In-situ Monitoring and Prediction of the Height of the Water-conducting Fractured Zone in a Jurassic Coal Seam in Northwestern China

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In-situ monitoring and prediction of the height of the water-conducting fractured zone in a Jurassic coal seam in northwestern China

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Abstract: The height of the water-conducting fractured zone (HWFZ) plays a significant role in environmental protection and engineering safety during underground mining. In this study, to measure the HWFZ in the Cuimu coal mine (CCM), in-situ monitoring, including water leakage tests and video capture through a borehole camera, were conducted. Considering mining height, panel width, and buried depth, 26 sets of samples were collected from mines in the northwest to obtain a multi-factor regression formula. Additionally, we used the 26 sets of samples as training material for machine learning to predict the HWFZ. Then, to assess why the traditional empirical formula proposed to measure the HWFZ is inapplicable for the Jurassic coal mines in the northwest, the sedimentary environment of the Ordos Basin, the RQD of drilled cores, and the overburden structure characteristics were investigated. Finally, a strata subsidence model was built to analyze the mathematical mechanism of the HWFZ induced by mining activity. The results show that the proposed regression formula and machine learning model can accurately predict the HWFZ of mines in the northwest. Due to the more stable sedimentary environment, the RQD of drilled cores from the Jurassic coal seam is higher and the strata tend to have better continuity as compared to the cores from the Carboniferous coal seam. The strata subsidence model indicates that the residual bulging coefficient influences the HWFZ significantly, which can explain why the measured HWFZ in the northwest is much larger than the predicted values based on the traditional empirical formula. This study is useful to accurately predict and understand the HWFZ in Jurassic coal seams in northwestern China.

Keywords: HWFZ; Jurassic coal seam; In-situ monitoring; Prediction method; Overburden structure.

1. Introduction

At present, coal is the most important energy resource in China. With the depletion of coal resources in eastern China, mining activity has moved to the arid and semi-arid northwestern part of China, where the ecological environment is

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extremely fragile. The residents, flora, and fauna in this area rely on the precious groundwater resources that are stored in the roof confined aquifer. Due to mining activity and the presence of overburden cracks, groundwater in the overlying aquifer can flow into the goaf. Additionally, overburden damage caused by mining activity can cause gas leakage and ground surface settlement, which are also potential threats to the ecological environment in the northwest. Therefore, it is important to study the formation and failure characteristics of mining overburden for both production safety and environmental protection.

Previous studies have investigated and modeled the movement, deformation, and failure of overburden rock masses during coal mining (**Majdi et al. 2012; Behrooz et al. 2017; Steven J et al. 2012**). The movement and failure of an overburden rock mass under mining can be classified into four zones: the caved zone, the fractured zone, the continuous bending or deformation zone, and the soil zone (**Fig. 1**) (**Peng 1992**). Generally, water does not flow through the continuous bending zone and soil zone since few effective fractures are contained within them; water does flow through the fractured and caved zones and they are referred to as the water-conducting fractured zone (WFZ).

The WFZ is an important factor to consider when designing mining support (**Wang et al. 2016**), recovering coal mine gas (**Karacan et al., 2011**), accurately predicting water inflow (**Qiao et al. 2017**), protecting water resources (**Meng et al. 2016**), and predicting ground subsidence (**Xuan et al. 2016**). Therefore, it is important for engineers and geologists to understand and calculate the height of the WFZ (HWFZ) accurately. Numerous methods are currently available to characterize the movement of overburden rock strata and understand the WFZ, such as statistical and empirical equations (**State Administration of Work Safety 2017; Zhao et al. 2015;**), mechanical models or analysis (**Abbas Majdi et al. 2012**), numerical analysis (**Gao, 2018; Li, 2013**), physical models (**Sui et al. 2015; Wang et al. 2017**), and in-situ observations (**David, et al 2017; Zhang, et al 2012**).

The HWFZ in many locations has been estimated and measured by investigators. In order to investigate the HWFZ, 200 boreholes were drilled in 27 mines in eastern China in the 1970s and 1980s. Considering three factors (coal mining thickness, the uniaxial compressive strength (UCS) of rock samples, and the hardness degree of the overburden rock strata), **Liu (1981)** proposed an equation to predict the height of the WFZ, generalizing that the fractured zone showed a horse saddle shape in coal seams with different dip angles. The national standard for *Exploration and Evaluation of Hydrogeology, Engineering Geology and Environment geology in Coal Beds* (**State Administration of Work Safety 2009**) (SAWS 2009) in China also offered empirical equations for preventing the HWFZ. **SAWS (2009)** considered three factors to predict the height of WFZ, these being the dip angle of the coal bed, the coal mining thickness, and the UCS of rock samples.

However, on account of different engineering geological conditions, the failure characteristics of overburden vary

between the east and northwest of China. The research findings from eastern mines cannot be used for predicting engineering properties in northwestern mines and designing them. There have been a few studies on the overburden failure characteristics in northwestern mines. **Guo et al (2019)** provided a theoretical prediction method for the HWFZ in the Gequan coal mine under high-intensity mining. Based on the process of strata failure, they established an overburden model characterized by limit suspension-distance and limit overhanging distance to calculate the HWFZ.

Cheng et al (2020) used in-situ monitoring and numerical simulation to analyze strata movement caused by multi-coal seam mining in the Xiqu coal mine, Shanxi province. Their results show that the failure of the key strata between the upper and lower seams causes the floor damage zone of the upper seam to connect with the roof fractured zone of the lower seam. Once the connection occurs, mining in the lower coal seam results in secondary strata movement.

Ning et al (2020) studied the mechanical mechanism of overburden cracking and proposed a method for calculating the HWFZ during close-distance mining. They used separation distance and the ultimate subsidence value to predict the HWFZ of the Gaojialiang coal mine in Ordos city, inner Mongolia. Then, they modified the traditional empirical formula to predict the HWFZ in the northwest more accurately.

Sun et al (2021) performed Brillouin optical time-domain reflectometer and borehole resistivity measurements to study the overburden deformation and movement of the deep and super-thick coal seam in the Ordos mining area. They found that the overburden lithology and structure influences strata failure significantly.

He et al (2021) conducted a similar simulation and built a mechanical model to study the HWFZ of layered overburden. They proposed that the strata crack when the tensile stress exceeds the tensile strength, while the fractures penetrate the strata when the compression stress exceeds the compressive strength. Based on the geomechanical method, they predicted the HWFZ in the Buliantian and Qidong coal mines located in the transition zone between the Maowusu desert and the loess plateau.

Although these studies are useful to understand the overburden movement in the northwest, they are not sufficient to accurately predict the WFZ of Jurassic coal seam for effective ecological environment protection. Almost no studies have systematically investigated the characteristics of the WFZ in northwestern China using in-situ monitoring, theoretical prediction methods, and analysis of the overburden structure and geological environment. In this study, the Cuimu coal mine (CCM) was chosen to monitor and predict the HWFZ. We conducted water leakage tests and captured video through a borehole camera to determine the HWFZ. Based on 26 samples, a multi-factor regression formula is proposed and machine learning was used to predict the HWFZ. Further, the subsidence environment and strata structure in the east and northwest of China are investigated and compared to study the failure characteristics of mining overburden in

northwestern China. Finally, an overburden subsidence model was built to explore the mechanical mechanism of the evolution of the WFZ under mining activity.

2. Conceptual model

Fractured overburden rock strata were first proposed to consist of three zones by Liu (1981): these are the caving zone, the fractured zone, and the sagging zone. Booth (2002) suggested that mining overburden rock strata should be divided into three zones (the intensely fractured zone, the intermediate zone, and the near-surface fractured zone). Peng (1992) proposed that fractured overburden rock strata could be divided into four zones. Forster and Enever (1992) also proposed four zones in their model for mining the overburden rock mass of a longwall panel; their proposed zones were the caved zone, the fractured zone, the constrained zone, and the surface zone in the vertical direction.

Figure 1 shows a widely accepted conceptual model representing the fracturing characteristics of overburden above a single longwall working face. Four zones are identified in this model, including cave zone, fractured zone, constrained zone, and surface zone.

The caved zone is the zone where broken roof rocks fall, resulting in broken rocks in the caved zone being fragmented. Strata bulking failure and the rotation of rock blocks result in high permeability and porosity in the caved zone. The height of this zone is mainly dependent on the type of the immediate roof and the mining height.

The fractured zone is where the rock blocks are hinged together, resulting in stable strata structures. However, since this zone has undergone considerable deformation in both the vertical and horizontal directions, the cracks (including pre-existing cracks and mining-induced cracks) connect with each other, and then water can flow through the connected cracks network in this zone. Consequently, the fractured zone and the caved zone are collectively termed as the water-conducting fractured zone. The term “height of the WFZ” refers to the vertical distance from the roof of a coal seam to the top of the fractured zone.

The constrained zone is where the strata curve but shows significantly less cracking; the fractures also do not connect with each other so that water depressurization does not occur to a great extent. Generally, this zone has an integral and stratiform structure during mining, and permeability will recover after coal mining has ceased.

The surface zone is the near-surface region where slight deformation is observed and mining-induced cracking occurs within a limited height. This zone is located next to the continuous bending zone and consists of loose deposits (**Fig. 1**). The deformation and movement characteristics of the soil zone are related to its thickness, components, geological structure, and physical and mechanical properties.

3. Methodology

3.1 In-situ monitoring

3.1.1 Engineering overview

The CCM, which is located in Shannxi Province, Yonglong coal field, Ordos Basin, Northwestern China, was chosen to conduct in-situ measurements in this study (**Figure 2**). The overall tectonic structure at the CCM is composed of alternating anticline and syncline structures trending NNW–NWW. The fault structures in this area are mainly normal faults that fall into two formations striking NW–SE and NE–SW, with a dip angle of 55° and fault fall of 0–24 m. As shown in **Table 1**, the overburden rock strata, from top to bottom, include Quaternary and Neogene sand and loess deposits (Q+N), Cretaceous sandstone and sandy conglomerates (Luohe Formation K1), Jurassic mudstone, sandy mudstone, and argillaceous sandstone (Anding Formation, J2a; Zhiluo Formation, J2z; Yanan Formation, J2y). Based on the lithology, thickness, and hydrological and burial conditions of the strata, the main water inrush aquifers can be divided into two categories. The top one is the Quaternary unconfined aquifer within the Quaternary sandstone and clay; the bottom one is the Cretaceous confined aquifer in the Luohe Formation at a distance of 150–230 m from the coal seam. This aquifer provides direct hydro-sources for water-inrush during mining. The primary mining coal seam (No. 3) belongs to the Yanan Formation; it has an area of 1050 m $\times$ 200 m, an average height of 10 m, and a dip angle of $3\text{--}6^\circ$.

3.1.2 Borehole video and water leakage test

Monitoring water leakage inside boreholes is a direct method that can be used to gauge the fracturing extent of natural stratum and measure the HWFZ. Additional measuring tests include the indirect method, which involves taking photographs inside boreholes with video cameras. Both methods were used to determine the height of the WFZ in the CCM. Taking panel 21303 as an example, borehole G4 monitoring was carried out for two months after the working face went through the borehole position. To ensure reliable results, the water leakage monitoring method was used in the borehole after mining to assess the mining fracture distribution, and a borehole video was recorded to examine the fractures in the borehole wall. The designed drill diameters of borehole G4 for different stratum are shown in **Fig.3(a) and (b)**. The diameters of the monitoring borehole G4 were 311 mm, 190 mm, and 113 mm from top to bottom. The 311mm-section in the Quaternary soil strata required a casing pipe to prevent the borehole wall from collapsing. After mining, borehole G4 was drilled continuously to a depth of 548 m. The drilling diameter became 190 mm from the Cretaceous to the Jurassic stratum to enable the collection of data from the disturbed stratum.

The water leakage monitoring system shown in **Fig.3(c) and (d)** shows that the water volume was not less than 3 m³ in either the water tank or the settling pond. A floating ruler was used to measure the water table in the water tank. During drilling, clear water was used as the flushing fluid and cycled in the entire system. When water was cycled between the tank and the borehole, the water table of the tank was measured once, and the drilling depth was also recorded. The length of penetration was less than 4 m (less than 2 m in the fractured zone). In addition, the water tank

was cleaned frequently to prevent the fractures from sealing by rock powder. Then, the water table of the tank and the drilling depth was recorded at every 0.5 m of the drilling depth. With an increase in leakage, the observation frequency increased to every 0.3 m of the drilling depth.

3.2 Multi-factor regression formula

15 coal mines in northwestern China on which we were permitted by companies to conduct studies were investigated and 26 samples were collected for actual borehole measurements of the HWFZ (**Table 2**). A plot of the results shows a positive correlation between mining height and the HWFZ, but the other factors have little correlation with the HWFZ (**Figure 4(a), (b), (c)**). As a result, a nonlinear regression equation containing three influential factors was proposed based on the 26 investigated samples ($R=0.942$). The equation is as follows. **Figure 4(d)** shows the predicted results of the 26 samples based on the proposed formula.

$$H_{WfZ} = 4.82M + 60.13 \ln \frac{s}{100} + 3.43M \ln \frac{b}{100} + 16.17 \quad (1)$$

3.3 Machine learning based on the GRA-LS-SVM model

3.3.1 Calculating the weight based on GRA

First, GRA was used to calculate the weights of influential factors. To do this, the sequence was first standardized using the equation proposed by Zheng et al (2016):

$$x_0(k) = \frac{x_0^{(0)}(k)}{\frac{1}{n} \sum_{i=1}^n x_i^{(0)}(k)} \quad (2)$$

where $i = 1, 2, \dots, n$; $k = 1, 2, \dots, m$; and $x_i(k)$ represents the standard values of the k th evaluation factor in the evaluation samples. The standardized equation for the reference sequence was:

$$x_i(k) = \frac{x_i^{(0)}(k)}{\frac{1}{n} \sum_{i=1}^n x_i^{(0)}(k)} \quad (3)$$

where $i = 1, 2, \dots, n$; $k = 1, 2, \dots, m$; and $x_i(k)$ represents the standard values of the k th evaluation factor of level i in the evaluation standard.

The gray correlation coefficient was expressed as:

$$r(x_0^{(0)}(k), x_i^{(0)}(k)) = \frac{\min_{1 \leq i \leq n} \min_{1 \leq j \leq m} |x_0^{(0)}(k) - x_i^{(0)}(k)| + \rho \max_{1 \leq i \leq n} \max_{1 \leq j \leq m} |x_0^{(0)}(k) - x_i^{(0)}(k)|}{|x_0^{(0)}(k) - x_i^{(0)}(k)| + \rho \max_{1 \leq i \leq n} \max_{1 \leq j \leq m} |x_0^{(0)}(k) - x_i^{(0)}(k)|} \quad (4)$$

where r is the gray correlation coefficient. Generally, $\rho=0.5$.

The weighted correlation of the sequence was evaluated as follows:

$$\xi_i(x_0^{(0)}, x_i^{(0)}) = \sum_{k=1}^m w_k r(x_0^{(0)}(k), x_i^{(0)}(k)) \quad (5)$$

where ξ is the grey weighted correlation; w_k is the weight; $i = 1, \dots, n$; and $k = 1, \dots, m$.

Based on the GRA, equations (2) to (5) were used to calculate the three eigenvalues of the mining height, mining panel width, and mining depth. The reference sequence was the measured HWFZ. Results show that the mining height, panel width, and buried depth have correlation coefficients of 0.95, 0.57, and 0.62, respectively; this reveals that the selected three factors have a close relationship with the HWFZ and can be used for further machine learning.

3.3.2 Training and testing model based on LS-SVM

As highlighted by **Satar et al. (2012)**, artificial intelligence (AI) algorithms are suitable tools when the relationships between dependent and independent variables are not easily understood. Currently, tools such as artificial neural networks (ANN), maximum likelihood classification (MLC), the genetic algorithm (GA), techniques for order preference similarity to ideal solutions (TOSIS), and least squares support vector machines (LS-SVM) have been frequently used for predicting engineering issues. For example, numerous studies have been conducted on the use of SVM in engineering geology, such as subsidence prediction (**Zhang et al. 2009**), slope stability prediction (**Zhao et al. 2009**), and methane prevention in coal mines (**Zhao et al. 2009**). **Satar et al. (2012)** reported that AI methods are more effective for predicting tunnel convergence, and SVM models are better than ANN models for predicting surrounding rock replacement.

The LS-SVM model is better for solving problems that have high dimension, small samples, are nonlinear, and have a local minimum point (**Vapnik 1993; Vapnik and Bottou 1993; Vapnik 1998**). However, to achieve accurate predictions, the regularization parameter (r) and Kernel function width (σ) of LS-SVM must first be confirmed. Imprecise r and σ values lead to huge errors in predictions. We used coupled simulated annealing (CSA) (**Xavier 2010**) to optimize the regularization parameter (r) and the Kernel function width (σ) of LS-SVM for the prediction model.

Before the nonlinear model (LS-SVM) is trained, the number of samples used to train the model should be considered to ensure that the obtained model is sufficiently accurate. We selected different numbers for training and used the remaining samples for the test. **Figure 5 (a)** shows the relative error of the remaining test samples with different sample sizes for training. As is shown, the prediction results tend to be more stable and the relative error is smaller with the increase in the sample size for training. **Figure 5 (b)** plots the average relative error of the LS-SVM model with a training sample size. As shown, initially, the ARE of the model decreases rapidly. Then it reaches a plateau when the sample size for training is 9 to 20. Accordingly, from the 26 investigated samples, we selected 15 samples to train the model and 11 samples to verify it. As is shown in **Figure 5(c)**, the predicted results based on the GRA-LS-SVM model are roughly consistent with the actual values, which indicates that the trained model can be used to predict the HWFZ of

mines in northwest China.

4. Results

4.1 Borehole video and water leakage test

Water leakage changes with depth in borehole G4 after coal mining is shown in **Figure 6**. As can be seen, the water leakage increased to $1.28 \text{ L}\cdot\text{s}^{-1}\cdot\text{m}^{-1}$ at a depth of 357.1 m. When the borehole depth reached 504.5 m, the water leakage rate suddenly increased to $3.75 \text{ L}\cdot\text{s}^{-1}\cdot\text{m}^{-1}$ (point C1). At 527.60 m, because the impact of mining on overburden is great, the stratum was severely deformed and fractured. As a result, the drilling bit became stuck, and drilling ceased. This confirms that the fractured zone in this borehole is from 357.1 m to 504.5 m, with a height of 146.8 m, and the caved zone is from 504.5 m to 552.2 m (the depth of coal seam roof), with a height of 47.7 m. Therefore, the HWFZ is 194.5 m (the sum of the fractured zone height and caved zone height); this is 19.45 times greater than the mining height (10 m). Some images that were captured after mining are shown in **Figure 6**; the images, in different vertical positions in G4, show the fracturing characteristics of strata at different depths. The image at 520 m shows that the strata have broken into blocks and lost their continuity. The strata at 490 m are broken, but to a lesser extent than that at 520 m. The strata at 450 m, 400 m, and 350 m are fractured, and the density of fractures decreases with increasing depth. The image at a depth of 300 m shows intact strata, which means that this part is out of the WFZ. The results of the video that was captured from the borehole verify the results of the water leakage test.

4.2 Multi-factor regression formula

In the CCM, the mining height, panel width, and buried depth of the coal seam are 10 m, 558.55 m, and 200 m, respectively. Substituting these parameters into the proposed regression formulas, the HWFZ is 183.92m, with an error of -0.015.

4.3 Machine learning prediction

According to the test result in section 3.3.2, the error between the predicted values and the actual values drops to a certain level and remains relatively stable when the number of sample size for the training model is greater than 9. Therefore, the 26 samples should be enough to predict the HWFZ in the CCM. Using Matlab software, the prediction model was initially trained, and the results are shown in **Figure 7**. Based on the parameters of the CCM, the prediction result is 204.78, with an absolute error of 0.054.

5. Discussion

5.1 Applicability of the traditional empirical formula

Based on a large amount of field measured data obtained from mines with Cretaceous coal seams in eastern China, the national standard for *Exploration and Evaluation of Hydrogeology, Engineering Geology, and Environment Geology*

in Coal Beds (State Administration of Work Safety 2017) in China has provided empirical equations to predict the HWFZ of Carboniferous coal seam in eastern China (Table 3). According to the experimental test of the rock sample in the CCM, the rock type of the CCM is medium-hard. As a result, using the two corresponding formulas, the HWFZ of panel 21303 is calculated to be 51.02 m and 73.25 m respectively, with a mining height of 10 m, which is significantly different from the measured value (195.1 m). This is because that the traditional empirical formula is deduced based on data from mines with Cretaceous coal seams in the eastern part of China. The CCM, however, is located in the Ordos basin in northwestern China. Different overburden lithology and structures make it difficult to apply the traditional empirical formula from SAWS to predict the HWFZ of mines with Jurassic coal seams in northwestern China.

5.2 Sedimentary environment of the northwestern part of China

Tectonic movement is dominant during the entire sedimentation process, including the distribution of sedimentary basins, position of the denudation zone, transition of deposited sediment, and late modification of sedimentary strata. Generally, a purer composition and greater maturity indicate a more stable environment; in contrast, complicated composition and poorer maturity are generated under an unstable tectonic environment.

Sedimentary facies is the sum of the environment, conditions, and characteristics of sediments. It is a stratigraphic unit that reflects certain natural environment features and has certain lithological and paleontological characteristics. Based on the lithology, color, structure, and paleontology of sedimentary rocks, we can determine the environment and active processes during the time of deposition. By drilling core observation, and logging curves, the sedimentary facies and main characteristics of the Jurassic - Lower Cretaceous Luohe Formation in the southern Ordos Basin are summarized below; this serves as a foundation for our investigation into the characteristics of the overburden structure in the study area.

(1) Fuxian Formation (J1f)

The Fuxian Formation of the Lower Jurassic was deposited after the Indosinian movement. The upper member of the Yanchang Formation was strongly eroded under the influence of the Indosinian movement, forming a rugged palaeogeomorphology. The Fuxian Formation was cut by strong erosion into rugged and filled sedimentary features that were deposited on the Yanchang Formation and show an unconformable contact with it (Liang, 2007).

(2) Yanan Formation (J2y)

The basin experienced a short uplift at the end of the Fuxian period and then entered the sedimentation process in the Yan'an period. In the early deposition stage of the Yanan Formation, the thickness of the strata was mainly controlled by the top tectonic palaeogeomorphology of the Late Triassic, and tectonism was not obvious. During the sedimentation, the ancient highlands gradually disappeared and the river and delta systems retreated to the basin margin; the lacustrine

center was located in Yan'an and its eastern area (He Yingna, 2019; Liang 2007). During the stable and slow subsidence environment, there was a deposition of eluvial facies, alluvial fans, fluvial facies, and lacustrine delta facies, among which the fluvial sedimentary system was widely developed between the alluvial fan and lacustrine system.

(3) Zhiluo Formation (J2z)

After the deposition of the Yanan Formation, the basin was generally uplifted in the early Yanshan, and the terrain was high in the east and low in the west. After the brief uplift, the basin began to accept the deposition of the stable Zhiluo Formation again, presenting an unconformable contact with the Yan'an Formation. The Zhiluo Formation is characterized by large sedimentary thickness and low water level system tracts. The distribution of sedimentary facies belts in this period is characterized by deposition in a stable tectonic environment (Liang, 2007).

(4) An'ding Formation (J2a)

After the deposition of the Zhiluo Formation, the northern, southern, and eastern edges of the basin were uplifted and denudated. The geomorphology in the early stable period was basically similar to that during the late Zhiluo period, but the sedimentation area was obviously reduced and the lake water was deepened. In contrast to the Yanan and Zhiluo stages, the deltaic facies did not develop in the Anding stage, and the sedimentary environment was a deep lake - semi - deep lake - shallow lake under inland semi-arid climate conditions. Fluvial action was weak, with less debris carried by it, and the ancient flow direction was characterized by convergence to the center of the lake basin, indicating that the Anding Formation was deposited in a lake with the characteristics of an inner flowing lake (Liang, 2007).

(5) Luohe Formation (K1l)

Influenced by the main tectonic movement of the Yanshanian movement, the basin was uplifted in the late Jurassic and entered another sedimentary stage in the Early Cretaceous. The Luohe Formation has a good outcrops in the southern margin of the basin; it is thick in the south and thin in the north and thins from the basin margin to the interior. The sedimentary area of the basin during this period was much larger than that during the Late Jurassic. The sedimentary environment during deposition of the Luohe Formation shows the evolution of a braided river and distributary channel in a delta plain and aeolian desert characterized by the development of scour bedding and obvious scour erosion structures at the bottom. Large cross-bedding is developed in the sandstone, which is a typical aeolian sand mound and dry valley deposit.

5.3 Overburden structure

The overburden structure significantly influences the fracturing characteristics of strata under mining activity. The rock quality designation (RQD) is the ratio of the cumulative length of drilled rock core whose length is no less than 10 cm and the total drilling depth. It is widely used to quantificationally represent the integrity of rock strata. Generally,

when the RQD is more than 90%, the strata quality is considered as good; when the RQD is from 75%-90%, the quality is relatively good; when the RQD is from 50%-75%, the rock quality is relatively poor; when the RQD is from 25%-50% and no more than 25%, the rock quality is regarded as poor and extremely poor, respectively.

To compare the strata structure between mines in the east and northwest, drilling tests were conducted in the Xihu coal mine, which is located in Anhui province, eastern China, and the CCM to obtain the RQD. The partially drilled cores are shown in **Figure 8**, where **Figure 8 a and b** are the cores drilled from the Xihu coal mine, and c and d are from the CCM. Obviously, the cores from the Xihu coal mine are more broken than those from the CCM. Statistical calculations reveal that the RQD of the cores from the Xihu coal mine ranges from 47%-15%, which belongs to the poor and extremely poor quality category; the RQD of the cores from the Cuimu coal mine ranges from 53%-94%, which belongs to the relatively good and good quality category.

To further characterize the difference in the strata structure between the eastern and northwestern parts of China, outcrops of Carboniferous overburden in the east and Jurassic overburden in the northwest were investigated. **Figure 9 a and b** shows the outcrops in the east, while c and d are in the Ordos Basin, northwestern China. As shown in **Figure 9**, the strata in different locations reflect different degrees of transformation during tectonic movements. According to the geometric characteristics, the strata structure is divided into the following types:

(1) Stratified structure. As shown in **Figure 9 a**, this structure contains a formation of a weak plane rock mass with good continuity and low shear performance, and its lithology is generally uneven. According to the development density of the soft surface, it can be divided into lamellar and thin lamellar. According to the degree of lithology inhomogeneity, it can be divided into a kind of interbedded structure with soft and hard phases. The rocks belonging to this structure include stratified or interstratified carbonate rocks, clastic rocks and other sedimentary rocks, volcanic rocks with obvious eruptive cycles or discontinuities, metamorphic rocks, and rocks with ancient weathering interlayers.

(2) Fragmentary structure. This structure represents a rock mass with multiple formations of dense structural planes, and the rock mass is divided into fragments (**Figure 9 b**). The rock masses with such structures have generally been subjected to more complex and intense tectonic movements. According to the degree of change, it can be divided into four grades: integrity, block cracking, fragmentation, and loosening.

(3) Monolithic structure. This structure represents rock masses with uniform lithology and no soft surface, as is shown in **Figure 9 c**. The contained primary structural planes have a strong binding force and the spacing is greater than 100 cm. The rock mass belonging to this structure includes thick or very thick layers of carbonate rocks, clastic rocks and other sedimentary rocks, large volcanic intrusions, and metamorphic rocks with less developed primary joints.

(4) Blocky structure. **Figure 9 d** represents a homogeneous lithology and contains 2-3 formations of rocks with

relatively weak discontinuities; the interval between discontinuities is 100~50cm. The rock masses in this category include thick sandstone or mudstone with well-developed diagenetic fissures, sedimentary rocks such as fluvial sandstone bodies on the trough scour surface, and volcanic rock masses with well-developed primary joints.

5.4 Theoretical explanation

As discussed above, since the tectonic movement in the northwest was more stable, the overburden structure here is generally characterized by monolithic structure and blocky structure. The overburden in the east, which underwent more intensive tectonic movement, presents a poorer continuity. In order to study the reason why the traditional empirical formula is inapplicable for the northwestern mines, some assumptions are made: 1) the advance distance and mining width are large enough over strata thickness so that the overlying strata can be modeled as an elastic thin plate. 2) the overlying load is large enough that strata can be compacted with subsidence. 3) the horizontal separation layer between strata is ignored.

First, the separation distance of strata is analyzed based on the subsidence model, as shown in **Figure 10 (a)**. In this model, after a coal seam is mined, the immediate roof (strata 1) breaks and forms gangue. The overlying strata gradually suspends, breaks, and falls until the gangue and broken strata are compacted. The difference between the initial and final positions of the disturbed strata is termed the separation distance (w). Based on the geometrical relationship in **Figure 10(a)**, the equations of the first, second,, (n-1)th, nth strata are derived as follows (**Ning et al 2020**):

$$M + h_1 = w_2 + K_{p1}h_1 \quad (6)$$

$$M + h_1 + h_2 = w_3 + K_{p1}h_1 + K_{p2}h_2 \quad (7)$$

$$\begin{aligned} M + h_1 + h_2 + L + h_{n-1} \\ = w_n + K_{p1}h_1 + K_{p2}h_2 + L + K_{pn-1}h_{n-1} \end{aligned} \quad (8)$$

$$\begin{aligned} M + h_1 + h_2 + L + h_{n-1} + h_n \\ = w_{n+1} + K_{p1}h_1 + K_{p2}h_2 + L + K_{pn-1}h_{n-1} + K_{pn}h_n \end{aligned} \quad (9)$$

Therefore, the separation distance of strata is derived by:

$$K_{pn} = 1 + (w_n - w_{n+1}) / h_n \quad (10)$$

$$w_{n+1} = w_n - (K_{pn} - 1)h_n \quad (11)$$

In these equations, $K_{pi} (i=1,2,...,n)$ represents the residual bulging coefficient of strata i . Based on the in-situ measurement, the residual bulging coefficients of mudstone and sandstone are 1.035 and 1.03 respectively; h_i is the thickness of strata i ; M represents the mining thickness of the coal seam; w_i is the absolute subsidence values of strata i .

The strata is modeled as an elastic thin plate with clumped edges (**Figure 10(b)**). The relationships between moment and deflection are as follows (Xu, 1978):

$$\begin{cases} M_x = -\frac{E_i h_i^3}{12(1-\mu_i^2)} \cdot \left(\frac{\partial^2 w_i}{\partial x^2} + \mu \frac{\partial^2 w_i}{\partial y^2} \right) \\ M_y = -\frac{E_i h_i^3}{12(1-\mu_i^2)} \cdot \left(\frac{\partial^2 w_i}{\partial y^2} + \mu \frac{\partial^2 w_i}{\partial x^2} \right) \end{cases} \quad (12)$$

The normal stress of an elastic plate can be calculated using the following formulas:

$$\begin{cases} \sigma_x = -z \frac{12M_x}{h_i^3} = \frac{E_i z}{(1-\mu_i^2)} \cdot \left(\frac{\partial^2 w_i}{\partial x^2} + \mu \frac{\partial^2 w_i}{\partial y^2} \right) \\ \sigma_y = -z \frac{12M_y}{h_i^3} = \frac{E_i z}{(1-\mu_i^2)} \cdot \left(\frac{\partial^2 w_i}{\partial y^2} + \mu \frac{\partial^2 w_i}{\partial x^2} \right) \end{cases} \quad (13)$$

where E_i and μ_i are the elastic modulus and poison ratio of strata i respectively. The rock strata breaks when

$$\sigma_{x|\max} \geq \sigma_t \text{ or } \sigma_{y|\max} \geq \sigma_t \text{ where } \sigma_t \text{ is the tensile strength of the rock.}$$

According to the mechanical model, the separation distance between strata is dependent on the residual bulging coefficient. Because greater separated distances contribute to the bulking failure of overlying strata, the HWFZ has a close relationship with the residual bulging coefficient. In other words, the disturbance of the overlying strata is constrained with larger residual bulging coefficients, and the HWFZ is consequently smaller. Based on the geological conditions presented in sections 5.1 and 5.2, the less strenuous tectonic movement in the northwest, as compared to the east, allowed for a more stable sedimentation environment during the strata-forming period in northwestern China. Thus, the overlying strata of mines in the northwest tends to have an intact layer structure, while that of mines in the eastern part generally have broken structures with many irregular joints.

Therefore, when impacted by mining activity, the strata characterized by intact structure breaks into larger and more regular blocks. As a result, the strata with more joints in the northwest has a smaller residual bulging coefficient, and thus, the greater separated distance between layers causes a higher WFZ under mining-induced disturbance (**Liu, 2018**); this can explain why the field measured HWFZ is much greater than the calculated values using the traditional empirical formulas that are based on the gathered data from mines in the east.

5.5 Deficiencies and prospects

Overburden structure and subsidence environment play an important role in causing the difference in the HWFZ between the eastern and northwestern parts of China. However, the HWFZ is also dependent on many other factors, including lithology, mining velocity, strata composition, and so on. At present, fully mechanical longwall mining and top-coal caving methods have been widely used in northwestern mines, which can cause more severe damage of

overburden and a higher WFZ as compared to the eastern mines. Consequently, due to the nonlinear relationship and different geological engineering conditions, accurate prediction of the HWFZ in northwestern mines cannot be achieved solely by relying on the traditional empirical formulas. The geological background, including tectonic movement, sedimentary environment, lithology, and overburden composition, should be further considered when attempting to predict the HWFZ in northwestern mines.

6. Conclusions

In this study, in-situ monitoring, multi-factor regression formulae, and machine learning were performed to study the HWFZ in the CCM. The conclusions are as follows:

(1) Based on the water leakage test, the height of the surface zone, constrained zone, fractured zone, and caved zone were determined, and the HWFZ was determined to be 194.5 m. Borehole video images show different fracturing degrees of the mining overburden. The HWFZ based on the regression formula with three factors is 183.92m. 26 samples were used to conduct machine learning based on the GRA-LS-SVM model, and the prediction result is 204.78m.

(2) Using the traditional empirical formula in SAWS (2017), the HWFZ in the CCM is 73.25 m, which is a significant deviation from the measured results. Through the collection of geological data, the sedimentary environment during the deposition of the Jurassic coal seam in northwestern China was analyzed. The results indicate that, in the Ordos Basin, the sedimentary environment was more stable and that the tectonic movement was less complex than that in eastern China. The RQD of samples from the Xinhua coal mine and the CCM were measured by a borehole test. The higher RQD of specimens from the CCM indicates that the overburden in the Jurassic coal seams in the northwest is of better quality than that of the Carboniferous coal seams in the east.

Outcrops of Jurassic strata in the northwest and Carboniferous strata in the east were investigated. According to the continuity and geometrical shape, the Carboniferous strata is categorized into stratified structure and fragmentary structure, while the Jurassic strata in the northwest are divided into monolithic structure and blocky structure. To further study the impact of overburden structure on the HWFZ, a subsidence model was built. The results show that more broken strata have a larger residual bulging coefficient, leading to the separated distance between strata becoming relatively smaller as compared to overburden characterized by good integrity.

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Figures

Figure 1

Conceptual model of disturbed overburden under mining

Figure 2

locations of Cuimu coal mine and engineering map of panel 21303 Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

(a)

(b)

(c)

(d)

Figure 3

Structure diagram and in situ monitoring

Figure 4

Relationships between factors and HWFZ and the prediction results

(a)

(b)

(c)

Figure 5

Relative error with sample size for training and the prediction results of machine learning

Strata system	Thickness(m)	Buried depth(m)	Lithology
Q+N	87.39	87.39	Soil
K1l	43.92	131.31	MS
	28.28	169.59	PS
	114.47	274.06	CS
	3.35	277.41	MS
	36.95	334.36	CS
	31.24	345.6	CS
	27.94	373.54	CS
	12.1	385.64	MS
	5.79	391.43	SM
K1y	2.2	393.63	CS
J2a	5.79	399.42	SM
	11.68	431.1	M
	5.7	438.8	CS
	31.97	448.77	M
	2	450.77	CS
	21	471.77	SM
	4.26	478.03	CS
	18.46	494.49	SM
	2.9	497.39	CS
J2z	6.32	503.71	MS
	5.52	509.25	CS
J2y	11.26	520.51	CS
	2.6	523.11	S
	9.21	532.32	M
	3.56	535.88	FS
	15.72	551.6	M
	6.32	557.92	CS
	0.63	558.55	M
	16.15	574.7	Coal

Figure 6

Results of in situ monitoring including water leakage test and borehole video

```
Determine initial tuning parameters for simplex...: # cooling cycle(s) 1
|------|
***** done

1. Coupled Simulated Annealing results: [gam] 3795.297
                                         [sig2] 178.1393
                                         F(X)= 830.2955

TUNELSSVM: chosen specifications:
2. optimization routine: simplex
   cost function: leaveoneoutssvm
   kernel function RBF_kernel
3. starting values: 3795.297 178.13935

Iteration  Func-count  min f(x)  log(gamma)  log(sig2)  Procedure
-----
1          3          7.938808e+02  9.4415      5.1826     initial
2          5          7.938808e+02  9.4415      5.1826     contract inside
3          9          7.938808e+02  9.4415      5.1826     shrink
4         11          7.938808e+02  9.4415      5.1826     contract inside
5         13          7.852006e+02  10.0228     5.4451     expand
6         15          7.852006e+02  10.0228     5.4451     contract inside
7         16          7.852006e+02  10.0228     5.4451     reflect
8         18          7.755990e+02  10.6720     5.5060     expand
9         20          7.635200e+02  11.6810     6.1552     expand
10        22          7.532739e+02  13.4839     6.6017     expand
11        24          7.313850e+02  16.4033     8.1234     expand
12        26          7.313850e+02  16.4033     8.1234     contract outside

optimisation terminated successfully (MaxFunEvals criterion)
Simplex results:
X=13300794.968727 3372.421800, F(X)=7.313850e+02
Obtained hyper-parameters: [gamma sig2]: 13300794.9687 3372.4217996
Start Plotting...finished
Xt = 10.0000 200.0000 558.5000
Yt = 204.7803
```

(b)

Figure 7

Comparison of predicted and measured values for the 26 samples and the prediction result of Cuimu coal mine

Figure 8

Drilled cores from Xinhu coal mine and Cuimu coal mine

Figure 9

Outcrops of Carboniferous and Jurassic system

Figure 10

Overburden subsidence model under mining