



Mechanism and Control of Roadway Floor Heave in the Paleogene Soft Rock Surroundings

Jun Yang · Kaifang Zhou · Yu Cheng · Yubing Gao · Qinglong Wei · Yongguang Hu

Received: 23 February 2019 / Accepted: 29 May 2019 / Published online: 4 June 2019
© Springer Nature Switzerland AG 2019

Abstract To analyze the mechanism of roadway floor heave in the Paleogene soft rocks and provide corresponding control strategies, taking the monorail lane of the Liu Hai Mine as the research background, the special geological conditions of the deep soft rock roadway and failure characteristics of the roadway floor are analyzed by means of an indoor physical experiment and numerical simulation. Through research on the mechanism of the floor heave of the roadway, the main influencing factors of the floor heave are determined. It was found that the high stress jointed strong swelling composite soft rock is the main cause, and the lack of supporting theory and backwardness of support design methods are the direct reasons for the floor heave of the roadway. On this basis, a new coupling support technology of a bolt-mesh-anchor-base angle bolt-flexible layer truss for controlling roadway floor heave has been proposed and applied in the field. The numerical analysis and field monitoring results show that the roadway floor

heave control technology can improve the stress state of the surrounding rock of the floor, cut off the shearing and sliding deformation of the bottom corner, effectively control the roadway floor heave deformation, and ensure the overall stability of the roadway. It provides a reference for the mechanism and control of roadway floor heave under similar conditions.

Keywords Deep soft rock roadway in the Paleogene · Floor heave · Deformation mechanical mechanism · Numerical simulation · Coupling roadway support

1 Introduction

In recent years, with the increasing depth of mine exploitation, the engineering problems of large deformation, high ground pressure and difficult support of soft rock roadways have become increasingly serious. The roadway floor heave phenomenon has become one of the main features and forms of deformation and destruction of surrounding rock in soft rock roadways. The deep soft rock roadway is in a complex environment of three “high” and one “disturbance” conditions (high ground stress, high ground temperature, high karst water pressure and strong mining disturbance), and its mechanical properties are often very different from those of shallow mining. The traditional support theory, design method and technology

J. Yang · K. Zhou · Y. Cheng · Y. Gao (✉) · Q. Wei · Y. Hu
State Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining and Technology (Beijing), Beijing 100083, China
e-mail: yubing_gao@163.com

J. Yang · K. Zhou · Y. Cheng · Y. Gao · Q. Wei · Y. Hu
School of Mechanics and Civil Engineering, China University of Mining and Technology (Beijing), Beijing 100083, China

developed on the basis of shallow mining have been difficult to adapt to the design and practical needs of deep roadway support (He et al. 2006; Xie 2006; Qian 2004; Wang et al. 2012). Especially for strong swelling soft rock roadways, high-stress soft rock roadways and large section roadways, a general support form is difficult to guarantee the stability of the roadway (He and Sun 2004).

Scholars have undertaken numerous research studies on the mechanism of floor heave. The research content mainly focuses on three aspects (Kang 1993; Wang et al. 2000; Chu et al. 2011; Yang et al. 2012; Lin et al. 2013) the first of which regards the nature of soft rock. First, regarding the properties of weak rock layers, the mineral composition and microstructure characteristics of weak rock layers are studied by various means, and the relationship between the physical properties and strength deformation of weak rock is preliminarily discussed. Second, the mechanism of softening in water, disintegration and swelling of soft rock layers and the influence of water physical properties on mechanical parameters of weak rock formations are analyzed. The third is in terms of mechanical properties. The mechanical properties of elastic–plastic, dilatancy and rheology exhibited by weak rock are studied. Regarding the control technologies of roadway floor heave, compared with the slow progress of roadway floor heave mechanism research, exploratory work on various control floor heave measures is very active, and a large number of floor heave control theories and technical application results have been obtained and can be summarized as the reinforcement method, destressing method, combined method and reinforcement roadside, angle of the roadway and other methods (Li 2004). Zheng et al. (2015) analyzed the main controlling factors of roadway floor heave on the basis of physical and mechanical properties of roadway surrounding rock, rock mineral composition analysis, in situ stress measurement and large-scale true triaxial rheological test, proposing the floor heave control strategy of compressible steel arch and foam concrete combined with pre-stressed anchor cable. Jiang et al. (2018) established a numerical model of complex jointed rock mass roadway through on-site joint parameter survey, Monte Carlo simulation of dominant joint group and FISH language programming, and analyzed the non-uniform bottom drum mechanism of roadway. Liu et al. (2015) used FLAC 3D to simulate and analyze

the deformation and stress distribution characteristics of surrounding rock before the support of winch chamber, aiming at the characteristics of serious outburst of winch chamber floor and easy to occur tension-shear failure, based on the theory of stepwise supporting, the supporting method for winch room floor is optimized, and the surface and deep displacement, anchor cable tensile force and the internal stress of concrete foundation are monitored. Wang et al. (2017a, b) developed end anchor cable bundles suitable for floor reinforcement, and proposed a floor heave control scheme with end anchor cable bundles as the main part. Wang et al. (2017a, b) analyzed the deformation and failure mechanism of surrounding rock of deep high stress roadway by means of surrounding rock deformation monitoring, detection of damage range and stress monitoring of supporting components, and established a confined concrete support system, which is of great significance for effective control of surrounding rock of deep high stress roadway. These floor heave control measures are suitable for different conditions, but the application effect is far from the difference between the mining areas, shallow and deep coal mines. In addition, most roadway floor heave control techniques only reinforce the roadway floor and lack complete research on other parts. A number of studies (Wang and Feng 2005; Hou et al. 1995; Bai et al. 2011) have shown that the stability of the roadway floor is related to the strength of the tunnel roof, both sides and bottom angle. They influence and interact with each other.

The Liuhai Mine is one of the deepest Paleogene system weak rock mines in China. Due to its complex physical geological environment, the conventional support methods have failed, roadway floor heave is serious, and the construction roadway has been completely destroyed. Thus, the characteristics of roadway floor heave and the mechanism of roadway floor heave of the deep soft rock roadway of the Paleogene system of the Liuhai Mine need further study, and it is urgent to reasonably determine new technologies for heaving floor control. To that end, this paper studies the damage characteristics and failure modes of the roadway floor in the deep soft rock engineering of the Paleogene system of the Liuhai Mine and combines the numerical simulation analysis to study the mechanism of roadway floor heave. On that basis, the new technology of a bolt-

mesh-anchor-base angle bolt-flexible layer truss for roadway floor heave of the deep soft rock roadway of the Paleogene system of the Liuhai Mine is proposed (He et al. 2005; Guo et al. 2009, 2015; Yang et al. 2015a, b), and the research results are applied to the engineering examples.

2 Engineering Condition Analysis

2.1 Engineering Situation

The Liuhai Mine is located at the northern edge of the middle section of the Huangxian Coalfield. It verges on the Bohai Sea. The elevation of the ground is + 10.3 m ~ + 25.74 m. The design elevation of the shaft station is - 480 m. The monorail lane is located in the middle of a shaft station. The roadway has the shape of the straight wall semicircular rock cave. Arched, the gross section size is 3820 mm × 4690 mm (width × height). The Liuhai Mine has adopted a variety of advanced support technologies from home and abroad such as cable anchor + U₂₅ steel combined support, 600 thick reinforced concrete support, cable anchor + U₂₉ fully closed combined support, reinforced concrete preform and other support forms, and after many repairs, the difficult support, hard maintenance, large deformation, serious floor heave, etc., have remained unchanged, and the roadway of the shaft station has been basically destroyed.

The burial depth of the Liuhai mine roadway is 500 m. The mine has the greatest burial depth of Paleogene soft rock mines built in China. The tunnel is pierced by mudstone, calcareous mudstone, oil-bearing mudstone, oil shale, sandstone and a coal seam. The vertical gravity stress of the excavation site is approximately 12 MPa, the concentrated stress levels are up to 24 MPa, the rock block strength is 8 MPa on average, and the rock mass strength is 1–2 MPa. The hydrogeology of the Liuhai Mine is relatively simple, and the geological structure is complex. The coal-bearing strata in the minefield are soft, the faults are all normal faults, and the fault zone is filled with muddy materials resulting in water conductivity. The dip angle of the strata in the minefield area is gentle, generally 5°–8°, with a slight sublevel fluctuation. The general view is a wide, gentle and asymmetric syncline after transformation, and the total trend is SW–NE. In general, the surrounding rock is relatively

broken, and the joints, bedding and faults are very developed. The surrounding rock structure of the roadway is broken and fragmented, which makes supporting the roadway difficult. The lithology of coal and roof slab is shown in the comprehensive histogram of Fig. 1.

2.2 Microstructure Analysis of the Roadway Rock Surroundings

Through on-site sampling, the microstructure of the surrounding rock was tested and analyzed by scanning electron microscopy. The microstructure scanning results are shown in Fig. 2.

It can be seen from the scanning results that for the rock containing clay minerals, its montmorillonite or illite–smectite layer-mixed minerals have a flaky, directional distribution on the surface of the rock, some localized cavities are developed, and some are filled in microcracks of rock particles. Another obvious feature is that the microcracks of the rock are generally more developed, most of the connectivity is better, and some of the fractures are filled with dolomite, quartz or feldspar.

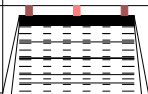
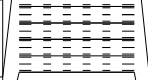


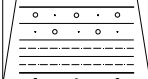

Rock name	Lithologic characteristics	Histogram	Thickness (m)
Oil shale	Brown-black, horizontally stratified development, high toughness, small bulk density, high oil content, easy to produce floor heave.		0.72~0.98 0.80
Small coal	Grayish black and brownish black, poor coal quality, high gray powder, layer development		0.25~0.57 0.45
Oil-bearing mudstone	Gray ~ light gray, layered, horizontal joint development, harder, oil lowering from bottom to top.		4.50~8.50 7.50
Mudstone	Brown and dark gray, flat fault, horizontally developed bedding, with water absorption and disintegration, poor bearing capacity		3.20~4.50 3.50
Coal seam	Gray-brown lignite, complex structure, brittle and brittle, easy to produce net pocket after sinking and crushing, not easy to be used as the roof of the roadway.		1.98~3.46 2.44
Mudstone, glutenite interbed	Light gray - grayish white, muddy glued, harder, lower hardness, sand-like, not conducive to roadway support.		7.82~10.60 8.52

Fig. 1 Comprehensive histogram

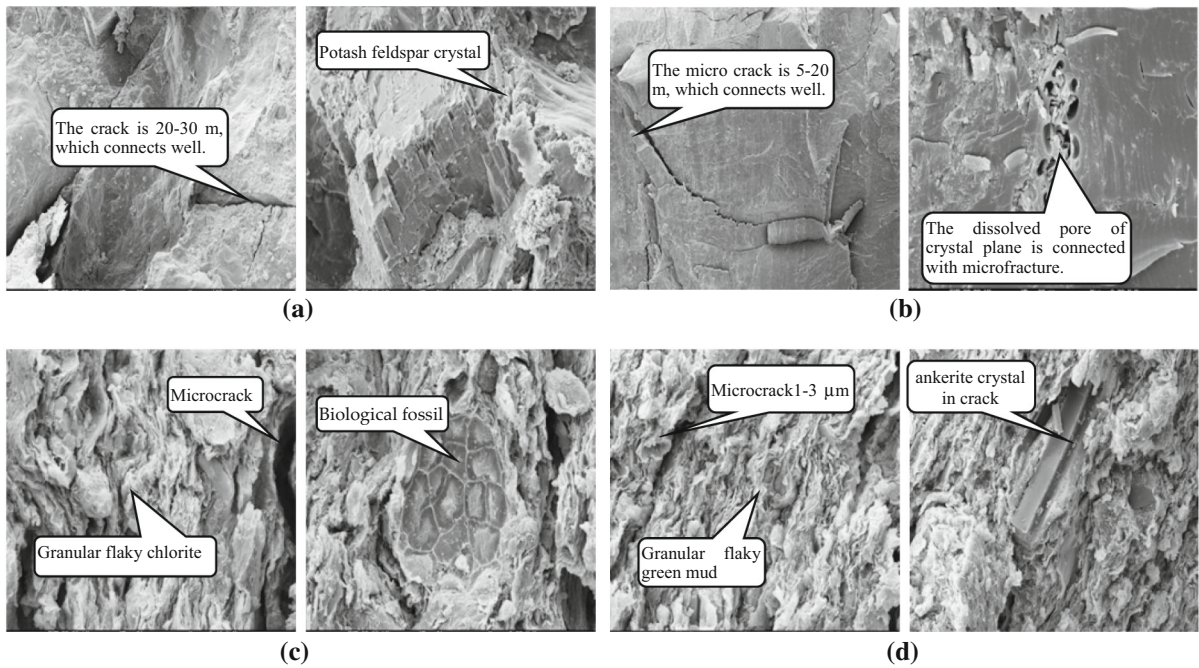


Fig. 2 Microstructural scanning results. **a** Floor glutenite, **b** coal seam, **c** roof oil shale and **d** roof shale

2.3 Analysis of the Mineral Composition of Surrounding Rock

To determine the mineral composition and clay mineral content of the surrounding rock of the Paleogene system soft rock engineering of the Lihai Mine and the content of swelling minerals in clay minerals, whole rock and clay mineral analysis experiments were carried out. The X-ray spectrum of the whole rock minerals and the X-ray diffraction spectrum of clay minerals in some rock samples are

shown in Figs. 3 and 4 respectively. The results of the analysis are shown in Tables 1 and 2.

From the X-ray diffraction analysis results, the clay mineral content of the surrounding rock of the roadway is 56.6–60.9%, and the clay minerals are mainly montmorillonite, illite–smectite layer-mixed, illite, kaolinite and chlorite. Among them, the relative content of montmorillonite minerals with strong swelling and water absorption is 80–96%, the highest is 96%, and the average is 86%; the mixed layer ratio is more generally 60–70%, the maximum reachable is 70%, and the average is 65%. Therefore, the

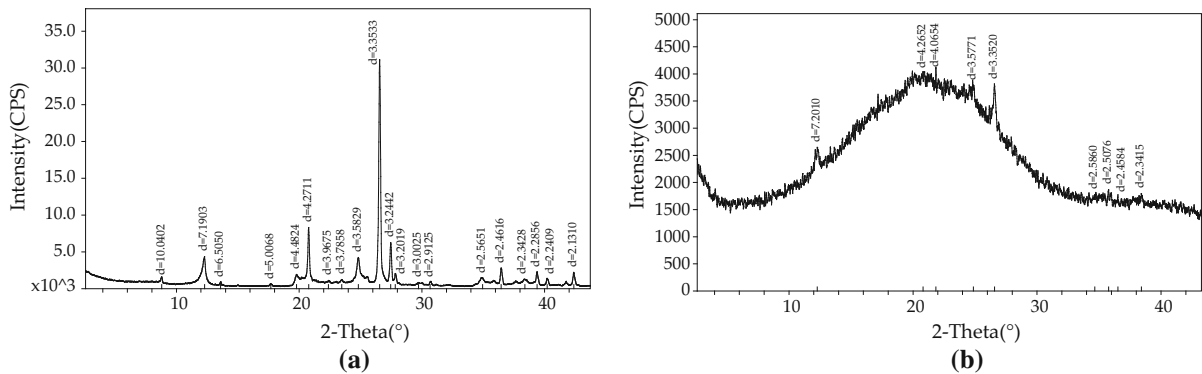


Fig. 3 X-ray spectra of whole rock minerals. **a** Floor glutenite and **b** coal seam

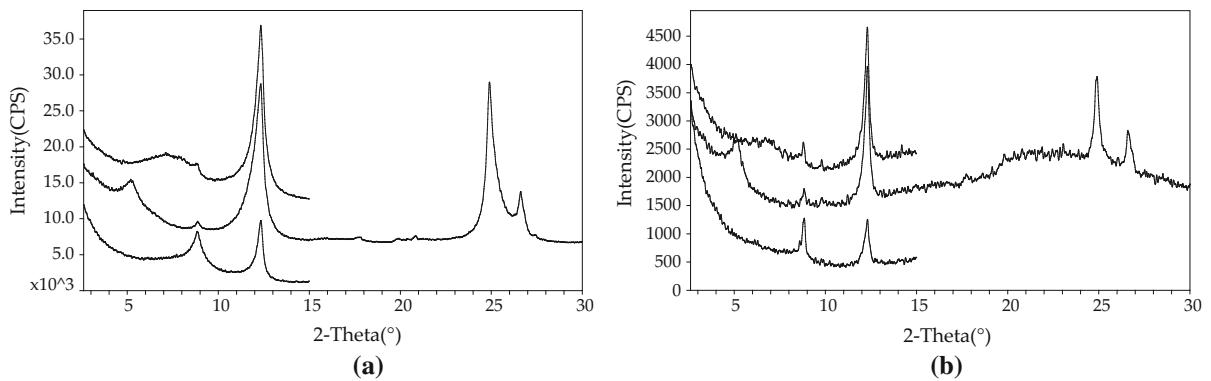


Fig. 4 X-ray diffraction spectra of clay minerals. **a** Floor glutenite and **b** coal seam

surrounding rock of the roadway is easy to absorb and weather, the strength of the surrounding rock is reduced, the bottom plate often accumulates water, the floor of the roadway produces a strong expansion force, and roadway floor heave is more serious.

3 Mechanism Analysis of Roadway Floor Heave

3.1 Roadway Floor Heave Feature

The surrounding rock deformation and failure of the Liuhai Mine roadway is extremely serious, with rapid deformation speed and large deformation, showing obvious large nonlinear deformation and failure phenomenon. The maximum deformation speed of the waiting room roadway is 150 mm/day without support after excavation. The shaft station used U-shaped steel support, concrete brickwork and other support methods, but all ended in failure. Among them, the characteristics of the roadway floor heave of the Liuhai Mine Roadway are mainly reflected in the following.

1. The deformation of the bottom plate is the most serious, accounting for the main part of the deformation of the roadway. The destructive power of the bottom plate is strong, and the entire section of the roadway is unstable. The roadway floor heave volume is 500–2000 mm, the shrinkage of both sides is 800–1800 mm, and the top shrinkage is 400–1300 mm, which far exceeds the allowable amount of deformation.
2. The surrounding rock of the roadway is pressed on all four sides, the bottom plate is weak, and the

damage occurs first; roadway floor heave bends the U-shaped steel of the side, the steel frame is greatly deformed, and the bearing capacity is lost, causing damage to the two sides of the roadway. Shear compression failure, the concrete shedding, and the overall destruction of the roadway occur at the top of the roadway due to closure.

3. Roadway floor heave has an obvious temporal impact, and the rock mass of the roadway floor continues to flow; the initial speed of the roadway floor heave is large, and the roadway floor heave speed tends to be stable over a long time. When the total heaving floor volume exceeds a certain value, the roadway floor heave speed will increase again, causing further damage to the deep rock strata. The deformation and damage of the Liuhai mine roadway is shown in Fig. 5.

3.2 Research on the Mechanism of Roadway Floor Heave

Through the comprehensive analysis of floor heave of the soft rock roadway in the Liuhai Mine, according to its formation mechanism, it can be divided into three types: strong swelling floor heave, high-stress rheology floor heave and composite heaving floor.

3.2.1 Strong Expansion Type Heaving Floor

The expansion type heaving floor is mainly caused by the water physical properties, which causes the expansion of the rock floor of the roadway and the strain softening of the rock mass. The floor of the roadway containing expansive minerals, under the

Table 1 Full rock mineral X-ray analysis results table

Serial number	Rock name	Mineral type and content (%)										Total amount of clay minerals
		Quartz	Potash feldspar	Plagioclase	Calcite	Dolomite	Pyrite	Siderite	Clinoptilolite	Amorphous substance		
1	Roof oil-bearing mudstone	20.5	2.5	3.5	-	-	2.0	13.5	-	-	-	58.0
2	Coal seam	1.0	-	-	-	-	-	-	-	-	97.0	2.0
3	Floor glutenite	40.3	12.3	2.5	-	3.0	-	-	-	-	-	41.9

action of water, the expansive minerals absorb water and swell, resulting in strong expansion force, the floor strata is further damaged, and the rock mass is accompanied by more cracks, allowing the water to more easily enter deep rock strata, resulting in increased damage to the bottom rock strata. Under the action of expansive minerals, roadway floor heave is also intensified. Therefore, the role of water is a process that continuously reduces and continuously destroys the strength of the rock at the bottom of the roadway. The floor of the soft rock roadway in the Lihai Mine often accumulates water. A large amount of clay minerals expands, and the volume increases due to water absorption, upon which a strong expansion type heaving floor occurs.

Because the floor of the roadway contains a large amount of expansive minerals, the floor of the roadway will have a large degree of expansion and deformation when it meets water. The amount of heaving floor in this way can be solved by the expansion constitutive Eq. (1) (one-dimensional expansion constitutive equation) or (2) (three-dimensional expansion constitutive equation) (Li 2004). Estimate the amount of heaving floor caused by water expansion of the surrounding rock of the deep soft rock roadway in the Lihai Mine.

$$\varepsilon = K \left(1 - \frac{\log \sigma}{\log \sigma_0} \right) \quad (1)$$

where ε is the axial expansion strain; σ_0 is the maximum expansion stress; σ is the expansion stress; and K is the axial expansion strain at $\sigma = 0.1$ MPa.

$$\varepsilon_V = K \left[1 - \frac{\log \left(\sigma_V \frac{1-\mu}{1+\mu} \right)}{\log \left(\sigma_{V_{\max}} \frac{1-\mu}{1+\mu} \right)} \right] \quad (2)$$

where ε_V is the volume expansion strain; σ_V is the first stress invariant; $\sigma_{V_{\max}}$ is the maximum volume expansion stress; and μ is the Poisson's ratio.

The water mainly penetrates into the surrounding rock where the dilated deformation has occurred, that is, the permeability zone is mainly the loosening range of the surrounding rock of the bottom plate. Therefore, it can be estimated based on the surrounding rock loose circle (Wang et al. 2017a) of the roadway:

$$U_f = K_S L_p = K_S \left(57.80 \frac{P_0}{R} - 51.56 \right). \quad (3)$$

Table 2 Clay mineral X-ray analysis table

Serial number	Rock name	Relative content of clay minerals (%)						Mixed-layer ratio (%S)	
		S	I/S	I	K	C	C/S	I/S	C/S
1	Roof oil-bearing mudstone	88	–	1	11	–	–	–	–
2	Coal seam	–	30	5	63	2	–	70	–
3	Floor glutenite	–	40	2	58	–	–	60	–

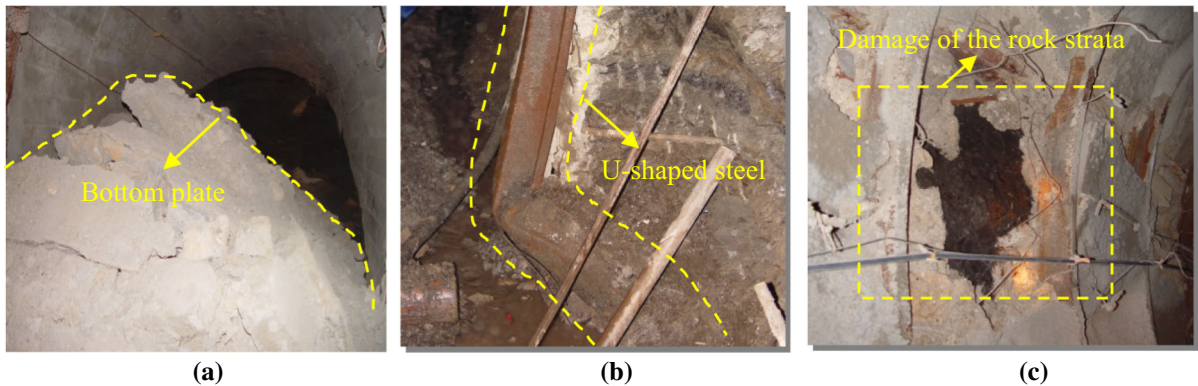


Fig. 5 Deformation and damage of Liuhai mine roadway. **a** Roadway floor heave seriously, **b** steel frame sprain and **c** concrete shedding

where U_f is the amount of bottom heave generated by the water expansion of the floor rock formation; K_S is the free expansion ratio; L_p is the thickness of the surrounding rock loose circle of the floor; P_0 is the ground stress; and R is the uniaxial compressive strength of the floor rock.

When the floor rock is floor mudstone, according to the rock mechanics parameters, the amount of bottom heave is $U_f = 326$ mm.

3.2.2 High-Stress Rheological Floor Heave

The strength of the rock mass of the floor of the soft rock roadway in the Liuhai Mine is extremely low, and the fissure is extremely developed. During excavation or expansion, the high stress acting on the roof and the two sides is transmitted to the bottom plate. The rock mass of the bottom plate is subjected to high stress and undergoes rheology such as bending, puckering, and abscission layer.

The rock mass of the floor of the Liuhai mine roadway is weak, the strength is extremely low and the bearing capacity is insufficient, which is the main

factor causing the high-stress rheological heaving floor. The support strength of the two sides and the roof of the roadway is greater than that of the bottom plate. Under the action of the compression mode effect and the far field stress of the two sides of the rock pillar, the soft rock strata of the floor produce plastic deformation, rheology and dilatancy, resulting in high-stress rheologic floor heave. Due to the infiltration of water, especially in the saturated state, the bearing capacity of the rock mass is reduced to the lowest point or even completely lost, and at the same time, the plastic rheology of the rock mass is enhanced. Roadway floor heave deformation in this way can be solved by Eq. (4), and the rheological model uses the Kelvin model (Li 2004).

$$u = \frac{\sigma_0 r_0^2}{2Gr} e^{-\frac{c_r}{\eta t}} \left[1 - e^{-\frac{c_r}{\eta t}} \right] \tag{4}$$

where r_0 is the roadway radius, m; u is the radial displacement of the surrounding rock, m; and σ_0 is the original rock stress. After determining the size of η , the relationship between radial displacement and time and roadway radius can be obtained. Therefore, it can be seen that the value of the creep increases over time.

Table 3 Numerical simulation calculation parameter list

Lithology	Tensile strength (MPa)	Elastic modulus (103 MPa)	Bulk density (kg/m ³)	Poisson ratio	Internal friction angle (°)	Cohesion (MPa)
Mudstone	0.78	0.98	1662	0.28	31.6	0.7
Oil shale	1.1	1.18	1510	0.30	36	0.9
Coal seam	0.2	1.5	1280	0.28	24	1.2
Mudstone gravel Interbedded rock	1.0	3.138	2370	0.25	34	0.8

3.2.3 Composite Heaving Floor

Roadway floor heave of the deep soft rock roadway of the Paleogene system of the Liuhai Mine is not that of a single expansion type or high-stress rheology type heaving floor but a combination of the two. Under the strong expansion force and high stress of the floor clay mineral, the damage to the roadway floor is more serious. At this time, the heaving floor volume of the roadway is greater than the sum of the roadway floor heaves of the two roadways.

3.3 Heaving Floor Process Analysis

To further study the mechanism of the deep soft rock heaving floor in the Liuhai Mine, a numerical analysis of the strong expansion type, high-stress rheology type and composite heaving floor was carried out. Since the swelling of clay minerals is a physical process, the results of FLAC^{3D} program cannot be directly analyzed. According to the actual situation, the

parameters after softening in water are used for calculation. In order to make the stress state, deformation and plastic zone development process of surrounding rock accurately and intuitively displayed in the simulation process, according to the data of engineering geological model, the grid is divided according to the principle of distance roadway from near to far, from dense to sparse, and the grid is discretized by the method of combining equal and unequal spacing.

3.3.1 Calculation Model and Parameters

The calculation simulation uses FLAC^{3D} numerical analysis software. The constitutive model uses the Mohr–Coulomb model. The calculation range is length × width × height = 20 m × 30 m × 30 m, and a total of 35,280 units and 386,882 nodes are divided. The side of the model is limited to horizontal movement, the bottom is fixed, the upper surface of the model is a stress boundary, and the applied load is 12 MPa, simulating the self-weight boundary of the overlying rock mass. The physical and mechanical calculation parameters of the engineering rock mass are shown in Table 3.

This simulation object selects the representative support method of the Liuhai mine loaded car line (anchor net spray + U₂₉ steel joint support) to establish the support engineering model, as shown in Fig. 6. The support parameters are as follows: the adopted bolt is a φ18 mm × 2000 mm thread steel anchor bolt, the row & line space is 800 × 800 mm; the φ4 mm cold drawn steel wire metal mesh is used, and the mesh specification is 1000 mm × 2000 mm; the U₂₉ steel frame is used, and the distance between two rows 3 frames/m; and the shotcrete thickness is 100 mm.

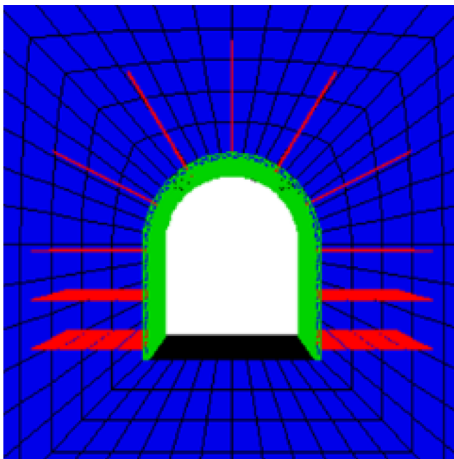
**Fig. 6** Support engineering model

Fig. 7 Displacement diagram of expandable floor heave. **a** Vertical displacement and **b** displacement vector diagram of roadway surrounding rock

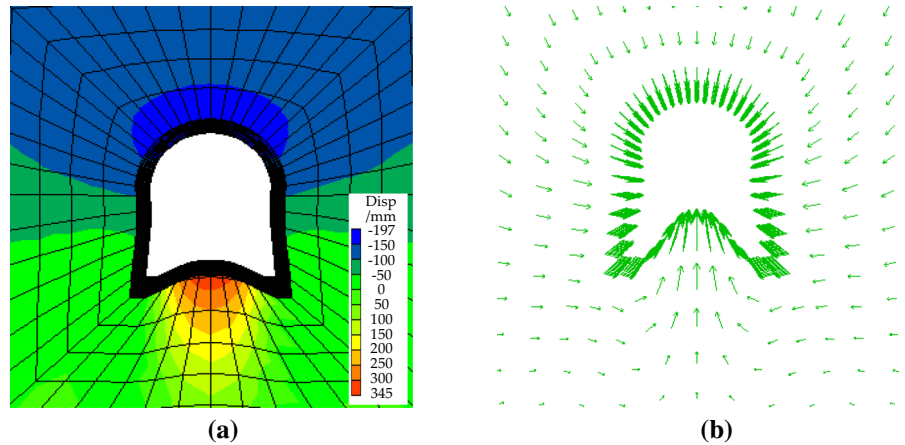
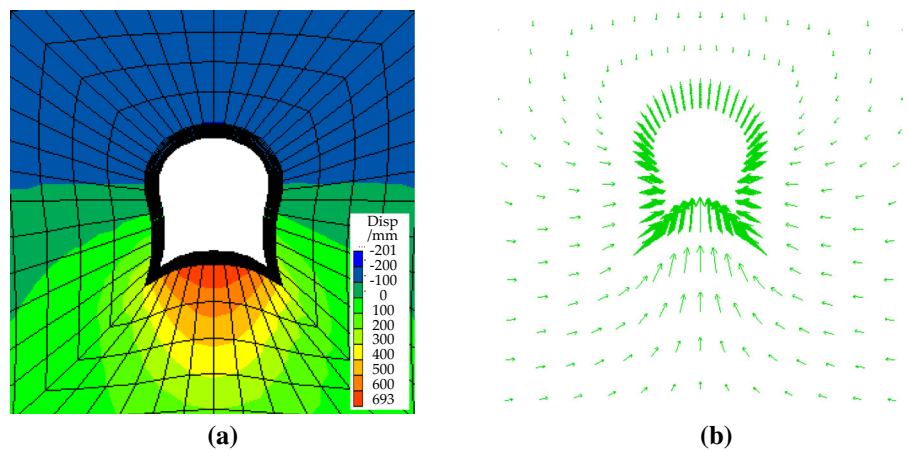


Fig. 8 Displacement diagram of high-stress floor heave. **a** Vertical displacement and **b** displacement vector diagram of roadway surrounding rock



3.3.2 Analysis of the Numerical Simulation Results

After numerical calculation of the model, the displacement diagrams of the expansion, high stress and composite heaving floors were obtained, as shown in Figs. 7, 8 and 9. The deformation values of the roadway under different types are shown in the table.

From the simulation result graph and the deformation values of the roadway under different types (see Table 4), it can be seen that the surrounding rock of the roadway has undergone large deformation under the action of the three types, and roadway floor heave is more severe than the roof and the two sides of deformation. The results are in good agreement with the measured heaving floor volume at the site. It can be seen from the displacement vector diagrams of the three types of heaving floor that the direction of the surrounding rock movement of the bottom plate is very different. In addition, the amount of high-stress

heaving floor is larger than the amount of expansion heaving floor, the composite heaving floor is larger than the sum of the expansion type and the stress type heaving floor, and the swelling and stress types of floor heave account for 27.5% and 55.3% of the composite floor heave, respectively. The bottom heave of 17.2% is a compound value of the two added. This shows that under the joint expansion of clay minerals and high stress, the damage to the floor of the roadway is aggravated.

Due to the “four-sided pressure” state after the excavation of the roadway, the U₂₉ steel support (semiclosed structure without bottom arch) is used as the secondary support so that the roadway support body becomes an open structure, and the rock mass of the roadway floor is extremely low. It also contains a large amount of expansive minerals. Under the action of high composite stress and bottom water, the deformation and damage to the roadway floor are

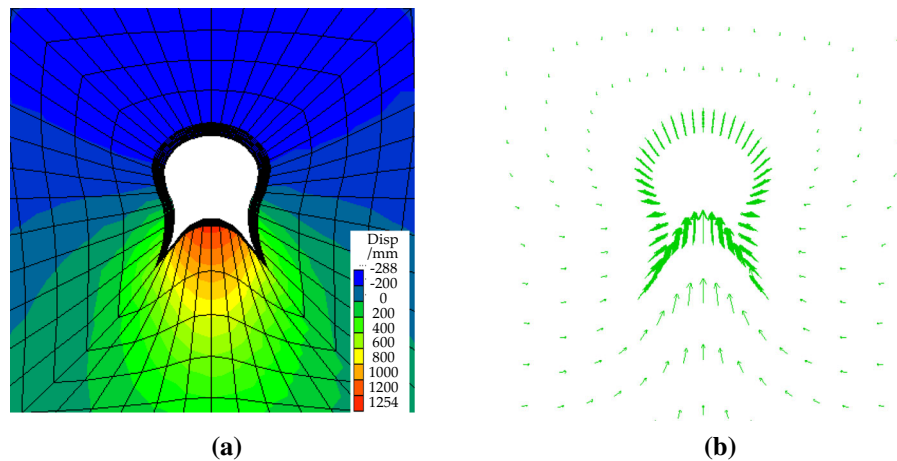


Fig. 9 Displacement diagram of the compound bottom drum. **a** Vertical displacement and **b** displacement vector diagram of the roadway's surrounding rock

intensified, and at the same time, the stress concentration of the roadside and the top is caused, resulting in large deformation of the roadside and the top. The entire roadway is destroyed. Through process analysis, the following conclusions can be drawn.

1. The anchor net spray + U_{29} steel frame support form (not closed) is unreasonable, resulting in serious road heaving floor.
2. The amount of floor heave under the combined actions of expansive minerals and high stress exceeds the sum of the two actions.
3. The lithology of the floor, the surrounding rock stress and the supporting form are the three main control elements for the stability control of the roadway floor.

3.4 Analysis of the Cause of the Floor Heave

Through the above analysis of the deformation and failure characteristics of the roadway and the characteristics of the surrounding rock, the main reasons for roadway floor heave of the deep soft rock roadway of the Paleogene system of the Liuhai Mine are as follows.

1. The engineering geological conditions are complex. The surrounding rock has a large depth of occurrence, the environmental ground stress level is high, joint fissures are extremely developed, and the rock mass strength is low. The deep soft rock project of the Paleogene of the Liuhai Mine has

been in a high ground stress environment for a long time, and the stress level is as high as 12 MPa. Moreover, because the main roadway is located near the Liuhai fault and the Caobo fault, it is subject to large tectonic stress and engineering deviatoric stress; the rock mass strength is only 1–2 MPa, and the ratio of self-heavy stress to rock mass strength is 6–12. From the macroscopic structure and the microscopic structure, it is found that the rock mass is relatively broken, the joints and fissure are relatively developed, and there are many microfissures and pores. At the same time, the surrounding rock contains a large amount of swelling clay minerals such as montmorillonite, which is strong after water contact. Under the joint actions of high ground stress and high expansion stress, the lower rock mass strength worsens the surrounding rock deformation, and the tunnel heaving floor is especially prominent. Due to the expansion force, the surrounding rock creeps for a long time. Therefore, high-stress jointed strong expansive soft rock (HJS) is the root cause of the roadway floor heave of the deep soft rock project of the Paleogene system of the Liuhai Mine.

2. The support theory basis is improper. The buried depth of the deep soft rock project of the Paleogene system of the Liuhai Mine reached 500 m. The linear theory of the original shallow support could not be effective. The nonlinear large deformation mechanics design method should be adopted. The traditional support method does not

Table 4 Different types of roadway deformation values

Types	Maximum heaving floor (mm)	Maximum top settlement (mm)	Maximum shrinkage of sides (mm)
Intumescent	345	197	217
High stress	693	201	395
Compound	1254	288	622

account for the coupling between the supporting materials, the supporting material and the surrounding rock but passively and mechanically through the combined use of various supporting materials to increase the supporting strength due to the different support materials. However, due to the uncoupling of stiffness and strength between the different supporting materials, one or several of the supporting materials did not play their due role and finally caused the failure of the support. In deep soft rock engineering, different characteristics of the supporting materials must be considered to achieve coupling between different the supporting materials. For the Liuhai Mine, the surrounding rock media has joints, is under tectonic stress and is inhomogeneous so that the load acting on the support body is not uniform, and the surrounding rock and the support are not coupled in strength.

- Support technology is backward. In the deep soft rock engineering of the Paleogene in the Liuhai Mine, due to its nonlinear large deformation characteristics, its support design should consider the process and carry out related process design and research on the application methods and application processes of various mechanical countermeasures. In the original support design and on-site construction process, the process correlation is not considered, and several support methods are applied simultaneously, resulting in uncoupling support, or because the order of different roadway constructions is not considered, causing mutual disturbance between the roadways, and the roadway is destroyed. The roadway bottom drum is especially prominent. At the same time, the roadway is subjected to composite stresses such as tectonic stress, self-weight stress, engineering deviatoric stress and materialized expansion stress, and most of the original stent and the stent do not have a tie rod connection; the support is

easily broken, and the overall support ability cannot be exerted.

4 Roadway Floor Heave Control Technology

The causes of deformation, failure and instability in deep soft rock engineering are various, but the root cause is complex deformation mechanics. To successfully control the floor heave of the deep soft rock roadway in Liu Hai Mine, three key technologies must be applied:

- Correctly determine the mechanical mechanism of deep soft rock deformation in the Paleogene of Liuhai Mine;
- Effectively transforming the complex deformation mechanics mechanism into a single type;
- Reasonable use of transformation techniques of complex deformation mechanics mechanism.

4.1 Analysis and Transformation of Deformation Mechanics

According to a large number of engineering practices, the deformation mechanics of roadway surrounding rock is divided into three categories: I, II, and III, namely, physical and chemical expansion, stress expansion type, and structural deformation. Among the various types, they are classified into five grades A, B, C, D, and E according to the severity of the deformation of the surrounding rock.

Different types of deformation mechanics have different supporting technical countermeasures. To effectively control the roadway floor heave of the deep soft rock roadway and maintain stability in the surrounding rock, we must first determine the deformation mechanics of the soft rock, propose reasonable

support measures, and then design the support parameters.

According to the analysis of physicochemical composition and microstructure test, the roadway surrounding rock contains a large number of expansive minerals. The expansive minerals are mainly montmorillonite, and the roadway surrounding rock microfissures are more developed. Therefore, the roadway surrounding rock has the expansive mechanism of montmorillonite and micro-fissures, that is, I_{AC} type.

According to the geological conditions, the whole mining area is affected by the tectonic stress in varying degrees. Under the action of this, the monorail roadway is damaged to varying degrees; with the increase of the depth, the deformation and failure of the roadway become serious, showing obvious depth-related and direction-independent characteristics.

In addition, due to the construction of adjacent transport roadway, strong engineering deviatoric stress is produced, resulting in deformation and failure of surrounding rock of roadway. Therefore, the deformation mechanism of monorail roadway caused by structural stress, gravity stress and engineering deviation stress, that is, II_{ABD} type.

According to the engineering geological survey, the monorail roadway is located near two normal faults. The fault and the roadway strike at an angle of 60° – 90° . There is a fault-type mechanical mechanism, that is, III_{AC} type.

The surrounding rock fissure joints of the roadway are relatively developed, and the surrounding rock is

relatively broken. There is a random joint deformation mechanics mechanism, that is, III_E type.

In summary, the deformation mechanics of the surrounding rock of the Liuhai Mine can be determined as the $I_{AC}II_{ABD}III_{AC}III_E$ composite deformation mechanics mechanism, which is a composite deformation mechanics mechanism with montmorillonite and microfracture expansion, tectonic stress, self-weight stress, engineering deviatoric stress, faults and random joints.

For the soft-rock roadway floor heave problem of composite deformation mechanics, the key to a successful support technology is to determine how to effectively transform the composite deformation mechanics mechanism into a single gravity mechanical mechanism through various transformation support techniques. The following are countermeasures for each of the deformation mechanics.

Type I_{AC} : The roadway is enlarged and reworked, the deformation layer is reserved to release the expansion and deformation performance, and roadway floor heave is controlled by the base angle bolt.

Type II_{ABD} : The tectonic stress and fault mechanics are transformed employing a three-dimensional anchor and anchor cable optimization technique.

Type $III_{AC}III_E$: The mechanical mechanism of fault and random joint types is transformed by employing the anchor net spray coupling technique and three-dimensional anchor (cable) optimization technique.

Type II_B : The gravity type mechanism is controlled by the three-dimensional truss technology and the key

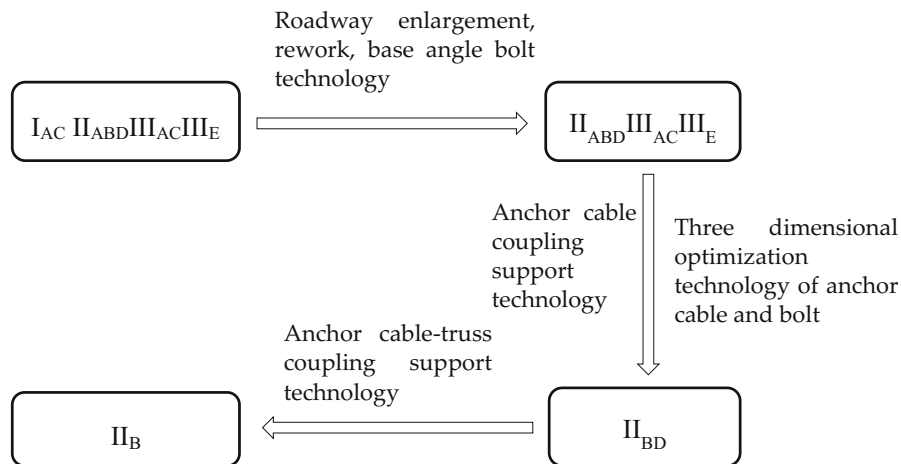


Fig. 10 Flowchart of the transformation mechanism of the compound deformation mechanism in the roadway

part coupling technology of the anchor cable, and finally the roadway is stabilized.

Through the above support technology, the composite deformation mechanics mechanism of the soft rock roadway in the Liuhai Mine is transformed into a single deformation mechanics mechanism. The transformation process is shown in Fig. 10.

4.2 Roadway Floor Heave Control Countermeasures

Through the analysis of the failure phenomena and causes of the deep soft rock engineering in the Paleogene, the high-stress jointed strong expansion (HJS) composite soft rock is the main reason for the project damage. The improper support design theory and the backward support technology are direct the reason. Therefore, to control roadway floor heave and make the roadway overall stable, we must first resolve the main contradictions and transform the direct contradictions.

Therefore, in the new design, the nonlinear large deformation mechanics design method conforming to the actual deep soft rock engineering of the Paleogene should be adopted, and the coupling mechanism of different supporting materials should be analyzed in detail so that the mutual coupling of strength, rigidity and space can be achieved between the supporting materials. According to its specific geological conditions and surrounding rock failure characteristics, to effectively control roadway floor heave, a full-section coupling support technology for the roadway is proposed, namely, an Anchor net cable + base angle bolt + flexible layer truss coupling support technology.

The single-track roadway is in a state of nonlinear stress, and the construction sequence determines the success or failure of the roadway support. Through the optimization of the construction process, the construction sequence is that the roadway is expanded according to the designed semicircular arch section of the straight wall, and the good forming is ensured → Erect forestop as the advanced temporary support → Anchor net support → Initial shotcrete concrete → according to the design of the row and line space plus anchor cable and base angle bolt → bottom cutting, erecting the truss → mine pressure observation → respray to contact with the steel frame → permanent support.

4.3 Anchor Net Cable + Base Angle Bolt + Flexible Layer Truss Coupling Support Technology

4.3.1 Analysis of the Role of Support Form

The anchor cable anchors unstable rock formations in deep stable rock formations, prestressing and actively supporting the surrounding rock, which can fully mobilize the strength of the surrounding rock in the deep roadway, thereby limiting the harmful deformation damage to the surrounding rock and realizing the support integration and load homogenize. The main function of the net is to prevent the soft rock between the anchors from collapsing and improve the integrity of the support. The bottom angle of the roadway is usually the part with high-stress concentration, and it is also the fastest growing and largest part of the plastic zone. The soft rock roadway in the deep sea of the Liuhai Mine is dented, and the bottom angle anchors are used to strengthen the angle of the roadway and control the plastic zone diffusion. Improve the strength of the angle of the surrounding rock, reduce the amount of roadway floor heave, further control the deformation of the surrounding rock, and continue to release the deformation energy. Due to its high strength, use of three-dimensional truss support can ensure that the support has sufficient strength to support the surrounding rock after releasing a certain amount of deformation energy, and through the connection between the truss tie rod and the function of the removed force joint, the truss is integrated into a whole, and the force can be transmitted to each other to evenly stress the truss.

4.3.2 Coupling Support Parameter Design

1. Bolt: $\phi 20$ thread steel with a length of 2200 mm. The row and line space between the bolts is $800 \text{ mm} \times 800 \text{ mm}$, a three flowers arrangement is used, the inclination of the base angle bolt is 45° , end lengthening anchoring is used as the anchoring form, and each anchor rod adopts two K2540 resin explosive rolls.
2. Anchor cable: the anchor cable is $\phi 18$ mm steel strand, the design length is 8 m, arranged in '2-1-2', and the row and line space is 1600×1600 mm. Each anchor cable uses one

internal CK2540, and the outer three are K2540 resin explosive roll end anchorages. The pretightening force of the anchor cable is 10 t when it is installed close to the head, and the pretightening force is 12 t when the head is installed.

3. Pallet: the anchor tray adopts a composite pallet consisting of a wooden pallet and an iron pallet. The specification of the wooden pallet is $200 \times 200 \times 50$ mm, the specification of the external iron pallet is $120 \times 120 \times 10$ mm, and the specification of the anchor tray is a $200 \times 200 \times 10$ mm iron tray.
4. Metal mesh: The mesh is a welded steel mesh with a 6.5 mm diameter, the netting size is 700×1000 mm, the grip is 100×100 mm, the overlap length between the grips is 100 mm, and the snap connection is performed.
5. Concrete: C20 strength grade shotcrete and an initial spray thickness 60 mm are employed, and after the surrounding rock contacts the truss, multiple sprays are used to fill the back clearance of the truss. According to the monitoring results, the deformation of the surrounding rock is stable, and the spraying is repeated to cover the double truss.
6. Bottom arch: after the truss is erected, pouring concrete is used, the thickness is covered by a 200 mm truss, and pouring concrete strength grade is C20.
7. Truss: the inner and outer layers of the flexible truss are all made of No. 11 mining joist steel with a spacing of 200 mm. Each bracket is divided into four sections, and the bracket spacing is 1000 mm. The design value of reserved deformation of internal and external trusses is 180 mm. The top arch stents are bolted through the splint connectors, and the balance stilling interface connector and bolts are connected between the wall brackets and the bottom arch stents.
8. Pull rod: the stents are connected by the equilateral 9# angle tie and the welded A3 steel connecting piece, and the welding position of the tie rod connecting piece space is 800 mm.

See Fig. 11 for the support parameters.

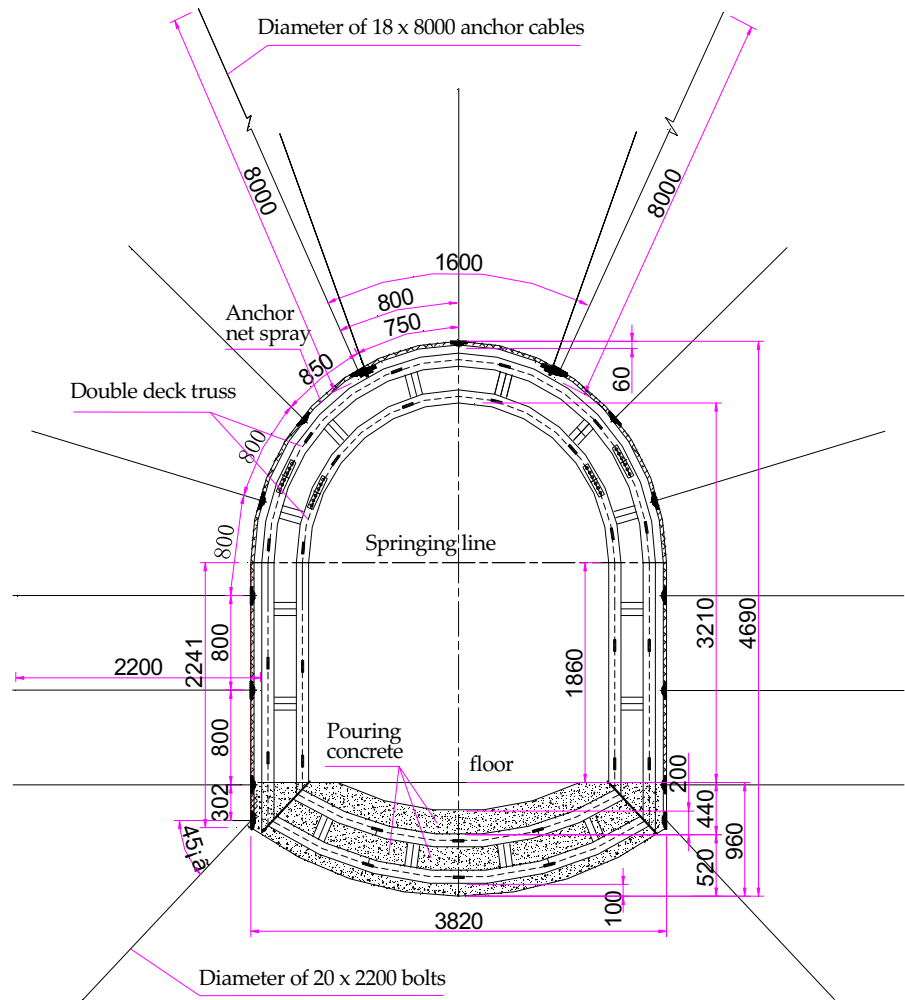
4.3.3 Numerical Simulation Analysis

In view of the difficulty encountered in support and maintenance and the large amount of heaving floor in the Liuhai mine, the cable anchor + bottom corner anchor + soft layer truss joint support form is adopted in the single track lane rework project. For that reason, the numerical analysis of the entire anchor net → anchor net cable → anchor net cable + base angle bolt → erecting soft layer truss process is carried out to study the deformation law of the surrounding rock under different support methods and different parameters and verify the feasibility and reliability of the anchor net cable + base angle bolt + flexible truss coupling support technology. The constitutive model uses the Mohr–Coulomb elastoplastic model when determining the computational model. Figures 12, 13 and 14 are the displacement diagrams of the surrounding rock of the roadway under different supporting forms. Table 5 shows the deformation values of the surrounding rock of the roadway under different supporting forms.

Under the surrounding rock conditions of the monorail lane of the Liuhai Mine and the anchor net spray support (as shown in Fig. 11), the surrounding rock is greatly deformed, and the roadway floor heave is particularly serious. The contraction of the two sides of the roadway was 812 mm, the roof sank 337 mm, and the roadway floor heave actually reached 1080 mm. The floor of the roadway is bare. Under the action of water, the clay minerals of the bottom plate expand and increase the amount of heaving floor. The cracks and joints of the surrounding rock of the floor are relatively developed, and the strength is extremely low. Under the action of high stress, the relative slip along the crack surface between the rock masses in the rock mass of the floor plate produces the squeeze flow deformation.

Under the anchor net spray + anchor support condition (as shown in Fig. 12), the roadway deformation is reduced, the contraction of the two sides is 478 mm, the maximum amount of sinking of the top plate is 253 mm, and roadway floor heave volume is 712 mm, which are 41.1%, 24.9% and 34.1% lower than under the anchor net spray support condition, respectively. It shows that under this support condition, not only the amount of roof sinking is reduced but also the amount of roadway heaving floor and the deformation of the two sides can be effectively

Fig. 11 Schematic diagram of the coupling support section layout



reduced. The anchored cable at the top of the roadway suspends the overlying unstable strata to the deep stable strata and uses the strength of the deep surrounding rock to reduce the pressure of the overlying strata transmitted to the bottom plate, thereby reducing the amount of roadway floor heave.

Under the anchor net spray + anchor cable + base angle bolt support conditions (as shown in Fig. 13), the roadway deformation is further reduced, especially the roadway floor heave. The shrinkage of the two sides is 342 mm, the maximum amount of sinking of the top plate is 159 mm, and the roadway floor heave volume of the roadway is 137 mm, which are reduced by 28.5%, 37.2% and 80.8%, respectively, under the conditions of the anchor net spray + anchor cable support. The anchoring rod at the bottom angle of the roadway can improve the overall strength of the

surrounding rock of the bottom angle, avoid the shear slip of the bottom corner, and effectively control the development of the plastic zone of the surrounding rock of the sides and angle and the volume expansion of the loose ruptured surrounding rock. This technical measure can reduce rock deformation around the roadway and the sinking of the roof in addition to effectively reducing or controlling the amount of floor heave of the roadway.

To understand the deformation of the surrounding rock of the roadway after erection, the numerical calculation of the cable anchor + base angle bolt + soft truss support was carried out to analyze the displacement changes after contact between the surrounding rock and soft layer truss. The numerical analysis results are shown in Fig. 15.

Fig. 12 Anchor network support surrounding rock displacement diagram. **a** Vertical direction and **b** horizontal direction

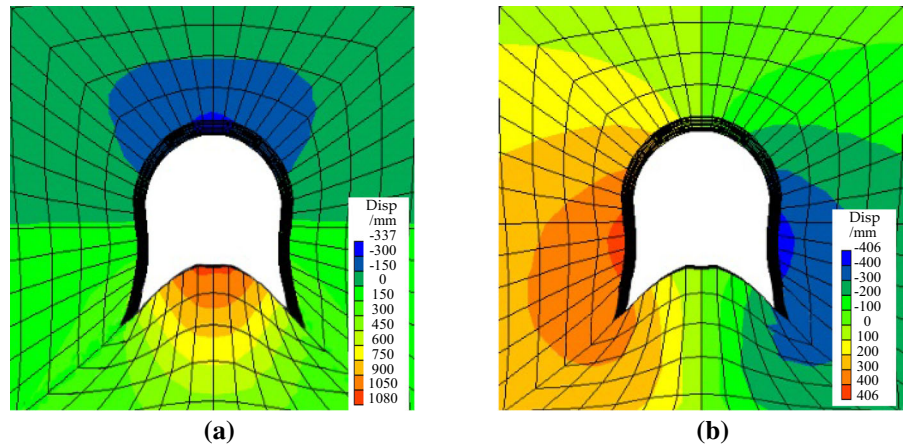


Fig. 13 Anchor network cable support surrounding rock displacement diagram. **a** Vertical direction and **b** horizontal direction

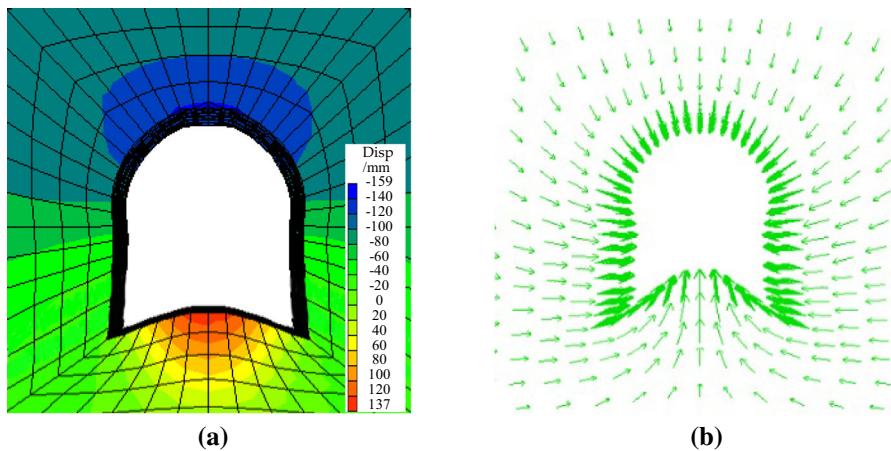
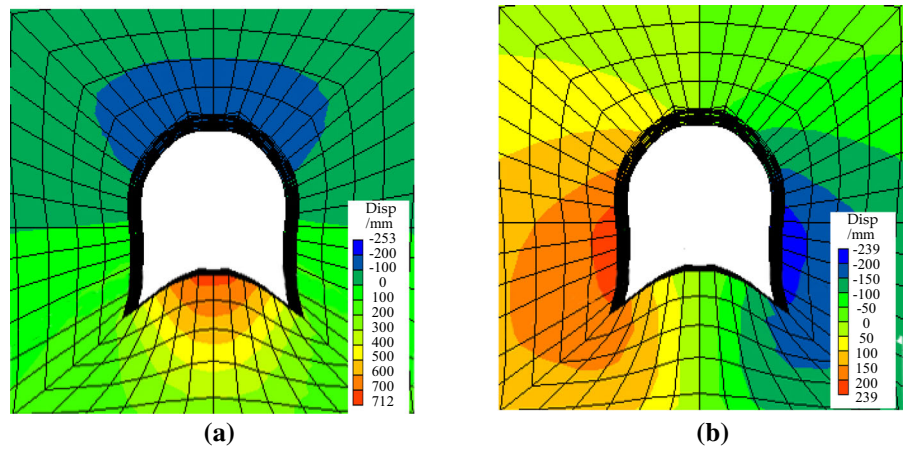


Fig. 14 Cable anchor + base angle bolt support surrounding rock displacement diagram. **a** Vertical direction and **b** displacement vector diagram of the roadway surrounding rock

Table 5 Deformation value of the surrounding rock of the roadway under different supporting forms

Support form	Contraction of the two sides (mm)	Amount of sinking of the roof (mm)	Floor heaves (mm)
Bolt-mesh-spurting supporting	812	337	1080
Bolt-mesh-spurting supporting + cable supporting	478	253	712
Bolt-mesh-spurting supporting + cable supporting + base angle bolt	342	159	137

After the truss is erected and contacts the surrounding rock, the soft layer truss coordinates with the surrounding rock to release the deformation energy. Because the flexible truss has sufficient strength and rigidity to prevent the surrounding rock from moving outward, the displacement of the surrounding rock of the roadway is very small. The maximum amount of the roadway floor heave is only 4.3 mm. Through the structural design, the concentrated stress of the surrounding rock is transformed into tensile, compressive or shear stress through the tie rods between the trusses, and the trusses are transferred to each other to exert the overall supporting effect between the flexible trusses so that the surrounding rock stress is uniformized. While releasing a large amount of deformation energy, the large deformation of the surrounding rock of the roadway is well controlled.

In summary, the cable anchor + base angle bolt + soft layer truss support technology employed to control roadway floor heave and maintain the overall stability of the roadway is feasible and reliable.

5 Engineering Application Effects

The cable anchor + base angle bolt + flexible layer truss coupling support technology is applied to the rework project of the monorail lane of the Liuhai Mine. To verify the control effect of the technology on the tunnel heaving floor, layout station to monitor roadway deformation. Part of the results are shown in Fig. 16.

It can be seen from the graph that before the truss is erected, the surrounding rock is greatly deformed, and the surrounding rock deformation tends to be stable after the surrounding rock contacts the truss. The maximum displacement of the two sides is 295 mm, and the average deformation rate is

6.9 mm/day. The amount of sinking of the top plate is 132 mm, and the average sinking rate is 3.1 mm/day. The maximum heaving floor is 116 mm, and the average heaving floor is 2.7 mm/day. The results show that the cable anchor + base angle bolt + flexible layer truss coupling support technology has a good effect, which fundamentally controls roadway floor heave and ensures the stability of the full section of the roadway. The effect of on-site support is shown in Fig. 17.

6 Conclusions

1. Based on the analysis of deformation failure phenomena and floor heave characteristics of deep soft rock roadway in the Paleogene, according to its forming mechanism, it can be divided into three types: strong expansion floor heave, high stress rheologic floor heave and compound floor heave. Through comprehensive analysis, it is pointed out that the main reason of floor heave in Paleogene deep soft rock roadway is the composite soft rock (HJS) with high stress joints and strong expansion. The direct reason is the improper supporting theory and the backward supporting design method.
2. The composite deformation mechanics mechanism of the monorail lane is determined, namely, $I_{AC} II_{ABD} III_{AC} III_E$. The transformation of the complex deformation mechanics mechanism into a single deformation mechanics mechanism through reasonable technology is the key to the support success. According to the specific situation for the Liuhai Mine, the cable anchor + base angle bolt + soft layer truss coupling support technology is proposed to control roadway floor heave.

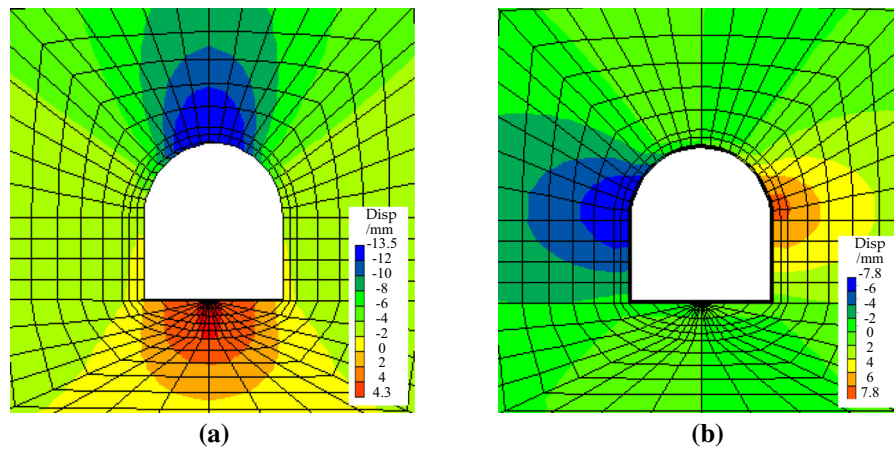


Fig. 15 Displacement diagram of the surrounding rock after contact between the surrounding rock and soft layer truss. **a** Vertical direction and **b** horizontal direction

Fig. 16 Monitored displacement–time curve in the field

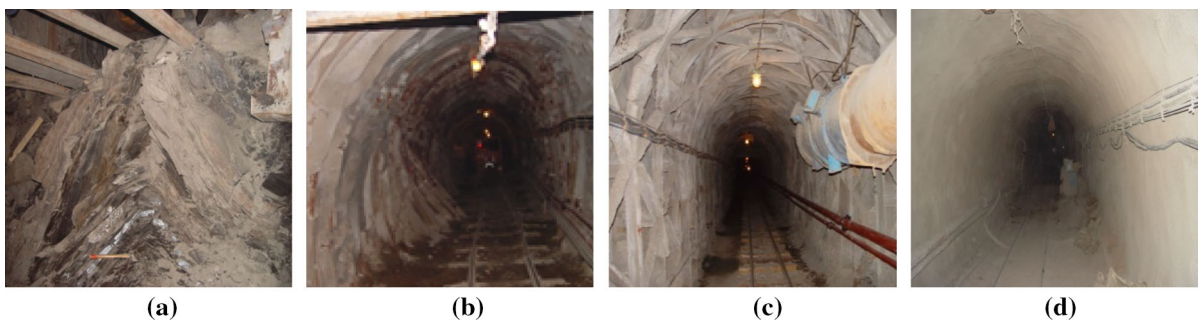
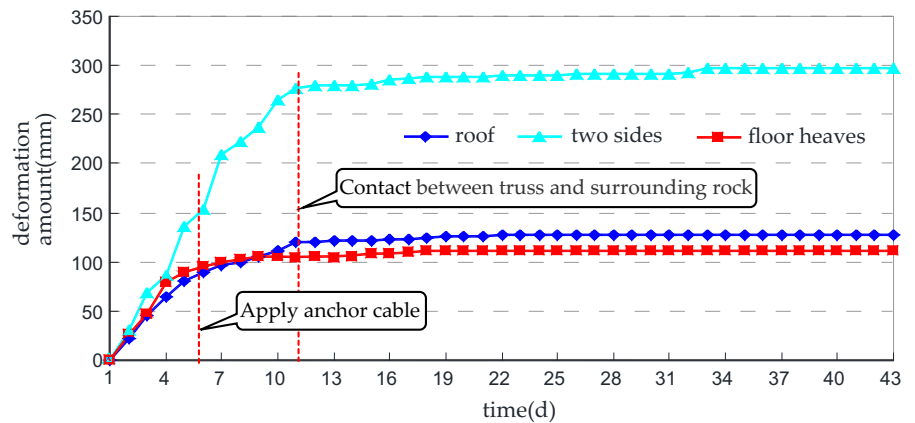


Fig. 17 On-site support effect diagram. **a** Original support for severe floor heave, **b** original support for floor heave and harvested sides, **c** new technology shotcrete and **d** new technology permanent support

3. Through the numerical analysis and field application, the rationality and reliability of the support scheme have been verified. The cable anchor +

base angle bolt + truss coupling support technology is successful in controlling roadway floor heave. Not only does it fundamentally change the

situation whereby the Liuhai mine is difficult to support and maintain, the rate of repair is high, and serious roadway floor heave occurs, it also saves much support costs as a permanent lane.

Acknowledgements This work is supported by the National Key Research and Development Program (Grant Nos. 2018YFC0603705 and 2016YFC0600901) and National Natural Science Foundation of China (Grant No. 51674265) and China Postdoctoral Science Foundation (Grant No. 2019M650896), which are gratefully acknowledged.

Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

References

- Bai JB, Li WF, Wang XY et al (2011) Mechanism of floor heave and control technology of roadway induced by mining. *J Min Saf Eng* 28(1):1–5 (**in Chinese**)
- Chu MX, Wang QB, Xia JM (2011) Study on formation mechanism and prevention technology of heaving floor in goaf side roadway. *Rock Soil Mech* 32(S2):413–417 (**in Chinese**)
- Guo ZB, Li Q, Wang J (2009) Coupling technology of cable-column-truss coupling in deep soft rock roadway and its engineering application. *Chin J Rock Mechan Eng* 28(S2):3914–3919 (**in Chinese**)
- Guo ZB, Wang J, Zhang YL (2015) Failure mechanism and supporting measures for large deformation of Tertiary deep soft rock. *Int J Min Sci Technol* 25(01):121–126
- He MC, Sun XM (2004) Guidelines for design and construction of support for soft rock roadway engineering in China. Beijing, Science Press, pp. 280–281
- He MC, Guo ZB, Ren AW et al (2005) Research on deep soft rock support design for rehabilitated works of Liuhai Mine Transportation Roadway. *Chin J Geotech Eng* 27(9):977–980 (**in Chinese**)
- He MC, Xie HP, Peng SP et al (2006) Study on rock mechanics in deep mining engineering. *Chin J Rock Mech Eng* 24(16):2803–2813
- Hou CJ, He YN, Li X et al (1995) Reinforcing sidewalls and corners of gateway to control floor. *J China Coal Soc* 20(3):229–234 (**in Chinese**)
- Jiang DH, Li GJ, Ma WQ et al (2018) Mechanism of non-harmonious roadway floor heave in complex jointed rock mass and control measures. *J Min Saf Eng* 35(02):238–244 (**in Chinese**)
- Kang HP (1993) Mechanism and prevention of bottom sill in soft rock roadway. Beijing, China Coal Industry Publishing House, pp 5–10
- Li SQ (2004) Research on the mechanism and control of floor heave of roadway of soft rock in Gequan Mine. Doctor's Thesis, Central South University (**in Chinese**)
- Lin QS, Liu XW, Huang X et al (2013) Research on the floor heave reasons and supporting measures of deep soft-fractured rock roadway. *J China Coal Soc* 38(4):566–571 (**in Chinese**)
- Liu QS, Huang SB, Cui XZ et al (2015) Control measures and monitoring analysis for floor heave of the chamber in deep coal mine. *Rock Soil Mech* 36(12):3506–3515 (**in Chinese**)
- Qian QH (2004) The characteristic scientific phenomenon of deep rock engineering response and the definition of “deep”. *J East China Univ Technol* 27(1):1–5 (**in Chinese**)
- Wang WJ, Feng T (2005) Study on mechanism of reinforcing sides to control floor heave of extraction opening. *Chin J Rock Mechan Eng* 24(5):808–811 (**in Chinese**)
- Wang C, Wang Y, Lu S (2000) Deformational behavior of roadway rocks in underground coal mines and principles for stability control. *Int J Rock Mech Min Sci* 37(6):937–946
- Wang J, Guo ZB, Yan YB et al (2012) Floor heave in the west wing track haulage roadway of the Tingnan Coal Mine: mechanism and control. *Int J Min Sci Technol* 22:295–299
- Wang XQ, Kan JG, Jiao JK (2017a) Mechanism of floor heave in the roadway with high stress and soft rock and its control practice. *J Min Saf Eng* 34(02):214–220, 227 (**in Chinese**)
- Wang Q, Jiang B, Pan R et al (2017b) Failure mechanism of surrounding rock with high stress and confined concrete support system. *Int J Rock Mech Min Sci* 102:89–100
- Xie HP (2006) Engineering disasters and basic science problems induced by deep mining 1–12 (**in Chinese**)
- Yang BS, Geng XL, Sun LH et al (2012) Research on floor heave mechanism of thick seam road-way in Wuyang coal mine and its control. *J Min Saf Eng* 29(1):8–13 (**in Chinese**)
- Yang XJ, Lou HP, Cui N et al (2015a) Study on large deformation mechanism and support of soft rock roadway. *Coal Sci Technol* 43(09):1–6 (**in Chinese**)
- Yang J, Wang D, Shi HY et al (2015b) Deformation failure and countermeasures of deep tertiary extremely soft rock roadway in Liuhai coal mine. *Int J Min Sci Technol* 25(02):231–236
- Zheng PQ, Chen WZ, Tan XJ et al (2015) Study of failure mechanism of floor heave and supporting technology in soft rock of large deformation roadway. *Chin J Rock Mechan Eng* 34(S1):3143–3150 (**in Chinese**)

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.