Failure mechanisms of soft rock roadways in steeply inclined layered rock formations

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\textbf{ABSTRACT}

In recent years, with the increasing depth of coal mining around the world, traditional shallow geology mechanics are no longer suitable for the research on deep geological problems. In terms of deep mining, soft rock roadways in inclined rock formations show different deformation types compared with soft rock roadways in shallow horizontal strata. Based on the \textminus 1000 m track contact roadway in Qishan Mine of Xuzhou, physical model tests on the failure process of 45\degree and 60\degree inclined layered soft rock formations are carried out using physical models. The real-time monitoring of strain inside the model during the failure of soft rock formation is conducted to explore the failure mechanisms of 45\degree and 60\degree inclined layered soft rock formations in terms of in-depth high self-weight stress and horizontal tectonic stress. FLAC3D is also used for numerical simulation and comparative analysis. The roof and floor of the tunnels through 45\degree and 60\degree inclined formations fail on the left, and left and right walls fail near the bottom. The maximum displacement of the roof and floor of the 60\degree inclined formation is larger than that of the 45\degree inclined formation, and the maximum amount of deformation of left and right walls of the 45\degree inclined formation is larger than that of the 60\degree inclined formation, indicating failure features of different steeply inclined layered soft rocks roadways under high lithostatic stress and horizontal tectonic stress can provide a theoretical basis for mining and support of deep roadways.

\section{1. Introduction}

In recent years, as shallow coal resources diminish, people have turned to the mining of deep mineral resources worldwide (Xie et al. 2006). At present, the mining depth in China is increasing by 8 to 12 m per year. It is estimated that the mining depth of
35% of the coal mines in China will reach 10000 to 1500 m in the next 20 years (He et al. 2005). With the increasing depth of coal mining and intensified influence of ‘three highs and one disturbance’ (high crustal stress, high crustal temperature, high karst water pressure, and strong mining disturbance), traditional shallow geology mechanics are no longer suitable for analyzing deep mines. In terms of deep roadway mining, when surrounding rock is under complex stresses, the stable adjustment stage of the roadway surrounding rock equilibrium can be represented by a non-linear system problem. Rocks subjected to high and low pressures behave quite differently. Therefore, in-depth research on deformation, failure mechanisms, features, and classification of deep surrounding rock needs to be carried out (He et al. 2005; Wang et al. 2012; Yin et al. 2018).

Domestic and foreign scholars have done much theoretical research on the deformation and failure of deep roadways (Deng et al. 2017; Dong et al. 2017; Gao et al. 2017; He et al. 2017; Ma et al. 2017; Piotr et al. 2017; Sun et al. 2017; Wang and Meng 2018). Zhang et al. (2011) calculated the size of the plastic zone in roadway surrounding rock in order to calculate the risk affinity index (FAI), which was used to evaluate the stability of large-scale underground rock engineering. Osgoui and Oreste (2007) put forward the concept of the ‘equivalent plastic zone,’ that is, the roadway surrounding rock reinforced by grouting bolts, which is regarded as a homogeneous body in order to study roadway failure mechanisms. In this way, the roadway surrounding rock plastic zone is divided into three scopes: small yield, middle yield, and over-yield. He (1996) examined the rheological mechanics, damage mechanisms, and fracture mechanics of deep soft rocks forming the theory of soft rock nonlinear large deformation. Through the research on the nonlinear deformation mechanisms of deep soft rock roadways, He (1996) analyzed the deformation features and failure mechanisms of soft rock roadways and pointed out the idea of asymmetric control.

The most widely used method for analyzing roadway failure is numerical simulation. Anagnostou and Kovari (1995) and Tang and Tang (2012) used numerical simulations to explore roadway floor heave and the deformation under wet conditions; Islam et al. (2009) explored water flow in coal mines by taking stress redistribution and strata damage into consideration; Coggan et al. (2012) used different numerical simulation technologies to simulate deformation features in a coal seam; He et al. (2008) used three-dimensional numerical simulation to study the distribution of surrounding rock mass in terms of asymmetric deformation and analyze the stress distribution when the roadway advanced below the upper work surface. However, due to the complex environment, difficult theoretical calculations, and engineering problems with many influencing factors, physical models are a relatively good solution. Domestic and foreign experts completed significant research on the instability of roadway surrounding rock, for example, Ma et al. (2004), Shen et al. (2008), Fekete et al. (2010), He et al. (2010, 2011), and Piotr (2015) used the physical model method. Kang et al. (2018) conducted a large-scale physical model based on a case study to simulate massive roof collapse during longwall coal retreat mining, a good agreement was achieved between field observation and physical result in terms of monitored working resistance. Hou and Yang (2018) created a physical modelling of the
underground roadway in horizontal strata, the numerical 2D digital image correlation technology is used to monitor the surface displacement of the model, and the axial force monitoring devices called the small constant resistance bolt (SCRB) is designed for the real-time detection of the roadway mechanics data. Li et al. (2018) carried out physical modelling test to research on the deformation and breakage of overlying strata, the deformation of strata and development of cracks in the process of coal seam excavation were acquired by using digital image correlation technique. Sun et al. (2018) carried out a physical modelling experiment to study deformation mechanisms in tunnel excavated in deep soft strata, and results showed that driving footage produced an effect on the deformation of surrounding rock, and the bedding planes had an influence on deformation of surrounding rock during excavation. In terms of deep mining, soft rock roadways in inclined rock formations show different deformation and failure mechanisms compared with soft rock roadways in horizontal rock formations. In general, soft rock roadways in horizontal rock formation show symmetrical deformation while soft rock roadways in inclined rock formations show asymmetric deformation. In existing physical models, the failure mechanisms of soft rock roadways in steeply inclined strata have not been thoroughly investigated.

To solve the problem of soft rock roadway deformation and failure in deep steeply inclined strata and explore the distribution of the damage zone, failure mechanism, and displacement field of roadway surrounding rock, large scale physical modelling tests are carried out. A strain and digital camera monitoring is used to capture the variation law and failure mechanisms of the displacement field of the surrounding rock.

2. Engineering background

Located in the eastern mining area of Qishan Mine, Xuzhou, is one of the important production mines in the Xuzhou mining area, which has a total area of 2094 km² and an annual output of more than 1.5 million tons of coal. This mining area is primarily mined through vertical shaft multi-level partitioned uphill and downhill mining with a maximum mining depth of 1032 m.

2.1. Roadway lithology and physical and mechanical properties

The north wing track contact roadway has an elevation of −1000 m and a length of approximately 650 m. The rock surrounding this roadway is primarily coal, shale, and sandstone. The surrounding rock contains fractures and faults, which have a significant impact on the stability of surrounding rock. To better study the failure mechanisms of the north wing track contact roadway, three holes are drilled to obtain

| Lithology | Volume weight /kN/m³ | Porosity /% | Water absorption/% | Compressive strength/MPa | Softening coefficient | Compressive strength/MPa | Modulus of elasticity/GPa | Poisson’s ratio |
|-----------|----------------------|-------------|--------------------|--------------------------|----------------------|--------------------------|--------------------------|------------------|
| Mudstone  | 25.3                 | 5.88        | 2.74               | 35.56                    | 0.16                 | 3.31                     | 9.11                     | 0.149            |
| Sandstone | 25.6                 | 2.63        | 1.22               | 50.36                    | 0.91                 | 4.78                     | 18.25                    | 0.135            |

Table 1. Physical and mechanical parameters of different petrofabric.
standard rock samples. Based on a series of indoor experiments, the physical and mechanical properties of two main lithology of roadway surrounding rock are obtained (Table 1).

The strength of the roadway surrounding rock is relatively low, and the strength of mudstone is the minimum (Table 1). The tensile strength of mudstone is 3.31 MPa, compressive strength is 35.56 MPa, and the softening coefficient is relatively small (0.16). The mudstone easily absorbs water decreasing its strength, which is unfavourable for maintaining a stable roadway.

2.2. Roadway deformation and failure

The complex geological structure of Qishan Mine contains both fold and fractures. The crustal stress on the −1000 m level north wing track contact roadway is different from the conventional roadway and has a relatively large impact on roadway stability. Crustal stress test results indicate that the maximum stress at the −1000 m level of Qishan Mine is the horizontal stress of 40.5 MPa in the NE140° direction. The trend of the −1000 m level north wing track contact roadway is NE6°, and the angle between the maximum horizontal stress and the trend of the roadway is 46°. The maximum horizontal stress has a significant impact on the roadway and is extremely unfavourable for roadway stability.

Field measurements show at the early stage of roadway excavation, surrounding rock and roadway support structures are experience serious deformation and damage. Because the stress is uneven, the roadway roof sinks at varying degrees. During tunnelling, large asymmetric deformation appears on both sides of the roadway, the surrounding rock is exposed, and the support structure is significantly deformed. Significant floor heave appears in the roadway, which has posed a threat to roadway stability (Figure 1).

In order to monitor surrounding rock deformation, multiple monitoring stations have been set up to observe roadway surface displacement. Figure 2(a) shows the engineering geological profile and station layout of a severely deformed roadway section of the −1000 m level north wing track contact roadway. Figure 2(b,c) shows the curve of the deformation of the monitoring points in the roadway over time.

The total roof subsidence, lane deformation, and floor heave near the No. 9 and No. 12 measuring points are large, which poses a great threat to mine safety [Figure 2(b,c)]. The main reason for this deformation is that the roadway is supported by the
shallow roadway supporting design scheme. There is no sufficient thorough research on the deformation mechanisms of soft rock roadways in steeply inclined strata, resulting in the significant deformation of the supported roadway. Therefore, it is urgent to investigate the failure mechanisms of surrounding rock in soft rock roadways through deep steeply inclined strata, so as to provide reasonable reference for future roadway support systems.

3. Roadway failure mechanism physical model test

3.1. Test system

This test uses the deep rock mass engineering and geological disaster simulation test system developed by Academician He Manchao from China University of Mining & Technology, Beijing. The test device is composed of five major parts: the host, hydraulic control system, model transport vehicle, specimen mould, and data collection system. In order to add the load on the model, six uniform loaders are set into each sides of host structure. Thus, in the experimental process, the top, bottom, and both sides of the model can be applied with different pressures by controlling the uniform loaders on each side of the host [Figure 3(a)].

3.2. Similarity ratio and similar material design

The main purpose of the test is to explore failure features of the physical model when loaded; therefore, in terms of model design, strength similarity is the main similarity condition. The loading size of the physical model test system is 1,600 mm*1,600 mm*400 mm [Figure 3(b)], which can simulate the actual conditions of ~1000 m level north wing roadway in Qishan Mine, which has a width of 3 m, height of 2.4 m, and a dimension of the surrounding rockmass of 19.2 × 19.2 m.
Based on the surrounding rock circle of influence and test system mining conditions, the geometric similarity ratio is $C_l = 12$ and the length of the model roadway is 250 mm with the height of 200 mm. The stress similarity ratio is $C_Y = 8$ based on engineering rock mass mechanical parameters and the maximum load intensity (2 MPa) that can be applied to the load system of this test, and the unit weight similarity ratio $C_Y$ can be calculated using the geometric similarity ratio and stress similarity ratio based on the following formula:

$$C_Y = C_l/C_l = 0.67$$

Coal, mudstone, and sandstone are main three major rock types in Qishan Mine (He et al. 2006), and the main mechanical parameters of the model design can be obtained based on the stress similarity ratio, unit weight similarity ratio, and various mechanical parameters of the protolith. The test model body is built with different physical and finite unit boards, the finite unit board is made of gypsum and water, and physical and mechanical parameters of the unit board can be adjusted through adjusting the water-gypsum ratio. Based on the theory of similarity, finite unit boards with three different water-gypsum ratios are made to simulate the three rock formations in the mine, that is, coal, shale, and sandstone. Each lithology is made into boards of different geometric dimensions. Specimens with three different water-gypsum ratios can be used to carry out Brazilian tests, uniaxial compression tests, etc. to obtain the compressive strength, Poisson’s ratio, modulus of elasticity, tensile strength under different water-gypsum ratios, and mechanical parameters of physical and finite unit boards (Tables 2 and 3).

### 3.3. Construction of the physical model

The rock formations approximated by the model specimens are: sandy mudstone, coal, mudstone, coal, mudstone, coal, mudstone, coal, and mudstone from top to bottom in turn (Table 4). The model body built of physical and finite unit boards can reproduce the real structure of the rock mass, and a rock mass with different formation dips can be simulated through the adjustment of the dip of the unit boards. The following model is used to simulate the soft rock roadway of Qishan Mine and its
surrounding rock structure. The location of the soft rock roadway excavation area is in the middle of the model with the size of 250 mm × 200 mm, crossing the coal formation.

Failure in the gypsum boards is relatively slow, therefore, DH3818 static strain test system is used in this test, and multiple groups of strain gauges are arranged around the model in the X and Y directions. X is the direction along the rock formation and Y is the direction perpendicular to the rock formation. More strain gauges are arranged closer to the roadway excavation area and fewer strain gauges are arranged farther away the excavation area. The real-time failure process is captured using a video camera, and the model is loaded at the top and through the left and right sides (Figure 4).

### Table 2. The main mechanical parameters of the original rock and model design.

| Geological profile | Rock group       | Volume weight /kN/m³ | Compressive strength/MPa | Compressive strength/MPa | Modulus of elasticity/GPa | Poisson’s ratio | Internal friction angle /° |
|--------------------|------------------|----------------------|---------------------------|--------------------------|---------------------------|-----------------|--------------------------|
| Protolith          | Sandstone group  | 26.55                | 63.98                     | 5.83                     | 25.77                     | 0.15            | 33.71                   |
|                    | Mudstone group   | 25.78                | 43.78                     | 5.59                     | 21.01                     | 0.13            | 36.35                   |
|                    | Coal rock group  | 13.50                | 26.15                     | 0.90                     | 4.51                      | 0.36            | 40.07                   |

### Table 3. The physical and mechanical parameters of the simulated materials used in the physical model.

| Model material | Geological profile | Simulated rock formation Dimension/cm | Water-gypsum ratio | Volume weight /kN/m³ | Compressive strength/MPa | Compressive strength/MPa | Modulus of elasticity/GPa | Poisson’s ratio | Internal friction angle /° |
|----------------|--------------------|---------------------------------------|--------------------|----------------------|--------------------------|--------------------------|---------------------------|----------------|--------------------------|
| Sandstone      |                    | 40 × 40 × 3                           | 0.8: 1             | 21.24                | 8.00                     | 0.73                     | 3.22                      | 0.12           | 32.06                   |
| Mudstone       |                    | 40 × 40 × 2                           | 1: 1               | 20.62                | 5.47                     | 0.70                     | 2.63                      | 0.13           | 33.28                   |
| Coal rock      |                    | 40 × 40 × 1                           | 1.2: 1             | 10.80                | 3.27                     | 0.11                     | 0.56                      | 0.32           | 33.28                   |

### Table 4. Geological profile.

| S/N | Lithology  | Thickness/mm | Explanatory legend |
|-----|------------|--------------|--------------------|
| 1   | Sandstone  | 440          |                    |
| 2   | Coal rock  | 140          |                    |
| 3   | Mudstone   | 120          |                    |
| 4   | Coal rock  | 250          |                    |
| 5   | Mudstone   | 150          |                    |
| 6   | Coal rock  | 60           |                    |
| 7   | Mudstone   | 140          |                    |
| 8   | Coal rock  | 60           |                    |
| 9   | Mudstone   | 240          |                    |
4. Experiment results and analysis

4.1. 45° inclined rock formation test

4.1.1. Loading test design

Unit boards are arranged at an inclination of 45° to simulate the north wing contact track roadway in Qishan Mine. Failure of the roadway surrounding rock is monitored while accounting for the roadway self-weight stress and horizontal tectonic stress. The model is pre-pressed to 300 m self-weight stress to stabilise the model. After excavating the model, the influence of the horizontal tectonic stress can be considered, and the model is loaded step by step until failure. Critical points are set up in the inclined rock formation to monitor changes in strain. The loading process is divided into three stages: Pre-pressure Stage I (0–720 s) before excavation, Excavation Stage II (720–4000 s), and Failure Load Stage III (4000–12,820 s). The test loading path is shown in Figure 5.

![Figure 4. Model and laboratory diagram of testing system. (a) Model diagram for testing system (b) Laboratory test diagram.](image)

![Figure 5. The Loading path design of the physical model.](image)
4.1.2. Key point strain analysis of 45° inclined rock formation

Four key points (A, B, C, and D) are setup around the roadway. As the roadway is excavated, all for key points experience significant displacement (Figure 6).

As the model is excavated, micro-strain values at Point D and Point B always fluctuate around a fixed value (Figure 7). Stress is relatively small in this direction without stress concentration. The free face causes left and right walls to move inside the roadway, and stress in the X-direction stress here is released (Figure 6).

Loading stress has a relatively large impact on Direction Y, and strain in Direction Y fluctuates up and down. As time elapses, strain in the Y direction of key points on left and right walls in the pre-pressure stage before excavation slowly increases. Point D on the left wall is first experiences stretching, which gradually changes into compression state and finally stability. Point B on the right wall is always under compression. During excavation, strain in the Y direction on the left and right walls continues to increase slowly, and due to the free face, stress redistribution occurs. Stress distribution tends to be balanced.

The failure stage is also divided into three phases for loading. The physical model becomes increase the boundary stress when 4000s, it does not reach the strength of the plasterboard. Strain in the Y direction on the left and right walls suddenly increases, and when stress increases, tiny cracks appear. Strain begins to rebound when the stress on Point D on the left wall in the Y direction is released. After the partial stress on Point B on the right wall in the Y direction is released, the point is in a steady state. In terms of 6100s, the model continues to load, stress concentration reappears at Point D on the left wall and reaches an equilibrium state again. Cracks begin to appear slowly near Point B on the right wall, however, at this time, the system is still relatively stable state. In terms of 9150s, disorderly loading is carried out, and stress at Point D on the left wall continues to increase, and crack failure occurs at Point D. Cracks at Point B on the right wall start to form suddenly, stress is released, and strain begins to rebound rapidly. In general, key Point D on the left is always under compression and fractured, however, failure does not occur. Relatively large cracks and displacement form Key Point B on the right wall.

The trend of strain in the X and Y directions at Point A of the roof is almost the same (Figure 8). Due to the ‘arch effect’ and tendency of the rock formation, the strain at Point C on the floor is almost exactly the opposite of Point A.

Strain at Point A in the pre-pressure stage before excavation slowly increases with time, and this process is a compressive process. In the excavation stage, strain trends in the X and Y directions are completely opposite while still in an elastic state. The surrounding rock at point A enters a steady state; however, the change of strain trends in the X and Y directions Point C is basically the same during the loading process. During the excavation stage, due to the ‘arch effect’ and appearance of a free face, strain trends of X and Y gradually become opposite from the initial consistent changes. During the failure load stage, when load starts at 4000s, point A is stable, but the stress at Point C in the X and Y directions is partially released due to the presence of a free face. When stress increases at 4380s, the stress at Point A in the X and Y directions concentrate, followed by the formation of small cracks, which releases part of the stress. At this time, Y-direction stress at Point C cannot be...
Figure 6. 45° Roadway Model Failure. (a) Before the failure of the roadway model (b) After the failure of the roadway model.

Figure 7. The strain and time curve of key points of the left and right sides in directions of X and Y.

Figure 8. Strain and time curves of key points of the roof and floor in the X and Y directions.
released, and the roof in the X-direction begins to sink, which results in a sudden increase of stress in the Y-direction and a release of stress in the X-direction. At 6100 s cracks appear near Point A, which results in a partial stress release. The X direction at Point C is in a stable equilibrium state. Y-direction stress is released due to nearby fractures. Disorderly load at 9150 s causes more cracks to appear near point A. Stress in the X and Y directions is released due to floor heave. X-direction stress at point C continues to increase due to the ‘arch effect’, Y-direction stress increases to reach the strength of the gypsum unit board, and shear fracturing occurs near C point, such that the Y-direction stress is released. There are no large fractures or failure at Point A regardless of a slight decline in the roof at Point C with a large fracture nearby.

As a whole, X-direction strains in the left and right walls are small because the surrounding rock formation above the roadway inclines towards a free face and

Figure 9. The failure evolution process of physical model. (1) Compaction stage (2) Crack expansion stage (3) Complete failure stage.
moves towards the roadway over time. X-direction stress will continue to be released, X-direction stress will be small and at the same level. During Stage III, the strain trend in the roof of the 45° inclined layered soft rock formation in the X direction is the same as Y, but the strain trend in the floor in the X and Y direction is opposite. The sudden plunge in strain curves results from the increased boundary stress during each loading. The rise in the strain curve represents the release of stress, during which fractures form. A relatively large strain rebound occurs, which indicates there are fractures near this point. If the stress continues to increase or the rebound range is small, the range around this area must have been always been under compression.

4.1.3. Analysis of 45° inclined rock formation failure process

Throughout the experiment, we film the entire deformation and failure process of the physical roadway model during the loading stage with a digital camera and cut out a series of model photos reflecting the physical model’s changes from the video. The deformation and failure process of the 45°inclined rock formation physical roadway model into three stages, namely: the model compaction stage, crack development stage, and complete failure stage (Figure 9).

Figure 9(a–c) shows a series of changes to the physical model during the initial loading stage: Figure (a) shows a photo of the completed roadway, the red tape square around the roadway is used to characterise the smoothness of roof, floor, and walls of the roadway. It can be seen from Figure (b) that the red tape square is no longer straight, indicating the roof and floor are deformed from the external load and the model’s own weight. The model is in the compaction stage at this time, leading to the occurrence of strong static friction between internal unit boards, which increases the possibility of the appearance of micro-cracks. As is shown in Figure (c), due to the convergence of internal micro-cracks within the roadway, a longitudinal crack visible to the naked eye appears, indicating the rapid development of micro-cracks under external load.

Figure 9(d–f) shows the physical model’s crack expansion progress during loading: as is shown in Figure (d), the first fracture appears on the roadway roof indicating a large concentrated stress is present, which leads to roof fracture and more prominent longitudinal cracks in Figure (c). As is shown in Figure (e), when under external load, the left wall of the roadway continues to incline towards the free area, hence the further development and expansion of the cracks in the roof; it can be seen from Figure (f) that as a result of roof fracture and displacement of the left wall of roadway to the free area. Failure occurs on the left side of the surrounding rock mass and the rock mass near the left side of the roadway roof.

Figure 9(g–i) is a photograph taken during the complete failure stage, which reflects the destruction process at high stress levels: it can be seen from Figure (g) that there is another horizontal crack in the left wall, which is perpendicular to the longitudinal crack in Figure (c). Layer movement in the left wall becomes distinct, resulting in tilted unit board on left wall’s rock formation. Large displacement to the free area of the left and right walls leads to a serious contraction of the roadway section. As is shown in Figure (h), the roof continues to fracture and is stripped under the external load, and in Figure (c) vertical cracks extend vertically downwards from
the top of the roadway to form a larger penetration crack. It can be seen from Figure (i) that cracks in the horizontal direction continue to expand into a larger crack. Cracks in the vertical direction continue to cut down to the bottom of the roadway. Both walls deform into the free area, which leads to serious section contraction and damaged. Overall, the deformation and failure characteristics of the model are relatively consistent with the field project in Qishan coal mine.

4. 2. Experimental analysis of 60°/C14 inclined rock formation

4.2.1. Experimental results of 60°/C14 inclined rock

Under the same engineering conditions, the unit plate is placed with an inclination of 60° to investigate the deformation and failure characteristics of a 60° inclined rock formation under loading condition. The experimental loading path and strain gauge positions are basically the same as those in the 45° inclined rock formation experiment. The characteristics of rock mass before and after the experiment are shown in Figure 10.

4.2.2. Comparative analysis of experimental failure results of 60° and 45° inclined rock formations

The asymmetry of the steeply inclined layered surrounding rock structure results in stress concentration asymmetry. As is indicated in comparison between 45° and 60° tunnel model failure tests, failure locations slightly differ. In the 45° inclined surrounding rock failure locations are at the lower left corner of the left wall and upper left corner of roof, but there is no failure on floor or right wall. In the 60° inclined surrounding rock, failure locations are at the lower left corner near mid-point on the left wall, upper left corner of roof, and lower right corner of the right wall, but there is no significant destruction on the floor.

Both cases have very small stress in the X direction on left and right walls because both of their rock formations move gradually towards the free face. X-direction stress will keep being released and are relatively small. In Stage III, strain trends of the roof of 45° and 60° inclined surround rock in the X and Y directions are the same, while those of floor are opposite.
5. Numerical simulation analysis of roadway failure mechanisms

5.1. Establishment of the numerical model

Based on the actual geology of Qishan Mine, a model is established using FLAC3D to simulate the effect of excavation on 45°/C14 and 60°/C14 inclined layered soft rock, in which the external force is first exerted to put it in a balanced stress status under actual geological conditions, and the excavation is conducted until the model calculation stops. The deformation characteristics and laws of the roof, floor, and left and right walls of the soft rock tunnel in 45°/C14 and 60° inclined layered soft rock are analyzed.

A model is constructed using FLAC3D, with a length x width x thickness of 19.2 m x 19.2 m x 4.8 m. A rectangular roadway with an excavation surface area of 3 m x 2.4 m is constructed (Figure 11). Table 5 shows the parameters for physical and mechanical calculation of actual rock mass.

Based on Mohr-Coulomb Failure Theory, this calculation model fixes the displacement limit on the border in the X and Y directions and at bottom in the X direction. Excavation is carried out after achieving a balanced model under the effect of the self-weight stress. This model mainly analyses the roof and floor of the roadway model, and displacement and strain variation laws to study the deformation mechanisms of the surrounding rock.

5.2. Simulation analysis of displacement variation laws

5.2.1. Displacement cloud image of roof and floor

As is shown in Figure 12(a), asymmetric deformation occurs on the roof and floor of surrounding rock of the 45° inclined soft rock roadway’s surrounding rock. Asymmetry of the structure leads to stress concentration. Roof subsidence is much greater than the floor heave. Significant asymmetric deformation appears in the roof with a maximum displacement of approximately 52 cm inclined to the left side. Maximum floor heave, approximately 30 cm, inclines towards the left wall. Significant asymmetric deformation appears on the floor. Deformation of both roof and floor causes instability and destroys the roadway.
As is shown in Figure 12(b), significant asymmetric deformation occurs on the roof and floor of the 60° inclined rock formation. Asymmetry of the structure results in stress concentration asymmetry. The amount of roof subsidence is significantly greater than that floor heave. Maximum roof and floor displacements are approximately 59 cm and 37 cm respectively, all of which incline to the left. Significantly larger asymmetric deformation appears on the roof and floor, which results in roadway instability and failure. Compared with Figure 12(a), the failure position in the roof and floor of the roadway begin to gradually shift to the respective mid-points.

After comparing Figures 12(a,b), the displacement field cloud images for the 45° and 60° inclined rock formations are basically the same, and the maximum deformations of roof and floor in the 45° inclined soft rock formation all incline to left side. The maximum deformations of the 60° inclined formation roof and floor all move towards the midpoint. The maximum deformation of the 45° inclined formation is smaller than the 60° inclined formation.

### 5.2.2. Displacement cloud images of left and right wall

As can be seen from Figure 13(a), significant asymmetric deformation is present in both left and right walls. After excavation of the tunnel in the 45° formation and the surrounding rock deforms, the deformation degree of the left wall is larger than the right wall. The maximum deformation of left wall is located along the lower side near the midpoint. The maximum deformation in the right wall is located at a similar point. The maximum deformation of the left wall is about 32 cm, while that of the right wall is about 13 cm.

As can be seen from Figure 13(b), significant asymmetric deformations appear in the both left and right walls. After excavation of the 60° inclined formation and the surrounding rock deforms, and the deformation degree of the left wall is larger than the right wall. The maximum deformation of left wall is located along the lower side near the midpoint. The maximum deformation in the right wall is located at a similar point. The maximum deformation of the left wall is about 21 cm, while that of the right wall is about 10 cm.

After comparing the horizontal displacement fields of the left and right walls in the 45° and 60° inclined formations, the maximum deformation of the left walls in the 45° and 60° inclined formations are located at the lower left corner, but that of the 60° inclined formation the wall inclines to the mid-point of left wall. The maximum deformations of right walls in the 45° and 60° formations are located at the lower right corner, but that of 60° formation inclines towards the lower corner of the right wall compared with 45° inclined formation.

### Table 5. shows the parameters for physical and mechanical calculation of the actual rock mass.

| Geological profile | Lithology | Volume weight /kN/m³ | Compressive strength/MPa | Modulus of volume/GPa | Modulus of shearing/GPa | Internal friction angle /° | Cohesion/MPa |
|--------------------|-----------|----------------------|--------------------------|-----------------------|------------------------|---------------------------|-------------|
| Coal               | 26.55     | 5.832                | 18.5                     | 11.2                  | 33.71                  | 16.51                     |
| Mudstone           | 25.78     | 5.59                 | 14.1                     | 9.3                   | 36.35                  | 23.59                     |
| Sandstone          | 13.50     | 0.90                 | 8                        | 1.7                   | 40.07                  | 5.42                      |
5.3. Numerical simulation and experimental comparative analysis

Figure 14 shows a comparison between a numerical simulation and experimental deformation of a 45° inclined rock formation. Deformation of the left wall is significantly greater than that of the right wall, which is called asymmetric structural deformation. In the left wall the maximum deformation which is quite large appears at the left corner. In the right wall, the maximum deformation is located at the midpoint near the lower side. Deformation of left wall is larger than that of the right wall, but the maximum deformation amounts and locations are approximately the same in the experiment except for a slight difference in deformation shape.

Failure locations in the roof and floor are almost on the left side. Fractures are all almost perpendicular to the slope of the roadway. The amount of deformation in the roof is greater than the floor heave. The maximum deformation of the roof and floor are all located on the left side, not exactly at the upper left corner, but a bit near the right side. Furthermore, the maximum roof deformation is greater than the maximum floor heave.
After destruction of the model, the experiment and numerical simulation are almost identical except for some slight differences caused by human error. In general, deformation and failure characteristics of the model test and numerical simulation results are relatively consistent with field data.

Figure 15 shows a comparison between numerical simulation and experimental deformation failure of the 60° inclined rock formation. The roadway has been severely damaged and the fractures are all perpendicular to the inclination direction of the roadway.

After destruction of the model, the experiment and numerical simulation are almost identical except for some slight differences caused by human error. In general, deformation and failure characteristics of the model test and numerical simulation results are relatively consistent with field data.

Figure 15 shows a comparison between numerical simulation and experimental deformation failure of the 60° inclined rock formation. The roadway has been severely damaged and the fractures are all perpendicular to the inclination direction of the roadway.

Comparative experimental photos before excavation and after failure show that serious damage appears on both left and right walls. The maximum deformation of left wall is located at the lower left corner near mid-point, which is completely fractured. As for the right wall, the maximum deformation is located at the lower right corner, which is severely fractured. With the failure locations being basically the same, deformation of the left wall is much larger than that of the right wall, which is a different from the experimental results.

Corresponding deformations appear on roof, which are relatively intact without any large failure. The maximum subsidence appears at the upper left corner while the maximum floor heave is difficult to locate. Deformation of the roof is greater than
that of the floor. The maximum deformation of the roof is located near the mid-point and left side, which is different from that of the experiment but roughly the same as the maximum floor heave whose exact location cannot be seen in the experimental photo.

6. Conclusions

By contrasting the physical model experiment and numerical simulation of the failure process of 45° and 60° inclined soft rock formations, this paper examines the deformation and failure mechanisms and characteristics of roadways through deep steeply inclined soft rock formations. The following conclusions drawn:

1. The asymmetry of the steeply inclined rock formation structure results in asymmetric failure. Failure locations slightly differ: the 45° inclined formation failure locations are in the lower left corner of the left wall and upper left corner of roof, but there is no failure in the floor or right wall. The 60° inclined formation failure locations are lower left corner near mid-point on the left wall, upper left corner of roof, and lower right corner of the right wall, but there's no significant...
destruction on the floor. The strains of both left and right walls in the X direction are all small. In Stage III, strain trends of the roof of 45° and 60° inclined formations in the X and Y directions are the same, while those of the floor are opposite.

2. Numerical simulation analysis shows that the maximum deformation locations of the 45° and 60° inclined formations are roughly the same. The maximum deformation of the left and right walls of the 45° and 60° inclined formations are located at the lower sides, while that of roof and floor are located near the left side. Compared with the maximum deformation of left wall of the 45° inclined formation, that of 60° inclined formation is higher. The maximum deformation of the right wall, roof, and floor are located on the lower side and mid-point respectively. The maximum deformations of the 45° and 60° inclined formation are inconsistent. As for the maximum displacement of roof and floor, the latter is greater than the former. As for the maximum displacement of left and right walls, the latter is smaller than the former.

3. After comparatively analyzing the experiment and numerical simulation, we find that the failure locations of the roof and floor of the 45° and 60° inclined formations are located on the left side, while the left and right walls have failure points on the lower sides. The maximum deformation locations in the numerical simulation and model experiment are relatively consistent. In the numerical simulation and experiment for the 45° inclined formation, the deformation shapes of left and right walls are similar with those of the roof and floor, with the almost same maximum deformation locations. In the numerical simulation and experiment of the 60° inclined formation, the failure locations of left and right walls are almost the same, while those of roof and floor are slightly different, which proves numerical simulation results can serve as some reference for model experiments and engineering practice.

4. The physical unit plate method can simulate the rock mass structure in practical engineering situations and changing the size and strength of the unit plate can simulate rock formations of different thickness and dip. Through experimental simulation of deep rock mass engineering and geological disasters, different stress conditions are loaded into the physical model to simulate deformations, including asymmetrical floor heave, roof and floor detachment, and abscission, caused by the lithostatic stress and horizontal tectonic stress on the roadway. Therefore, the experimental system and research methods in this paper can serve as a reference for further exploration of mechanical laws of complex geological bodies under excavation and loading conditions.

**Disclosure statement**

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