

Study on the Developmental Characteristics of Water-Conducting Fracture Zones in Multi-Slice Mining of Thick Coal Seams within the Gondwana Stratigraphy

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Abstract. The geological strata of the Barapukuria Coal Mine in Bangladesh are affiliated with the Gondwana Formation. To ensure safe future mining of thick coal seams under aquifers, the development law of the Water-Flowing Fractured Zone (WFZ) during slice extraction was investigated. The development height of the WFZ was predicted via numerical simulation. Field measurements of the WFZ height were subsequently conducted for each mining slice, and regression analysis was performed to establish a mine-specific predictive formula. Analysis of extensive case studies identified mining depth, overburden lithology, dip angle, mining method, and extraction thickness as the primary factors influencing WFZ development. A predictive model for the WFZ based on a Back-Propagation (BP) neural network was developed using MATLAB R2014a. The model was subsequently trained and tested, and then applied to predict the WFZ height in the mine's panels. These predictions were compared against the empirical formula from the "Under-Three" Regulations, the site-specific regression formula, and actual field measurements. The results demonstrated that the WFZ height increased approximately linearly with the cumulative extraction thickness after the first and second slices. During the third mining slice, the rate of WFZ height increase was significantly reduced. Among all predictive models evaluated, the BP neural network-based model achieved the highest accuracy. Finally, the predicted WFZ height for the third mining slice was presented.

Keywords: Gondwana Strata; Height of the Water-conducting Fracture Zone; Leakage Observation; BP Neural Network.

1. Introduction

Bangladesh is one of the 64 key countries along the Belt and Road Initiative. The Barapukuria Coal Mine (hereinafter referred to as the BCM), operated by a consortium formed by China's Xuzhou Coal Mining Group and China National Machinery Import & Export (Group) Co., Ltd., has been responsible for its construction, production, and management since 2005. Over more than a decade of cooperation between the consortium and Bangladesh, the project has served not only as a pioneering project of the Belt and Road Initiative but also as the only coal mine in Bangladesh, playing an indispensable role in the country's economic development. The mining geological conditions of the BCM are characterized by "three-thick" features: a thick and water-rich loose

sandstone aquifer, a thick coal seam roof, and a thick coal seam itself. Safe mining operations are threatened by multiple hazards, including water inrush, rock burst, spontaneous combustion in goaf areas, and geothermal heat. Currently, a water hazard control strategy described as “upper protection and lower drainage” is implemented. This is achieved through a coordinated and height-limited extraction method with staggered slicing in thick coal seams, enabling safe mining under multiple overlying aquifers. The key to this approach lies in ensuring that the WFZ does not extend into the protective aquifer.

In China, the prediction of the maximum heights of the caved zone and water-conducted fractured zone primarily relies on the “Regulations for Coal Pillar Retention and Pressure Mining under Buildings, Water Bodies, Railways, and Main Shafts” (abbreviated as the “Under-three” regulations). These regulations provide empirical formulas that relate overburden failure height to mining height for gently inclined, moderately inclined, and steeply inclined coal seams under various overburden lithological conditions[1]. Owing to the limited factors considered and restrictive application conditions of the “Under-three” regulations, numerous studies have adopted diverse methodologies to re-examine overburden failure mechanisms. For example, Wang Lianguo and Wang Zhansheng et al. developed mechanical models tailored to the Shendong mining area, deriving fracture criteria and prediction methods for the water-conducted fractured zone under various lithological conditions[2]. Chen Ronghua and Bai Haibo et al. employed RFPA2D software for numerical simulation of overburden deformation and collapse during fully mechanized top-coal caving operations, enabling determination of the fractured zone height[3]. Zhang Jun and Wang Jianpeng conducted similar material simulations based on mining-induced overburden failure characteristics, obtaining heights of the three zones (caved, fractured, and bending zones) at the Du'erping mine[4]. Hu Xiaojuan, Li Wenping et al. performed multiple regression analysis on 39 measured datasets of the fractured zone height from fully mechanized mining, establishing a nonlinear statistical model incorporating factors such as mining height, depth, and advance rate; this model was subsequently applied to predict the fractured zone height in the first panel of the Xieqiao mine, Huainan[5].

Current well-established theories and findings on the development of the water-conducted fractured zone are primarily derived from studies under typical Chinese geological settings. However, the unique Gondwana geological features of the Barapukuria mine (Bangladesh), coupled with its role as a flagship project under the “Belt and Road” Initiative and Sino-Bangladeshi energy cooperation, necessitate specific investigation into the fractured zone development during thick coal seam slicing at this mine. Such research is crucial for ensuring both safety and economic viability in mining operations.

2. Comprehensive Evaluation of Mining-Geological Conditions

As revealed by geological exploration and mining operations, the stratigraphic sequence of the Barapukuria Coalfield is summarized in Table 1. From top to bottom, the succession comprises: the Cenozoic Quaternary Madhupur Clay Formation, the Neogene Upper Dupi Tila unconsolidated strata, the Paleogene Lower Dupi Tila Formation, the Paleozoic coal-bearing Carboniferous-Permian Gondwana Formation, and a Cambrian complex basement.

The Barapukuria mine is situated within the Gondwana strata, which are characterized by poor overall diagenesis, leading to low rock strength, high porosity, and elevated water content[6]. Notably, Mesozoic sedimentary records are absent, and competent aquiclude layers are scarce within the formation.

The “three-thick” characteristics are defined as follows:

- (1) Thick Aquifer: A approximately 110-meter-thick unconsolidated sandstone aquifer, situated below 10 meters of topsoil, exhibits a permeability coefficient ranging from 0.44 to 40.16 m/d.
- (2) Thick Coal Seam: The primary mining seam (Seam VI) is stable, with a thickness ranging from 29.00 to 41.52 meters (average 36.14 m) and a dip angle of 5° to 30°.

(3) **Thick Roof Strata:** The immediate roof, averaging 120 meters in thickness, consists predominantly of medium- to coarse-grained sandstone and pebbly coarse sandstone. It is classified as a soft to medium-hard rock with an average uniaxial compressive strength of 17.08 MPa, corresponding to an easy-to-medium caving roof. This thick roof sequence is marked by poor internal stratification and high structural integrity.

The seam floor is composed of interbedded fine sandstone, medium-fine sandstone, siltstone, and carbonaceous mudstone. It is classified as a medium-hard rock stratum with low susceptibility to water softening and high resistance to disintegration.

Tab 1. The field layer profiles of Barapukuria mine

Eonothem	System	Formation	Thickness/m
Cenozoic	Quaternary	Madhupur	4.3~15.9
	Neogene	Upper Dupi TiLa	90.70~110.00
	Paleogene	Lower Dupi TiLa	0~80.4
Paleozoic	Carboniferous-Permian	Gondwana	117.72~475.4
	Cambrian	Basement	Very Thick

Based on preliminary hydrogeological surveys, the Barapukuria Mine is classified as having a moderately complex hydrogeological type, falling into the category of a water-rich mine[7]. As shown in Figure 1, the aquifers influencing mining operations mainly include the Neogene Upper Dupi Tila (UDT) unconsolidated aquifer, the weathered and oxidized zone aquifer of the Gondwana Formation at the base of the Paleogene Lower Dupi Tila (LDT) aquitard, and the bedrock aquifer within the Gondwana coal-bearing strata. According to their position, water abundance, and occurrence characteristics, the aquifers in the area can be categorized, from top to bottom, as follows: the UDT aquifer, the aquifer group between the Roof of Seam V and the floor of the LDT, and the aquifer group between the Roof of Seam VI and the floor of Seam V.

During the mining process, groundwater within the aquifers has been progressively drained according to the mine's dewatering capacity. To date, two slices of the thick coal seam have been extracted. The first slice was predominantly mined using the fully mechanized longwall method, with an average extraction thickness of 3.0 m. Post-mining, the aquifer between the roof of Seam VI and the floor of Seam V was successfully drained. The second slice was mainly extracted using the fully mechanized top-coal caving method, with extraction thicknesses ranging from 3.0 to 7.5 m. Following this stage, the aquifer group between the roof of Seam V and the floor of the LDT formation was drained.

A critical control measure ensured that the WFZ did not extend into the LDT aquitard. This precaution allowed the LDT layer to subside steadily, preventing a hydraulic connection where water from the UDT aquifer could breach the LDT aquitard and interconnect various aquifers, thereby ensuring mining safety.

Currently, the first and second slices have been fully extracted, and mining of the third slice is imminent. To enhance the overall resource recovery rate while guaranteeing safe mining conditions, it is essential to study the development height of the WFZ following the first two slices of extraction. The findings will provide vital guidance for the planned third slice mining operation.

3. Detection of Water-Flowing Fractured Zone Height after First and Second Slice Extraction

3.1 Height Detection of the Water-Flowing Fractured Zone after First-Slice Mining

During the first slicing mining, a downhole upward drilling leak detection test with plugging at both ends was conducted on the 1112 fully mechanized mining face to determine the height of the water-conducting fracture zone induced by the first slicing mining[9,10]. Four drill holes were arranged in the experiment, including three observation holes and one comparison hole. The leakage volume data measured during the test are presented in Figure 1.

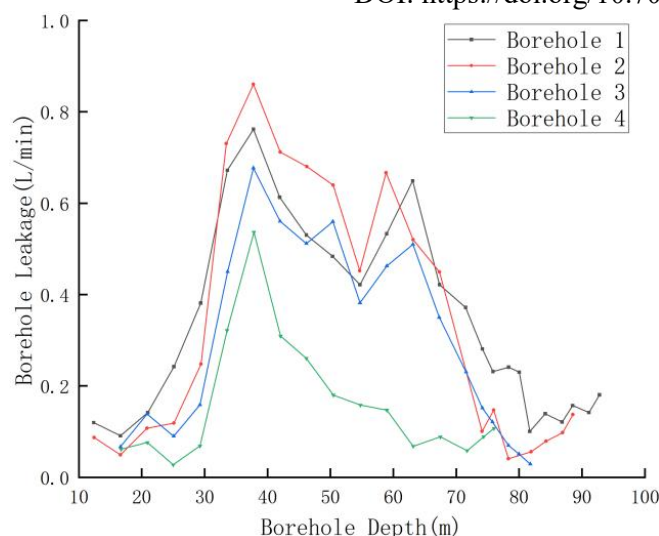


Fig. 1 Observation results of leakage volume in the 1112 working face

According to the observation results, the leakage volume of the comparison hole exhibits a wide variation range. However, its maximum and minimum values are smaller than those of the other three holes, and the curve flattens at a relatively fast rate. This phenomenon can be attributed to the following factors: the comparison hole is situated in the downhill coal pillar area, with goafs distributed on both flanks of the pillar. After the fracture of the hard rock stratum in the main roof, high stress is induced in the upper part of the downhill coal pillar, which generates surrounding fractures. Consequently, the observed values of the comparison hole in the 36~63 m interval increase. When the drill hole penetrates into the non-high-stress zone, the observed values decrease rapidly to less than 0.2 L/min. Thus, 0.2 L/min is defined as the threshold value. The interval where the leakage volume does not exceed this threshold can be considered as the rock mass without fracture development. Through comparative analysis of the leakage volume, the development law of the water-conducting fracture zone in the three observation holes is identified. Based on the spatial relationship, the height of the water-conducting fracture zone in the direction perpendicular to the coal seam floor of the inclined coal seam is calculated, and the results are presented in Table 2.

Tab 2. Development characteristics of the water-conducting fracture zone in the 1112 working face

ID	Undamaged zone of the overlying strata	Top of the water-conducting fracture zone	Water-Flowing Fractured Zone Height /m
1	93.48m~82.08m	82.08m~74.48m	61.47
2	88.92m~73.72m	73.72m~69.92m	58.53
3	82.84m~73.72m	73.72m~66.12m	59.31

As the downhole observation was conducted approximately 10 months after the completion of working face mining, the overlying strata gradually settled over time and compacted the goaf. This process reduced or even closed the fractures formed in the overlying strata, resulting in a certain degree of decline in the caving and fracture zone. Based on previous mining experience, the effective decline height is estimated to be no more than 15% of the actually detected water-conducting fracture zone height[8]. Thus, the maximum detected height of the water-conducting fracture zone was corrected to 70.68 m, with a maximum fracture-mining ratio of 23.56.

3.2 Height Detection of the Water-Flowing Fractured Zone after Second-Slice Mining

Following the second slicing mining, the water-conducting fractures in the overlying strata developed to a relatively greater height. This necessitated a longer drilling length for downhole upward drilling detection in the second slicing. Owing to severe damage to the overlying strata

caused by the first slicing mining, maintaining downhole observation holes proved challenging. Therefore, surface drilling was adopted to determine the height of the WFZ in the overlying strata following the second slicing working face mining.

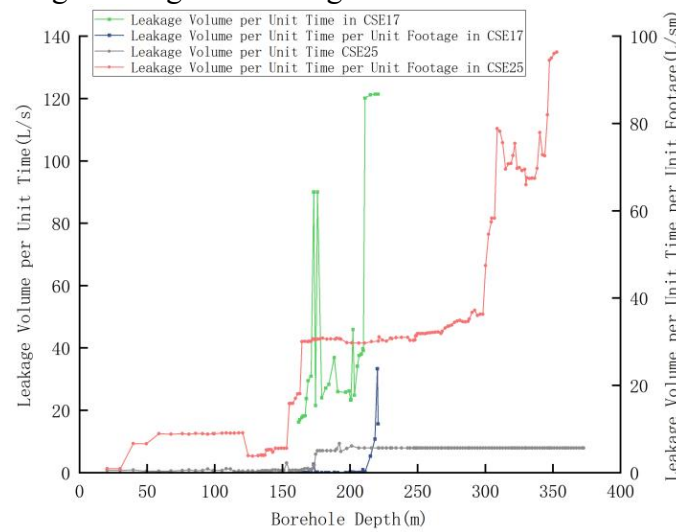


Fig. 2 Drilling fluid loss observation

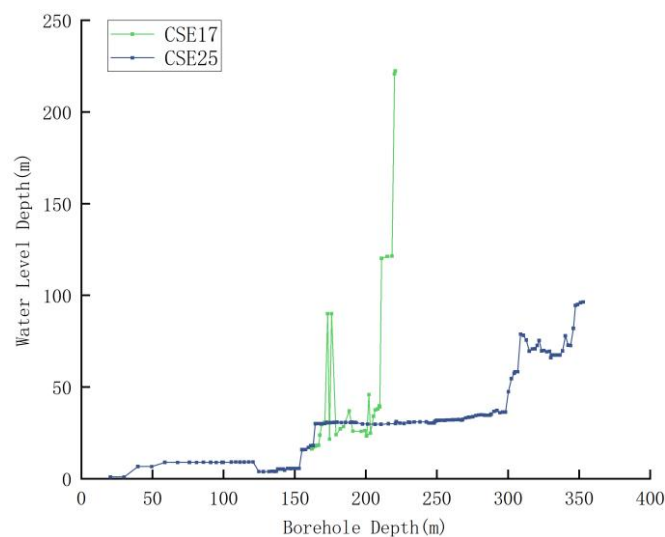


Fig. 3 Depth change of water level in hole

The surface drilling fluid leakage observation method is the most conventional and well-established technique for exploring the damage characteristics of overlying strata. This technique primarily relies on surface drilling. During drilling operations, abnormal phenomena (e.g., drilling sticking, air suction) are monitored, and drilling fluid leakage volume as well as borehole water level are recorded. Where conditions allow, rock cores are collected for integrity analysis. After drilling completion, fracture development within the borehole is observed via borehole television imaging. The development height of the WFZ in the overlying strata of the coal seam roof is determined by analyzing these indicators[11,12].

Subsequent to the completion of the second slicing mining, surface drilling fluid leakage and borehole water level observations were conducted sequentially in the 1204 fully mechanized mining face (CSE17) and the 1214 fully mechanized top-coal caving face (CSE25) to analyze the height of the water-conducting fracture zone.

The observation results are presented in Figures 2 and 3. By integrating the variation trends of flushing fluid leakage volume per unit time, flushing fluid leakage volume per unit time per unit footage, and borehole water level depth, along with abnormal phenomena (e.g., drilling sticking) encountered during construction, the following conclusions are drawn: The maximum development

height of the water-conducting fracture zone in the 1204 fully mechanized mining face is at a borehole depth of 209.49 m, 110.51 m above the roof of Coal Seam VI. Specifically, with a mining height of 3 m for the second slicing fully mechanized mining, the fracture-mining ratio of the second slicing is 36.84, and the fracture-mining ratio based on the cumulative mining thickness is 18.42. The maximum development height of the water-conducting fracture zone in the 1214 fully mechanized top-coal caving face is at a borehole depth of 173.61 m, 215.59 m above the roof of Coal Seam VI. Specifically, with a mining height of 7 m for the second slicing fully mechanized top-coal caving, the fracture-mining ratio of the second slicing is 30.85, and the fracture-mining ratio based on the cumulative mining thickness is 21.59. The safe water-resistant coal-rock pillar required for the two slicings is 5 times the individual slicing mining height[13,14].

3.3 Analysis of Water-Flowing Fractured Zone Height Following First and Second Slice Mining

The development characteristics of the WFZ directly influence the allowable underwater mining height[15,16]. This study investigates the development height of the water-conducting fracture zone, aiming to clarify its development characteristics during the slicing mining of thick coal seams in the Gondwana strata. The summarized detection data of the WFZ in Barapukuria Mine are presented in Table 3.

Based on the geological conditions of the mine, the overlying strata of the mined coal seam exhibit moderately hard comprehensive lithology. Although the mined coal seam in Barapukuria Mine is part of the Gondwana strata, soft rock formations (e.g., mudstone and shale) are essentially absent. The strata are dominated by coarse-fine sandstone and conglomerate, characterized by indistinct stratification and considerable single-layer thickness. This differs significantly from the Carboniferous-Permian strata in China. Detection results have verified that the overall damage to the strata within the boreholes is minor, with a high degree of discreteness in fracture distribution. This is primarily attributed to the indistinct stratification and considerable thickness of the overlying strata of the mined coal seam. Within the fracture zone, the strata are fragmented into large blocks, exhibiting a low bulking coefficient. Consequently, the development height of the water-conducting fracture zone is higher than that observed in domestic mines.

Tab 3. Statistics of WFZ Detection Results at Barapukuria Mine

Panel	Mining Method	Slice	Cumulative Extraction Thickness/m	Water-Flowing Fractured Zone Height/m	Cumulative Fracture-to-Mining Ratio
1112	Fully Mechanized Longwall Mining	First Slice	3	70.68	23.56
1210	Fully Mechanized Top-coal Caving Mining	First Slice	5	105	21
1204	Fully Mechanized Longwall Mining	Second Slice	6	110.52	18.42
1214	Fully Mechanized Top-coal Caving Mining	Second Slice	10	215.59	21.59

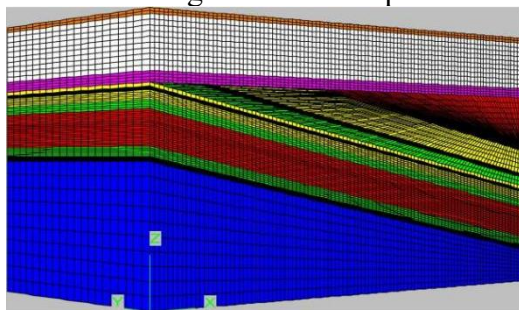
4. Simulation and Predictive Analysis

4.1 FLAC3D Numerical Simulation

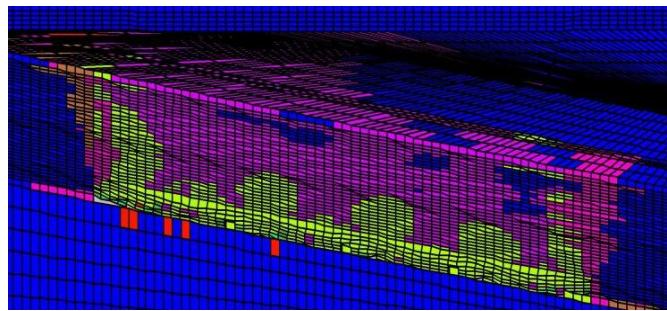
This study represents the first investigation into the development height of the WFZ for thick coal seam slice mining within the Gondwana strata of Bangladesh, with no prior local experience for reference. Consequently, numerical simulation was employed for pre-mining analysis. In mining engineering research, FLAC3D is widely recognized as a technically mature and representative software for analyzing mining-induced stress fields in surrounding rock and surface subsidence.

Based on the mine's geological conditions, a numerical model was established, as illustrated in Figure 2. The simulation scheme included the following stages: first-slice mining (3.0 m extraction height) of four fully mechanized longwall faces; second-slice mining (3.0 m and 7.0 m extraction heights) of four fully mechanized top-coal caving faces, based on the first-slice mining; and third-slice mining (3.0 m extraction height) of four fully mechanized longwall faces. The simulation results are shown in Figure 4, and the statistics of the WFZ heights after the extraction of each panel are summarized in Table 4.

The development behavior of the WFZ directly governs the safe mining height under aquifers[15,16]. Studying the development patterns of the WFZ provides critical guidance for determining feasible mining heights under water bodies. The empirical formulas provided in the “Under-three” Regulations were derived from statistical correlation analysis of mining experience primarily from Chinese coal mines. Since the Gondwana strata, which host the Barapukuria Mine, are not found in China, applying these standard formulas directly to predict the WFZ height at this mine leads to significant discrepancies.



a) Establishment of the Numerical Model



b) Results of the Numerical Simulation

Fig. 4 FLAC3D Numerical Simulation

Tab 4. Statistics of Water-Flowing Fractured Zone Height After Simulated Mining

Mining Height/m		Water-Flowing Fractured Zone Height/m			
		One Panel	Two Panels	Three Panels	Four Panels
First Slice	3	60	66	68	68
Second Slice	3	100	112	116	116
	7	173	198	203	203
Third Slice	3	190	220	229	229

Based on the numerical simulation results, the predicted data for the WFZ development at the Barapukuria Mine were compiled and subjected to regression analysis, establishing the following site-specific predictive formula for the WFZ height in this unique geological setting:

$$h = (n + 27) \cdot \sum m - 15 \cdot n^2 \quad (1)$$

Where: h is Height of the Water-Flowing Fractured Zone (m); n is Number of extraction slices (dimensionless); m is Cumulative extraction thickness (m).

4.2 Neural Network-Based Prediction and Analysis

Research indicates that the development height of the WFZ is influenced by numerous factors, with mining depth, overburden lithology, dip angle, mining method, and extraction thickness generally considered the primary contributors[17]. Various methods exist for predicting WFZ height, among which in-situ measurements typically yield the most reliable results. While the engineering analogy method can be applied to predict the WFZ height under similar mining-geological conditions, it is inherently constrained by subjective judgment. Moreover, when multiple influencing factors must be considered, the increased number of variables makes regression analysis particularly challenging. Given these limitations, a neural network-based predictive approach incorporating multi-factor analysis has been proposed for estimating WFZ height[18].

Compared with direct data regression of engineering data, the neural network approach incorporates hidden layers and iterative learning steps, thereby reducing errors arising from directly mapping influencing factors to outcomes. This study employs the Levenberg-Marquardt algorithm to construct a three-layer Backpropagation (BP) network model with one hidden layer, as illustrated in Figure 6. The network structure is configured as follows: the input layer consists of five nodes, representing mining depth (H), overburden lithology (F), dip angle (α), mining method (f), and extraction thickness (M); the output layer contains one node, corresponding to the height of the Water-Flowing Fractured Zone (h); for the hidden layer, the number of nodes is determined as 13 based on the Kolmogorov theorem.

The collected representative field measurement data of Water-Flowing Fractured Zones from China were utilized for training. Working faces from 45 Chinese mines and the predicted data from simulation experiments at the Barapukuria Mine were selected as the training samples for the BP neural network. The field measurement data from the Barapukuria Mine were ultimately used as the testing samples. The actual measured data from the Barapukuria Mine were ultimately used as the testing samples. Simulation training was conducted using programs written in MATLAB R2014a.

During the training process, the matrix P (5×46) served as the input layer, representing the factors influencing the WFZ development. The matrix T (1×46) served as the output layer, representing the corresponding heights of the WFZ. The overburden lithology was categorized into four types: very weak, weak, medium-hard, and hard, assigned values of -1, -0.5, 0.5, and 1, respectively. The mining method was classified as fully mechanized mining or fully mechanized top-coal caving, assigned values of -1 and 1, respectively. Due to significant variations and a wide distribution range in the collected dataset, normalization was necessary[19].

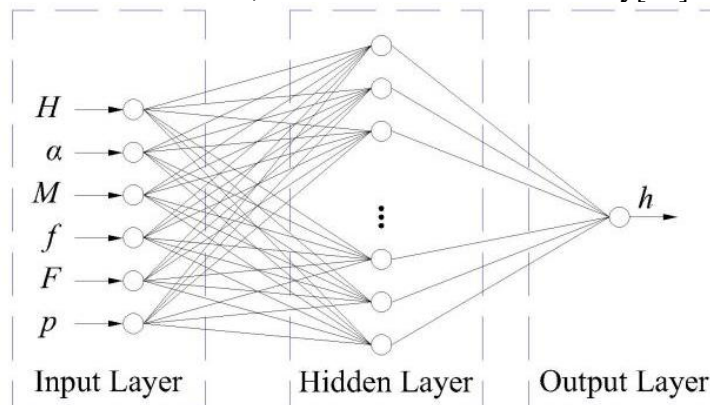


Fig. 5 Neural network model structure for predicting water fractured zone height

The training function was set as `traindm`, and the transfer function was `tansig`. A learning rate of 0.01 was adopted. The training stopping criteria were defined as follows: a maximum of 1,000,000 epochs, a target accuracy of 1×10^{-5} , or a performance gradient below 1×10^{-5} . Training would terminate upon meeting any one of these conditions.

Upon completion of training, the process is illustrated in Figure 6. The training duration was relatively long, attributable to the substantial variation within the dataset. Figure 8 shows the curve of training error versus the number of iterations. The error converged to 9.99×10^{-6} after 785,057 epochs, meeting the predefined target accuracy and thus deemed sufficient for engineering prediction purposes.

In Figure 7, the predicted values of the samples are marked with “×”, while the actual measured values are denoted by “o”. The comparison between the measured and predicted data is displayed in this distribution plot. Samples 43 to 46 correspond to the field measurement data from the Barapukuria Mine. The results indicate that the neural network achieved a high fitting accuracy to the training samples.

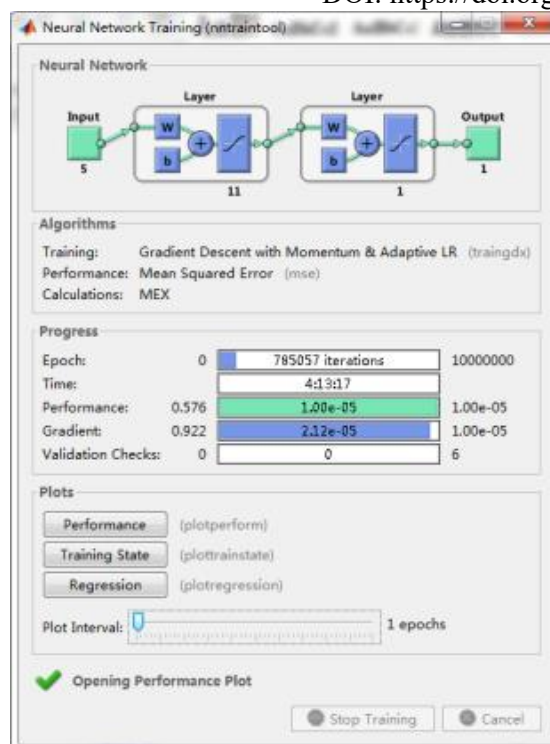


Fig. 6 Neural network training complete

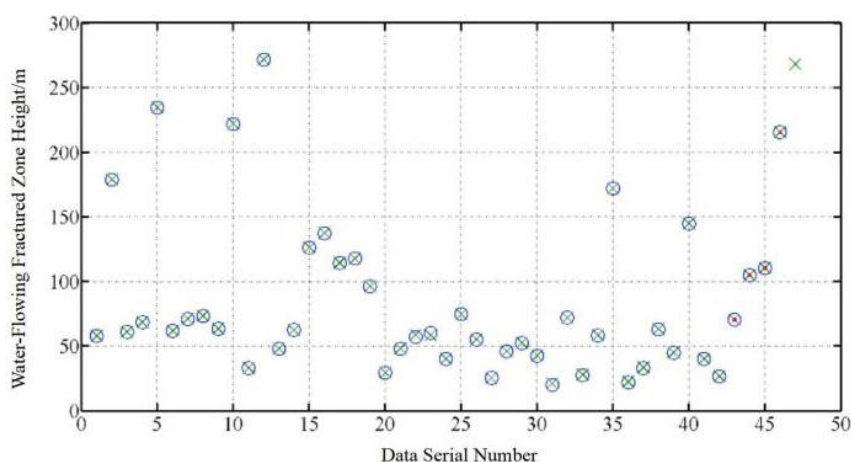


Fig. 7 Variation chart of sample distribution error

Tab 6. Predicted Height of the Water-Flowing Fractured Zone at the Barapukuria Mine

Panel	Theoretical Value (Regulations)	Predicted Value [Formula (1)]	Neural Network Predicted Value
1112	44.64	62	70.43
1214	73.25	242	215.58
1314	82.11	282	268.15

Two mining panels from the Barapukuria Mine were selected as testing samples. The predicted results from the “Under-three” Regulations, Formula (1), and the neural network model were compared, as summarized in Table 6.

Analysis of the computational results demonstrates that the WFZ heights predicted by the Levenberg-Marquardt algorithm-based neural network exhibited a maximum absolute error of 22.54 m and a maximum relative error of 10.46% compared to the field measurements. In contrast, the empirical formula from the “Under-three” Regulations yielded predictions with a maximum absolute error of -142.34 m and a maximum relative error of 66.02%. Similarly, the results

calculated using the statistically derived Formula (1) showed a maximum absolute error of 26.41 m and a maximum relative error of 12.28%.

These comparisons confirm that the computational results from the BP neural network model align most closely with the engineering measurements, exhibiting the smallest relative error and thus demonstrating superior prediction accuracy for this specific geological and mining context.

The empirical formula specified in the Regulations considers only overburden lithology, dip angle, and extraction thickness, with applicable conditions limited to single-layer extraction thickness not exceeding 3 m and cumulative extraction thickness not exceeding 15 m. Consequently, its predictions yield the largest errors among the compared methods. Formula (1), derived from field measurement data at the Barapukuria Mine, provides more accurate predictions under similar geological conditions, as the influence of factors such as overburden lithology, dip angle, and mining depth on the WFZ development remains approximately consistent. In contrast, the neural network model produces the smallest errors. This is attributed to its comprehensive consideration of multiple influencing factors during model construction. During the training process, more detailed and extensive input data further enhance prediction accuracy.

The neural network prediction model based on the Levenberg-Marquardt algorithm incorporates five influencing factors and utilizes both case data from China and observation data from the Barapukuria Mine for training. As a result, this model is applicable not only in China but also to the Barapukuria Mine. The predicted WFZ height for the third mining slice is approximately 268.15 m, with a cumulative fracture-to-mining ratio of 18.5. To prevent the WFZ from penetrating the LDT aquitard, the extraction height for the third slice should be less than 3 m, as calculated based on the distance between the roof of Seam VI and the LDT formation.

5. Conclusion

(1) Significant differences exist in properties between the Gondwana strata and domestic strata. Owing to inadequate diagenesis, the strata as a whole display lower lithological strength and higher porosity, resulting in a greater development height of the water-conducting fracture zone during mining compared with that observed in domestic coal mines.

(2) The neural network incorporating multi-factor analysis yields the smallest prediction error, followed by Formula (1) derived from Barapukuria Mine data, while the theoretical formula specified in the “Three Unders” Mining Regulations exhibits the largest prediction error. For predicting the water-conducting fracture zone height in subsequent working face mining, a comprehensive consideration of both the neural network and Formula (1) is recommended.

(3) The high-precision neural network predicts that the water-conducting fracture zone height after three-slice mining in Barapukuria Mine will be 240.5 m, with a cumulative fracture-mining ratio of 18.6. To ensure the safety of working face extraction, it is recommended that the mining height for subsequent three-slice mining should not exceed 3 m.

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