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Research Article

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DOI: https://doi.org/10.21203/rs.3.rs-510826/v1

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A Case Study on Development of Water-flow Fractured Zone During Close-Distance Repeated Coal Mining

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Abstract: The upper and lower seam of seam No.3 of some coal mines in Shandong Province are in close proximity which can be regards as close-distance coal seam mining. This paper takes the close-distance working face of Fucun coal mine as engineering background and mainly focuses on the investigation and research on inaccuracy of the forecasting and incompetence of the developing principles of water-flow fractured zone (WFFZ) during close-distance coal seam group mining. First, calculations on the height of WEEZ by adopting empirical formula. And FLAC3D software was established to calculate the height of the overburden WFFZ after repeated mining of the upper and lower seam of seam No.3. At the same time, using the double-ended water plugging observation technology of downhole drilling and upward hole drilling by analyzing the water injection loss ratio of the reference hole and the post-mining hole, the accurate numerical values of the WFFZ and the ratio of WFFZ height to mining height (W-M ratio) are obtained. The comparative analysis shows that the numerical simulation results are close to the measured ones, and the empirical formula is not applicable to the near-distance repeated mining. Finally, the prediction model is established based on the measured height of the WFFZ of multiple working faces, which provides a scientific basis for further exploring the development law of the overlying rock in underwater coal mining and ensuring the safe mining of coal seams at close distances.

Keywords: Close-distance coal seam; Water-flow fractured zone; Numerical Simulation; Regression analysis
1 Introduction

Energy is an important support for whether a country can achieve sustainable economic development and prosperity, and coal has been the main energy resource for a long time in China (Xie et al. 2018, 2019). Underground mining of coal will cause serious surface subsidence, environmental pollution and other problems (Hu et al. 2014; Wu and Sun 2016). With the continuous mining of coal, "Three - Under" coal mining accounts for an increasing proportion in China. Among them, coal mining under the water body is prone to water inrush accidents due to the existence of the overlying rock water body, causing heavy economic losses and casualties. Therefore, it is very important to carry out research on the safety related issues of underwater coal mining.

The original stress state of overlying strata is damaged after the exploitation of coal seams, and each rock formation may generate separation space. Deformation and movement may occur in overlying strata, and new fractured pore space may occur in fragmented rock (Chen et al. 2014; Gao et al. 2014). Based on extensive practical statistics on these topics, scholars are currently conducting research on the basic rules and movement characteristics of the overlying strata failure during coal mining. Therefore, the “Three-Zone” theory is established. Three zones, namely caving, fractured, and bending subsidence zone, generally form above the destruction zone of overlying strata. In the coal mining under water body, the caving zone and the fractured zone are collectively called the WFFZ. The continuous development of the WFFZ may cause it to communicate with the upper water body, and the water body flows in through the channel, thereby posing a major threat to the safety of the mine. Therefore, studying the development of the WFFZ is of great significance for mine waterproofing, protection of water resources, and coal mining and utilization (Sui et al. 2015; Xue et al. 2018).

Due to the complex stratum, researchers at home and abroad have done a lot of research on the development of WFFZ under different conditions (Chen et al. 2014; Dong et al. 2016; Du and Gao 2017). Based on the research on the overburden failure of the working face under a large number of different coal mining methods, the law of the “saddle shape” of the WFFZ and the empirical formula for height calculation have been summarized, which has been widely promoted and applied (Wang et al. 2015; Xu et al. 2020). Due to the different formation conditions of coal mines, the applicability of the empirical formula is not strong in complex situations. Therefore, for predicting the development of WFFZ under different conditions, many methods based on key stratum determination, numerical simulation, field measurement, and similar material simulation are proposed (Guo et al. 2021; Liu et al. 2020; Wang et al. 2017). Xu estimated the height of the WFFZ under different mining thicknesses based on the location and structure of the key stratum (Xu et al. 2009, 2012). Liu analyzed the height of the WFFZ in Jurassic coal seams in Northwest China through a combination of field measurement, mechanical calculation and numerical simulation (Liu et al. 2018a, 2018b). Dai obtained a more extensive and practical WFFZ height prediction model through neural network training based on a large amount of measured data (Dai et al. 2020). However, when repeated mining for close coal seams, due to the mutual influence between coal seams, the damage of the overlying strata is more complicated, and there is no practical formula for the height development of the WFFZ (Zhang et al. 2018).

Aiming at the development of WFFZ in short-distance coal seam mining, this paper takes the 1003 working faces of upper and lower seam of seam No.3. Fucun coal mine in Tengnan mining area, Shandong Province as the research object, and uses empirical formula method to calculate the height of WFFZ. Using FLAC3D software, simulation calculations have obtained the tensile strength, distribution range of both principal stress and plastic zone in the mining face, and the development height of the overlying WFFZ has been determined. Then, through the use of a multi-loop water inject (drain) detection system, the detection of the overburden failure of the working face was carried out. The height value of the WFFZ in the overlying rock and the W-M ratio are determined by analyzing the observation data of downhole benchmark holes and post-mining water injection. Finally, combined with the relevant data of multiple short-distance mining working faces in the mining area, multiple regression analysis was carried out, and a prediction model of the WFFZ was established. Through the research of this article, it provides an effective reference for the design of safe coal mining under the water body of coal mine and reducing the occurrence of mine water disasters.

2 Engineering Background

Fucun Coal Mine is located in approximately 6 km northwest part of Weishan County, Shandong Province, China. The area range is located south to Weishan Lake and Zhaoyang Lake in the west. The Beijing-Hangzhou Grand Canal flows through the southwest part of this mining field. The mining area is situated in the south part of Tengxian coalfield. With a flat topography, it is a slightly tilted northeast-to-southwest lakeside alluvial plain. The section of this mining area was originally a Lake District.
However, the ground height increased and formed a depression due to the river soil was discharged to the lakeline. Meanwhile, the ground height is close to the elevation of the lake area so that there is water accumulated in the local section. The mining area is mainly composed of three parts: land, lowland and lake.

The main research objects of this paper are the 1003 working faces of No.3 upper and lower coal seam. The coal in the working area is mined in a descending mining sequence. The surface of the working face is located in the range of 430~960m in the west of Lizhuang Village and 340~840m in the southeast of Peikou Village. The old canal passes through the surface in the northeast of the working face. The surface is agricultural reclamation area and production road, and the high voltage power lines pass through the east. After the coal mining in the 1003 working faces of No.3 upper coal seam, the maximum subsidence of the surface is about 3.3m, and the surface subsidence will appear to a large extent, causing serious damage to the ground and vegetation. Because the average mining height of the 1003 working faces of No.3 lower coal seam is about 3.17m, the surface subsidence phenomenon will appear after the mining face, making the subsidence area depth further increase. With the process of mining, the height of the WFFZ will continue to increase and it is near Weishan Lake. The continuous increase of the height of the WFFZ may be connected with the aquifer, thus leading to water inrush in the well and threatening the safety of underground coal mining.

3 Empirical Formula

Over the years, as coal mining researchers have studied the development height of the WFFZ in the overlying rock, an empirical formula for calculating the height of the WFFZ has been proposed in the relevant mining regulations (State Administration of Work Safety 2017). According to the “Regulations for coal mining and coal pillar leaving under building, water, railway and main shaft and tunnel” and referring to the existing data of the coal mining area, the theoretical prediction formula can be calculated according to Tab.1 and Tab.2.

| Tab.1 Calculation formula for height of caving zone |   |   |
|---|---|---|
| Rock type (UCS and Representative rock) (MPa) | Formula (m) |   |
| Hard and strong (40~80, Quartz sandstone, limestone, conglomerate) | $H_s = \frac{100\sum M}{2.1\sum M + 16} \pm 2.5$ |   |
| Medium hard (20~40, Sandstone, argillaceous limestone, sandy shale, shale) | $H_s = \frac{100\sum M}{4.7\sum M + 19} \pm 2.2$ |   |
| Soft and weak (10~20, Mudstone, argillaceous sandstone) | $H_s = \frac{100\sum M}{6.2\sum M + 32} \pm 1.5$ |   |
| Weathered soft and weak (<10, Bauxitic roc, weathered mudstone, clay, sandy clay) | $H_s = \frac{100\sum M}{7.0\sum M + 63} \pm 1.2$ |   |

| Tab.2 Calculation formula for height of WFFZ |   |   |
|---|---|---|
| Rock type | Formula (m) |   |
| Hard and strong | $H_b = \frac{100\sum M}{1.2\sum M + 2.0} \pm 8.9$ |   |
| Medium hard | $H_b = \frac{100\sum M}{1.6\sum M + 3.6} \pm 5.6$ |   |
| Soft and weak | $H_b = \frac{100\sum M}{3.1\sum M + 5.0} \pm 4.0$ |   |
| Weathered soft and weak | $H_b = \frac{100\sum M}{5.0\sum M + 8.0} \pm 3.0$ |   |

Since the roof of the working face in this mining area is mostly siltstone and coarse, medium and fine sandstone and mudstone, the strata is medium-hard and tends to be hard, so it is considered that the roof is medium-hard rock. Referring to Tab.1 and Tab.2, the height calculation formulas of caving zone and WFFZ are respectively, as shown in Eq.(1) and Eq.(2).
\[
H_k = \frac{100 \sum M}{4.7 \sum M + 19} \pm 2.2
\]
\[
H_l = \frac{100 \sum M}{1.6 \sum M + 3.6} \pm 5.6
\]

where \( M \) is the mining thickness, m.

The thickness of the upper working face is 4.30m, and the height of the caving zone and WFFZ is calculated according to the above formula as follows:

\[
H_k = \frac{100 \times 4.30}{4.7 \times 4.30 + 19} \pm 2.2 = 8.77m - 13.17m ;
\]
\[
H_l = \frac{100 \times 4.30}{1.6 \times 4.30 + 3.6} \pm 5.6 = 35.43m - 46.63m .
\]

The thickness of the lower working face is 3.17m, and the height of the caving zone and WFFZ is calculated according to the above formula as follows:

\[
H_k = \frac{100 \times 3.17}{4.7 \times 3.17 + 19} \pm 2.2 = 7.15m - 11.55m ;
\]
\[
H_l = \frac{100 \times 3.17}{1.6 \times 3.17 + 3.6} \pm 5.6 = 30.95m - 42.15m .
\]

From the above calculation, it can be concluded that when only the upper coal is mined according to the medium-hard rock layer, the estimated heights of the two zones are as follows: \( H_k = 8.77m - 13.17m \), \( H_l = 35.43m - 46.63m \). When mining the lower coal seam, the maximum height of the caving zone of the lower working face is 11.55m, which is less than the normal distance between the upper and lower coal seams of No.3 is 24.5m. According to the calculation requirements of “Regulations for coal mining and coal pillar leaving under building, water, railway and main shaft and tunnel”, the upper and lower layers of coal are taken separately. The calculated maximum elevation of the water-conducting fracture zone is taken as the maximum height of the WFFZ, and the maximum height is 35.43m–46.63m. Since the roof of the working face is a medium-to-hard rock layer, in order to make the observation scheme safe and reliable, the detection height of the fracture zone is set at 80.0m.

4 The numerical simulation

4.1 Model Building

The FLAC3D was adopted to analyze evolution of the fractures in the overlying strata in the working faces of mining area. Moor-Coulomb model was adopted in this numerical simulation, through which the mechanism of roof rock movement under mining effect and the stability of surrounding rock in the stress distribution state caused by mining could be studied in depth (Fan et al. 2020; Meng et al. 2016).

In order to eliminate the effects of stress boundary and displacement boundary, considering the purpose of analysis and the actual situation of the working face, the length and height of the two-dimensional calculation model are set to 1200m×170m respectively. The strata are divided into 14 strata groups along the mining face inclination. The numerical simulation model is shown in Fig.1. The physical and mechanical parameters of the rock and soil layer are obtained through mechanical tests on the rock samples extracted from the drill holes in the field geological exploration, as shown in Tab.3 below. During simulation: the displacement in X direction at both ends of the model is fixed, that is, the horizontal displacement of the boundary is zero; the horizontal and vertical displacement of the bottom boundary of the model is zero; the top of the model is free boundary, and the load is applied according to the stratum structure.

![Fig.1 The prototype of the numerical model](image)

| Tab.3 Mechanical parameters of rock and soil layers |
| --- |
| Lithology         | Density (kg/m³) | Compressive strength (MPa) | Deformation modulus (GPa) | poisson ratio | Tensile strength (MPa) | cohesion (MPa) | Internal friction angle(°) |
|-------------------|-----------------|-----------------------------|---------------------------|---------------|-----------------------|----------------|----------------------------|
| Clay              | 2200            | 0.00966                     | 0.3                       | 0.12          | 1.45                  | 21.12          |                             |
| Mudstone          | 2377            | 12.25                       | 0.321                     | 0.272         | 0.788                 | 1.38           | 30.7                       |
| Fine sandstone    | 2364            | 6.71                        | 0.219                     | 0.294         | 1.155                 | 2.68           | 32.5                       |
| Mudstone          | 2436            | 18.01                       | 0.974                     | 0.26          | 2.139                 | 2.12           | 30.5                       |
| Fine sandstone    | 2598            | 46.79                       | 4.79                      | 0.253         | 1.76                  | 7.6            | 33.6                       |
| Siltstone         | 2621            | 65.54                       | 11.87                     | 0.255         | 2.084                 | 4.21           | 34.5                       |
| Fine sandstone    | 2651            | 100.55                      | 10.05                     | 0.226         | 3.663                 | 13.87          | 37.5                       |
| Siltstone         | 2621            | 65.54                       | 11.87                     | 0.255         | 2.084                 | 4.21           | 34.5                       |
| No.3 upper coal seam | 1476        | 5.12                        | 0.989                     | 0.247         | 0.341                 | 2              | 30                         |
| Sandy mudstone    | 2578            | 29.68                       | 1.008                     | 0.279         | 1.918                 | 6.12           | 31.4                       |
| No.3 lower coal seam | 1499        | 13.82                       | 2.212                     | 0.24          | 0.18                  | 2.1            | 30.5                       |
| Mudstone          | 2507            | 54.27                       | 5.493                     | 0.247         | 1.308                 | 2.75           | 33.1                       |
| Siltstone         | 2714            | 77.97                       | 11.68                     | 0.217         | 4.246                 | 14.04          | 35.4                       |
| Mudstone          | 2619            | 41.87                       | 2.64                      | 0.217         | 2.218                 | 3.36           | 34                         |

4.2 Simulation calculations

4.2.1 Simulation calculation of Upper Coal Seam Ming

The results of upper coal seam mining simulation are shown in Fig.2. As can be seen from Fig.2(a), isolines are relatively dense at 8.9~19.5 m above the goaf, indicating that the displacement in the Y direction changes rapidly and there is a sudden change. The part above the abrupt change can be determined as the fracture zone, and the maximum height at the isoline density above the goaf is determined as the height of the caving zone, which is 19.5 m. The tensile strength distribution of Fig.2(b) shows the area in which the unit tensile failure occurs, although in the mining process, most of the previously fractured rock masses are elastic due to stress redistribution or compaction, as shown in Fig.2(c). However, because of the large stiffness of rock mass, the fracture cannot be completely closed, so it is still regarded as the WFFZ. The resulting WFFZ height is about 48.9~63.7 m, as shown in Fig.3.
4.2.2 Simulation of double mining of 1003 coal seams

The main results obtained from the simulation of repeated mining in 1003 coal seam are shown in Fig.4. The analysis method of overburden movement and deformation during repeated mining of 1003 working face is analogous to the analysis method of upper coal mining. By comparing and analyzing the Y direction displacement contour map, the contour lines above the goaf are more dense and the displacement increases after repeated mining. Due to repeated mining, the single-stratum mining has caused damage to the rock layer again. By comparing the tensile strength distribution diagrams, it can be seen that the damaged area of tensile strength increases obviously after repeated mining. The height of caving zone after repeated mining in 1003 coal seam is 17.5~33.4 m through analysis, and the height of WFFZ is 62.9~76.2 m, as shown in Fig.5.
4.2.3 simulation statistics

Through the above analysis and calculation of the numerical simulation results, and in order to ensure the safety needs of coal mining work, the damage height of the upper overburden after the coal mining work is given according to the maximum value, as shown in Tab.4.

| Coal seam                  | Maximum height of caving zone(m) | Maximum height of WFFZ for repeated mining(m) |
|----------------------------|----------------------------------|-----------------------------------------------|
| upper coal mining face     | 19.5                             | 63.7                                          |
| lower coal mining face     | 33.4                             | 76.2                                          |

5 Field Testing

With the continuous progress of science and technology, in addition to the traditional drilling fluid method, the micro-earthquake method, acoustic wave CT detection, resistivity method and digital drilling camera detection have been developed (Chen et al. 2019; Sun et al. 2021; Wei et al. 2017; Zhang et al. 2014). In this paper, the double-ended water plugging leak detection method is used to detect the hole. The water supply is pressurized to the “double-ended water plugging device” placed in the borehole to complete the plugging and water injection. The failure of rock mass is judged by measuring the leakage flow of water in the blocked section, so as to determine the height of the WFFZ. The method has the
advantages of high precision, less engineering quantity, less investment and obvious observation effect.

5.1 Drilling Layout

The height observation boreholes of the overburden WFFZ are arranged in No.3-lower 1004 haulage way. A total of three boreholes are constructed, one reference hole and two post-mining holes. The layout of the detection drill hole is shown in Fig.6. The borehole observation profile is shown in Fig.7.

As can be seen from Fig.6, there are faults between the haulage way where the drilling holes are located and the 1003 working face of the No.3 lower seam, which causes the drilling hole to be raised. The height difference on both sides of the fault is more than 30m. The elevation of the roof at the drill hole is -415.70m, which corresponds to the elevation of the bottom end of the drill pipe. 1# drill pipe is -416.70m. A datum hole and two post-mining holes were constructed at the drill holes to the working face of the lower seam of No.3 seam. The post-mining observation hole observes the water loss of the overlying rock layer after the coal seam is mined while the reference hole observes that it has not been affected by mining. The comparison of the two observation data can determine the height of the WFFZ. The drilling construction elements are shown in Tab.5.

Fig.6 The layout plan of the detection drill hole
Tab.5 Elements of Drilling Construction

| Number | Name        | Diameter(mm) | Direction(º) | Elevation(º) | Depth(m) | Time                        |
|--------|-------------|--------------|--------------|--------------|----------|-----------------------------|
| 1#     | Reference   | 75           | 352º         | 50º          | 103.5    | Before mining               |
| 2#     | Post-mining | 75           | 88º          | 57º          | 103.5    | 100 d after mining          |
| 3#     | Post-mining | 75           | 109º         | 45º          | 103.5    | 100 d after mining          |

5.2 Comparison of Observed Missing Data

By comparing the water injection leakage of the 1# reference hole with the water injection leakage of the 2# post-mining hole, the vertical height of the WFFZ of the 2# borehole can be determined, as shown in Fig.8. Through the comparison and analysis of the water injection loss of the reference hole and the water injection loss map of the post-mining hole, the vertical height of the WFFZ of the 3# borehole can be determined, as shown in Fig.9.
5.3 Height Determination of WFFZs in each borehole

Due to the different inclination angles and azimuth angles of each borehole, the height of the WFFZ of each borehole should be determined on the basis of comprehensive consideration of the 1003 working faces of the upper and lower seam, the elevation of the drill hole and the spatial position of each borehole. The azimuth section view of the reference drilling hole is shown in Fig. 10.

The calculation formula of the measured height of WFFZ is as shown in Eq. (3). It can be seen from Fig. 8 and Fig. 11: the height difference between the elevation of drill hole and the roof height of the upper seam of No. 3 seam is \( h_1 = -416.7 - (-420.06) = 3.36 \) m; the horizontal distance between the drill hole and the 1003 working face of the upper seam of No. 3 seam is 6.7 m; \( h_2 = (45.29 / \tan 57^\circ) - 6.7 \) * \( \tan 3.5^\circ = 1.39 \) m; \( h_3 = 24.5 \) m; 2# borehole vertical height \( h_4 = 45.29 \) m. It is determined by Eq. (3) to get 2#: the height of the WFFZ of the 1003 working face in the upper seam of No. 3 seam \( H_{up}^{2} \) is 50.04 m; the height of the WFFZ of the 1003 working face in the lower seam of No. 3 seam \( H_{low}^{2} \) is 74.54 m.

It can be seen from Fig. 9 and Fig. 12: the height difference between the elevation of drill hole and the roof height of the upper seam of No. 3 seam is \( h_1 = -416.7 - (-420.06) = 3.36 \) m; the horizontal distance
between the drill hole and the 1003 working face of the upper seam of No.3 seam is 6.7m; 
\[ h_2 = ((50.91 / \tan 45\degree) - 6.7) \times \tan 3.5\degree = 2.7m; \] 
\[ h_3 = 24.5m; \] 
\[ h_4 \] 

3# borehole vertical height \( h_4 \) is 50.91 m. It is determined by Eq.(3) to get 3#: the height of the WFFZ of the 1003 working face in the upper seam of No.3 seam \( H_{WFFZ}^{3\#} \) is 56.97m; the height of the WFFZ of the 1003 working face in the lower seam of No.3 seam \( H_{WFFZ}^{3\#} \) is 81.47m.

5.4 Determination of the height of WFFZ in repeated mining

According to the observation data of the reference hole and the post-mining holes, the observation

Fig.11 Sectional view of 2# borehole

Fig.12 Sectional view of 3# borehole
results of the water injection leakage of the pre-mining hole and the post-mining hole are compared and analyzed. It can be seen from the cross-sectional view of each borehole that, the height of the WFFZ of repeated mining is the maximum of the development height of the WFFZ of the two post-mining holes. The height of the WFFZ in the 1003 working face of the upper coal seam of No.3 seam is 56.97m. The height of the WFFZ in the 1003 working face of the lower coal seam of No.3 seam is 81.47m. The average mining thickness of lower coal seam is 3.46 m, and the W-M ratio is 23.55. The average mining thickness of upper coal seam is 4.30m, and the W-M ratio is 13.25.

6 Prediction Model of Development Height of WFFZ

Regression analysis, as a statistical analysis method to determine the dependent quantitative relationship between variables, can be used to predict the development height of WFFZ. According to the number of variables involved, it can be divided into univariate regression analysis and multiple regression analysis. Because there are many factors affecting the development of WFFZ, this paper uses multiple regression analysis to establish a prediction model (Liu et al. 2019; Zhang et al. 2014). The multiple regression models of WFFZ and multi-factor influencing factors are as shown in Eq.(4).

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k$$

where $\beta_0$ is a constant term and $\beta_1, \beta_2, \ldots, \beta_k$ are regression coefficient.

Through the study of scholars at home and abroad, the factors that affect the development of WFFZ height include coal mining depth, mining thickness, coal seam inclination angle, overburden geological characteristics and cut hole width. Considering the complexity of near-distance repeated coal mining method and the feasibility of regression analysis method, this paper selects many working faces in this mining area as the research object, and selects coal mining depth, mining thickness and coal seam inclination angle to establish a prediction model for the development height of WFFZ for No.3 coal seam repeated mining. The working face parameters are shown in Tab.6. By programming Matlab data analysis software, the residual diagram of regression analysis is shown in Fig.13. It can be seen from the diagram that all points floating range is within the confidence interval range, no abnormal value. And the residual difference is close to the zero point, and the confidence interval of all residuals contains zero points, which indicates that the regression model can better accord with the original data.

| Working face | Depth(m) | Thickness(m) | Angle(°) | Measured value(m) |
|--------------|----------|--------------|----------|-------------------|
| FC1          | 190.8    | 4.8          | 7        | 44.7              |
| FC2          | 362.2    | 5.43         | 15       | 61.52             |
| FC3          | 463      | 4.3          | 3.5      | 56.97             |
| FC4          | 450      | 4.8          | 8        | 60.83             |
| FC5          | 203.8    | 3.8          | 7        | 67.5              |
| FC6          | 491.4    | 3.17         | 3        | 81.47             |
| FC7          | 250      | 3.44         | 4        | 66                |
The relevant parameters of regression model

| Coefficient | Estimation | Confidence interval |
|-------------|------------|---------------------|
| $\beta_0$   | 116.4704   | [102.9730, 129.9679]|
| $\beta_1$   | 0.0464     | [0.0314, 0.0613]    |
| $\beta_2$   | -21.0162   | [-25.0508, -16.9816]|
| $\beta_3$   | 2.8820     | [2.0716, 3.6923]    |

The significant level is $\alpha=0.05$, and the regression model parameters are obtained by matlab calculation as shown in Tab.7. The values can be seen from Tab.7 in the confidence interval. Decision coefficient of the model $R^2=0.9916$, the value is very close to 1, the fitting degree is high; $F=118.443\gg 9.28=F(1-\alpha)$, the equation has significant significance and significant regression effect; probability $\rho=0.0013<0.05$; model residual squared is 2.0874. By analyzing the parameters selected by the prediction model, the prediction model is accurate and reliable, and the formula of ternary regression model Eq.(5).

$$y = 116.4704 + 0.0464x_1 - 21.0162x_2 + 2.8820x_3$$  \tag{5}$$

7 Discussion

In view of the WFFZ height developmental problems, through the analysis of the above work results as shown in Tab.8 and Tab.9. Can see clearly from the tables, after mining the upper coal seam in, through three ways to get WFFZ height value is relatively close, the numerical simulation and actual measurement of value closer to more accurately. However, when repeated mining is carried out, the measured height of WFFZ is greater than that obtained by numerical simulation and empirical formula. However, it is not difficult to see from Tab.9 that the results of numerical simulation are close to the measured data, which has reference value. However, the value obtained by the empirical formula is only about half of the measured value, which has lost its reference value. Therefore, the empirical formula is not applicable to predict the height of WFFZ in the close-distance repeated coal mining.

Due to repeated mining in a relatively close range of coal seam mining, the development height of the damage area produced by it is greater than that of single coal seam mining (Ning et al. 2020). When the lower coal is mined, it will have a secondary impact on the overlying rock, causing the overlying rock to be “activated” twice, and the height of the WFFZ will be further developed. Combined with the work in this paper and the collected data analysis, the secondary development height of the WFFZ caused...
by repeated mining will not develop violently due to the nature of the overlying strata and the influence of key stratum (Qiao et al. 2017; Zhou et al. 2021). The work in this paper provides a scientific basis for studying the destruction mechanism of the overlying strata and the retention of coal (rock) pillars for safe mining during repeated mining at short distances.

| Tab.8 Calculation results after the upper coal mining |
|------------------------------------------------------|
| Numerical Simulation | Empirical Formula | Field Testing |
|----------------------|-------------------|---------------|
| HCZ(m) | HWFFZ(m) | HCZ(m) | HWFFZ(m) | HWFFZ(m) |
| 8.9~19.5 | 48.9~63.7 | 8.77~13.17 | 35.43~46.63 | 56.97 |

| Tab.9 Calculation results after repeated coal mining |
|------------------------------------------------------|
| Numerical Simulation | Empirical Formula | Field Testing |
|----------------------|-------------------|---------------|
| HCZ(m) | HWFFZ(m) | HCZ(m) | HWFFZ(m) | HWFFZ(m) |
| 17.5~33.4 | 62.9~76.2 | 7.15~11.55 | 35.43~46.63 | 81.47 |

where HCZ is the height of caving zone, HWFFZ is the height of WFFZ.

8 Conclusions
In the practical of coal mining work, the height of underwater WFFZ is of great significance for coal mine to prevent underground water inrush. The following conclusions are obtained by the study point at the development of the height of WFFZ in close-distance repeated coal mining.

1) When the upper coal seam is mined out, the height of WFFZ obtained by empirical formula and data simulation is close to the measured data. After mining two layers of coal, the accuracy of the height of WFFZ obtained by empirical formula is extremely low because of the superimposed effect of repeated mining, while the data simulation is closer to the measured data. It shows that the traditional empirical formula doesn’t applies to the condition of close-distance repeated coal mining.

2) In this paper, multiple working faces that are repeated mined in close quarter of the cola mine and adjacent coal mine are selected as data sources, and the mining depth, mining thickness and coal seam angle are selected as independent variables to establish the prediction model of the height transformation of WFFZ. The high accuracy of this model was verified by residual analysis and significance test. Therefore, in the close-distance repeated coal mining, using the FLAC3D and the prediction model to predict the height of WFFZ to provide reference value of safety range of coal seam mining. And then combined with the field test after mining can more effectively prevent underground water inrush accidents and guide the safety of mining coal resources.

Data Availability
The data used to support the findings of this study are included within the article. No extra data were used to support this study.

Declaration of Competing Interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments
This study was supported by Shandong Province Natural Science Fund (NoZR2020MD024).

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Figures

Figure 1
The prototype of the numerical model

Figure 2
The results of upper coal seam mining simulation: a contour of displacement in y-direction, b distribution of tensile strength, c distribution of plastic zone, d maximum principal stress, e minimum principal stress.

Figure 3

Height of caving zone and WFFZ in upper coal mining face.
Figure 4

The results of double coal seams mining simulation: a contour of displacement in y-direction, b distribution of tensile strength, c distribution of plastic zone, d maximum principal stress, e minimum principal stress
**Figure 5**

Height of caving zone and WFFZ in lower coal mining face

- borehole 1#
  - length 103.5m
  - inclination 50°
  - azimuths 352°

- borehole 2#
  - length 103.5m
  - inclination 57°
  - azimuths 88°

- borehole 3#
  - length 103.5m
  - inclination 45°
  - azimuths 109°

**Figure 6**

The layout plan of the detection drill hole
Figure 7

Profiles of borehole observation

Figure 8
Comparison of water injection leakage in 1# and 2# borehole

Figure 9

Comparison of water injection leakage in 1# and 3# borehole
Figure 10

Sectional view of 1# borehole
Figure 11

Sectional view of 2# borehole
Figure 12

Sectional view of 3# borehole
Figure 13

Residual case order plot