose zone of approximately 6.8 m exists. The range of the loose zone on the side of the roadway is approximately 3 m, while that at the apex angle of the roadway is approximately 6.3 m. Figure 6b shows the loose area of the rectangular roadway. There is a notable loose zone of approximately 6.8 m at the bottom angle of the roadway. The range of the loose zone on the side of the roadway is approximately 3.7 m, while that at the apex angle of the roadway is approximately 5.5 m. Figure 6c shows the loose area of the trapezoidal roadway, which is symmetrically distributed around the center of the roadway. A loose zone of approximately 6.9 m can be observed at the bottom angle of the roadway. The range of the loose zone at the side of the roadway gradually increases with an increase in height. The range of the loose zone at the bottom angle of the roadway is approximately 2.2 m, which increases to approximately 3.5 m at the apex angle of the roadway. The distribution range of the loose zone at the apex angle of the roadway is approximately 6.4 m. The specific data parameters are presented in Table 2.

To evaluate the influence of different roadway shapes on the loose zone of rock roadway from the perspective of mechanics, a simulation software was used to analyze the stress distribution for different cross-sectional shapes at a buried depth of 660 m and cross-sectional area of 20 m$^2$. Figure 7 shows the first principal stress distribution results for different cross-sectional shapes. Figure 8 presents the horizontal stress distribution data for sections 1 and 2.

Figure 7 shows the results of the first principal stress distribution in the vertical direction. The maximum principal stresses of the straight-walled semicircle, rectangle, and trapezoid in the vertical direction are 10.1, 10.4, and 12.4 MPa, respectively. Figure 8 shows the stress distribution in the horizontal direction. For the three cross-sectional area shapes, in the process of tunnel excavation, the primary stress balance of the rock mass is broken, so that the stress in the rock mass is

| Table 1. Rock Geological Parameters of Yuxi Coal Mine |
|-----------------------------------------------|
| rock                        | Young’s modulus (GPa) | Poisson ratio (GPa) | density (kg m$^{-3}$) | cohesion (MPa) | internal friction angle (deg) | thickness (m) |
| sandy mudstone              | 6.2                  | 0.17               | 2676                  | 7.80           | 36                              | 4.35           |
| fine sandstone              | 7.3                  | 0.17               | 2787                  | 3.5            | 37                              | 2.5            |
| mudstone                    | 5.6                  | 0.18               | 2700                  | 2.60           | 38                              | 3.0            |
| coal                        | 1.06                 | 0.30               | 1460                  | 2.35           | 22                              | 6.11           |
| siltstone                   | 5.65                 | 0.22               | 2672                  | 4.0            | 32                              | 2.7            |

| Table 2. Range of the Zone of Rock Loosening under Different Roadway Shapes |
|-------------------------------|
| roadway shape | the bottom angle of the roadway (m) | the side of the roadway (m) | the apex angle of the roadway (m) |
| straight-walled semicircular | 6.8 | 3.0 | 6.3 |
| rectangular       | 6.8 | 3.7 | 5.5 |
| trapezoidal       | 6.9 | 2.2–3.5 | 6.4 |

To further study the influence of different roadway shapes on the loose zone, the loose zone around the roadway was divided into the following three areas: the apex angle of the roadway, side of the roadway, and bottom angle of the roadway. Figure 6a shows the loose area of a straight-walled semicircular roadway, which is symmetrically distributed around the center of the roadway. At the bottom angle of the roadway, a notable loose zone of approximately 6.8 m exists. The range of the loose zone on the side of the roadway is approximately 3 m, while that at the apex angle of the roadway is approximately 6.3 m. Figure 6b shows the loose area of the rectangular roadway. There is a notable loose zone of approximately 6.8 m at the bottom angle of the roadway. The range of the loose zone on the side of the roadway is approximately 3.7 m, while that at the apex angle of the roadway is approximately 5.5 m, and that on the left side of the roadway is approximately 5.0 m. Figure 6c shows the loose area of the trapezoidal roadway, which is symmetrically distributed around the center of the roadway. A loose zone of approximately 6.9 m can be observed at the bottom angle of the roadway. The range of the loose zone at the side of the roadway gradually increases with an increase in height. The range of the loose zone at the bottom angle of the roadway is approximately 2.2 m, which increases to approximately 3.5 m at the apex angle of the roadway. The distribution range of the loose zone at the apex angle of the roadway is approximately 6.4 m. The specific data parameters are presented in Table 2.

To evaluate the influence of different roadway shapes on the loose zone of rock roadway from the perspective of mechanics, a simulation software was used to analyze the stress distribution for different cross-sectional shapes at a buried depth of 660 m and cross-sectional area of 20 m$^2$. Figure 7 shows the first principal stress distribution results for different cross-sectional shapes. Figure 8 presents the horizontal stress distribution data for sections 1 and 2.

Figure 7 shows the results of the first principal stress distribution in the vertical direction. The maximum principal stresses of the straight-walled semicircle, rectangle, and trapezoid in the vertical direction are 10.1, 10.4, and 12.4 MPa, respectively. Figure 8 shows the stress distribution in the horizontal direction. For the three cross-sectional area shapes, in the process of tunnel excavation, the primary stress balance of the rock mass is broken, so that the stress in the rock mass is
redistributed, as the distance from the center of the roadway increases, the horizontal stress first increases, and then, decreases; finally, it stabilizes at a constant value. There are three zones of surrounding rock in the horizontal direction, i.e., the pressure relief zone (stress relaxation zone), the stress concentration zone, and the original stress zone (the primary stress zone), as shown in Figure 9. The rock loosening zone is primarily concentrated in the pressure relief and stress concentration zones.
Therefore, the stress distributions of the pressure relief and stress concentration zones are studied thoroughly. For the straight-walled semicircle, the horizontal stress distribution is 0–3.99 MPa within the range of 0–1.0 m from the roadway, with an average stress of 1.38 MPa. The horizontal stress gradually increases in the range of 0–1.0 m but is lower than the primary surrounding rock stress. Based on these results, it can be determined that the arched roadway is a pressure relief zone in the range of 0–1.0 m. Within the range of 1.0–19 m from the roadway, the horizontal stress distribution is 3.99–8.87 MPa, with an average stress of 6.51 MPa. In the range of 1.0–19 m, the stress first increases, and then, decreases; it is also higher than the primary surrounding rock stress. Therefore, the range of 1.3–19 m in the straight-walled semicircular roadway is a concentrated stress zone. Similarly, the rectangular roadway is a pressure relief zone in the range of 0–1.0 m; the horizontal stress distribution in this zone is 0–3.85 MPa, with an average stress of 1.61 MPa. The range of 1.1–21 m is a concentrated stress zone, with a horizontal stress distribution between 3.85 and 7.71 MPa and an average stress of 5.51 MPa. The trapezoidal roadway is a pressure relief zone within the range of 0–1.6 m; its horizontal stress distribution is between 0 and 3.95 MPa, with an average

| depth (m) | 260 | 460 | 660 | 860 |
|-----------|-----|-----|-----|-----|
| the bottom angle of the roadway (m) | 0.6 | 1.6 | 6.8 | 11 |
| the side of the roadway (m) | 1.2 | 3.0 | 16 |
| the apex angle of the roadway (m) | 6.3 | 8.6 |
| cumulative sum of rock loose zone (m) | 0.6 | 2.8 | 13.4 | 35.6 |

Figure 9. Stress distribution in rock mass.

Figure 10. Distribution shapes of the loose zone at different burial depths.

Figure 11. Variation in the range of the rock.
Figure 12. First principal stress under different buried depth conditions.

Figure 13. Stress distribution in the horizontal direction at different burial depths.
distribution, it is difficult to determine the minimum principal stress of the stress field. According to eq 2, the average stress of the pressure relief zone is selected as the stress of the stress field in the surrounding rock region; therefore, the stress concentration zone of the roadway is larger than that of the rectangular and straight-walled semicircular roadways, and the stress concentration zone of the trapezoidal roadway is smaller than that of the rectangular and straight-walled semicircular roadways. Because of the three-zone distribution, it is difficult to determine the minimum principal stress of the stress field in the surrounding rock region; therefore, the average stress of the pressure relief zone is selected as the minimum principal stress of the stress field. According to eq 2, the \( \eta \) values of the arched, rectangular, and trapezoidal roadways can be calculated as 7.32, 6.46, and 7.66, respectively. Because the values of \( \eta \) are all greater than 3, the shape of the loose zone shows a butterfly distribution for all three cases. When the confining pressure ratio reaches 3.5, the butterfly-shaped plastic zone of the surrounding rock of the roadway only expands in scope, and the shape of the plastic zone no longer changes. Because the rock strength at 10 m below the roadway floor in the Yuxi coal mine is greater than that of other rock formations, the range of the loose zone at the bottom angle of the straight-walled semicircular roadway is larger than that on the side of the roadway and the apex angle of the roadway. The rectangular roadway (trapezoid roadway) has a larger range of the loose zone at the bottom angle and at the apex angle than on the side of the roadway. This shows that a sharp angle easily forms a stress concentration zone, which increases the range of the loose zone; this conclusion is verified by the stress distribution diagram (Figure 7). Based on the site construction experience, although the range of the loose zone of the apex angle of the rectangular roadway is small, the roof and floor of the rectangular roadway are damaged more seriously, and roof sinks and floor heave are prone to occur. Therefore, when the cross section in the roadway design is "smoother", the range of the rock loosening zone is smaller, leading to better stability than that of roadways with sharp angles.

### Numerical Simulation Analysis of Rock Loosening Zone for Different Buried Depths

The initial ground stress, before excavating the rock mass around the roadway, is caused by the buried depth of the roadway; this stress determines the stability of the roadway after excavation. Based on the site conditions, a 20 m² straight-walled semicircular roadway with buried depths of 260, 460, 660, and 860 m was selected to study the influence of different buried depths on the distribution of the loose zone of the roadway. Figure 10 shows the distribution of the loose zone for different buried depths.

Figure 10a shows the distribution of the loose zone with a buried depth of 260 m, wherein the loose zone is symmetrically distributed around the center of the roadway. At the bottom angle of the roadway, the range of the loose zone is small (0.5–0.6 m), and there is no apparent loose zone distribution on the side of the roadway or at the apex angle of the roadway. This is because the sharp angle at the bottom of the straight-walled semicircular roadway causes stress concentration such that the

| depth (m) | average stress (MPa) | range (m) | average stress (MPa) | range (m) | average stress (MPa) | range (m) |
|-----------|---------------------|-----------|---------------------|-----------|---------------------|-----------|
| 260       | 0.77                | 0–0.8     | 2.13                | 0.8–1.4   | 1.47                | >14       |
| 460       | 0.84                | 0–0.9     | 4.18                | 0.9–1.6   | 2.54                | >16       |
| 660       | 1.38                | 0–1.0     | 6.51                | 1.0–1.9   | 3.99                | >19       |
| 860       | 2.05                | 0–1.2     | 9.27                | 1.2–2.1   | 6.29                | >21       |

**Table 4. Stress Data Parameters and the Three-Zone Distribution**

![Figure 14](https://doi.org/10.1021/acsomega.2c03811)

**Figure 14. Variation rule of hole sealing depth with burial depth.**

By combining the results of the actual on-site construction application and those of the numerical simulation, a comprehensive analysis of roadways of the three shapes was performed. As shown in Figure 6 and Table 2, the range of the loose zone at the bottom angle of the straight-walled semicircular roadway is larger than that on the side of the roadway and the apex angle of the roadway. The rectangular roadway (trapezoid roadway) has a larger range of the loose zone at the bottom angle and at the apex angle than on the side of the roadway. This shows that a sharp angle easily forms a stress concentration zone, which increases the range of the loose zone; this conclusion is verified by the stress distribution diagram (Figure 7). Based on the site construction experience, although the range of the loose zone of the apex angle of the rectangular roadway is small, the roof and floor of the rectangular roadway are damaged more seriously, and roof sinks and floor heave are prone to occur. Therefore, when the cross section in the roadway design is "smoother", the range of the rock loosening zone is smaller, leading to better stability than that of roadways with sharp angles.

**Numerical Simulation Analysis of Rock Loosening Zone for Different Buried Depths.** The initial ground stress, before excavating the rock mass around the roadway, is caused by the buried depth of the roadway; this stress determines the stability of the roadway after excavation. Based on the site conditions, a 20 m² straight-walled semicircular roadway with buried depths of 260, 460, 660, and 860 m was selected to study the influence of different buried depths on the distribution of the loose zone of the roadway. Figure 10 shows the distribution of the loose zone for different buried depths.

Figure 10a shows the distribution of the loose zone with a buried depth of 260 m, wherein the loose zone is symmetrically distributed around the center of the roadway. At the bottom angle of the roadway, the range of the loose zone is small (0.5–0.6 m), and there is no apparent loose zone distribution on the side of the roadway or at the apex angle of the roadway. This is because the sharp angle at the bottom of the straight-walled semicircular roadway causes stress concentration such that the

**Figure 14. Variation rule of hole sealing depth with burial depth.**

![Figure 14](https://doi.org/10.1021/acsomega.2c03811)

**Table 4. Stress Data Parameters and the Three-Zone Distribution**

| depth (m) | average stress (MPa) | range (m) | average stress (MPa) | range (m) | average stress (MPa) | range (m) |
|-----------|---------------------|-----------|---------------------|-----------|---------------------|-----------|
| 260       | 0.77                | 0–0.8     | 2.13                | 0.8–1.4   | 1.47                | >14       |
| 460       | 0.84                | 0–0.9     | 4.18                | 0.9–1.6   | 2.54                | >16       |
| 660       | 1.38                | 0–1.0     | 6.51                | 1.0–1.9   | 3.99                | >19       |
| 860       | 2.05                | 0–1.2     | 9.27                | 1.2–2.1   | 6.29                | >21       |
loose zone preferentially appears at the bottom angle of the roadway.

Figure 10b shows the distribution of the loose zone with a buried depth of 460 m, wherein the loose zone is symmetrically distributed around the center of the roadway. Compared to the roadway with a buried depth of 260 m, the range of the roadway loose zone is noticeably larger. There is an evident loose zone of approximately 1.6 m at the bottom angle of the roadway; the range of the loose zone on the side of the roadway is 1.0−1.2 m, and the distribution of the loose zone is relatively small at the apex angle. This is because as the buried depth increases, the ground stress on the roadway increases, causing the loose zone to continue to extend at the bottom angle of the roadway. Meanwhile, the ground stress reaches the breaking strength of the rock layer, where the roadway is located; therefore, the loose zone starts to develop gradually on the side of the roadway.

Figure 10c shows the distribution of the loose zone with a buried depth of 660 m. The loose zone is butterfly-shaped and symmetrically distributed around the center of the roadway. Compared to the roadway with a buried depth of 460 m, the range of the loose zone is larger at the side, bottom angle, and apex angle of the roadway. At the bottom angle of the roadway, a notable loose zone of approximately 6.8 m is observed, which implies 2.5 times increase. The range of the loose zone on the side of the roadway is approximately 3 m, which is 1.5 times increase. The loose zone is distributed approximately 6.3 m at the apex angle of the roadway. Owing to the increase in ground stress, the loose zone continues to develop around the roadway. When η is greater than 3, the loose zone develops more noticeably at the apex angle of the roadway; it also exhibits a butterfly-shaped distribution and continues to extend at the bottom angle and side of the roadway.

Figure 10d shows the distribution of the loose zone with a buried depth of 860 m, wherein the loose zone is symmetrically distributed around the center of the roadway. Compared to the roadway with a buried depth of 660 m, the range of the loose zone is larger at the side, bottom angle, and apex angle of the roadway. At the bottom angle of the roadway, an evident loose zone of approximately 11 m is observed, which implies a 6 times increase. The range of the loose zone on the side of the roadway is approximately 15−16 m, which is a 4 times increase. The range of the loose zone at the bottom angle of the roadway is approximately 16−18 m, which is a 5 times increase. The distribution of loose circles at the apex angle of the roadway is approximately 8.6 m, which is a 0.4 times increase. This is because, as the buried depth increases, the roadway is subjected to extremely high ground stress, and the strength of the rock layer is smaller than the ground stress where the roadway is located; this leads to significant development of the loose zone on the side of the roadway. The range of data parameters of the loose zone at different depths is presented in Table 3.

According to the abovementioned analysis, as the buried depth increases, the range of the loose zone gradually increases, and the increased speed at the side of the roadway is greater than that at the apex angle and bottom angle of the roadway. To further study the relationship between the range of the loose zone and buried depth, the maximum influence range of the loose zone in the three areas (the bottom angle of the roadway, side of the roadway, and apex angle of the roadway) is considered to accumulate. Figure 11 shows the variation in the range of the rock loosening zone with depth.

Loosening Zone with Depth. Figure 11 shows that the relationship between the rock loose zone and buried depth satisfies the power function relationship of the rock loosening zone range = 2.82 × 10−10 H1.78 (R2 = 0.99915). Therefore, with an increase in buried depth, the range of the roadway loose zone gradually increases, and the speed of this increase accelerates.

To evaluate the influence of different roadway depths on the loose zone of rock roadway from the perspective of mechanics, a simulation software was used to analyze the stress distribution for different roadway depths at straight-walled semicircular roadway and a cross-sectional area of 20 m². Figure 12 shows the first principal stress distribution results for different roadway depths. Figure 13 presents the horizontal stress distribution data for sections 1 and 2. Figure 12 shows the maximum principal stresses of the buried depth 260, 460, 660, and 860 m in the vertical direction are 2.78, 6.88, 10.1, and 13.02 MPa, respectively. Figure 13 shows the stress distribution in the horizontal direction. For the buried depth of 260 m, the horizontal stress distribution is 0−1.47 MPa within the range of 0−0.8 m from the roadway, with an average stress of 0.77 MPa. The horizontal stress gradually increases in the range of 0−0.8 m but is lower than the primary surrounding rock stress. Based on these results, it can be determined that the arched roadway is a pressure relief zone in the range of 0−0.8 m from the roadway. Within the range of 0.8−14 m from the roadway, the horizontal stress distribution is 1.47−2.78 MPa, with an average stress of 2.13 MPa. In the range of 1.0−19 m, the stress first increases, and then, decreases; it is also higher than the primary surrounding rock stress. Therefore, the range of 0.8−14 m in the straight-walled semicircular roadway is a concentrated stress zone. In the same way, we can get the stress data of the other three depths and the three-zone distribution. Table 4 shows the stress data parameters and the three-zone distribution.

The average stress of the pressure relief zone is selected as the minimum principal stress of the stress field. From Figure 12 and Table 4, it can be seen that both the maximum stress and the minimum stress show an increasing trend with increasing depth, and the stress difference gradually increases. It can be seen that with the increase of the excavation depth, the stability of the roadway will not only face the hazard of high stress but will also be affected by the difference of high stress distribution. A higher stress difference will reduce the stability of the roadway and accelerate the deformation of the roadway. This verifies the evolution of the loose zone with depth from the mechanical mechanism.

According to previous studies, when sealing holes, the pressure relief zone and stress concentration zone of the roadway should be avoided, and the junction of the elastic zone and the primary stress zone should be selected. Therefore, the variation law of the sealing depth with the buried depth is shown in Figure 13.

Analysis of Figure 14 shows that the sealing depth and burial depth satisfy the linear relationship of R = 0.0129H + 10.78 (R² = 0.989), so the sealing depth gradually increases with the increase of burial depth.

CONCLUSIONS

In this study, we conducted acoustic field tests to investigate the influence of the section shape and buried depth on the rock loosening zone. In addition, rock roadways with different cross-sectional shapes and depths were evaluated using numerical simulation. The simulation results were consistent with the field test results, and the relationship between the loose zone of the roadway and the cross-sectional shape and depth was analyzed. Our conclusions are as follows.
When the ratio of the maximum principal stress to the minimum principal stress is $\eta > 3$, the distribution of the loose circle is roughly butterfly-shaped, and when the cross section in the design of the roadway is smoother, the range of the zone of rock loosening is smaller. Compared to roadways with sharp angles, smoother roadways exhibited better stability.

(2) With the increase of burial depth, the rock loosening zone and sealing depth also increase; the rock loosening zone and burial depth have a power function relationship the rock loosening zone range $= a$-burial depth$^b$; the sealing depth and burial depth have a linear relationship $R = aH + b$.

(3) Based on the actual situation of the Yuxi coal mine (the buried depth is 660 m), the range of the loose zone of the central auxiliary transportation roadway was found to be 2.7–2.9 m, through field testing and numerical simulation.

Because of the particularity of the roof and floor lithology in the Yuxi coal mine, the strength of the rock 10 m below the roadway floor was larger than that of other rock layers, resulting in the roadway loosening zone confined to the bottom corner of the roadway. Further analysis and discussion should be conducted for different top and bottom slate conditions.

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Notes

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