The height of fractured zones caused by strip Wongawilli mining in a shallow buried coal seam underlying a hard roof

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The exact determination of the height of fractured zones in overlying sedimentary strata is important in coal mining performed underneath water bodies and for a safe production. To prevent the inrush of water and sand during strip Wongawilli mining, we studied the height of fractured zones in shallow coal seams underlying a hard roof. Based on the geological setting and mining conditions at the Zhaowu coal mine, the height of the fractured zones in overlying strata was measured using the loss of drilling fluid method and by numerical simulation. The height of the fractured zones and its development characteristics during strip Wongawilli mining in shallow buried coal seam underlying a hard roof were obtained. The results demonstrate that the disturbance of the overlying strata during strip Wongawilli mining is reduced and the height of the fractured zones is smaller relative to that occurring during critical mining. The height of fractured zones increases with mining width in a stepped-finger line, and it manifests stable in each stage, but turns into the next stage by sudden increase. The existing method of calculation and the traditional empirical formula to obtain the height of the fractured zones are not suitable for strip Wongawilli mining. The calculation should be based on the size of mining.

Keywords: Fractured zone, hard roof, loses of drilling fluid, strip Wongawilli mining, subcritical mining.

THE height of fractured zones, including the caving zone, associated with overburden failure is an important index of prediction and prevention of the inrush of roof water during mining underneath a body of water[1–3]. Buildings, water, railways and main well lane of coal pillar and mining regulations (referred to as the ‘three under regulation’), based on general mining procedures and fully mechanized face mining were established in the 1990s (ref. 4). With the popularity of top-caving mining and fully mechanized mining technologies of coal seams, the increasing speed of advancing working face and mining height increased significantly; so did the height of fractured zones[5,6]. Researchers noticed the limitations of the formula used for calculating the height of fractured zones under the ‘three under regulation’. They undertook studies on the condition of large-scale mining of thin and shallow-depth bedrock by a fully mechanized top-caving procedure[7–13], obtaining useful conclusions. With increasing mining depth, the procedures of strip mining the working face, room and pillar mining, Wongawilli mining and long wall mining in the direction of tilt can become subcritical[14,15]. However, there are few relevant studies on the height of fractured zones under subcritical mining. Therefore, studying the height of fractured zones during strip Wongawilli mining of shallow seams underlying a hard roof will improve the basic theory of the method and help guide coal production.

The Zhaowu coal mine no. 15 seam is selected for research purposes. We studied the height of fractured zones during strip Wongawilli mining of a shallow seam under a hard roof using theoretical analyses, numerical simulation and field measurement. This communication presents a new formula to calculate the height of the fractured zones and achieves significant results.

The strip Wongawilli is a strip pillar mining technique combining a strip pillar mining layout with a Wongawilli high-efficient mining technology[16,17]. It is a new technology for mining under buildings (structures) that can fully utilize the advantages of both methods to control surface subsidence. The new technology can overcome the disadvantages such as frequent face move, and low mining efficiency in strip pillar mining, and poor ventilation condition and long-term stability problems of coal pillars. Strip Wongawilli mining can safely and efficiently extract coal located under buildings (structures). Based on general geological settings and mining conditions, the strip Wongawilli mining method is divided into five types which are: (1) single entry and single wing, (2) double entry and single wing, (3) single entry and double wing, (4) double entry and double wing, (5) a hybrid of single entry and single wing.

Production at the Zhaowu coal mine on the no. 3 and no. 15 coal seams reaches 900 kt/a. The elevation of the no. 15 coal seam is +1385 m to +1060 m. The mine uses the strip Wongawilli mining technology to recover the boundary coal of the no. 15 seam and implements the fully caving method to manage the roof.

The no. 3 coal seam forms the lower section of the Shanxi Formation. It is a 4.95 m-thick simple structure coal seam devoid of clip stone. The roof of the coal seam is composed of sandy mudstone and the floor is defined by mudstones. The no. 3 coal seam mine field was destroyed by erosion or extracted by mining. The no. 15 coal seam is located at the bottom of the Taiyuan Formation, commonly known as ‘smelly coal’. It is a simple structure situated 105.86 m from the no. 3 coal seam, presenting a thickness ranging from 2.32 to 5.38 m, averaging 4.19 m and containing 0–2 layers of banded mudstone. The floor of the coal seam is formed by mudstone and sandy mudstone or aluminum-rich mudstone. The

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roof of the coal seam is constituted of sandy mudstone with a mudstone pseudo-roof, which belongs to a hard roof.

The Zhaowu coal mine no. 15 mining area is located at the northwestward end of the mine and uses a strip Wongawilli mining layout. The upper part of the no. 3 coal seam is eroded. The length of the branch entry is 80–140 m, with a distance of 15.5–23 m at the centre of two adjacent openings. The conditions of the coal seam roof and floor necessitate the usage of a single entry and double wing Wongawilli mining method with a 3.3 m-wide room, leaving a space of 0.5–1 m of isolated coal wall between adjacent mining rooms. The width of the mining area is 26 m. Every 1–5 branch entries is mined forming 10 m of a protective coal pillar. The roadway layout and mining technology are as shown in Figure 1.

The mining process uses the branch entry proceeding from the inside to outside, left to right with double wings cutting the coal seams. The room is 3.3 m wide and 11 m deep, with an inclination angle of 40–45°. The height of the mining area varies with the thickness of the coal seam, which can reach up to 5 m. A continuous miner (type: EML340) continuously cuts the coal seam and the shuttle cart transports the coal. The order of the wings dug from the branch entry and the equipment used are shown in Figure 2.

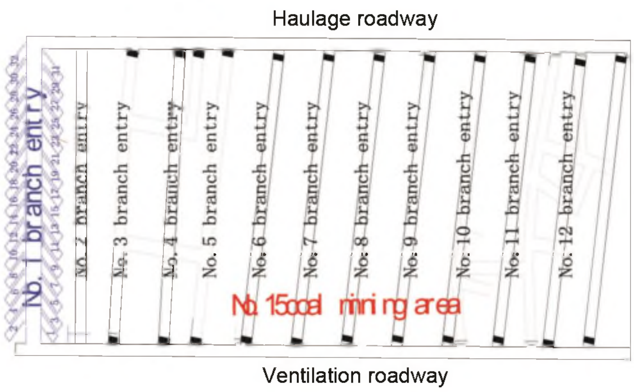

Figure 1. Roadway layout and mining plan.

Surface losses of drilling fluids, change in drill water level method and various anomalous phenomena occurring during drilling are all used to accurately measure and analyse the height of fractured zones. The latter is related to rock properties and mining height[18]. The caving-to-height ratio increases with the degree of hardness in the overlying rocks. In general, the caving height ratio of soft rocks is 9–12, 12–18 for medium hard rocks and 18–28 for hard rocks.

The surface elevation of the Zhaowu coal mine is +1175 to +1220 m and underground exploitation occurs at +1120 to +1130 m, with a relative drop-off of 55–90 m. The field data reveals that the fractured zones do not break through the roof reaching the surface. The height of fractured zone measurement is conducted by surface drilling taking into account the geological settings and mining conditions and the Wongawilli mining method used at the Zhaowu coal mine. The drilling method is shown in Figure 3.

According to the 'loss of drilling fluid test method for measuring the height of fractured zones' (MT/T865-2000), the depth of casing sealing section is set at 5 m for measurement of lost drilling fluids incorporating the thickness of loess layer at the surface of Zhaowu coal mine. The Zhaowu mine coal seams are nearly horizontal. One side of the branch entry for the fractured zones height is defined by two boreholes from the surface. The recorded procedures and results of the drilling are given in Table 1 and the loss of drilling fluids relative to the depth of the drilling curve illustrated in Figure 4.

Table 1 reveals a sharp decline in the water return appearing at 26 m depth for no. 1 borehole which is the height of fractured zones. For no. 2 borehole, the decline occurred at 31 m. Figure 4 shows that the no. 1 borehole fluid leakage was about 20 l/s at a depth varying from 15 to 22 m. The leakage began to increase at 23 m and then jumped to 171 l/s. The overall leakage trend for no. 2 borehole is similar to no. 1, but it varies with a lag of

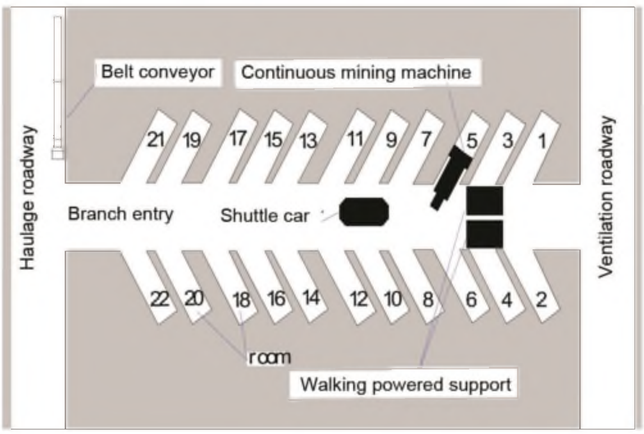

Figure 2. Roadway mining sequence and equipment layout.

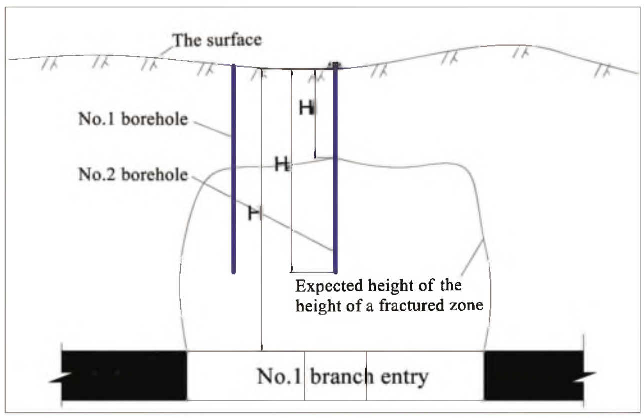

Figure 3. Borehole layout plan.

Table 1. Recorded procedures and results of the drilling

Borehole	Design depth/m	Depth/m	Leakage/ L min^{-1}	Conditions in the borehole	Note
1	40	5–22	15–27	–	No. 1 borehole appeared a sharp decline in water return in 26 m.
		23–26	51–88		
		26–33.4	163–178	Drop blocks appear in the borehole	Drilling to 33.4 m, stuck drill, stop construction
2	40	5–26	12–25	–	No. 2 borehole appeared a sharp decline in water return in 31 m.
		27–31	57–92	Drop blocks appear in the borehole	
		31–40	158–179	Water injection did not see the return of water	35 m, very little return water

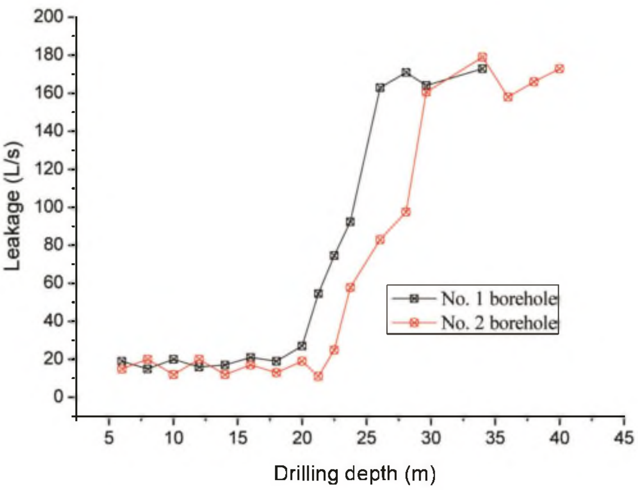

Figure 4. Change curves of leakage loss.

5–6 m due to the relative height difference from drilling location in the surface to the coal seam. From the coal mine surface and underground maps, the depth of the coal seam relative to the collars of no. 1 and no. 2 boreholes are 55 and 61 m respectively, thus showing a 6 m relative difference in elevation.

After measuring the loss of drilling fluids, combined with the observed results of the borehole water level, core drilling, stuck drill, induced draft and so on, we found that the vertex position of fractured zones was located at a depth of 55–61 m. The equation of height of the fractured zone is expressed as

$$H_d = H - H_1 + W, \quad (1)$$

where H_d is the maximum height of the fractured zone (m), H the height of the roof (m), H_1 the distance from the surface to the top of the fractured zone (m) and W defines the value for fractured zone strata compression in the drilling measurement (m). From the above formula, the calculated heights of the fractured zones for no. 1 and no. 2 borehole are: no. 1 borehole: $H_{d1} = H - H_1 + W = 55-(23-26) + 2 \times 4.19 = 29.8$ to 32.8 m, average value: 31.3 m; No. 2 borehole: $H_{d2} = H - H_1 + W = 61-(27-31) + 2 \times 4.19 = 30.8$ to 34.8 m, average value: 32.8 m. Therefore, $H_d = (H_{d1} + H_{d2})/2 = (31.3 + 32.8)/2 = 32.05$ m.

The thickness of the coal seam is 4.19 m under the collar locations of the boreholes, thus $W = 2 \times 4.19 = 8.38$ m. Combining the average value of two boreholes, the average height of the fractured zones is 32.05 m.

We investigated the relation between fractured zones and mining width during the strip Wongawilli mining. According to the contradicting map of the Zhaowu coal mine no. 15 mining area, the relative height difference of the no. 1 branch roadway is 60 m. Commonly, the width-to-depth ratio (D/H) during subcritical mining is usually <1.2 to 1.4 (ref. 14). Therefore, we infer the deficient mining conditions occurred when the width of mining is <72 m.

Previous studies analysed the overburden rock fracture using the unit tensile failure method through the Universal Distinct Element Code numerical simulation software[19,20]. The physical model is established from a synthetic column map, rock mass strength data obtained from the geological mechanics evaluation and, experiments conducted on rock failure. Sedimentary strata possessing similar mechanical properties are merged to simplify the model. The final model contains 8 strata. The physical and mechanical parameters of the strata are presented in Table 2. Three branch entries undergoing strip Wongawilli mining (140 m in length × 60 m in height) are chosen for our simulation.

The horizontal direction model boundary is a single constraint boundary: $u = 0$, $v \neq 0$ (u represents the displacement along the X direction, v is the displacement along the Y direction). For the vertical direction model boundary; the lower boundary is a fully constrained boundary ($u = v = 0$) with the upper boundary being a free boundary.

The burial depth of the coal bed is 60 m. When the mining width reaches 40 m, the fractured zones come to the surface. The maximum value of the ratio of the height of fractured zones to the height of mining is 14.32, as shown in Figure 5 *a*.

Figure 5 shows the overburden failure related to the height of fractured zone getting larger when the mining width is increased. The enlargement is sporadic since there are stages of stability followed by a jumping stage.

A plastic zone initially appeared in the side wall of the branch entry and the damage depth is about 2 m

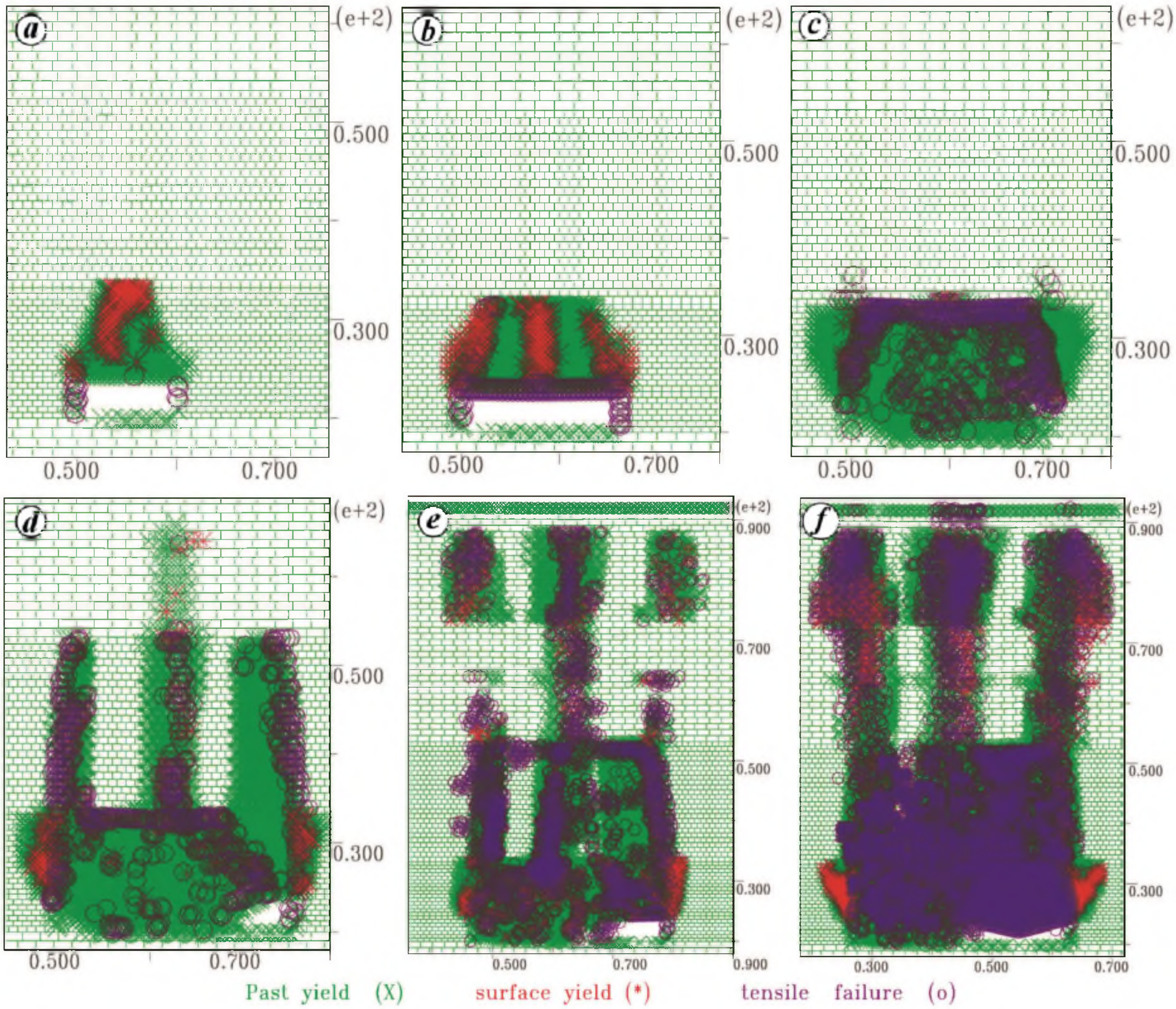

Figure 5. Plastic zones occurring during numerical simulation. ***a***, 6 m mining width; ***b***, 12 m mining width; ***c***, 20 m mining width; ***d***, 26 m mining width; ***e***, 32 m mining width; ***f***, 40 m mining width. Note: the *X* axis represent the buried depth; the *Y* axis represents the mining width.

Table 2. Physical and mechanic parameters of the chosen eight sedimentary strata

Lithology	Internal friction angle φ(°)	Bulk modulus (GPa)	Shear modulus (GPa)	*C* (MPa)	Tensile strength (MPa)	Bulk density ρ(kg/m^3)
Topsoil	15	1.53	1.19	0.02	0.2	1860
Fine sandstone	46	20.1	16.92	5.4	1.8	2500
Sandy mudstone	27	4.6	2.86	4.0	3.3	2300
Mudstone	22	3.8	2.56	2.5	1.5	2540
Sandy mudstone	27	4.6	2.86	4.0	1.8	1800
Coal	21	2.24	2.09	1.8	1.1	1410
Mudstone	23	4.8	2.56	2.5	1.5	2220
Sandy mudstone	27	4.6	2.86	4.0	1.8	2300

(Figure 5 *a*). The plastic zone height increased to 12 m when the mining width augmented from 4 m to 20 m (Figure 5 *b*). The height of the plastic zone displayed almost no change when the mining width progressed from 12 m to 20 m, but the build-up of the plastic zone still took place. At the same time, a small plastic zone appeared at the top of the roadway side wall (Figurer 5 *c*). It further expanded with increase of mining width (Figure 5 *d*). When the latter reached 32 m, the fractured zones located at the top of the mining boundary went almost completely through the roof. The height of fractured zones located at the top of the central goaf was 54.6 m (Figure 5 *e*). When mining width attained 40 m, the fractured zones located at the top of the mining boundary went completely through and the height of fractured zones located in the top of the central goaf jumped from

55 to 60 m. The amount of fractured zones augmented with increase of mining width until it reached the top of the goaf (Figure 5 *f*).

Figure 6 illustrates, under the condition of subcritical mining, step changes in the height of the fractured zones related to the mining width. This is explained by the layered structure of the overburden on top of the goaf. When the overburden reaches its tensile limit, the roof breaks or is suddenly destroyed, and the height of fractured zones manifests stable in each stage but turns into the next stage by sudden increase.

In stage 1, the mining width <10 m, the height of fractured zones is 2.48 to 2.73 m, the ratio of height of the fractured zones to the mining height <1. The mining condition is at the subcritical mining stage.

In stage 2, the mining width is 10–20 m, the height of fractured zones is 11.38–14.61 m, the ratio of height of the fractured zones to mining height is ~3.

In stage 3, the mining width is 20–32 m, the height of fractured zones is ~30 m, the ratio of the height of fractured zones to the mining height is ~7.5.

In stage 4, the mining width is 32–40 m, the height of fractured zones is ~55 m, the ratio of the height of fractured zones to the mining height is 13.1. During stage 4, when the mining width is >40 m, when mined to 40 m the fractured zones would break through the roof, reaching the surface; the maximum ratio of the height of fractured zones to mining height is 14.32.

With increasing mining width, the fractured zones keep enlarging. When $D/H = 1.2$–1.4, the mining condition changed from a non-suitable mining stage to a suitable and full mining stage. The height of fractured zones to the mining height ratio increased and remained stable, corresponding to the value provided by the equation for fractured zone and to the empirical value; exceeding 18–28 times the value of the 'three under regulation'. Origin is the current popular data analysis software, developed by the United States Origin Lab company. Origin is used to simulate the height of fractured zones in different mining widths in subcritical mining. Therefore

$$y = A_1 + \frac{A_2 - A_1}{1 + 10^{(\log x_0 - x)p}} = 1.2321 + \frac{61.4409}{1 + 10^{0.0742(25.436 - x)}}, \tag{2}$$

where y provides the height of the fractured zones (m), x gives the mining width (m), A_1, A_2 and p are constants.

The no. 15 coal seam is gently dipping and the roof strata are mostly limestone. The empirical formula obtained from mine regulations during 'three under regulation' is used to calculate the height of the fractured zone. Thus

$$H_{Ii} = \frac{100\sum M}{1.2\sum M + 2.0} \pm 8.9 = 65.08 \text{ to } 70.42 \text{ m}, \tag{3}$$

$$H_{Ii} = 30\sqrt{\sum M} + 10 = 65.72 \text{ to } 75.04 \text{ m}, \tag{4}$$

where H_{Ii} is the height of the fractured zones (including the caving zone) (m), $\sum M$ gives the accumulative thickness of the mined seam (m) (e.g. 3.45–4.70 m).

The calculation results show that the maximum height of fractured zones for the no. 15 coal seam is 75.04 m.

During the process of strip Wongawilli mining, we obtained various data in hard rock fractured zone associated with rules of 'three under regulation', numerical simulation, matching equation and drilling fluid method. The results are presented in Table 3.

The calculated values using the empirical formula are different from the results obtained during field testing (Table 3). The former values are 2.34 times higher than the field values. The value acquired through the matching formula is close to the result of the field tests, with an error <5%. The calculation of the height of fractured zones during subcritical mining produces a result different from that of the traditional empirical formula. The numerical simulation and matching equation can provide reliable reference data for engineering, but some errors attributed to the selection of parameters used in the numerical simulation can occur. Therefore, the measured data should always be associated with the results of numerical simulation during the engineering work surveying the height of fractured zone; this is to ensure the safety and reliability of the mining procedures.

(1) By measuring the loss of drilling fluids from surface boreholes during strip Wongawilli mining in the Zhaowu coal mine, we obtained a maximum height of fractured zone of 32.05 m with a ratio of the height of the fractured zones to the mining height of 7.65. The latter is 18–28 times lower than the ratio given by empirical equation or by traditional experience.

(2) Under strip Wongawilli mining, the height of fractured zones increases in parallel with mining width, but

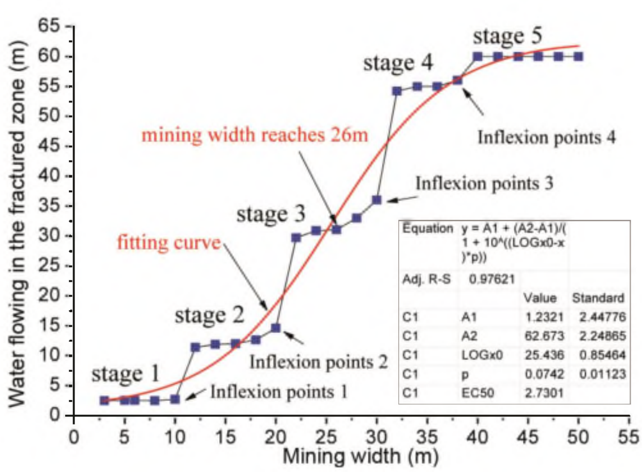

Figure 6. Prediction curve of the height of the fractured zones for different mining widths.

Table 3. Analysis of the height of the fractured zone

Types		Coal seam thickness/m	Calculated (prospecting) value/m	Final value/ m	Ratio of the height of fractured zones to mining height	Remarks
Empirical data	1	4.19	65.08–70.42	75.04	17.91	Fractured zone height ratio of the hard rock is 18–28 (ref. 16)
	2		65.72–75.04			
Numerical simulation		4.19	30.7–31.8	31.4	7.5	The actual value should be considered in the simulation based on the safety factor of 1 or higher.
Matching formula		4.19	33.4	33.4	7.97	–
Measured data	No. 1 borehole	4.19	29.8–33.8 (31.3)	32.05	7.65	–
	No. 2 borehole		30.8–35.8 (32.8)			

the process manifests stable phases and sudden jumps. When the width of mining increases and the sedimentary strata reach their ultimate tensile failure, the height of fractured zones does not augment until attaining a certain value. The height data of fractured zones in different mining widths is be matched by the Origin software, and this provides the relationship between the height of fractured zones and mining width under subcritical mining conditions.

(3) The disturbance on overlying strata in strip Wongawilli mining with hard roof in low buried depth decreases significantly, and the overlying strata is prone to keep stable. The overburden failure decreases remarkably compared to critical mining. The empirical equation related to 'three under regulation' needs to consider the adequacy of mining.

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