Study of the height of water flowing fracture zone based on strain energy failure criterion

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Abstract: In order to determine the development height of the overburden water flowing fracturing zone in the upper 15 coal seam of the Zhubai Coal Mine, the 15101 working face is taken as an example. The FLAC3D numerical simulation software is used to establish the stope model, and the strain energy failure criterion is used as the extension criterion of overburden water flowing fracturing zone. The development range of the fracture zone is determined by the strain energy failure criterion, and the numerical simulation of the overlying strata movement law of the coal seam roof caused by mine exploitation is carried out. A numerical simulation method based on the strain energy failure criterion for determining the plastic zone is proposed. By analyzing the damage range, the height of the overburden water flowing fracturing zone is determined. The results of theoretical and field observation are used to validate the simulation result. The height of the overburden water flowing fractured zone according to the numerical simulation result is 22.8 m. The theoretical calculations are from 14.4 m to 27.3 m and the field observation is 21.44 m. The result obtained by the strain energy failure criterion is closer to the field observations. The accuracy of the development height of the overburden water flowing fracturing zone obtained by the strain energy failure criterion is validated. This stope model may have a scientific guidance for Mining Engineer.

1. Introduction

During the mining process of underground coal, the overlying strata of the coal seam will inevitably be displaced, deformed or destroyed. According to the damage condition, the overlying strata of the stope will be divided into the fall zone, the fracture zone and the curved zone from bottom to top. A certain range of rock formations above the falling belt breaks and migrates, resulting in fissures. In the range of water-bearing rock layers, it is called water-conducting fissure belt [1-4].

In order to study the overburden water-fracture fissures, relevant scholars have carried out a lot of research in recent years. Among them, Xu Jialin et al. [5] proposed a method for predicting the height of water-conducting fracture zone in the key layer of overlying strata, and at the same time, the hydrocrack zone is highly developed. The situation is judged. Shi Longqing et al. [6] derived the theoretical calculation formula for the water-conducting fracture zone under various influencing factors. Wu Yongping et al. [7] used the rock mechanics parameters of the working face to establish a similar material model to explore the height of the water-cracking zone of the overlying strata. Relevant scholars' research provides important guidance for mine safety production, but the idealized theoretical calculation model cannot accurately reflect the structural characteristics of water-conducting fracture
zone under complex geological conditions. It is difficult to simulate the geological material by simplified similar material simulation. High-cost on-site measurement is very precise, but it consumes a lot of manpower and material resources [8]. Therefore, the strain energy is used as a criterion for damage, the development of the fracture zone is explored from the perspective of energy, and it is believed that the destruction of the rock mass is caused by the external work on the rock mass exceeding the energy limit of the rock mass itself, resulting in the destruction of the rock mass. Moreover, the greater the energy released by the outside world for the work of the rock mass, the higher the degree of rock damage. The rock breaks down and forms fissures, and the external energy is continuously released, which leads to the expansion of the crack development. It can be considered as a more suitable method that analyze the development process of rock fissures by energy, and combine with the strain energy criterion to determine the numerical simulation results, and then to determine the development height of the water-conducting fracture zone.

In view of above analyze, this paper establishes the 15101 working face stope model based on the FLAC3D simulation software, and uses the strain energy as the criterion for the development of the water-conducting fracture zone, and judges the development height of the fractured plastic zone from the energy point of view. For the comparison of the plastic zone range at different propulsion distances, the development rules of the water-conducting fissure zone are summarized, and the calculation results were compared with the theoretical analysis results, and then the accuracy was verified with the field drilling measurements. Finally, the development height of water-conducting fracture zone in overburden rock is determined.

2. Water conduction fracture zone height prediction

2.1. Strain energy failure criterion
The development of the water-crushing fissure zone of the overburden is the extension process of the fracture zone of the rock mass. The expansion of the fracture is essentially the failure process of the rock mass. According to the energy angle analysis, the rock mass will break when the applied load exceeds its own energy value. As the applied load continues to increase, the rock fissures gradually connect to form a through-face. When the elements on the failure surface reach the ultimate stress value, the strain of the rock mass is changed abruptly, which eventually leads to the overall collapse of the rock mass [9,10].

Based on the criterion of strain energy failure criterion, the rock mass is divided into several units or differential units for solving. When the value of the physical quantity in the unit exceeds the value corresponding to a given material, the unit nodes are separated and the unit body is destroyed. After the damage to a certain extent, the destroyed unit begins to connects and expands continuously. When the ultimate tensile stress is reached, the fracture of the rock mass penetrates and collapses.

Based on the strain energy failure criterion, the judgment expression is established from the energy point of view:

\[
W = f(w) = \int_0^{\varepsilon_{ij}} \delta_{ij} d\varepsilon_{ij} 
\]

\[
W_0 \leq W \tag{2}
\]

Where: \( W \) is the strain energy of the rock mass; \( W_0 \) is the axially allowable strain energy of the rock mass, that is, the fracture energy of the rock mass is greater than the strain energy.

2.2. Establishment of numerical model
This simulation takes the coal seam occurrence condition of the 15101 working face in Zhubai Coal Mine as the background. The 15101 working face is the first working face of the 15 coal seam in first mining area of Zhubai Coal Mine. The average mining height of the working face is 1.2 m and the depth of coal seam is 225 m. From 0.6 m to 0.9 m of thickness is a shallow horizontal buried deep coal seam with a simple geological structure. According to the actual mining situation of the project, the height of
the model is 150 m, the width of the working face is 140 m, and the length along the direction of the working face is 300 m. The occurrence of coal seam and the rock stratum structure are established according to the actual geological conditions. The final numerical model is 300 m × 140 m × 150 m, and the entire model is divided into 1,819,170 units and 1,864,712 nodes.

The units are defined by Mohr-Coulomb constitutive model. The y-direction is fixed in the y-direction and the other directions are free. The left and right directions of the model are fixed in the x direction, and the remaining directions are free. The bottom of the model is displaced in three directions. Equivalent load is applied on the top of the model to simulate the overburden pressure to the surface soil, which means the dead weight stress: \( \sigma_z = \gamma H \), where \( H \) is the average gravity density from overburden to surface soil, taking 20.05 kN/m\(^3\); \( H \) is the depth of the top boundary of the model. Set the force imbalance proportional coefficient to \( 1 \times 10^{-5} \).

According to the strain energy to determine whether the rock mass element is damaged. If it is damaged, the residual cohesion of the rock is 0.1 MPa [11].

The Mohr-Coulomb criterion is selected for the rock mass strength failure criterion, and the rock mechanics parameters selected by the model are shown in table 1.

| strata        | thick /m | \( \sigma \) /MPa | shear/GPa | bulk/GPa | \( \mu \) | cohesion /MPa | friction /\(^\circ\) | elasticity modulus /MPa | strain energy /N•m |
|---------------|----------|------------------|-----------|----------|---------|----------------|------------------------|----------------------|-------------------|
| clay stone    | 2.3      | 25               | 2.13      | 4.1      | 0.24    | 0.6            | 45                     | 0.86                 | 268               |
| mud-siltstone | 3.5      | 27               | 2.33      | 4.4      | 0.25    | 3.78           | 32                     | 0.93                 | 340               |
| 8th limestone | 4.7      | 38.2             | 4.1       | 4.4      | 0.32    | 6.7            | 39                     | 1.55                 | 1133              |
| 14# coal seam | 0.5      | 6.7              | 0.45      | 0.97     | 0.2     | 0.4            | 31                     | 0.19                 | 4                 |
| sandstone     | 12.1     | 33.7             | 2.8       | 3.7      | 0.24    | 4.6            | 37                     | 1.13                 | 641               |
| 9th limestone | 0.5      | 33.2             | 4.3       | 4.8      | 0.22    | 3.2            | 35                     | 1.76                 | 971               |
| 15# coal seam | 1.2      | 0.8              | 1.05      | 1.4      | 0.2     | 0.4            | 30                     | 0.44                 | 3                 |
| fine sandstone| 21       | 12               | 3.2       | 4.54     | 0.23    | 2.9            | 40                     | 1.30                 | 94                |

2.3. Simulation results and analysis
The parameters are assigned to the model by FLAC3D software. After the initial balance, the model is excavating compute according to the step of each 30m excavation. After the balance is calculated, do the next excavation until the excavation is completed at 180 m. The strain energy is used as the crack extension criterion to determine the range of the plastic zone to determine the development height of the water-conducting fracture zone. The height of the hydraulic fracture zone of the overburden is determined by extracting the distribution of the plastic zone of the overlying strata at different propulsion distances.

Through the analysis of the plastic zone of the model, it can be visually seen that the overburden damage in the goaf is different when the working face has different propulsion distances. Figure 1 shows the simulation results of the plastic zone distribution at different propulsion distances of the working face. The analysis shows that as the working face advances, the plastic zone of the overburden fracture gradually increases. When the working face is advanced to 30 m, the failure type of overburden is mainly shear failure, plastic zone appears at both ends of the goaf, and the development height is larger than the middle position of the goaf. The roof rock layer transitions from elastic deformation to plastic deformation during excavation, and some rock layers lose their balance and begin to fall. When the working face is advanced to 60 m, the plastic zone of the overburden is mainly shear failure, and the density and width of the plastic fracture increase continuously with the increase of the advancement distance.
When the working face is advanced by 90m-120m, the plastic zone in the direct roof area is obviously damaged. The rock layer above the goaf is bent and sunk more than its own tensile strength. The rock fissures expand rapidly in the vertical direction, the cracks are dense, and the fracture is broken. obviously. When the working surface is advanced by 120 m-150 m, the plastic zone damage range continues to extend to the upper level. At this time, the crack propagation height of the overburden is 22.28 m, and the plastic zone damage area above the goaf shows that the direct roof is mainly tensile failure, and the shear failure mode of the rock above the direct roof is obvious. When the working face is propelled from 150 m to 180 m, the plastic zone range shows that the fracture zone height extends to 22.21 m, and the overburden stratum damage height and damage extent are basically stable.

![Figure 1](image1.png)

Figure 1. Distribution of Plastic Deformation of the Overlying Strata at Different Mining Distances: (a) working face mined to 30 m, (b) working face mined to 60 m, (c) working face mined to 90 m, (d) working face mined to 120 m, (e) working face mined to 150 m, (f) working face mined to 180 m.

The height variation height of the water-conducting fissure development is shown in figure 2 With the extension of the excavation area, the overburden rock continues to fall, accompanied by the continuous development of the fracture-breaking gap. But when the working surface develops to a
certain distance, the goaf height of the overburden strata is changed slowly, and the meteorites in the goaf are compacted. Since then, the fracture density and the crack width have remained basically the same, and the development height of the fracture zone is basically a straight line. Therefore, according to the simulation of the overburden strata in the goaf, the development height of the water-crushing fissure zone is 22.28 m.

Figure 2. Relationship between working face mined distance and the damage of the overburden

3. Empirical formula prediction
The development height of the water-conducting fissure zone is related to the stratigraphic structure, rock mechanics properties and mining methods. The top plate of the 15101 mining working face is a medium hard rock formation with a mining height of $M \approx 1.2$ m at the height observation section. Experience has shown that, in general, the height-to-height ratio of the top hard rock roof is 12-18 [12,13]. The heights of overburden layer are expected to be as follows:

Upper limit of height: $H_{\text{upper}} = 18M = 18 \times 1.2 = 21.6$ m
Lower limit of height: $H_{\text{lower}} = 12M = 12 \times 1.2 = 14.4$ m

According to the revised “Code for the setting and mining of coal pillars in buildings, water bodies, railways and main roadways” revised in 2017, and “calculation formula for the height of water-conducting fissures in thick coal seams”, combined with the lithology and hard state of the roof. The following formula calculates the "two bands" height:

$$H = \frac{100\sum M}{1.6\sum M + 3.6} \pm 5.6$$

Where: $M$ is the cumulative mining height, the value is 1.2m.

According to the formula, the minimum predicted water-conducting fracture zone height is 16.1 m and the maximum is 27.3 m.

In summary, the upper and lower limits of the water-conducting fracture zone are 14.4–27.3 m, and the maximum water-conducting fracture zone height is expected to be 27.3 m.

4. Height measurement of water-conducting fissure zone

4.1. Water injection fracturing test system detection
According to the engineering geological conditions of the working face of the 15101 working face, the “drilling height observation method for underground downhole drilling” is applied to drill the borehole above the goaf in the vicinity of the working face, and the hole is sealed by water injection and leak detection [14]. According to the empirical formula, the upper limit of the water-conducting fracture zone is 27.3 m and the lower limit is 14.4 m. Based on those calculated results, the design of the borehole
parameters is designed. The observation position (drilling hole) of the designing high-conduction drilling hole is arranged in the 15103 belt lane at the position of 46m north of the 15101 working face stop line. The observation results from pre-mining observation hole 3 and post-mining observation hole 1 are shown in figures 3 and 4.

4.2. Observations and analysis

The 1st borehole of observation borehole adopts the upward observation mode. In the I section borehole area, the hole depth is 17.5m~26.3m, corresponding to the vertical height of 15.2~21.5m, and the lithology of the hole section is 14 coal and sandy shale. 8th limestone, sandy shale and 12 coal, where the loss of rock formation in the hole section is relatively large, reaching 20.2~28.3 L/min. In the section II drilling area, the hole depth is 28.5~32.35 m, corresponding to the vertical height of 23.12~25.89 m. The lithology of the hole section is mainly argillaceous fine sandstone, and the leakage loss of the hole section is obviously reduced, only 0.7~1.1. L/min. Compared with the leakage of 3rd drilling hole (pre-harvest comparison observation hole), it is found that the leakage loss of the corresponding I and II drilling areas is small, which proves that the 1st drilling I section has entered the fracture zone. The overlying strata in the area are affected by the mining of the working face, which produces a large number of secondary fissures. The water conductivity of the rock stratum is enhanced and the water injection loss is large. Compared with the leakage loss in the I section, the leakage loss of the 1st borehole II section is significantly reduced. It is considered that the II section has passed through the fissure zone and entered the curved subsidence zone, and the primary fracture in the overburden is not developed. The water conductivity of the rock formation in the hole section is weak.

The 3rd drilling hole is located above the overburden layer on the 15103 working face, and is not affected by the mining of the 15101 working face. It is symmetrically distributed with the 1st drilling hole as the axis of the roadway. The leakage loss of the entire borehole of 3rd drilling is between 0.1~3L/min. The drill pipe connection is well sealed during the observation process. The double-end water plugging capsule is well sealed, the water loss in the rock gap is small, and the overburden is the original. The crack is not developed.

In summary, it is determined that the development height H of the overburden water-fracture zone of the 15101 working face of Zhubai Coal Mine is measured to be 19.49 m. Considering that the observation time is longer than the end of the mining end of the 15101 working face, the upper boundary of the water guiding fracture zone may be compacted. To ensure that the observation result is closer to the true value, the safety correction factor is 1.1 according to the overburden structure analysis. Therefore, 15101 The actual development height H of the overburden water-fracturing zone of the working face is actually 1.49 m × 1.1 = 21.44 m. The average mining height of the coal seam at the working section at the observation section is M=1.2m. Therefore, the ratio of the height of the 15101 working face to the mining height (cracking ratio) is: H_{actual}/M=21.44/1.2≈17.87.
4.3. Comprehensive analysis
The height of the water-conducting fracture zone was simulated by using FLAC\textsuperscript{3D} software to be 22.28 m. The upper and lower limits of the water-conducting fracture zone obtained by the empirical formula range from 14.4 to 27.3 m. Through the field test, the height of the water-conducting fracture zone of the 15101 working face is 21.44 m. It can be seen that using the Fish language to construct a method based on the numerical simulation of the strain energy failure criterion to predict the height of the water-conducting fracture zone has certain feasibility.

5. Conclusion
The analysis of the damage extent of the overburden in the goaf shows that as the advancing distance increases, the overburden gradually bends downward, the fracture of the stratum expands upward, and the development height of the water-crushing fissure zone gradually extends to the upper level. When the working surface propulsion range is extended to 90 m, that is, when the initial stop is square, the damage height of the overburden is basically stable, and the fracture zone of the working face is developed to the highest. The development height of the water-conducting fracture zone is 22.28 m.

By comparing with the measured results of 15101 working face, it is verified that the Fish language is embedded in the stop model established by FLAC\textsuperscript{3D} software, and the strain energy is used as the crack extension criterion to determine the plastic zone. The method of determining the fracture zone height according to the plastic zone damage range is accurate. It is feasible to judge the development height of the water-conducting fracture zone based on the numerical simulation method of the strain energy failure criterion. This method provides theoretical support for Zhubai Coal Mine mining and scientific basis and reference for safe mining of similar thin coal seam.

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