Research Article

Experimental Study on Deformation Law of Rectangular Roadway in Horizontal Layered Rock Mass

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1. Introduction

With the exploitation of shallow resources, the mining industry began to focus on the exploitation of deep underground resources. The environment makes the deep rock mechanical characteristics and engineering responses very distinctive [1–4]. Due to the high stress of deep rock stratum, its strength is weaker than that of shallow rock stratum, which is prone to large deformation and failure. The large deformation of surrounding rock in deep roadway will lead to narrow road, hinder transportation, affect normal production and cause casualties [5–8].

Physical model experiment is an important research method of roadway deformation and failure. Reference [9] reproduced the zonal fracture process of surrounding rock in deep roadway through three-dimensional geomechanical model test of similar materials. Reference [10] used similar material simulation test to study the deformation and failure characteristics of roadway surrounding rock under different horizontal stress. Reference [11] studied the response characteristics of transient electromagnetic field of mine water rich abnormal body through physical model experiment. Reference [12] developed variable temperature similar materials, and carried out failure test on the model by combining overload and strength reduction. Reference [13] developed a large geomechanical model test system and carried out model tests on the anchor cable box girder support system. Reference [14] used similar materials of transparent rock mass to physically simulate the excavation process of rock mass.

In the process of physical model experiment, the deformation and failure characteristics of roadway surrounding rock can be obtained by means of displacement, infrared and strain measurement [15–21], physical modeling plays an indispensable and key role in understanding the deformation and failure mechanism of deep roadway [22, 23]. Constructing large-scale physical model experiment can avoid the scaling problem of parameters and variables, but it is expensive [24]. In recent years, a new physical modeling technique, that is, the Physically Finite Elemental
Slab Assemblage (PFESA) has been proposed to construct large-scale geological physical models for mimicking stratified rock masses [25, 26]. Although the Elemental Slabs are made of artificial materials, the physical and mechanical properties are similar to the real rocks. It can be put into mass production at low cost, and the cost of building a large-scale physical model is greatly reduced.

Based on the similarity theory, a physical model is established by using the PFESA technique to simulate the deep horizontal layered rock mass. Using camera, digital image correlation system and strain gauge, the deformation and strain of rock stratum are simulated by physical model under load, and the deformation and failure mechanism of surrounding rock of rectangular roadway in layered rock mass under high stress is analyzed.

2. Physical Model Construction

2.1. Physical Model Prototype. The physical model experimental prototype is located in the −510 m horizontal roadway with a buried depth of about 1000 m in Datai mine, Mentougou District, Beijing. The study area is monoclinal structure without large-scale geological structure. Diabase, green mudstone, and coal rock are distributed in the stratum where the roadway is located. According to the in situ stress test, the maximum principal stress of the studied stratum is 39.7 MPa, the included angle with the horizontal plane is 2.11°, and the minimum principal stress is 19.2 MPa. The direction of the maximum principal stress is basically consistent with the dip direction of the stratum, which is unfavorable to the stability of the surrounding rock of the roadway. According to the mechanical test, it is found that the bedding of roadway surrounding rock is developed, and the uniaxial strength along the bedding is greater than that perpendicular to the bedding, which has obvious anisotropic characteristics.

2.2. Similarity Principle and Materials. Based on the similarity proportion relationship, when studying the similarity of stress, deformation, and failure characteristics of roadway surrounding rock, the prototype and physical model should meet the similarity index [27, 28].

\[ I_\sigma = \frac{C_\sigma}{C_l C_I} = 1 \]  
\[ I_E = \frac{C_E}{C_l C_I} = 1 \]  

In equations (1) and (2), Cl is the geometric similarity factor, Cσ is the stress similarity factor, CE is the elastic modulus similarity factor, Cγ is the gravity similarity factor, Iσ is the stress similarity index, IE is the elastic modulus similarity index. The dimensions of the physical model are 1600 × 1600 × 400 mm³ and the roadway is designed as a rectangular space in the center of the physical model with the length and width of 200 × 300 mm². The geometric similarity factor is selected empirically as CI = 15, which meets the requirements in experimental system operating instruction of physical models in deep mine engineering. In addition, the physical model should also satisfy other similarity theories, including the stress similarity factor, defined as Cσ = 9.

The prototype rock mass to be simulated in this paper is diabase, green mudstone, and coal rock, and its mechanical parameters are given in Table 1. The PFESA technique is employed here. This method utilizes the assembly of rectangular plates which are made of artificial materials according to “similarity theory.” The elemental slabs are produced based on different ratio of water–gypsum. The material properties of the elemental slabs simulating the different rock masses are given in Table 2.

2.3. Model Design and Production. The elementary slabs are made through the process of pouring, demolding, and curing as shown in Figures 1(a)–1(c). In order to simulate the inclined rock strata, large numbers of these slabs are arranged at the specified orientation, which is 0° in this case, as shown in Figure 1(d). Different types of elementary slabs simulate different prototype rock masses. According to the on-site stratigraphic structure and geometric similarity factor, the type and range of rock mass simulated by physical model are shown in Figure 1(e).

3. Loading Conditions and Testing Techniques

3.1. Loading Scheme. The experimental loading scheme mainly simulates the stress conditions of rock mass, the process of roadway excavation and the deformation and failure process of roadway caused by high stress. The “Geological Disaster Simulation Testing Machine whose model type is YDMC-C” was equipped with a host machine, specimen mold, truck, hydraulic control system, and data collection system. By using YDMC-C, the top and two side boundaries were imposed uniform load, respectively; the bottom of the model was fixed on the basement of the machine, the loading boundary pressure conditions are shown in Figure 2.

The loading process can be divided into 23 load levels, and the loading scheme of model experiment is shown in Table 3. At load levels 1–4, vertical and horizontal pressures increase at the same time, resulting in stress conditions in the rock mass. After load level 4 loading, roadway excavation is carried out. The horizontal pressure of load levels 5–14 is maintained at 0.8 MPa, and the vertical pressure is increased to 2.8 MPa step-by-step. The simulated vertical stress value reaches the condition of 1000 m buried depth. The vertical pressure of load levels 15–24 is maintained at 2.8 MPa, and the horizontal pressure increases step-by-step until the model is damaged. In this paper, the roadway is deformed and damaged under 23 load level, and the experiment is stopped. The physical model and the prototype rock stress condition accord with the similarity theory.

3.2. Displacement Test. Digital image correlation (DIC) technology is a non-contact displacement measurement method [29, 30]. In this paper, MTI-2D digital image
correlation measurement system is used to measure the surface displacement field of physical model in real time [31]. When using DIC technology, it is necessary to arrange randomly distributed spots on the surface of the measured object. The spots arrangement is shown in Figure 3(a). These artificial random spots are used as the carrier of deformation information to realize the whole field displacement measurement. In the measurement, set the positive direction of vertical displacement downward and the positive direction of horizontal displacement to the right. During the measurement, real-time displacement monitoring points are set for the roof, floor, left and right sides of the roadway surrounding rock, as shown in Figure 3(b).

3.3. Strain Test. The strain of the model is measured by strain gauge. BA120-3BA strain gauge was used in the experiment, and the sensitive grid size of strain gauge is 3 mm × 2 mm, the sensitivity coefficient is $2.10 \pm 1\%$. A groove with a depth of about 2 mm shall be excavated in the thickness direction.

| Rock types          | Dimensions of the slabs (cm) | Ratio of water to gypsum | Unit weight (kN/m²) | Compressive strength (MPa) | Tensile strength (MPa) | Elastic modulus (GPa) | Poisson ratio | Friction angle (°) |
|---------------------|------------------------------|--------------------------|---------------------|-----------------------------|------------------------|----------------------|---------------|-------------------|
| Diabase             | 40 × 40 × 2                  | 0.8 : 1                  | 10.32               | 9.05                        | 1.01                   | 3.22                 | 0.11          |
| Green mudstone      | 40 × 40 × 2                  | 1 : 1                    | 9.45                | 4.53                        | 0.53                   | 2.13                 | 0.31          |
| Coal seam           | 40 × 40 × 1                  | 1.2 : 1                  | 7.33                | 2.01                        | 0.24                   | 0.69                 | 0.39          |

Table 1: Mechanical parameters of the prototype rock mas.

| Rock types          | Unite weight (kN/m³) | Compressive strength (MPa) | Tensile strength (MPa) | Elastic modulus (GPa) | Poisson ratio | Friction angle (°) |
|---------------------|----------------------|----------------------------|------------------------|----------------------|---------------|-------------------|
| Diabase             | 28.47                | 102.74                     | 8.72                   | 20.24                | 0.32          | 57                |
| Green mudstone      | 27.45                | 46.96                      | 4.57                   | 16.82                | 0.18          | 54                |
| Coal                | 18.29                | 14.82                      | 0.37                   | 7.20                 | 0.21          | 48                |

Table 2: Material properties parameters of the elementary slabs.
of the elementary slabs. When the strain gauge is bonded in the groove, it shall be flat and firm, and it shall be cured for ten mins. Because the rock stratum is horizontal and the loading direction is vertical and horizontal, two right angle strain flowers are adopted, and the strain measurement range is shown in Figure 1(e).

4. Deformation and Failure Process

4.1. Deformation Characteristics

4.1.1. Video Images Analysis. During the experiment, the physical model was videotaped. According to the loading scheme and deformation phenomenon, the video screenshot shown in Figure 4 is obtained. The deformation of roadway surrounding rock is not obvious under level 4 and 14 loads. Under the 23 load level, the corresponding vertical stress is 25.2 MPa and the horizontal stress is 39.6 MPa, the deformation phenomenon is obvious. When the cumulative duration is 541 mins, the floor heave of the roadway appears, the scope of the floor heave expands at 542 mins, the floor heave continues to expand at 543 mins, and the roof begins to sink. In the cumulative duration 544 mins, the surrounding rock of the roadway was greatly deformed and damaged due to roof subsidence and floor heave. After the similarity ratio conversion, the stress conditions are close to

![Figure 2: Loading boundary pressure conditions.](image)

| Load level | Simulated depth (m) | Applied pressure (MPa) | Horizontal pressure coefficient | Duration (mins) | Cumulative duration (mins) |
|------------|---------------------|------------------------|---------------------------------|-----------------|---------------------------|
| 1          | 70                  | 0.2 0.2                | 1                               | 30              | 1–30                      |
| 2          | 140                 | 0.4 0.4                | 1                               | 30              | 31–60                     |
| 3          | 210                 | 0.6 0.6                | 1                               | 30              | 61–90                     |
| 4          | 280                 | 0.8 0.8                | 1                               | 30              | 91–120                    |
| 5          | 350                 | 1.0 0.8                | 0.8                             | 30              | 121–150                   |
| 6          | 420                 | 1.2 0.8                | 0.67                            | 30              | 151–180                   |
| 7          | 490                 | 1.4 0.8                | 0.57                            | 30              | 181–210                   |
| 8          | 560                 | 1.6 0.8                | 0.5                             | 30              | 211–240                   |
| 9          | 630                 | 1.8 0.8                | 0.44                            | 30              | 241–270                   |
| 10         | 700                 | 2.0 0.8                | 0.4                             | 30              | 271–300                   |
| 11         | 770                 | 2.2 0.8                | 0.36                            | 30              | 301–330                   |
| 12         | 840                 | 2.4 0.8                | 0.33                            | 30              | 331–360                   |
| 13         | 910                 | 2.6 0.8                | 0.31                            | 30              | 361–390                   |
| 14         | 1000                | 2.8 0.8                | 0.29                            | 30              | 391–420                   |
| 15         | 1000                | 2.8 1.2                | 0.43                            | 15              | 421–435                   |
| 16         | 1000                | 2.8 1.6                | 0.57                            | 15              | 436–450                   |
| 17         | 1000                | 2.8 2.0                | 0.71                            | 15              | 451–465                   |
| 18         | 1000                | 2.8 2.4                | 0.86                            | 15              | 466–480                   |
| 19         | 1000                | 2.8 2.8                | 1                               | 15              | 481–495                   |
| 20         | 1000                | 2.8 3.2                | 1.07                            | 15              | 496–510                   |
| 21         | 1000                | 2.8 3.6                | 1.29                            | 15              | 511–525                   |
| 22         | 1000                | 2.8 4.0                | 1.43                            | 15              | 526–540                   |
| 23         | 1000                | 2.8 4.4                | 1.57                            | 10              | 541–550                   |
the in situ stress test results of the roadway. Based on the above analysis, the stability of roadway surrounding rock can be divided into stable stage with cumulative duration of 0–540 mins, failure stage with cumulative duration of 541–544 min and post-failure stage after 544 min.

4.1.2. Displacement Analysis. The vertical displacement field of the model under different load levels is shown in Figure 5. The vertical displacement of the upper part of the physical model is large under 4 and 14 level loads. Under the load level 23, the floor of the roadway produces floor heave, and the vertical displacement reaches 15.1 mm. With the progress of loading, the roadway roof sinks by 75.9 mm and the floor bulges by 118.7 mm.

The variation of horizontal displacement field of the model under different loads is shown in Figure 6. The maximum horizontal displacement occurs on both sides of the roadway under level 4 and 14 loads. Under the action of horizontal pressure, the elementary slabs are easy to slip along the bedding plane, and the two surrounding rocks move integrally into the roadway. When the load is
level 23, the two sides move integrally into the roadway, and there are horizontal displacement staggered zones in the roadway floor and roof strata, resulting in shear deformation.

4.1.3. Displacement Analysis of Measuring Points. When the cumulative duration of the experiment is 541 to 544 mins, it is the roadway failure stage. Extract the displacement data of floor, roof, left side, and right side monitoring points in the failure stage and adjacent time of roadway surrounding rock. The layout of monitoring points is shown in Figure 3(b).

The vertical displacement curve of roadway surrounding rock measuring points with a cumulative duration of 539–550 mins and a total of 660 sec is shown in Figure 7. In the failure stage, the F01 monitoring point of roadway floor first produces floor heave, and the vertical displacement is 120 mm, then the R01 monitoring point of roadway roof sinks, and the final vertical displacement is 44 mm. During the vertical change of roadway floor and roof, the vertical displacement of left and right sides fluctuates slightly.

The horizontal displacement curve of roadway surrounding rock measuring points with a cumulative duration of 539–550 mins and a total of 660 sec is shown in Figure 8. In the failure stage, the monitoring point F01 of the roadway floor moves 25 mm horizontally to the roadway, and the movement amount of F02 and F03 is lower than F01. R01 monitoring point of roadway roof moves horizontally to the right by 16 mm, and R02 and R03 monitoring points move horizontally to the left. The monitoring points LS01, LS02, and LS03 on the left side of the roadway move horizontally into the roadway, with a displacement of about 20 mm. The monitoring points RS01, RS02, and RS03 on the right side of the roadway move about 20 mm into the roadway.

By analyzing the deformation characteristics of the model, it can be concluded that the surrounding rock of the roadway can be divided into stable stage, failure stage, and post-failure stage, and the displacement in the failure stage appears sudden change. The failure form of roadway surrounding rock is roof collapse, floor heave, and the two sides slide into the roadway as a whole.

4.2. Strain Characteristic Analysis

4.2.1. Strain Field Analysis. The vertical and horizontal strain values of the measuring points during the experiment can be obtained by sticking the strain gauge. Based on Kriging interpolation algorithm, calculate the strain values of each strain monitoring point to obtain the evolution of vertical strain field of physical model, as shown in Figure 9.

At the level 4 load, the vertical compressive strain is distributed in the lower part of the model, and the tensile strain is distributed in the upper part of the model and the surrounding rock of the roadway. The range of vertical compressive strain and strain value of the model increase under level 14 load. Under the 23 level load, the surrounding rock of the roadway enters the failure stage, and the vertical tensile strain area is concentrated in the roof and floor of the roadway.

Figure 5: Evolution of vertical displacement field under different loads; (a) Under load level 4; (b) Under load level 14; and (c–e) Under load level 23 and cumulative duration is 541 mins, 542 mins, 543 mins and 544 mins, respectively. (unit: mm).
The evolution of horizontal strain field under different loads is shown in Figure 10. Under level 4 load, the roof and floor of the roadway are horizontal compressive strain, and the two sides of the roadway are horizontal tensile strain. There is horizontal strain concentration on the left and right sides of the roadway surrounding rock under level 14 load. After entering the failure stage under level 23 load, the strain concentration area appears in the roof, then the strain concentration occurs in the floor, and finally the compressive strain also occurs in the two sides of the roadway surrounding rock.

4.2.2. Strain Analysis of Measuring Point. When the cumulative duration is 539–550 mins, the vertical strain of the measuring points is shown in Figure 11. In the failure stage, the vertical tensile strain of R01 and R02 monitoring points suddenly increases, and the vertical compressive strain at R03 monitoring suddenly decreases. The vertical tensile strain at F01 monitoring decreases, and the horizontal compressive strain at F02 and F03 monitoring points increases. The vertical tensile strain of the monitoring points on the left side of the roadway are increased. RS01 on the right side of the roadway changes from vertical compressive strain to tensile strain, and the vertical compressive strain of RS02 and RS03 increases.

When the cumulative duration is 539–550 mins, the horizontal strain at the measuring points is shown in Figure 12. In the failure stage, the horizontal compressive strain at the monitoring points R01 and R02 increases and then falls back to close to the original value, and the horizontal strain at the monitoring point R03 does not change significantly. The horizontal tensile strain at F01 monitoring point decreases, and the horizontal compressive strain at F02 and F03 monitoring points increases. The horizontal compressive strain of LS01 and ls03 monitoring points decreases, and the strain of LS02 monitoring point approaches zero. The horizontal compressive strain of RS01 monitoring point is gradually transformed into tensile strain, the horizontal tensile strain of RS02 monitoring point rises and then falls, and the horizontal compressive strain of RS03 monitoring point drops suddenly.

Through the analysis of the strain characteristics of the model, it can be concluded that the vertical tensile strain area in the failure stage is concentrated in the roof and floor of the roadway, and the horizontal compressive strain is concentrated in the left and right sides. When the surrounding rock of the roadway is unstable, the strain changes abruptly, accompanied by the transformation of tension and compression strain.

4.3. Stress Characteristic Analysis. Under the vertical and horizontal loading conditions of the physical model, the strain measuring point is subject to the vertical stress $\sigma_V$ and
horizontal stress \( \sigma_H \). The elastic modulus of the physical model material is \( E \), and the Poisson’s ratio is \( \mu \). Vertical strain of strain measuring point \( \epsilon_V \) and horizontal strain \( \epsilon_H \) can be expressed as:

\[
\epsilon_V = \frac{\sigma_V}{E} - \frac{\sigma_H}{E} = \frac{1}{E} (\sigma_V - \mu \sigma_H),
\]

\[
\epsilon_H = \frac{\sigma_H}{E} - \frac{\sigma_V}{E} = \frac{1}{E} (\sigma_H - \mu \sigma_V).
\]

Formula (3) is transformed to obtain

\[
\sigma_V = \frac{E}{1 - \mu} (\epsilon_V - \mu \epsilon_H),
\]

\[
\sigma_H = \frac{1}{1 - \mu} (\epsilon_H - \mu \epsilon_V).
\]

After the vertical strain and horizontal strain values of the measuring points are obtained through strain monitoring, the vertical stress \( \sigma_V \) and horizontal stress \( \sigma_H \) can be calculated according to formulas (3) and (4) [32]. Using Kriging interpolation algorithm, according to the location and value of stress monitoring points, the evolution diagrams of vertical and horizontal strain fields of physical model can be obtained.

4.3.1. Stress Field Analysis. The evolution of vertical stress field under different loads is shown in Figure 13. The surrounding rock of roadway is mainly subjected to vertical tensile stress under level 4 and 14 loads. When the load is level 23, the roadway enters the failure stage, the surrounding rock of the roadway is mainly affected by the vertical tensile strain, and there is an obvious concentration of tensile strain on the roof and floor.

The evolution of horizontal stress field under different loads is shown in Figure 14. Under level 4 load, the roof and floor of the roadway are horizontal compressive stress, and the two sides are horizontal tensile stress. Under level 14 load, there is horizontal compressive stress concentration on the left and right sides of the roadway surrounding rock. Under the level 23 load, the roadway enters the failure stage. At the beginning of the failure, the surrounding rock of the roadway produces compressive stress, and then the stress concentration area of the roof and floor appears. The roof and floor of the roadway are mainly subject to horizontal compressive stress, and the left and right sides are mainly subject to horizontal compressive stress.

4.3.2. Stress Analysis of Measuring Point. When the cumulative duration is 539–550 mins, the vertical stress at the measuring points is shown in Figure 15. In the failure stage, the vertical tensile stress of R01 and R02 monitoring points increases, and the vertical compressive stress of R03 suddenly decreases. The vertical tensile stress of F01 monitoring point drops suddenly, the vertical stress of F02 monitoring point changes from compressive stress to tensile stress, and the vertical stress of F03 monitoring point changes from tensile stress to compressive stress. The vertical tensile stress values of the monitoring points on the left side of the roadway are increased. The vertical stress of R01 monitoring point changes from compressive to tensile, and the vertical compressive stress of R02 and R03 monitoring points increases.

The horizontal stress of monitoring points when the cumulative duration is 539–550 mins is shown in Figure 16. The horizontal compressive stress of roof R01 monitoring point increases and then decreases, the compressive strain of R02 monitoring point increases, and the horizontal tensile stress of R03 monitoring point remains stable. The horizontal tensile stress at F01 monitoring point decreases, and then the stress decreases to zero. The horizontal compressive stress of R01 monitoring point is gradually transformed into tensile stress, the horizontal tensile stress of R02 monitoring point rises and then falls back, and the horizontal compressive stress of R03 monitoring point drops suddenly.

In the failure stage of roadway surrounding rock, the tensile stress concentration appears in the left and right sides, and the stress of roadway surrounding rock suddenly changes, accompanied by the transformation of tensile and compressive stress.

4.4. Comparative Analysis of Stress and Displacement. The stress and displacement of the monitoring points of the roof, floor, left side and right side of the roadway surrounding rock with a cumulative duration 539–550 mins and a total of 660 sec are shown in Figures 17–20. About 120–360 sec in the figures corresponds to the failure stage with cumulative duration of 541–544 mins. In the figures, where \( \sigma_V \) is vertical stress, \( \sigma_H \) is horizontal stress, \( \epsilon_V \) is the change in vertical displacement due to loading, \( \epsilon_H \) is the change in horizontal displacement due to loading.

The stress and displacement of roadway roof measuring points when the cumulative duration is 539–550 mins is shown in Figure 17. R1 is horizontally compressed and vertically tensioned, moving horizontally to the right and vertically downward. R2 monitoring point is horizontally compressed and vertically tensioned, moving horizontally to the left and vertically downward. R3 monitoring point is horizontally compressed, vertically compressed, horizontally moved to the left and vertically moved upward. It can be seen that in the deformation and failure area of roadway roof, the rock stratum is pulled vertically, sinks into the roadway, and is pressed horizontally, resulting in interlayer sliding.

The stress and displacement of roadway floor measuring points when the cumulative duration is 539–550 mins is shown in Figure 18. F1 monitoring point is horizontally compressed and vertically tensioned, moving horizontally to the right and vertically upward. F2 monitoring point is horizontally compressed and vertically tensioned, moving horizontally to the left and vertically upward. F3 monitoring point...
point is horizontally compressed and vertically compressed, moving horizontally to the left and vertically downward. It can be seen that the deformation and failure mode of roadway/ floor is that the rock stratum is vertically tensioned, bulged into the roadway, and horizontally compressed, resulting in interlayer sliding.

The stress and displacement of roadway left side measuring points when the cumulative duration is 539–550 mins is shown in Figure 19. LS1 monitoring point is horizontally compressed and vertically tensioned, moving horizontally to the right and vertically downward. LS2 monitoring point is horizontally compressed and vertically tensioned, moving horizontally to the left and vertically downward. LS3 monitoring point is horizontally compressed and vertically tensioned, moving horizontally to the left and vertically downward. It can be seen that the left side of the roadway slides into the roadway as a whole and sinks in the sliding.

The stress and displacement of roadway right side measuring points when the cumulative duration is 539–550 mins is shown in Figure 20. RS1 monitoring point is tensioned horizontally and vertically, moving horizontally to the left and vertically downward. RS2 monitoring point is tensioned horizontally and vertically, moving horizontally to the down. RS3 monitoring point is...
horizontally tensioned and vertically compressed, moving horizontally to the left and vertically downward. RS3 monitoring point is pressed horizontally and vertically, moving horizontally to the left and vertically to the down. It can be obtained that the right side of the roadway moves integrally into the roadway and sinks in sliding.

It can be seen that in the stage, the strata on the left and right sides of the roadway continue to slide toward the interior of the roadway, the displacement values of the two monitoring points continue to rise, and the strata around the roof and floor of the roadway are subject to shear sliding. With the increase of sliding value, the roof and floor strata are sheared and destroyed. At this time, the displacement of roof monitoring points and floor monitoring points increases abruptly, and the surrounding rock of the roadway is damaged.

4.5. Mechanism of Deformation and Failure of the Model.
Taking advantage of rock structural mechanics, combining the situation of the model test, the rock structural mechanics

![Figure 8: Horizontal displacement of measuring points when the cumulative duration is 539–550 mins; (a) R01, R02, and R03; (b) F01, F02, and F03; (c) LS01, LS02, and LS03; and (d) RS01, RS02, and RS03.](image)
Figure 9: Evolution of vertical strain field under different loads; (a) Under load level 4; (b) Under load level 14; and (c–e) Under load level 23 and cumulative duration is 541 mins, 542 mins, 543 mins, and 544 mins, respectively.

Figure 10: Evolution of horizontal strain field under different loads; (a) Under load level 4; (b) Under load level 14; and (c–e) Under load level 23 and cumulative duration is 541 mins, 542 mins, 543 mins, and 544 mins, respectively.
models are established, as shown in Figure 21(a). For the same rock stratum, the elastic deformation of rock is an elastic constraint condition. $Q_V$ and $Q_N$ are the loading provided by the constraints, $Q_H$ is the loading provided by hydraulic system.

For the same layer, the mechanical model of left side is shown in Figure 21(b), and the mechanical model of right side is shown in Figure 21(c), the mechanical analysis is

$$F_x = P_H = f + F_n,$$
$$F_y = P_V = N,$$  \hspace{1cm} (5)

where $F_x$ is the horizontal resultant force; $F_y$ is the vertical resultant force; $P_H$ is the horizontal load; $P_V$ is the vertical load; $f$ is the frictional force; $F_n$ is the axial force along the stratum; $N$ is the interlayer pressure.

It can be concluded that horizontal load $P_H$ and vertical load $P_V$ have the same effect on the left and right strata. In no excavated area, the sliding should conquer $f$ and $F_n$ and the sliding space is necessary, which comes from the construction gap and elastic deformation of rock itself.

The value of $f$ and $F_n$ is as the equation, respectively:

$$f = F_y \times \tan \beta,$$
$$F_n = E \Delta l,$$  \hspace{1cm} (6)

where $\beta$ is the frictional angle of rock interface; $E$ is the elasticity modulus of stratum along the layers; $\Delta l$ is the

Figure 11: Vertical strain of measuring points when the cumulative duration is 539–550 mins; (a) R01, R02, and R03; (b) F01, F02, and F03; (c) LS01, LS02, and LS03; and (d) RS01, RS02, and RS03.
deformation of the rock in the actuating range of $P_{II}$. When $F_x > f + F_n$, the sliding would happen. In the horizontal rock stratum, the left and right sides of the mechanical model are the same, so their sliding characteristics are consistent. The order of elastic modulus from small to large is coal seam, green mudstone, and diabase. Therefore, the order of model rock sliding from easy to difficult is also coal seam, green mudstone, and diabase.

After excavation, it turned into bidirectional compression stress state along the tangent direction of the roadway from triaxial stress state in a certain range of surrounding rock. Because there is no supporting measure for the tunnel, $F_n$ equals zero, when the friction $f$ between layers was overcome, and the strata move toward the tunnel along the inclined direction of strata. Under the action of horizontal load, the rock strata on both sides of the roadway are easy to slide to the interior of the roadway. The roof and floor strata of the roadway are easy to produce shear failure with the sliding, so they are easy to damage areas. The roof rock of the roadway is green mudstone, and coal seams are distributed.
Figure 13: Evolution of vertical stress field under different loads; (a) Under load level 4; (b) Under load level 14; and (c–e) Under load level 23 and cumulative duration is 541 mins, 542 mins, 543 mins, and 544 mins, respectively.

Figure 14: Evolution of horizontal stress field under different loads; (a) Under load level 4; (b) Under load level 14; and (c–e) Under load level 23 and cumulative duration is 541 mins, 542 mins, 543 mins, and 544 mins, respectively.
in the floor of the roadway, which has low shear modulus and is easier to slide.

According to the mechanical model analysis, in the 1–4 loading stage, the horizontal load \( P_H \) and vertical load \( P_V \) increase at the same time, \( P_H \) promotes the rock strata on the left and right sides of the roadway to slide into the roadway, \( P_V \) makes the rock strata more denser. In the 5–14 loading stage, the horizontal load remains unchanged, the vertical load increases, and the rock stratum is more denser. In the 15–23 loading stage, the vertical load remains unchanged and the horizontal load increases, which promotes the rock strata on the left and right sides of the roadway to slide into the roadway. The roof and floor strata of the roadway are easy to produce shear failure under the action of shear sliding, while the shear modulus of the coal seam of the roadway floor is lower than that of the roof green mudstone strata, which is more prone to deformation and failure. During the 23 loading, the balance was broken, the surrounding rock of the roadway is deformed and damaged.

4.6. Verification of Results By On-Site Monitoring. The deformation of the prototype roadway of the physical model experiment is monitored and analyzed to verify the accuracy.
of the physical model experiment. Displacement monitoring was carried out on multiple sections of the prototype roadway during the mining process (Figure 22). The plane position of the prototype roadway is shown in Figure 22(a). Each roadway monitoring section is arranged with four displacement monitoring points to measure the displacement of roof, floor, left side, and right side respectively. Figure 22(b) shows the layout of roadway displacement monitoring points.

During the mining process, instability failure occurred at the No. 1 monitoring section of the roadway, and the displacement curve of the failure section with time is statistically obtained, as shown in Figure 23. With the instability of roadway surrounding rock, the maximum value of roof subsidence is 0.67 m, the maximum value of floor heave is 0.94 m, and the maximum value of two sides moving into the roadway is 0.45 m. Through the comparison of the displacement monitoring data of the physical model.

**Figure 16:** Horizontal stress of measuring points when the cumulative duration is 539–550 mins; (a) R01, R02, and R03; (b) F01, F02, and F03; (c) LS01, LS02, and LS03; and (d) RS01, RS02, and RS03.
Figure 17: Stress and displacement of roadway roof measuring points when the cumulative duration is 539 to 550 mins; (a) monitoring curve of R01, R02, and R03; and (b–d) schematic diagram of R01, R02, and R03, respectively.

Figure 18: Continued.
It can be seen that the displacement changes of the two show the same change trend, which are the roof sinking, the floor bulging, the two sides sliding into the roadway, and the displacement change value basically conforms to the similarity theory.

The photographs after the instability of the No. 1 section of the prototype roadway are shown in Figure 24. The destruction form of the roadway surrounding rock is roof collapse, floor heave (Figure 24(a)), and the two sides move into the roadway as a whole (Figure 24(b)). The failure form of the prototype roadway is consistent with the physical model experiment. By comparing the physical model experiment with the prototype roadway displacement on-site monitoring and failure forms, it can be concluded that the roadway deformation characteristics obtained from the physical model experiment are consistent with the engineering practice, and the roadway deformation law obtained from the physical model experiment in this paper is reliable.
Figure 20: Stress and displacement of roadway right side measuring points when the cumulative duration is 539 to 550 mins; (a) monitoring curve of RS01, RS02, and RS03; and (b–d) schematic diagram of RS01, RS02, and RS03, respectively.

Figure 21: Diagrams of rock structural mechanics models; (a) diagram of rock structural mechanics model for the physical model; (b) diagram of rock structural mechanics model for stratum in the left of physical model; and (c) diagram of rock structural mechanics model for stratum in the right of physical model.
Figure 22: Design of roadway displacement monitoring; (a) Roadway plane position; (b) Layout of roadway displacement monitoring points.

Figure 23: Displacement monitoring curve of no. 1 section of prototype roadway.

Figure 24: Photos after instability of no. 1 section of prototype roadway; (a) Roof collapse and floor heave; (b) side sliding (unit: m).
5. Conclusions

This paper analyzed the characteristics and mechanisms of deformation based on the physical model test on deep rectangular roadway in layered rock. The main conclusions were summarized as follows.

(1) The physical model experiment process can be divided into three stages: stable stage, failure stage, and post-failure stage. In the stable stage, the physical model is compressed, the cracks between slabs are closed, and the model is gradually dense. After entering the load of failure stage, first the floor of the roadway heaves, then the roof sinks greatly, then the surrounding rocks of the two sides of the roadway slide into the roadway, and finally the surrounding rocks of the roadway are deformed and damaged.

(2) The deformation and failure of roadway surrounding rock occurs under the vertical load of 2.8 MPa and horizontal load of 4.4 MPa. After the surrounding rock of the roadway is damaged, the roof sinks 75.9 mm, the floor bulges 118.7 mm, the left side slides 39.7 mm horizontally into the roadway, and the right side slides 36.2 mm horizontally into the roadway. After similar calculation, the loading conditions are close to the field original rock stress after conversion, and the test results are in good agreement with the field test results of mine roadway surrounding rock.

(3) The failure stage of roadway surrounding rock is sudden, and the deformation and failure characteristics are greatly affected by the layered structure of horizontal strata. In the failure stage, the floor rock stratum is compressed horizontally and tensioned vertically, resulting in interlayer sliding and floor heave. The roof strata of the roadway are pulled vertically, sinking into the roadway, compressed horizontally and sliding along the layer. The roof and floor strata of roadway are easy to produce shear failure under the action of shear sliding. The rock strata on both sides of the roadway are easy to slide along the layer under horizontal load.

Data Availability

The data used to support the findings of this study are included within the paper.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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