INTRODUCTION

Soft rock support is very important for the safety production of underground mine. The instability of surrounding rock of soft rock roadway occurs frequently, which seriously affects the forming efficiency and supporting effect of roadway, and greatly restricts the mining work of mine. The common support forms of soft rock roadway include anchor injection steel frame support, full closed steel frame support, and multi-layer anchor spray mesh.
injection steel frame combined support. The main bearing of surrounding rock stress in these support modes is steel frame, and the deformation and failure of steel frame structure are the main characteristics of soft rock support instability. The failure modes of steel frame support body include reversal of steel frame, fracture of steel frame connection, deformation of leg, and waist or top key parts of the support. The deformation of steel frame leads to the reduction of support capacity and then the failure to steel frame fracture. Therefore, it is very important to study the bearing characteristics of the steel frame, the failure mode of the structure, and the weak points for the design of the support parameters. Selecting the steel frame with high cost performance is a key role to the support of the soft rock roadway.

Many scholars at home and abroad have done a lot of research on the bearing capacity of soft rock support steel structure. Timoshenko and Gere gave a systematic description of the buckling of various forms of shallow arches under different constraints. Komatsu and Shinke studied the elastic-plastic ultimate bearing capacity of two hinged parabolic arch under transverse uniform load. Schreyer et al used the energy method to obtain the critical load of the fixed circular arc shallow arch under the uniform radial load. Liu used ANSYS software to analyze the deviation longitudinal load and buckling failure of U-shaped steel support and evaluated the bearing capacity of the support. Sun et al used the two hinge arch model to calculate the internal force and bearing capacity of the arch support under the condition of empty roof and eccentric load and analyzed the bearing characteristics and influencing factors of the arch support. Wang et al considered the influence of axial force on bending deformation, obtained the analytical solution of dangerous section position of U-shaped steel support through theoretical analysis. Many scholars have made a lot of achievements in bearing capacity and stability of steel structure support. It mainly analyzes and studies the stress and yield state of steel support under different loads, but the optimal stress shape of steel structure support was rarely studied.

Based on the status quo of soft rock roadway support in Mengnuo lead-zinc mine, though three-dimensional stress calculation and analysis of surrounding rock and steel frame of roadway, the change law of displacement and stress of surrounding rock are studied when the roadway support is U-shaped steel, I-shaped steel, or track steel, respectively. In this paper, the bearing capacity characteristics of supporting steel structure in soft rock roadway are analyzed, and the key parts of support deformation are predicted, which provide experience for similar supporting engineering in soft rock roadway.
has no self-stable ability after the excavation of the tunnel, and large deformation occurs in a short time, which is manifested by the roof subsidence, the side rock strata fracturing and bulging, the floor heave obviously. The flow deformation occurred in surrounding rock, which not only has a large amount of deformation but also has a significant time effect.

3 | STUDY ON THE BEARING CAPACITY CHARACTERISTICS OF STEEL STRUCTURE SUPPORT

3.1 | Deformation and failure characteristics of steel frame

In Mengnuo lead-zinc mine area, with the increase of mining depth, the large deformation of the roadway leads to the obvious destruction of the support structure, increasing the difficulty of support, and the number of repairs. The main characteristics are as follows:

1. The surrounding rock of the roadway has large deformation and fast deformation speed

The surrounding rock of the roadway is phyllite. According to the mineral composition identification, it is found that it contains 22.4% Kaolin and has a strong expansibility in case of water, which is the main influencing factor of surrounding rock deformation. In the middle section of 500 m and below, the stability of the free face of the tunnel excavation is obviously poor, so it is necessary to increase the advance support bolt to ensure the construction safety of the blasthole. The deformation of the blasthole is serious. After the blasthole construction, the deformation occurs 120 minutes later. The blasthole becomes oblate, and the deformation speed is greater than that of the shallow surrounding rock.

2. The creep characteristic of surrounding rock is obvious, and the horizontal deformation of roadway support structure is serious

In the 500 m middle section, the roadway support adopts the same support parameters as the upper middle section, and the deformation duration of its steel frame support increases significantly, which is mainly reflected in the increase of repair times. Large deformation of the steel frame occurs every six months on average, affecting the safety of pedestrians and transportation, requiring repair. Under the action of horizontal stress, the surrounding rock bulged out from two sides of leg support, and the rail steel support is damaged, which occurs at the connection of two sections of steel frame, as shown in Figures 3 and 4.

3. Serious floor heave

In Mengnuo lead-zinc mine area, the rail transportation is adopted. There is no supporting measure for

FIGURE 2  Typical geological profile of Mengnuo Pb, and Zn mine

FIGURE 3  500 level steel support failure
3.2 Research scheme of numerical simulation

It can be seen from the structural deformation of a large number of supporting steel on site that it is very important for the tunnel supporting steel structure to bear the surrounding rock stress and maintain the supporting stable. The supporting results of steel frame with different types and supporting parameters are quite different. A large number of existing supporting steel frames in the tunnel use rail steel supports. Therefore, in order to fully understand the deformation law and bearing capacity change characteristics of U-shaped steel, I-shaped steel, and rail steel, three-dimensional stress analysis of three different forms of steel frame is carried out by numerical simulation method.

This numerical simulation is to simulate Mengnuo lead-zinc mine 500 middle level roadway support environment. FLAC3D finite difference numerical simulation software is used for model construction, and Mohr Coulomb constitutive model is used for calculation. The roadway support simulation scheme is as follows:

1. After the tunnel is excavated, the shotcrete is first used to close the tunnel, and then the metal mesh is hung. The diameter of the metal mesh is 6 mm, and the mesh is 20 cm × 20 cm;
2. Construct grouted rock bolt, the length of the bolt is 2 m, the diameter is 22 mm, and the arrangement spacing is 1 m;
3. Finally, steel frame support is carried out, 3 steel frames are arranged every 2 m, the length of model tunnel is 10 m, 15 steel frames are arranged in total, and the floor heave of the support is welded with 15 cm × 15 cm steel plate with thickness of 5 mm. During the installation of steel frame, splint and bolt connection are adopted; see Figure 4A for the schematic diagram of I-beam connection, see Figure 4B for the schematic diagram of U-shaped steel bracket, and see the above connection as rigid connection in this simulation calculation, all of which are considered as continuous components.

3.3 Establishment of numerical model

The roadway section is three-centered arch in the 500 m middle section of Mengnuo lead-zinc mine, with a roadway width of 2.1 m, a straight wall height of 1.7 m and a roadway height of 2.6 m. The calculation model size is 60 m × 60 m × 10 m, in which the roadway length direction is 10 m and the model is about 560 000 units. The original rock stress of Mengnuo lead-zinc mine is tested, and the three main stress distribution laws are as follows: \( \sigma_1 \) (East West horizontal principal stress) > \( \sigma_2 \) (vertical stress) > \( \sigma_3 \) (north-south horizontal stress), the maximum principal stress is 15.70-18.15 MPa, belonging to the range of medium to high ground pressure. The measured principal stress direction: the maximum principal stress direction is near east-west direction, and the minimum
principal stress is near north-south direction. The roadway direction is arranged along the north-south direction of the ore body, which is almost perpendicular to the direction of the maximum principal stress, which is unfavorable to the stability of the roadway. The initial stress field in the numerical model is based on the stress test results of the original rock, the vertical pressure is 13.8 MPa according to gravity, and the lateral pressure coefficient is 1.2, The lateral pressure is 16.6 MPa. The plane of roadway model x-z is as shown in Figure 5, and the I-steel support, rail steel support, and U-steel support model are shown in Figure 6.15

3.4 | Numerical simulation calculation parameters

The surrounding rock of roadway is mainly carbonaceous phyllite. Its compressive strength, tensile strength, and cohesion are relatively low. It is easy to quickly weathered and expand when encountering water, and the strength index will be greatly reduced, which further aggravates the deformation and instability of surrounding rock. The physical and mechanical indexes of phyllite are tested, and the mechanical parameters of rock mass are shown in Table 1, which are the mechanical parameters of surrounding rock mass in the numerical simulation calculation.

As the research focus is on the bearing capacity of the steel frame support, the mechanical calculation parameters of the steel frame are very important. The steel frame used in the actual support is the common No. 11 mining I-steel, 22 kg rail steel, and No. 25 U-shaped steel support. Main parameters of steel structure support are shown in Table 2.

3.5 | Analysis of simulation deformation law of roadway support

Through simulating the support of I-steel, rail steel, and U-steel support, it can be seen from Figure 7 that the simulated maximum deformation of the three kinds of steel frame support is within 12 cm. Compared with just shotcrete and anchor support without steel frame which showed in Figure 7D, the whole displacement is well controlled; in the case of no steel support, the maximum displacement of surrounding rock occurs at the waist of both sides of the roadway, the next is the top, and the displacement of the top is about 2-4 times of that of the surrounding rock supported by steel frame. The maximum horizontal deformation of the roadway occurs after the support of steel frame. The support effect of the surrounding rock at the top of the roadway is obvious, which shows that

![Bracket model diagram](image)

**FIGURE 6** Bracket model diagram

**TABLE 1** Main parameters of surrounding rock

| Name     | Density (g/cm^3) | Tensile strength (MPa) | Bulk modulus (GPa) | Shear modulus (GPa) | Cohesion (MPa) | Angle of internal friction (°) | Poisson’s ratio (µ) |
|----------|------------------|------------------------|-------------------|---------------------|----------------|-------------------------------|-------------------|
| Phyllite | 2.7              | 0.24                   | 1.54              | 0.71                | 0.5            | 23.48                         | 0.3               |

**TABLE 2** Main parameters of the support

| Type                  | Bulk density $G$ (kg/m) | Elastic modulus $E$ (GPa) | Poisson’s ratio (µ) | Yield strength (MPa) | Section area $A$ (cm^2) | Moment of inertia $I_x$ (cm^4) | Moment of inertia $I_y$ (cm^4) |
|-----------------------|-------------------------|---------------------------|---------------------|----------------------|------------------------|-------------------------------|-------------------------------|
| No. 11 mining I-steel | 26.10                   | 200                       | 0.3                 | 355                  | 33.2                   | 623.7                         | 137.7                         |
| 22 kg rail steel      | 22.30                   | 200                       | 0.3                 | 235                  | 28.39                  | 339                           | 82.9                          |
| No. 25 U-shaped steel | 24.74                   | 200                       | 0.3                 | 355                  | 31.52                  | 455.1                         | 506                           |
the control of the displacement of the top is good. The statistics of the total displacement of the three kinds of steel frame support show that the total displacement of U-shaped steel is 85.0% of that of track steel, and that of I-shaped steel is 92% of that of track steel. The track steel has the weakest anti-deformation ability and is easy to deform. Therefore, the control effect of three kinds of steel support on the deformation of surrounding rock of roadway is in order: U-shaped steel deformation < I-shaped steel deformation < rail steel deformation. Therefore, the deformation resistance of U-shaped steel is the best. From Figure 8, it can be seen that the maximum deformation of surrounding rock without steel support occurs at the waist of both sides of the roadway, with a maximum displacement of 0.15 m. The maximum displacement of U-shaped steel support occurs at the bottom of the roadway, with a maximum displacement of 0.114 m. The displacement of rock floor heave with U-shaped steel support decreases by about 24%. Therefore, steel support can improve the floor heave phenomenon in roadway deformation.17-19

According to the statistics of the maximum deformation of the feet on both sides of the 15 steel frames, the results are shown in Figure 9. During the simulation of 15 steel frame supports in the 10 m tunnel, the displacement of the steel frame increases from 1 to 4, the displacement of the steel frame of 5-9 remains stable, and the displacement of the steel frame of 11-14 decreases; that is, the overall deformation of the steel frame of 4-6 m in the middle is greater than that of the surrounding rock of the head and tail tunnels. According to the statistics of the maximum deformation at the top of 15 steel frames, the results are shown in Figure 10. It can be seen that the top displacement of the first 4 steel frames increases gradually, the middle 6 steel frames remain unchanged, and the last 4 steel frames decrease gradually. Moreover, the top displacement of the U-shaped steel frame at the same displacement is significantly smaller, the deformation is 10% less than that of the rail steel, and the deformation of the I-shaped steel is 4% less than that of the rail steel. Therefore, from the three-dimensional stress analysis of the roadway, in the 10 meter’s roadway support, the overall displacement of the support steel frame in the middle 4-6 m section is the largest, and the displacement of the top of the U-shaped steel frame is significantly lower than that of other steel frame parts. Therefore, the overall displacement of the support steel frame in the middle section of the soft rock roadway is larger than that of the two ends, and U-shaped steel support has the most obvious effect on deformation control of surrounding rock at the top of roadway. When supporting the roadway, the stress of the key sections and parts of the roadway should be considered.

3.6 Deformation law and stress distribution characteristics of steel frame

According to the displacement vector of steel frame support in Figure 11, the deformation of the contact part
between the foot of steel frame support and roadway is the largest. The main reason is that the two legs at the bottom of the steel frame are not closed, and the steel frame forms a closed support structure in the two-dimensional supporting plane. In the process of the floor heave of the surrounding rock of the roadway, the two legs of the steel frame deform toward the middle of the roadway, of which the deformation of the U-shaped steel support is relatively small, followed by the I-shaped displacement, which is the largest compared with the foot displacement of the rail steel frame. According to the stress distribution of the steel frame in Figure 12, the main force positions of
the three kinds of steel frame structures are the shoulder joint, waist, and foot. The compressive stress is concentrated in the inner side of the steel frame shoulder, and the compressive stress is the largest. This is also the connection position of the two steel frames. The connection position of the steel frame is the key force position of the support body, so the strength of the connection should be improved. The middle of the two legs and the foot position of the three kinds of support steel frames are under tensile stress, and around the steel plate at the foot position is under tensile stress, and its deformation is the largest.

4 | ENGINEERING APPLICATION

Through the comparative analysis of the bearing characteristics of different steel structures, it is found that it is very important to control the deformation of roadway surrounding rock in the process of soft rock support. For roadway surrounding rock with large deformation and obvious creep effect, steel structure support is the main way to bear and control soft rock deformation, and U-steel is a relatively good bearing structure of roadway support. Due to the widespread of soft rock, it is easy to expand in case of water, which leads to weathering due to long-term exposure to the air, resulting in creep effect under superposition. Therefore, in the actual of soft rock support, multi-mode combined support is required to control the surrounding rock deformation. This research project is applied to the main transportation roadway in the middle 500 m of Mengnuo lead-zinc mine to repair the roadway in the deformed area. The roadway deformation before support is mainly reflected in the floor heave, which seriously affects the track transportation. The deformation of the roadway side wall near the floor is relatively serious, and the deformation of the roadway roof is small. Therefore, the combined support method of “shotcrete + hanging mesh + anchor bolt + U-shaped steel support” is adopted.

Through the comparative analysis of numerical simulation method, the best support scheme is determined for on-site construction, and then according to the long-term tracking analysis of the support effect of the scheme, the
support mode that can be popularized in the area with the same rock mass quality of Mengnuo lead-zinc mine is finally determined. Therefore, sensitivity analysis is carried out to control the deformation of roadway surrounding rock. Under the same U-shaped steel support spacing of 0.6 m, the effect of support on controlling the deformation of surrounding rock is analyzed by changing different spray layer thickness and row spacing between bolts, and the sensitivity of parameters is determined. Figures 13 and 14 show the specific parameters and simulation results.

Through the simulation results, it is found that the row spacing between bolts is more sensitive to the deformation of surrounding rock, and the effect of changing the row spacing to control the deformation of surrounding rock is better. However, when the row spacing reaches 1 m × 1 m, the displacement of surrounding rock increases rapidly.

The thickness of shotcrete layer is less sensitive to controlling the deformation of surrounding rock. Therefore, through the comparative analysis of single-factor sensitivity, the support scheme is determined: shotcrete 80 mm, and then hang metal mesh with a diameter of 6 mm and a mesh of 20 cm × 20 cm; then construct the mortar anchor rod, with the length of 2 m, the diameter of 22 mm and the row spacing of 1 m × 1 m; finally install U-shaped steel frame support with a spacing of 0.6 m, and spray 10 mm thick concrete on the roadway surface for sealing.

Using the above scheme for on-site construction, through 120 days of support monitoring and observation, the subsidence of roadway roof and the convergence of two sides have been well controlled, and the roadway wall of shotcrete after support is dry and regular, which was shown in Figure 15. At present, the effect is
remarkable, there is no concrete cracking, the overall deformation of roof and side wall rock is negligible, and a small amount of floor heave occurs at the bottom of the roadway. According to the measurement, the floor heave is about 50 mm in the early 120 days, and the numerical simulation calculation of floor heave deformation is about 35 mm. The actual project monitoring data are slightly higher than the numerical simulation calculation results, and the floor heave deformation tends to be stable in the later stage. Therefore, the support mode and parameters realize the effective control of surrounding rock deformation of expansive soft rock roadway.

5 | CONCLUSIONS AND SUGGESTIONS

Steel frame is the main pressure-bearing mode of surrounding rock in soft rock support. By selecting reasonable support steel frame and layout parameters, the deformation and damage of soft rock roadway can be effectively controlled, the number of repairs can be reduced, and the safety of roadway pedestrian and transportation can be ensured. Based on the experience of roadway supporting engineering in Mengnuo lead-zinc mine, this paper discusses the bearing characteristics of different supporting steel frame structures.20-22 The main conclusions are as follows:

1. The deformation resistance of U-shaped steel is the best. The overall deformation of U-shaped steel is 85.0% of that of track steel, followed by that of I-shaped steel which is 92% of that of track steel;

2. The main force positions of three kinds of supporting steel structures are the joint of steel frame shoulder, waist, and foot. In the three-dimensional simulation support of 10 m roadway, the overall deformation of the middle 4-6 m roadway is greater than that of the surrounding rock of the head and tail roadway, and the stress of the key segment of the roadway should be considered from an overall angle during the support of the roadway;

3. When the soft rock roadway is not supported by steel frame only by bolting and shotcreting, its overall displacement deformation is 2-4 times that of support. When the steel frame is only supported by side wall and top, the displacement of floor heave still exists, which is 24% lower than that when the tunnel is not supported.

CONFLICT OF INTERESTS
The authors declare no competing interests.

ETHICAL APPROVAL
I certify that this manuscript is original and has not been published and will not be submitted elsewhere for publication while being considered by Royal society open science. And the study is not split up into several parts to increase the quantity of submissions and submitted to various journals or to one journal over time. The submission has been received explicitly from all co-authors, and authors whose names appear on the submission have contributed sufficiently to the scientific work and therefore share collective responsibility and accountability for the results.

DATA AVAILABILITY STATEMENT
Data are included in the manuscript.

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