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TECHNICAL ARTICLE

Formation and Height of the Interconnected Fractures Zone after Extraction of Thick Coal Seams with Weak Overburden in Western China

Jiuchuan Wei[1] · Fuzhu Wu[1] · Huiyong Yin[1] · Jianbin Guo[1] · Daolei Xie[1] · Lele Xiao[1] · Hongfeng Zhi[2] · Liliana Lefticariu[3]

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Abstract Formation of a zone of interconnected fractures during coal mining is a key factor in mine flooding. Coal mines in western China are characterized by thick coal seams with mechanically weak overburden. In situ studies including drill core analysis, drilling fluid loss measurement, and borehole video monitoring were used at the working face 101 in Shaanxi Jinjitan coal mine to explore the maximum height of the interconnected fractures zone (IFZ). Also, tests on a scaled physical model and numerical simulation based on the drilling data were used to study the formation of the fractured zone. By considering data from other mines with similar mining conditions, a logarithmic relationship was found between the maximum height of the IFZ and the thickness of coal excavation. The maximum height of the IFZ was found to be 27 times the thickness of the excavated coal seam, which is far more than in coal mining areas in eastern China. Also, the IFZ in overlying strata of the study area was arch-shaped, not saddle-shaped, as had been observed in previous studies.

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✉ Fuzhu Wu
710487271@qq.com

[1] College of Earth Sciences and Engineering, Shandong University of Science and Technology, Qingdao 266590, China

[2] Jinjitan Coal Mine of Shaanxi Future Energy Company, Yulin 719099, China

[3] Department of Geology, Southern Illinois University, Carbondale, IL 62901, USA

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Introduction

Based on the deformation and failure characteristics of overlying strata, Liu (1981) suggested that overburden could be divided into three zones: a caved zone, a fractured zone, and a continuous deformation zone. The combined thickness of the caved and fractured zones is the maximum height of the interconnected fractures zone (IFZ). Predicting and field-testing the maximum height of this fractured zone are very important for mine safety and in improving mining under aquifers in fragile ecological areas (Kendorski 1993; Ma et al. 2010).

Many experiments have been conducted to quantify the primary factors influencing the development of the IFZ, and simulation analysis has been used to evaluate the height of the zones. Hu et al. (2008) presented a predictive equation of the maximum height of the IFZ based on in situ studies at the underground workings in a Huainan coal mine where the thickness of extracted coal seam ranged from 4.0 to 6.0 m. Zhang et al. (2014) quantified the primary factors involved in the development of the fractured zones in backfilled mines and used numerical simulations to evaluate the height of the zones and backfilling ratios. Palchik (2002) discussed the formation of the fractured zones in overburden due to longwall mining by studying the methane emissions from overburden, and also described the main features of the fractured zones, which consisted of a system of channels that connected with the mined-out space.

It is commonly accepted that the overall shape of the IFZ is saddle-like (Peng and Zhang 2007). The maximum height of the IFZ is less than 15 times the thickness of the excavated coal seam in Kailuan and other 18 mining areas in eastern China (Ma et al. 2008). Recently, some new explanations of roof water inrush mechanisms have been proposed, including the "four-zone" rock movement theory and "two-zone height" theory, which allowed the calculation and interpretation of the height and shape of the IFZ (Zhang and Kang 2005).

The Jurassic coalfields in western China are characterized by the thick coal seams with mechanically weak overburden. Although numerous studies have dealt with the formation and height of the IFZ, very few have focused on the particular conditions of the Jurassic coalfields (Wang 2013). The main objective of this research was to study the development, shape, and other characteristics of the IFZ under these special mining conditions of a thick coal seam and weak overburden to establish a relationship between the maximum height of the IFZ and the thickness of the extracted coal seam.

Site Description

The study focused on the Jinjitan coal mine in the western part of the Yushen coalfield, in Yulin, Shaanxi province, China (Fig. 1). The coal is of the Jurassic Yan'an formation. In general, the compressive strength of the overlying rock is less than 40 MPa, which classifies the overburden as being mechanically weak. Based on the drilling data, the compressive strength of the overlying rock was generally less than 20 MPa and the buried depth of the coal seam ranges from 213.95 to 256.67 m. The average thickness of the seam, which is near-horizontal, is 8.69 m. The main roof consists of mudstone, fine-grained sandstone, and siltstone. The Quaternary aquifer contains a large amount of water and has a complex hydraulic connection with the bedrock aquifers. Therefore, changes occurring within the aquifers directly affect mining safety. Moreover, different geological conditions may lead to different mechanisms of fracture formation above the mined coal seams.

Methodology

The coal seam depth and thickness as well as the mining techniques vary from one area of the mine to another. A layered mining method was employed in the studied area where the thickness of the extracted coal seam was about 5.5 m. The width of working face 101 was 300 m. Three boreholes were drilled from the ground surface down to the underground workings (Fig. 2). The horizontal distance from the boreholes to the side of working face was 800 m. Borehole 2 was drilled in the center of gob, and the distance between the neighboring boreholes was 135 m. Boreholes were drilled after the coal seam had been mined for 2 months, the overlying strata deformation has stabilized and, therefore, the height of the IFZ had reached its maximum value. To accurately explore the maximum height of the IFZ caused by coal seam excavation under the particular geological conditions, multiple methods were used: drill core analysis, drilling fluid loss measurement, borehole video monitoring, physical simulation, and numerical simulation.

Drill Core Analysis

The rock quality designation (RQD), i.e. the ratio between the length of drill core longer than 10 cm and drilling depth (expressed as a percentage), can reflect the degree of rock integrity. The higher the RQD value, the better the rock

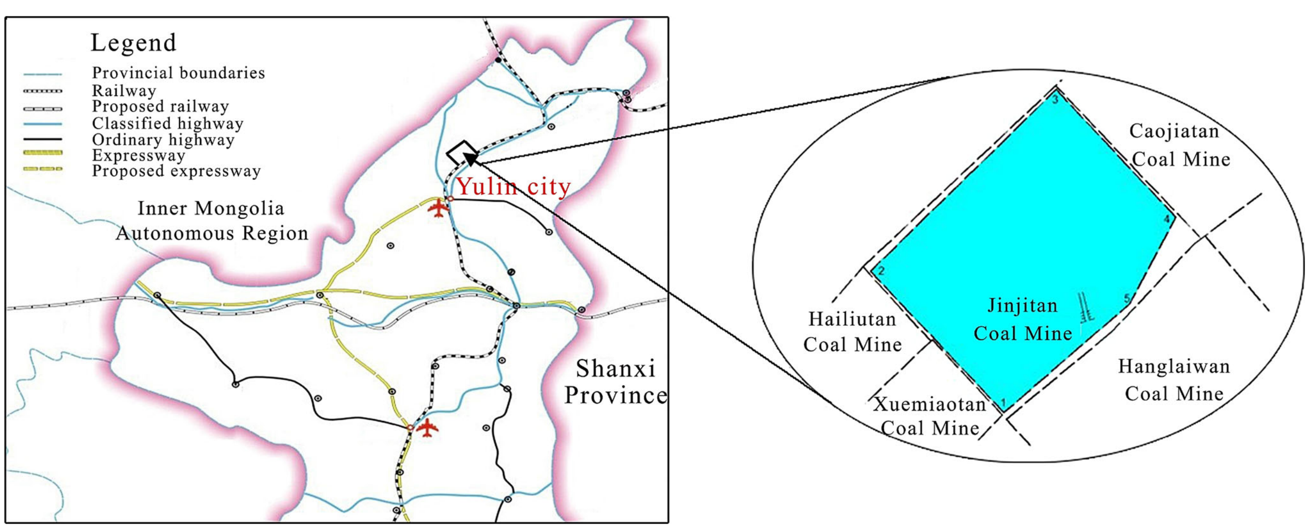


Fig. 1 Location of the study area

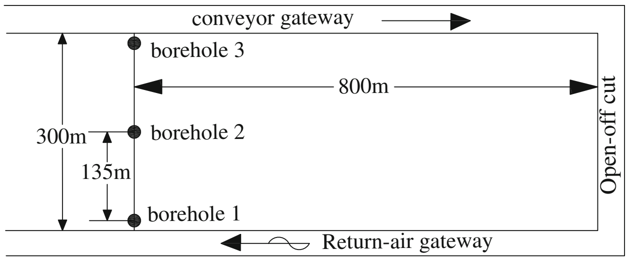


Fig. 2 Boreholes layout at working face 101

integrity. Hence, RQD is an important factor in the development of a fractured zone. The position where the fresh vertical fractures begin to appear and the value of RQD significantly drops is considered to be the top boundary of the IFZ.

Borehole Video Camera Observation

A JL-IDOI (B) video camera recording system produced by Wuhan Changsheng Engineering Testing Technology Development Co. Ltd., was used to videotape the boreholes and reveal fractures present in the borehole walls to confirm the top boundary of the IFZ.

Drilling Fluid Loss Measurement

The drilling fluid loss observation system was assigned according to MT/T865-2000 (China Coal Industry Bureau 2000). The fluid loss rate and fluid surface depth during drilling were measured by pumping drilling mud into the borehole. The position where the fluid surface depth started fluctuating before dropping steadily to the bottom of the borehole is considered the top boundary of the IFZ.

Similar Material Physical Simulation

Using materials similar to those in the field for coal mine simulations works well when studying the magnitude and patterns of overburden failure. The physical model should be geometrically, kinematically, and dynamically similar to the actual mine system (Ren et al. 2010; Wu et al. 2002).

The geological and mining conditions in the Jinjitan coal mine were simulated in this experiment. The model included 47 rock beds. The overall thickness was 320 m, including 50 m of coal seam floor and 12 m of coal seam. The working face advanced 320 m from left to right with an excavation step of 20 m. The scaled mine model was confined within 2000 mm × 200 mm × 1600 mm (length, width, and height) panel shelves. The mechanical parameters of the rock mass were obtained by testing the drill core materials. The tests helped choose the type and amount of materials for building the physical model (Table 1). The materials used in this experiment were: dry sand with particle size less than 1.5 mm, mica powder, and cement composed of calcium carbonate, plaster, and water. Mica fragments were used to simulate natural layering. Three models were built to simulate extracted coal seams that were 5.5, 8, and 12 m thick.

Numerical Simulation

Both fractures onset and final distribution can be explored with Fast Lagrangian Analysis of Continua (FLAC), which works by combining the failure mechanics methods of Mohr–Coulomb and Hoek–Brown and the fracture mechanics methods described by Griffith Theory and Linear Elastic Fracture Mechanics principles. With respect to fracture mechanics and the effects of coupled static and dynamic load, fracture propagation is fitted to always extend toward the direction of dynamic stress (Venticinque 2013). The FLAC overburden failure process analysis was used to simulate the formation of the IFZ caused by the excavation of working face 101. The mechanical parameters of the rock mass in this experiment were taken from the drill core analysis data. The formation thickness was 320 m, including a coal seam thickness of 12 m. The numerical model was 400 m × 200 m × 320 m (length, width, and height) and the mining advanced 400 m from

Table 1 Mechanical parameters and amount of rock used for the physical simulation

ID	Rock type	*H* (m)	*R* (MPa)	ρ (Kg/m^3)	μ	*K* (GPa)	*G* (GPa)	Material dosage (Kg)			
								a	b	c	d
13	Siltstone	5.50	21.7	2726	0.17	9.09	7.69	24.58	2.45	1.05	2.80
12	Argillaceous siltstone	5.04	19.2	2698	0.21	10.92	7.85	10.53	0.75	0.75	1.20
11	Coal seam	12	6.8	1350	0.29	0.98	0.48	36.57	2.85	1.22	4.06
10	Mudstone	4.55	18.73	2682	0.23	14.2	9.35	17.56	1.25	1.25	2.01

ID, order of rock stratum; *H*, the thickness of rock stratum; *R*, compressive strength; ρ, bulk density; μ, Poisson's ratio; *K*, bulk modulus; *G*, shear modulus

a, b, c and d are refer to the sand, calcium carbonate, plaster and water left to right with an excavation step of 20 m. The coal seam layer of the model was divided into 1 m^2 squares to improve calculation accuracy. Horizontal restraint was applied to the model in all directions, i.e. the horizontal displacement of boundary node was set to zero. The vertical stress at each point equaled the static pressure of the overlaying strata, whereas the lateral stress was determined using Poisson's ratio of rock strata. Three numerical models were built to simulate extracted coal seams that were 5.5, 8, and 12 m thick.

Results and Discussions

Drill Core and Video Monitoring Analysis

According to the drill core data (Supplemental Table 1), the depths of 211.50, 159.16, and 201.10 m were considered to be the top boundary of the IFZ in boreholes 1, 2, and 3, respectively. The maximum height of the IFZ was calculated as follows (China Coal Industry Bureau 2000):

$$H_L = H' - h_L - M \tag{1}$$

where H_L is the maximum height of the IFZ (m), H' is the vertical distance from the seam floor to the ground surface (m), h_L is the distance from the top boundary of the IFZ to the ground surface (m), and M is the thickness of the extracted coal seam (m).

The maximum height of the IFZ in boreholes 1, 2, and 3, as calculated with Eq. (1) and drill core analysis data, was 52.07, 101.39, and 60.60 m, respectively. Video camera images of borehole 2 are shown in Fig. 3. The first vertical fracture appeared at 159.70 m. The density of the vertical fractures increased with depth. Therefore, the depth of 159.70 m was considered the top boundary of the IFZ in borehole 2. The video camera images of boreholes 1 and 3 showed the top boundary of the IFZ at depths of 213.30 and 195.10 m, respectively.

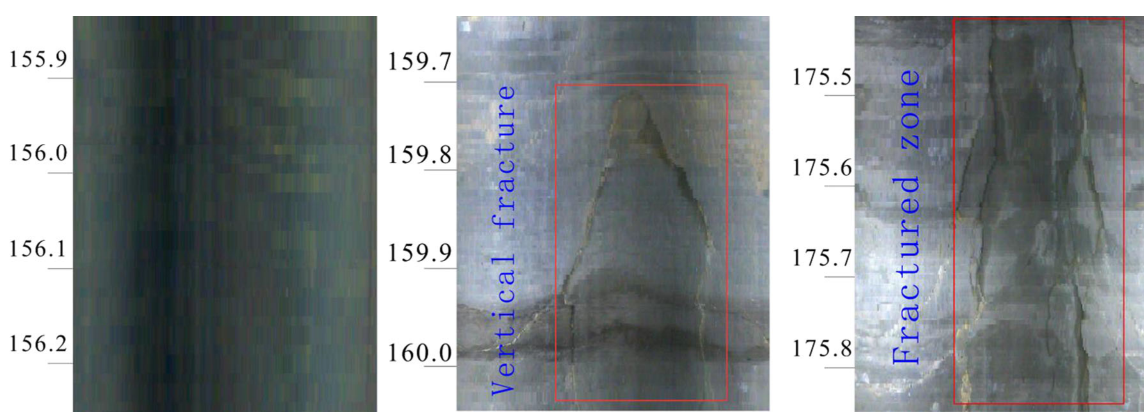
The maximum height of the IFZ in boreholes 1, 2, and 3, as calculated with Eq. (1) and video camera data, was 50.27, 100.85, and 66.60 m, respectively. Borehole 2, which was located in the center of the gob, had the maximum IFZ height.

Drilling Fluid Loss Measurement

The change in both drilling fluid loss rate and fluid surface depth in borehole 2 is shown in Fig. 4. The rate of fluid loss did not vary much (0.05–0.12 L/s) until the IFZ was encountered at a depth of 153.06 m when it increased to 0.47 L/s. Between 153.06 and 168.48 m, the rate of drilling fluid loss varied significantly and the depth of the fluid surface decreased gradually. At a depth of 209.36 m, the fluid was completely lost. Accordingly, the depth of 153.06 m was considered to be the top boundary of the IFZ in borehole 2. Similar measurements in boreholes 1 and 3 came up with the depths of 204.44 and 191.76 m, respectively, for the top boundary of the IFZ. The maximum height of the IFZ in boreholes 1, 2 and 3, as calculated with Eq. (1) and drilling fluid loss measurements data, was 59.13, 107.49, and 69.94 m, respectively.

Combining the Results of Drilling Core Analysis, Borehole Video Monitoring, and Drilling Fluid Loss Measurement for Working Face 101.

The height of the IFZ of the Jinjitan coal mine was measured by in situ studies (Supplemental Table 2). The greatest maximum height of the IFZ at working face 101 (107.49 m) was determined in borehole 2. As the thickness of the extracted coal seam was 5.5 m, the ratio between the maximum height of the IFZ and the thickness of extracted coal seam was 19.54. The maximum height of the IFZ for each borehole is shown on the geological profile of the mined sector (Fig. 5). As mentioned above, the greatest



(a) No fracture **(b)** First vertical fracture **(c)** Fractured zone

Fig. 3 Video camera images of borehole 2

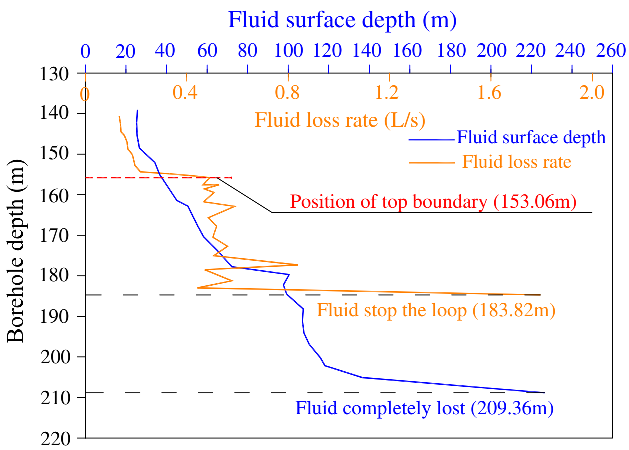


Fig. 4 The change of drilling fluid loss rate and fluid surface depth in borehole 2

value was determined in borehole 2, in the center of the working face. The IFZ was found not to be saddle-shaped but arch-shaped.

Similar Material Physical Modeling

Figure 6 shows the magnitude and spatial distribution of the overburden failure zone when the mining thickness was 5.5 m. The horizontal fractures began to form in the overburden strata after the simulated excavation advanced 20 m. By the time the working face advanced 40 m, the roof caved. When the working face advanced 120 m, the height of the caved zone had the maximum value of 27.2 m, which did not increase during further mining. However, the area of overburden failure continued growing until the mining advanced 300 m. At this point, the falling overlying strata filled the excavated coal seam and gradually gained supporting capacity. The height of the fractured zone reached its maximum value of 94 m. The ratio between the height of the IFZ and the thickness of the extracted coal seam was 17.09. The break angle at the open-off cut and terminal line was 59.7° and 60.9°, respectively. Table 2 lists the values of the maximum height of the IFZ for each model in this experiment.

Table 2 Physical modeling results

h(m)	δ(°)		H_1 (m)	H_2 (m)	H_2/h
	δ_1	σ_2			
5.5	59.7	60.9	27.2	94	17.09
8	60.8	59.1	38.2	152.4	19.05
12	61.2	57.6	61.3	192.6	16.05

h, mining thickness, δ_1, break angle at open-off cut, δ_2, break angle at terminal line, H_1, caved zone height, H_2, interconnected fractures zone height, H_2/h, ratio between fractures zone height and mining thickness

The overburden was subjected to continuous dynamic subsidence and formed the fractures during coal seam mining (Supplemental Fig. 1). With the working face advanced, the fractured zone gradually expanded both horizontally (mining direction) and vertically. The horizontal and vertical fractures formed gradually as the overlying strata were collapsing. The IFZ is roughly arch-shaped, which is consistent with the results of the in situ studies. Figure 7a shows the relationship between the height of the IFZ and the advancing working face for the three models. The height increased as the mining length increased. However, the upward trend of the fractured zone development become less and less pronounced after the mining advanced 280 m. And the height of the fractured zone did not increase after 300 m. Therefore, when the advancing distance was basically equal to the width of working face, the height of the IFZ reached a maximum.

Numerical Simulation

The initial diagram of numerical simulation is shown in Supplemental Fig. 2. In the process of simulation, the magnitude of overburden failure increased with the advancement of the working face. The peak support pressure of the coal seam increased during the advance of and followed the working face. The advancement of the gob caused a pronounced stress concentration. The peak support pressure was always located in the center of the gob. The height of the IFZ constantly increased as the advancing distance increased until the mining advanced about 300 m. In the center of the gob, the mining-induced fractures developed fully and the overburden failure zone reached a maximum. Hence, the overburden failure zone was roughly arch-shaped. According to the results of the numerical simulation, the maximum height of the IFZ was 103.7, 149.3, and 191.5 m for a mining thickness of 5.5, 8, and 12 m, respectively.

The height of the IFZ increased as the working face advanced (Fig. 7b). The upward development of the fractured zone slowed down gradually after the three models mining advanced 280 m. Moreover, the height of the IFZ reached a maximum when mining advanced about 300 m. Therefore, similar to the physical simulation, when the working face advanced a distance roughly equal to its width, the height of the fractured zone reached the maximum value.

A Comprehensive Assessment of the Interconnected Fractures Zone

Interconnected Fractures Zone Development

In situ measurements, physical simulation, and numerical simulation have revealed the formation and evolution of the IFZ. The excavation of the coal seam results in the

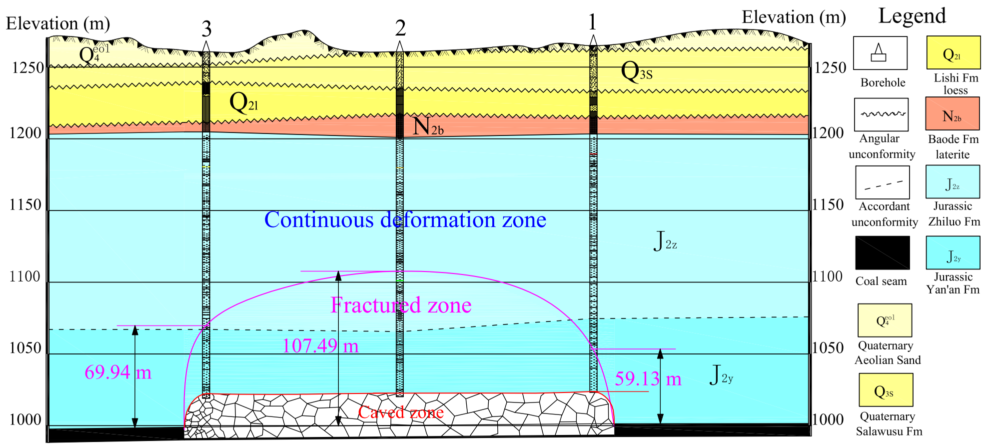


Fig. 5 Schematic observation section of interconne cted fractures zone

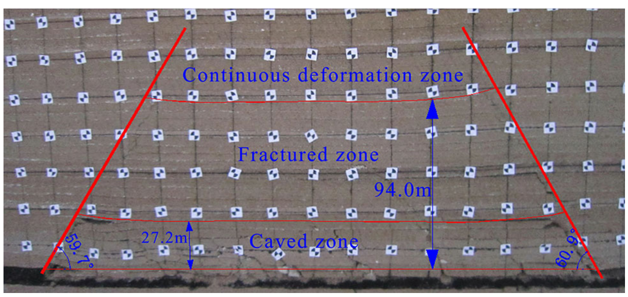


Fig. 6 The characteristics of overburden failure o n the model with mining thickness of 5.5 m

in situ stress being redistributed and thus causing fractures formation in the overburden failure zones. The tensile stress of coal seam roof reach a maximum above the center of the gob, where the vertical fractures fully developed. Hence, the IFZ in overlying strata is arch-shaped.

Fractured zone development can be divided into two stages according to the relationship between advancing distance and width of the working face. The first stage is when the advancing distance is less than the width of the working face (Supplemental Fig. 3a). The fractured zone gradually expand both horizontally (mining direction) and vertically. The second stage is when the advancing distance is equal to the width of the working face. At this point, the development of the fractured zone in the vertical direction reaches its maximum (Supplemental Fig. 3b). The fractured zone is no longer able to expand in the vertical direction, but only along the mining direction of the working face. The top boundary of the IFZ starts approximating a horizontal line.

Interconnected Fractures Zone Height

Generally, the height of the IFZ for weak strata (compressive strength <20 MPa) can be obtained by the empirical formula (SAWS and SACMS 2009):

$$H_f = \frac{100M}{-0.33M + 10.81} + 6.99 \quad (2)$$

where H_f is the maximum height of the IFZ (m); M is the thickness of the extracted coal seam (m).A comparison between the maximum heights of the IFZ from different coal mines with similar geological conditions, including the Jinjitan mine, is shown in Table 3. The difference between the in situ measured and calculated the height of the IFZ is large, especially when the mining thickness was less than 8 m. The relative difference can reach up to 55 %.

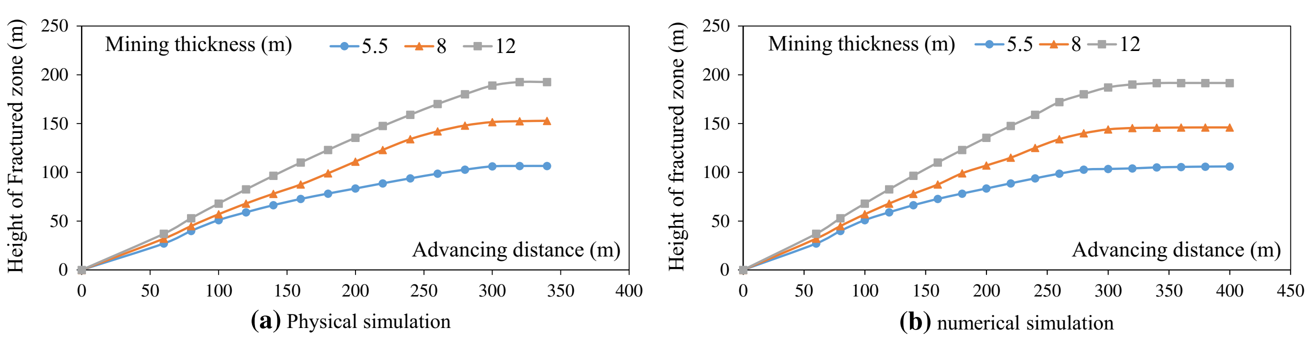


Fig. 7 Interconnected Fractures zone height versus advancing distance for the three models

Table 3 Statistics of interconnected fractures zone height of coal mines in western China

Mine name	*M* (m)	Face width (m)	Ming depth (m)	*H* (m)	Ratio (*H*/*M*)	H_1 (m)	$(H - H_1)/H$ (%)
Jinjitan	5.5	300	260	107.49	19.45	68.14	37
Zhuanlongwan	4.5	260	250	92.06	20.5	55.25	40
Yuyang	3.5	200	208	96.3	27.5	43.24	55
	3.5	200	188	84.8	24.2	43.24	49
Hanglaiwan	7.5	300	248	112.6	15.0	96.97	14
Shendong	2.47	310	130	62.89	25.5	31.70	49
	2.04	310	130	35.74	17.5	27.11	24
Chenjiagou	11.1	104	–	152.34	13.7	142.30	7

M, mining thickness; *H*, measured values of interconnected fractures zone height; H_1, calculated values by Eq. (2)

As mentioned above, the ratio between maximum height of the IFZ and thickness of the excavated coal seam is generally less than 15 times in the mining areas of eastern China. However, the ratio is 19 in Jinjitan coalfield and can be larger than 27 in some coal mines with similar conditions in western China (Yuyang coal mine). The reason for the wide range of ratio is mainly the different geological and mining conditions. Most coalfields in eastern China are of Carboniferous–Permian age with an overburden consisting mainly of sandstone and mudstone. The Jurassic coalfields in western China, which include Jinjitan, have weaker rocks with lower compressive strength (<20 MPa), such as siltstone, fine sandstone, and mudstone.

Relationship Between Interconnected Fractures Zone Height and Mining Thickness

Equation (2) is no longer applicable to predict the maximum height of the IFZ under the conditions of thick coal seams with weak overburden in western China because that the predicted height values are not confirmed by in situ measurements. The measured heights of the IFZ of coal mines are, therefore, considered reliable.

Based on the Table 3 data and the simulation results, a direct relationship between the height of the IFZ and the thickness of the excavated coal seam has been found by data fitting and regression analysis (Fig. 8). The best fit is a logarithmic one with the expression $H = 78.38 \ln(M) - 17.10$ ($R^2 = 0.9199$), where *H* is the height of the IFZ and *M* is the mining thickness. The standard deviation is 6.15.

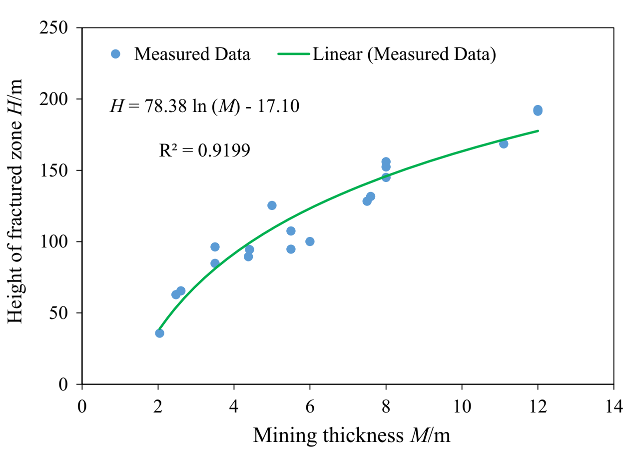


Fig. 8 Interconnected fractures zone height (H) versus mining thickness (M)

Conclusions

An IFZ develops above a coal seam during mining is critical for aquifer protection, mining safety, and the environment. Different approaches, including field observations and measurements (drill core analysis, drilling fluid loss and fluid surface depth recording, and borehole video monitoring) as well as physical and numerical modeling were used in this study in order to understand the formation and evolution of the fractured zone and predict its maximum height and shape in particular geological conditions. The shape and height of the IFZ in coal mines from western China, such as the studied Jinjitan mine, are greatly different from that observed in other coalfields from eastern China because of the distinctive mining and geological conditions, such as the presence of thick coal seams with weak overburden. The IFZ in the studied mine is arch-shaped.

In the studied Jinjitan mine, the maximum height of the IFZ is 19 times larger than the thickness of the excavated coal seam. The height/thickness ratio is up to 27 in other mines from western China and down to 15 in mines from eastern China, where the overburden is stronger mechanically. A logarithmic direct relationship between the IFZ height and mining thickness was found by using data from various mines located in western China. The results have the potential to predict the movement and deformation of overlying strata and thus to reduce the field testing workload.

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